Climate Change 2014
Mitigation of Climate Change

Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

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Foreword, Preface, Dedication and In Memoriam

Foreword

Climate Change 2014: Mitigation of Climate Change is the third part of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC)—Climate Change 2013/2014—and was prepared by its Working Group III. The volume provides a comprehensive and transparent assessment of relevant options for mitigating climate change through limiting or preventing greenhouse gas (GHG) emissions, as well as activities that reduce their concentrations in the atmosphere.

This report highlights that despite a growing number of mitigation policies, GHG emission growth has accelerated over the last decade. The evidence from hundreds of new mitigation scenarios suggests that stabilizing temperature increase within the 21st century requires a fundamental departure from business-as-usual. At the same time, it shows that a variety of emission pathways exists where the temperature increase can be limited to below 2 °C relative to pre-industrial level. But this goal is associated with considerable technological, economic and institutional challenges. A delay in mitigation efforts or the limited availability of low carbon technologies further increases these challenges. Less ambitious mitigation goals such as 2.5 °C or 3 °C involve similar challenges, but on a slower timescale. Complementing these insights, the report provides a comprehensive assessment of the technical and behavioural mitigation options available in the energy, transport, buildings, industry and land-use sectors and evaluates policy options across governance levels from the local to the international scale.

The findings in this report have considerably enhanced our understanding of the range of mitigation pathways available and their underlying technological, economic and institutional requirements. The timing of this report is thus critical, as it can provide crucial information for the negotiators responsible for concluding a new agreement under the United Nations Framework Convention on Climate Change in 2015. The report therefore demands the urgent attention of both policymakers and the general public.

As an intergovernmental body jointly established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), the IPCC has successfully provided policymakers with the most authoritative and objective scientific and technical assessments, which are clearly policy relevant without being policy prescriptive. Beginning in 1990, this series of IPCC Assessment Reports, Special Reports, Technical Papers, Methodology Reports and other products have become standard works of reference.

This Working Group III assessment was made possible thanks to the commitment and dedication of many hundreds of experts, representing a wide range of regions and scientific disciplines. WMO and UNEP are proud that so many of the experts belong to their communities and networks.

We express our deep gratitude to all authors, review editors and expert reviewers for devoting their knowledge, expertise and time. We would like to thank the staff of the Working Group III Technical Support Unit and the IPCC Secretariat for their dedication.

We are also thankful to the governments that supported their scientists' participation in developing this report and that contributed to the IPCC Trust Fund to provide for the essential participation of experts from developing countries and countries with economies in transition.

We would like to express our appreciation to the government of Italy for hosting the scoping meeting for the IPCC's Fifth Assessment Report, to the governments of Republic of Korea, New Zealand and Ethiopia as well as the University of Vigo and the Economics for Energy Research Centre in Spain for hosting drafting sessions of the Working Group III contribution and to the government of Germany for hosting the Twelfth Session of Working Group III in Berlin for approval of the Working Group III Report. In addition, we would like to thank the governments of India, Peru, Ghana, the United States and Germany for hosting the AR5 Expert meetings in Calcutta, Lima, Accra, Washington D.C., and Potsdam, respectively. The generous financial support by the government of Germany, and the logistical support by the Potsdam Institute for Climate Impact Research (Germany), enabled the effective operation of the Working Group III Technical Support Unit. This is gratefully acknowledged.

We would particularly like to thank Dr. Rajendra Pachauri, Chairman of the IPCC, for his direction and guidance of the IPCC and we express our deep gratitude to Professor Ottmar Edenhofer, Dr. Ramon Pichs-Madruga, and Dr. Youba Sokona, the Co-Chairs of Working Group III for their tireless leadership throughout the development and production of this report.

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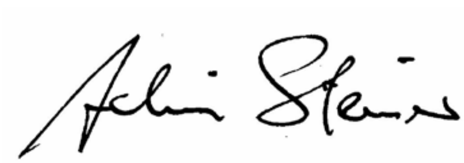

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Preface

The Working Group III contribution to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) provides a comprehensive and transparent assessment of the scientific literature on climate change mitigation. It builds upon the Working Group III contribution to the IPCC's Fourth Assessment Report (AR4) in 2007, the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) in 2011 and previous reports and incorporates subsequent new findings and research. The report assesses mitigation options at different levels of governance and in different economic sectors. It evaluates the societal implications of different mitigation policies, but does not recommend any particular option for mitigation.

Approach to the assessment

The Working Group III contribution to the AR5 explores the solution space of climate change mitigation drawing on experience and expectations for the future. This exploration is based on a comprehensive and transparent assessment of the scientific, technical, and socio-economic literature on the mitigation of climate change.

The intent of the report is to facilitate an integrated and inclusive deliberation of alternative climate policy goals and the different possible means to achieve them (e.g., technologies, policies, institutional settings). It does so through informing the policymakers and general public about the practical implications of alternative policy options, i.e., their associated costs and benefits, risks and trade-offs.

During the AR5 cycle, the role of the Working Group III scientists was akin to that of a cartographer: they mapped out different pathways within the solution space and assessed potential practical consequences and trade-offs; at the same time, they clearly marked implicit value assumptions and uncertainties. Consequently, this report may now be used by policymakers like a map for navigating the widely unknown territory of climate policy. Instead of providing recommendations for how to solve the complex policy problems, the report offers relevant information that enables policymakers to assess alternative mitigation options.

There are four major pillars to this cartography exercise:

Exploration of alternative climate policy goals: The report lays out the technological, economic and institutional requirements for stabilizing global mean temperature increases at different levels. It informs decision makers about the costs and benefits, risks and opportunities of these, acknowledging the fact that often more than one path can lead to a given policy goal.

Transparency over value judgments: The decision which mitigation path to take is influenced by a series of sometimes disputed normative choices which relate to the long-term stabilization goal itself, the weighing of other social priorities and the policies for achieving the goal. Facts are often inextricably interlinked with values and there is no purely scientific resolution of value dissent. What an assessment can do to support a rational public debate about value conflicts is to make implicit value judgments and ethical viewpoints as transparent as possible. Moreover, controversial policy goals and related ethical standpoints should be discussed in the context of the required means to reach these goals, in particular their possible consequences and side-effects. The potential for adverse side-effects of mitigation actions therefore requires an iterative assessment approach.

Multiple objectives in the context of sustainable development and equity: A comprehensive exploration of the solution space in the field of climate change mitigation recognizes that mitigation itself will only be one objective among others for decision makers. Decision makers may be interested in pursuing a broader concept of well-being. This broader concept also involves the sharing of limited resources within and across countries as well as across generations. Climate change mitigation is discussed here as a multi-objective problem embedded in a broader sustainable development and equity context.

Risk management: Climate change mitigation can be framed as a risk management exercise. It may provide large opportunities to humankind, but will also be associated with risks and uncertainties. Some of those may be of a fundamental nature and cannot be easily reduced or managed. It is therefore a basic requirement for a scientific assessment to communicate these uncertainties, wherever possible, both in their quantitative and qualitative dimension.

Scope of the report

During the process of scoping and approving the outline of the Working Group III contribution to the AR5, the IPCC focused on those aspects of the current understanding of the science of climate change mitigation that were judged to be most relevant to policymakers.

Working Group III included an extended framing section to provide full transparency over the concepts and methods used throughout the report, highlighting their underlying value judgments. This includes an improved treatment of risks and risk perception, uncertainties, ethical questions as well as sustainable development.

The exploration of the solution space for climate change mitigation starts from a new set of baseline and mitigation scenarios. The entire scenario set for the first time provides fully consistent information on radiative forcing and temperature in broad agreement with the information provided in the Working Group I contribution to the AR5. The United Nations Framework Convention on Climate Change requested the IPCC to provide relevant scientific evidence for reviewing the 2 °C goal as well as a potential 1.5 °C goal. Compared to the AR4 the report therefore assesses a large number of low stabilization scenarios broadly consistent with the 2 °C goal. It includes policy scenarios that investigate the impacts of delayed and fragmented international mitigation efforts and of restricted mitigation technologies portfolios on achieving specific mitigation goals and associated costs.

The WGIII contribution to the AR5 features several new elements. A full chapter is devoted to human settlements and infrastructures. Governance structures for the design of mitigation policies are discussed on the global, regional, national and sub-national level. The report closes with a novel chapter about investment needs and finance.

Structure of the report

The Working Group III contribution to the Fifth Assessment report is comprised of four parts:

Part I: Introduction (Chapter 1)
Part II: Framing Issues (Chapters 2–4)
Part III: Pathways for Mitigating Climate Change (Chapters 5–12)
Part IV: Assessment of Policies, Institutions and Finance (Chapters 13–16)

Part I provides an introduction to the Working Group III contribution and sets the stage for the subsequent chapters. It describes the 'Lessons learned since AR4' and the 'New challenges for AR5'. It gives a brief overview of 'Historical, current and future trends' regarding GHG emissions and discusses the issues involved in climate change response policies including the ultimate objective of the UNFCCC (Article 2) and the human dimensions of climate change (including sustainable development).

Part II deals with framing issues that provide transparency over methodological foundations and underlying concepts including the relevant value judgments for the detailed assessment of climate change mitigation policies and measures in the subsequent parts. Each chapter addresses key overarching issues (Chapter 2: Integrated Risk and Uncertainty Assessment of Climate Change Response Policies; Chapter 3: Social, Economic and Ethical Concepts and Methods; Chapter 4: Sustainable Development and Equity) and acts as a reference point for subsequent chapters.

Part III provides an integrated assessment of possible mitigation pathways and the respective sectoral contributions and implications. It combines cross-sectoral and sectoral information on long-term mitigation pathways and short- to mid-term mitigation options in major economic sectors. Chapter 5 (Drivers, Trends and Mitigation) provides the context for the subsequent chapters by outlining global trends in stocks and flows of greenhouse gases (GHGs) and short-lived climate pollutants by means of different accounting methods that provide complementary perspectives on the past. It also discusses emissions drivers, which informs the assessment of how GHG emissions have historically developed. Chapter 6 (Assessing Transformation Pathways) analyses 1200 new scenarios generated by 31 modelling teams around the world to explore the economic, technological and institutional prerequisites and implications of mitigation pathways with different levels of ambition. The sectoral chapters (Chapter 7–11) and Chapter 12 (Human Settlements, Infrastructure and Spatial Planning) provide information on the different mitigation options across energy systems, transport, buildings, industry, agriculture, forestry and other land use as well as options specific to human settlements and infrastructure, including the possible co-benefits, adverse side-effects and costs that may be associated with each of these options. Pathways described in Chapter 6 are discussed in a sector-specific context.

Part IV assesses policies across governance scales. Beginning with international cooperation (Chapter 13), it proceeds to the regional (Chapter 14), national and sub-national levels Chapter 15) before concluding with a chapter that assesses cross-cutting investment and financing issues (Chapter 16). It reviews experience with climate change mitigation policies — both the policies themselves and the interactions among policies across sectors and scales — to provide insights to policymakers on the structure of policies which best fulfill evaluation criteria such as environmental and economic effectiveness, and others.

The assessment process

This Working Group III contribution to the AR5 represents the combined efforts of hundreds of leading experts in the field of climate change mitigation and has been prepared in accordance with the rules and procedures established by the IPCC. A scoping meeting for the AR5 was held in July 2009 and the outlines for the contributions of the three Working Groups were approved at the 31st Session of the Panel in November 2009. Governments and IPCC observer organizations nominated experts for the author teams. The team of 235 Coordinating Lead Authors and Lead Authors plus 38 Review Editors selected by the Working Group III Bureau, was accepted at the 41st Session of the IPCC Bureau in May 2010. More than 170 Contributing Authors provided draft text and information to the author teams at their request. Drafts prepared by the authors were subject to two rounds of formal review and revision followed by a final round of government comments on the Summary for Policymakers. More than 38,000 written comments were submitted by more than 800 expert reviewers and 37 governments. The Review Editors for each chapter monitored the review process to ensure that all substantive review comments received appropriate consideration. The Summary for Policymakers was approved line-by-line and the underlying chapters were then accepted at the 12th Session of IPCC Working Group III from 7–11 April 2014 in Berlin.

Acknowledgements

Production of this report was a major effort, in which many people from around the world were involved, with a wide variety of contributions. We wish to thank the generous contributions by the governments and

institutions involved, which enabled the authors, Review Editors and Government and Expert Reviewers to participate in this process.

Writing this report was only possible thanks to the expertise, hard work and commitment to excellence shown throughout by our Coordinating Lead Authors and Lead Authors, with important assistance by many Contributing Authors and Chapter Science Assistants. We would also like to express our appreciation to the Government and Expert Reviewers, acknowledging their time and energy invested to provide constructive and useful comments to the various drafts. Our Review Editors were also critical in the AR5 process, supporting the author teams with processing the comments and assuring an objective discussion of relevant issues.

We would very much like to thank the governments of the Republic of Korea, New Zealand and Ethiopia as well as the University of Vigo and the Economics for Energy Research Centre in Spain, that, in collaboration with local institutions, hosted the crucial IPCC Lead Author Meetings in Changwon (July 2011), Wellington (March 2012), Vigo (November 2012) and Addis Ababa (July 2013). In addition, we would like to thank the governments of India, Peru, Ghana, the United States and Germany for hosting the Expert Meetings in Calcutta (March 2011), Lima (June 2011), Accra (August 2011), Washington D.C. (August 2012), and Potsdam (October 2013), respectively. Finally, we express our appreciation to the Potsdam Institute for Climate Impact Research (PIK) for welcoming our Coordinating Lead Authors on their campus for a concluding meeting (October 2013).

We are especially grateful for the contribution and support of the German Government, in particular the Bundesministerium für Bildung und Forschung (BMBF), in funding the Working Group III Technical Support Unit (TSU). Coordinating this funding, Gregor Laumann and Sylke Lenz of the Deutsches Zentrum für Luft- und Raumfahrt (DLR) were always ready to dedicate time and energy to the needs of the team. We would also like to express our gratitude to the Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) for the good collaboration throughout the AR5 cycle and the excellent organization of the 39th Session of the IPCC — and 12th Session of IPCC WGIII — particularly to Nicole Wilke and Lutz Morgenstern. Our thanks also go to Christiane Textor at Deutsche IPCC Koordinierungsstelle for the good collaboration and her dedicated work. We acknowledge the contribution of the Ministry for Science, Technology and Environment (CITMA) of the Republic of Cuba, the Cuban Institute of Meteorology (INSMET) and the Centre for World Economy Studies (CIEM) for their support as well as the United Nations Economic Commission for Africa (UNECA) and its African Climate Policy Centre (ACPC).

We extend our gratitude to our colleagues in the IPCC leadership. The Executive Committee strengthened and facilitated the scientific and procedural work of all three working groups to complete their contributions: Rajendra K. Pachauri, Vicente Barros, Ismail El Gizouli, Taka Hiraishi, Chris Field, Thelma Krug, Hoesung Lee, Qin Dahe, Thomas Stocker, and Jean-Pascal van Ypersele. For his dedication, leadership and insight, we specially thank IPCC chair Rajendra K. Pachauri.

The Working Group III Bureau — consisting of Antonina Ivanova Boncheva (Mexico), Carlo Carraro (Italy), Suzana Kahn Ribeiro (Brazil), Jim Skea (UK), Francis Yamba (Zambia), and Taha Zatari (Saudi Arabia) — provided continuous and thoughtful advice throughout the AR5 process. We would like to thank Renate Christ, Secretary of the IPCC, and the Secretariat staff Gaetano Leone, Jonathan Lynn, Mary Jean Burer, Sophie Schlingemann, Judith Ewa, Jesbin Baidya, Werani Zabula, Joelle Fernandez, Annie Courtin, Laura Biagioni, Amy Smith and Carlos Martin-Novella, Brenda Abrar-Milani and Nina Peeva, who provided logistical support for government liaison and travel of experts from developing and transitional economy countries. Thanks are due to Francis Hayes who served as the conference officer for the Working Group III Approval Session.

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Sincerely,

Ottmar Edenhofer
IPCC WG III CO-Chair

Ramon Pichs-Madruga
IPCC WG III CO-Chair

Youba Sokona
IPCC WG III CO-Chair

Dedication

Elinor Ostrom
(7 August 1933 – 12 June 2012)

We dedicate this report to the memory of Elinor Ostrom, Professor of Political Science at Indiana University and Nobel Laureate in Economics. Her work provided a fundamental contribution to the understanding of collective action, trust, and cooperation in the management of common pool resources, including the atmosphere. She launched a research agenda that has encouraged scientists to explore how a variety of overlapping policies at city, national, regional, and international levels can enable humankind to manage the climate problem. The assessment of climate change mitigation across different levels of governance, sectors and regions has been a new focus of the Working Group III contribution to AR5. We have benefited greatly from the vision and intellectual leadership of Elinor Ostrom.

In Memoriam

Luxin Huang (1965–2013)
Lead Author in Chapter 12 on Human Settlements, Infrastructure and Spatial Planning

Leon Jay (Lee) Schipper (1947–2011)
Review Editor in Chapter 8 on Transport

Luxin Huang contributed to Chapter 12 on Human Settlements, Infrastructure and Spatial Planning. During this time, he was the director of the Department of International Cooperation and Development at the China Academy of Urban Planning and Design (CAUPD) in Beijing, China, where he worked for 27 years. The untimely death of Luxin Huang at the young age of 48 has left the Intergovernmental Panel on Climate Change (IPCC) with great sorrow.

Lee Schipper was a leading scientist in the field of transport, energy and the environment. He was looking forward to his role as review editor for the Transport chapter when he passed away at the age of 64. Schipper had been intimately involved with the IPCC for many years, having contributed as a Lead Author to the IPCC's Second Assessment Report's chapter on Mitigation Options in the Transportation Sector. The IPCC misses his great expertise and guidance, as well as his humorous and musical contributions.

Both researchers were dedicated contributors to the IPCC assessment process. Their passing represents a deep loss for the international scientific community. Luxin Huang and Lee Schipper are dearly remembered by the authors and members of the IPCC Working Group III.

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Summary for Policymakers

SPM

Summary for Policymakers

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SPM

SPM.1 Introduction

The Working Group III contribution to the IPCC's Fifth Assessment Report (AR5) assesses literature on the scientific, technological, environmental, economic and social aspects of mitigation of climate change. It builds upon the Working Group III contribution to the IPCC's Fourth Assessment Report (AR4), the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) and previous reports and incorporates subsequent new findings and research. The report also assesses mitigation options at different levels of governance and in different economic sectors, and the societal implications of different mitigation policies, but does not recommend any particular option for mitigation.

This Summary for Policymakers (SPM) follows the structure of the Working Group III report. The narrative is supported by a series of highlighted conclusions which, taken together, provide a concise summary. The basis for the SPM can be found in the chapter sections of the underlying report and in the Technical Summary (TS). References to these are given in square brackets.

The degree of certainty in findings in this assessment, as in the reports of all three Working Groups, is based on the author teams' evaluations of underlying scientific understanding and is expressed as a qualitative level of confidence (from very low to very high) and, when possible, probabilistically with a quantified likelihood (from exceptionally unlikely to virtually certain). Confidence in the validity of a finding is based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement.[1] Probabilistic estimates of quantified measures of uncertainty in a finding are based on statistical analysis of observations or model results, or both, and expert judgment.[2] Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers. Within paragraphs of this summary, the confidence, evidence, and agreement terms given for a bolded finding apply to subsequent statements in the paragraph, unless additional terms are provided.

SPM.2 Approaches to climate change mitigation

Mitigation is a human intervention to reduce the sources or enhance the sinks of greenhouse gases. Mitigation, together with adaptation to climate change, contributes to the objective expressed in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC):

> *The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.*

Climate policies can be informed by the findings of science, and systematic methods from other disciplines. [1.2, 2.4, 2.5, Box 3.1]

---

1 The following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence. For more details, please refer to the guidance note for Lead Authors of the IPCC Fifth Assessment Report on consistent treatment of uncertainties.

2 The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100 % probability, very likely 90–100 %, likely 66–100 %, about as likely as not 33–66 %, unlikely 0–33 %, very unlikely 0–10 %, exceptionally unlikely 0–1 %. Additional terms (more likely than not >50–100 %, and more unlikely than likely 0–<50 %) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*.

Sustainable development and equity provide a basis for assessing climate policies and highlight the need for addressing the risks of climate change.[3] Limiting the effects of climate change is necessary to achieve sustainable development and equity, including poverty eradication. At the same time, some mitigation efforts could undermine action on the right to promote sustainable development, and on the achievement of poverty eradication and equity. Consequently, a comprehensive assessment of climate policies involves going beyond a focus on mitigation and adaptation policies alone to examine development pathways more broadly, along with their determinants. [4.2, 4.3, 4.4, 4.5, 4.6, 4.8]

Effective mitigation will not be achieved if individual agents advance their own interests independently. Climate change has the characteristics of a collective action problem at the global scale, because most greenhouse gases (GHGs) accumulate over time and mix globally, and emissions by any agent (e.g., individual, community, company, country) affect other agents.[4] International cooperation is therefore required to effectively mitigate GHG emissions and address other climate change issues [1.2.4, 2.6.4, 3.2, 4.2, 13.2, 13.3]. Furthermore, research and development in support of mitigation creates knowledge spillovers. International cooperation can play a constructive role in the development, diffusion and transfer of knowledge and environmentally sound technologies [1.4.4, 3.11.6, 11.8, 13.9, 14.4.3].

Issues of equity, justice, and fairness arise with respect to mitigation and adaptation.[5] Countries' past and future contributions to the accumulation of GHGs in the atmosphere are different, and countries also face varying challenges and circumstances, and have different capacities to address mitigation and adaptation. The evidence suggests that outcomes seen as equitable can lead to more effective cooperation. [3.10, 4.2.2, 4.6.2]

Many areas of climate policy-making involve value judgements and ethical considerations. These areas range from the question of how much mitigation is needed to prevent dangerous interference with the climate system to choices among specific policies for mitigation or adaptation [3.1, 3.2]. Social, economic and ethical analyses may be used to inform value judgements and may take into account values of various sorts, including human wellbeing, cultural values and non-human values [3.4, 3.10].

Among other methods, economic evaluation is commonly used to inform climate policy design. Practical tools for economic assessment include cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis and expected utility theory [2.5]. The limitations of these tools are well-documented [3.5]. Ethical theories based on social welfare functions imply that distributional weights, which take account of the different value of money to different people, should be applied to monetary measures of benefits and harms [3.6.1, Box TS.2]. Whereas distributional weighting has not frequently been applied for comparing the effects of climate policies on different people at a single time, it is standard practice, in the form of discounting, for comparing the effects at different times [3.6.2].

Climate policy intersects with other societal goals creating the possibility of co-benefits or adverse side-effects. These intersections, if well-managed, can strengthen the basis for undertaking climate action. Mitigation and adaptation can positively or negatively influence the achievement of other societal goals, such as those related to human health, food security, biodiversity, local environmental quality, energy access, livelihoods, and equitable sustainable development; and vice versa, policies toward other societal goals can influence the achievement of mitigation and adaptation objectives [4.2, 4.3, 4.4, 4.5, 4.6, 4.8]. These influences can be substantial, although sometimes difficult to quantify, especially in welfare terms [3.6.3]. This multi-objective perspective is important in part because it helps to identify areas where support for policies that advance multiple goals will be robust [1.2.1, 4.2, 4.8, 6.6.1].

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3 See WGII AR5 SPM.

4 In the social sciences this is referred to as a 'global commons problem'. As this expression is used in the social sciences, it has no specific implications for legal arrangements or for particular criteria regarding effort-sharing.

5 See FAQ 3.2 for clarification of these concepts. The philosophical literature on justice and other literature can illuminate these issues [3.2, 3.3, 4.6.2].

Climate policy may be informed by a consideration of a diverse array of risks and uncertainties, some of which are difficult to measure, notably events that are of low probability but which would have a significant impact if they occur. Since AR4, the scientific literature has examined risks related to climate change, adaptation, and mitigation strategies. Accurately estimating the benefits of mitigation takes into account the full range of possible impacts of climate change, including those with high consequences but a low probability of occurrence. The benefits of mitigation may otherwise be underestimated (*high confidence*) [2.5, 2.6, Box 3.9]. The choice of mitigation actions is also influenced by uncertainties in many socio-economic variables, including the rate of economic growth and the evolution of technology *(high confidence*) [2.6, 6.3].

The design of climate policy is influenced by how individuals and organizations perceive risks and uncertainties and take them into account. People often utilize simplified decision rules such as a preference for the status quo. Individuals and organizations differ in their degree of risk aversion and the relative importance placed on near-term versus long-term ramifications of specific actions [2.4]. With the help of formal methods, policy design can be improved by taking into account risks and uncertainties in natural, socio-economic, and technological systems as well as decision processes, perceptions, values and wealth [2.5].

SPM.3 Trends in stocks and flows of greenhouse gases and their drivers

Total anthropogenic GHG emissions have continued to increase over 1970 to 2010 with larger absolute decadal increases toward the end of this period (*high confidence*). Despite a growing number of climate change mitigation policies, annual GHG emissions grew on average by 1.0 gigatonne carbon dioxide equivalent ($GtCO_2eq$) (2.2 %) per year from 2000 to 2010 compared to 0.4 $GtCO_2eq$ (1.3 %) per year from 1970 to 2000 (Figure SPM.1).[6,7] Total anthropogenic GHG emissions were the highest in human history from 2000 to 2010 and reached 49 (±4.5) $GtCO_2eq$/yr in 2010. The global economic crisis 2007/2008 only temporarily reduced emissions. [1.3, 5.2, 13.3, 15.2.2, Box TS.5, Figure 15.1]

CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78 % of the total GHG emission increase from 1970 to 2010, with a similar percentage contribution for the period 2000–2010 (*high confidence*). Fossil fuel-related CO_2 emissions reached 32 (±2.7) $GtCO_2$/yr, in 2010, and grew further by about 3 % between 2010 and 2011 and by about 1–2 % between 2011 and 2012. Of the 49 (±4.5) $GtCO_2eq$/yr in total anthropogenic GHG emissions in 2010, CO_2 remains the major anthropogenic GHG accounting for 76 % (38±3.8 $GtCO_2eq$/yr) of total anthropogenic GHG emissions in 2010. 16 % (7.8±1.6 $GtCO_2eq$/yr) come from methane (CH_4), 6.2 % (3.1±1.9 $GtCO_2eq$/yr) from nitrous oxide (N_2O), and 2.0 % (1.0±0.2 $GtCO_2eq$/yr) from fluorinated gases (Figure SPM.1). Annually, since 1970, about 25 % of anthropogenic GHG emissions have been in the form of non-CO_2 gases.[8] [1.2, 5.2]

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6 Throughout the SPM, emissions of GHGs are weighed by Global Warming Potentials with a 100-year time horizon (GWP_{100}) from the IPCC Second Assessment Report. All metrics have limitations and uncertainties in assessing consequences of different emissions. [3.9.6, Box TS.5, Annex II.9, WGI SPM]

7 In this SPM, uncertainty in historic GHG emission data is reported using 90 % uncertainty intervals unless otherwise stated. GHG emission levels are rounded to two significant digits throughout this document; as a consequence, small differences in sums due to rounding may occur.

8 In this report, data on non-CO_2 GHGs, including fluorinated gases, are taken from the EDGAR database (Annex II.9), which covers substances included in the Kyoto Protocol in its first commitment period.

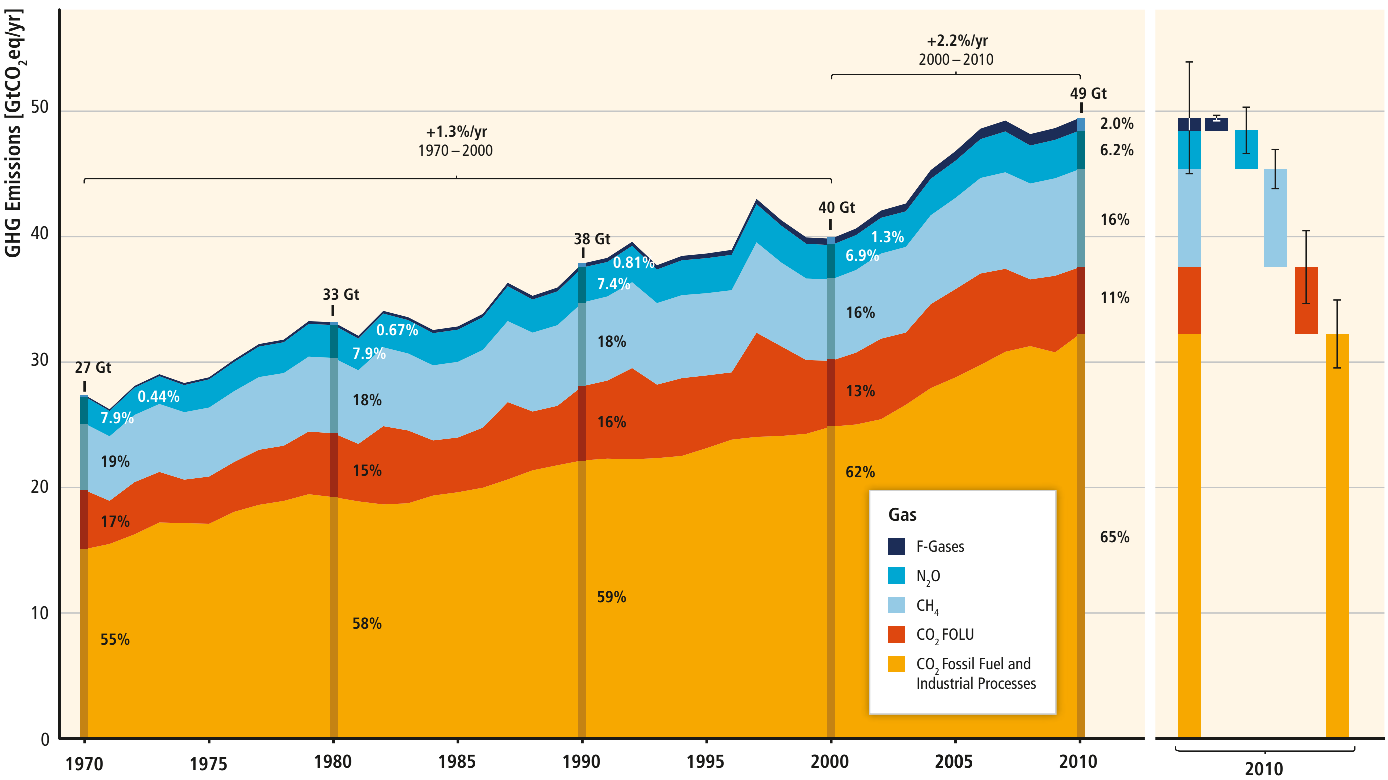

Figure SPM.1 | Total annual anthropogenic GHG emissions ($GtCO_2eq/yr$) by groups of gases 1970–2010: CO_2 from fossil fuel combustion and industrial processes; CO_2 from Forestry and Other Land Use (FOLU); methane (CH_4); nitrous oxide (N_2O); fluorinated gases[8] covered under the Kyoto Protocol (F-gases). At the right side of the figure GHG emissions in 2010 are shown again broken down into these components with the associated uncertainties (90 % confidence interval) indicated by the error bars. Total anthropogenic GHG emissions uncertainties are derived from the individual gas estimates as described in Chapter 5 [5.2.3.6]. Global CO_2 emissions from fossil fuel combustion are known within 8 % uncertainty (90 % confidence interval). CO_2 emissions from FOLU have very large uncertainties attached in the order of ±50 %. Uncertainty for global emissions of CH_4, N_2O and the F-gases has been estimated as 20 %, 60 % and 20 %, respectively. 2010 was the most recent year for which emission statistics on all gases as well as assessment of uncertainties were essentially complete at the time of data cut-off for this report. Emissions are converted into CO_2-equivalents based on GWP_{100}[6] from the IPCC Second Assessment Report. The emission data from FOLU represents land-based CO_2 emissions from forest fires, peat fires and peat decay that approximate to net CO_2 flux from FOLU as described in Chapter 11 of this report. Average annual growth rate over different periods is highlighted with the brackets. [Figure 1.3, Figure TS.1]

About half of cumulative anthropogenic CO_2 emissions between 1750 and 2010 have occurred in the last 40 years (*high confidence*). In 1970, cumulative CO_2 emissions from fossil fuel combustion, cement production and flaring since 1750 were 420±35 $GtCO_2$; in 2010, that cumulative total had tripled to 1300±110 $GtCO_2$. Cumulative CO_2 emissions from Forestry and Other Land Use (FOLU)[9] since 1750 increased from 490±180 $GtCO_2$ in 1970 to 680±300 $GtCO_2$ in 2010. [5.2]

Annual anthropogenic GHG emissions have increased by 10 $GtCO_2eq$ between 2000 and 2010, with this increase directly coming from energy supply (47 %), industry (30 %), transport (11 %) and buildings (3 %) sectors (*medium confidence*). **Accounting for indirect emissions raises the contributions of the buildings and industry sectors** (*high confidence*). Since 2000, GHG emissions have been growing in all sectors, except AFOLU. Of the 49 (±4.5) $GtCO_2eq$ emissions in 2010, 35 % (17 $GtCO_2eq$) of GHG emissions were released in the energy supply sector,

[9] Forestry and Other Land Use (FOLU)—also referred to as LULUCF (Land Use, Land-Use Change, and Forestry)—is the subset of Agriculture, Forestry and Other Land Use (AFOLU) emissions and removals of GHGs related to direct human-induced land use, land-use change and forestry activities excluding agricultural emissions and removals (see WGIII AR5 Glossary).

24 % (12 $GtCO_2eq$, net emissions) in AFOLU, 21 % (10 $GtCO_2eq$) in industry, 14 % (7.0 $GtCO_2eq$) in transport and 6.4 % (3.2 $GtCO_2eq$) in buildings. When emissions from electricity and heat production are attributed to the sectors that use the final energy (i.e. indirect emissions), the shares of the industry and buildings sectors in global GHG emissions are increased to 31 % and 19 %[7], respectively (Figure SPM.2). [7.3, 8.2, 9.2, 10.3, 11.2]

Globally, economic and population growth continue to be the most important drivers of increases in CO_2 emissions from fossil fuel combustion. The contribution of population growth between 2000 and 2010 remained roughly identical to the previous three decades, while the contribution of economic growth has risen sharply (*high confidence*). Between 2000 and 2010, both drivers outpaced emission reductions from improvements in energy intensity (Figure SPM.3). Increased use of coal relative to other energy sources has reversed the long-standing trend of gradual decarbonization of the world's energy supply. [1.3, 5.3, 7.2, 14.3, TS.2.2]

Without additional efforts to reduce GHG emissions beyond those in place today, emissions growth is expected to persist driven by growth in global population and economic activities. Baseline scenarios, those without additional mitigation, result in global mean surface temperature increases in 2100 from 3.7 °C to 4.8 °C compared to pre-industrial levels[10] (range based on median climate response; the range is 2.5 °C to 7.8 °C when including climate uncertainty, see Table SPM.1)[11] (*high confidence*). The emission scenarios collected for this assessment represent full radiative forcing including GHGs, tropospheric ozone, aerosols and albedo change. Baseline scenarios (scenarios without explicit additional efforts to constrain emissions) exceed 450 parts per million (ppm) CO_2eq by 2030 and reach CO_2eq concentration levels between 750 and more than 1300 ppm CO_2eq by 2100. This is similar to the range in atmospheric concentration levels between the RCP 6.0 and RCP 8.5 pathways in 2100.[12] For comparison, the CO_2eq concentration in 2011 is estimated to be 430 ppm (uncertainty range 340–520 ppm).[13] [6.3, Box TS.6; WGI Figure SPM.5, WGI 8.5, WGI 12.3]

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10 Based on the longest global surface temperature dataset available, the observed change between the average of the period 1850–1900 and of the AR5 reference period (1986–2005) is 0.61 °C (5–95 % confidence interval: 0.55–0.67 °C) [WGI SPM.E], which is used here as an approximation of the change in global mean surface temperature since pre-industrial times, referred to as the period before 1750.

11 The climate uncertainty reflects the 5th to 95th percentile of climate model calculations described in Table SPM.1.

12 For the purpose of this assessment, roughly 300 baseline scenarios and 900 mitigation scenarios were collected through an open call from integrated modelling teams around the world. These scenarios are complementary to the Representative Concentration Pathways (RCPs, see WGIII AR5 Glossary). The RCPs are identified by their approximate total radiative forcing in year 2100 relative to 1750: 2.6 Watts per square meter (W/m^2) for RCP2.6, 4.5 W/m^2 for RCP4.5, 6.0 W/m^2 for RCP6.0, and 8.5 W/m^2 for RCP8.5. The scenarios collected for this assessment span a slightly broader range of concentrations in the year 2100 than the four RCPs.

13 This is based on the assessment of total anthropogenic radiative forcing for 2011 relative to 1750 in WGI, i.e. 2.3 W/m^2, uncertainty range 1.1 to 3.3 W/m^2. [WGI Figure SPM.5, WGI 8.5, WGI 12.3]

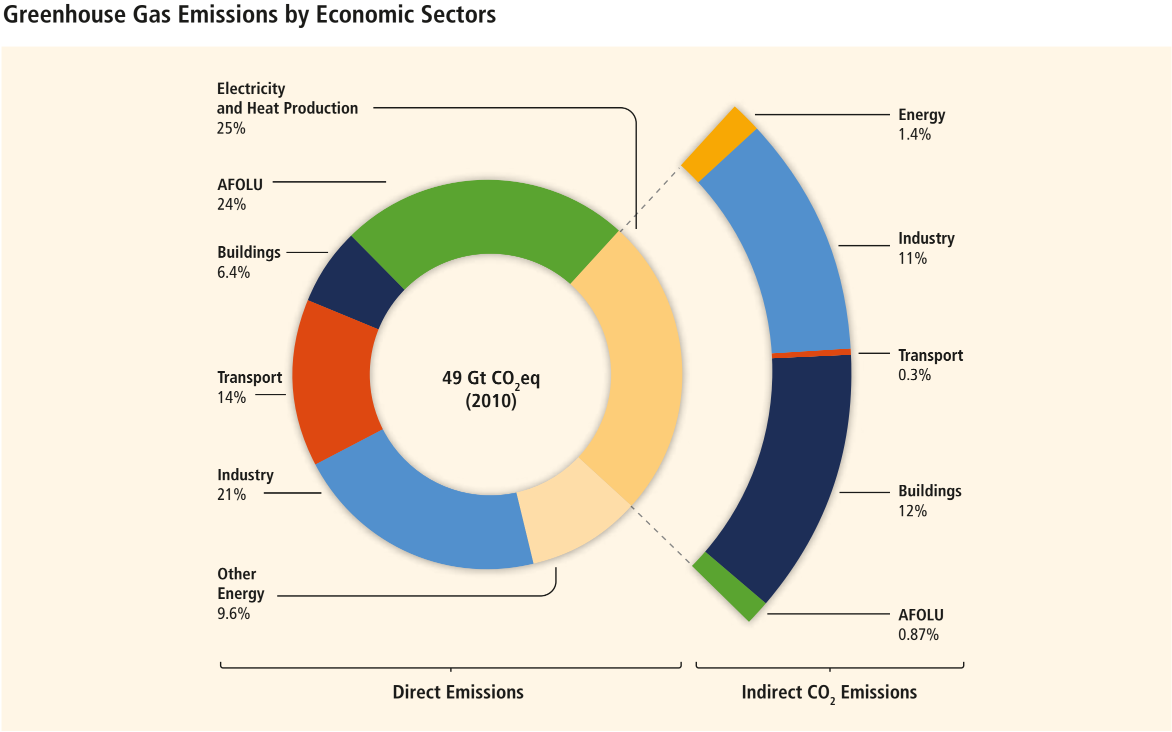

Figure SPM.2 | Total anthropogenic GHG emissions ($GtCO_2eq/yr$) by economic sectors. Inner circle shows direct GHG emission shares (in % of total anthropogenic GHG emissions) of five economic sectors in 2010. Pull-out shows how indirect CO_2 emission shares (in % of total anthropogenic GHG emissions) from electricity and heat production are attributed to sectors of final energy use. 'Other Energy' refers to all GHG emission sources in the energy sector as defined in Annex II other than electricity and heat production [A.II.9.1]. The emissions data from Agriculture, Forestry and Other Land Use (AFOLU) includes land-based CO_2 emissions from forest fires, peat fires and peat decay that approximate to net CO_2 flux from the Forestry and Other Land Use (FOLU) sub-sector as described in Chapter 11 of this report. Emissions are converted into CO_2-equivalents based on GWP_{100}[6] from the IPCC Second Assessment Report. Sector definitions are provided in Annex II.9. [Figure 1.3a, Figure TS.3 upper panel]

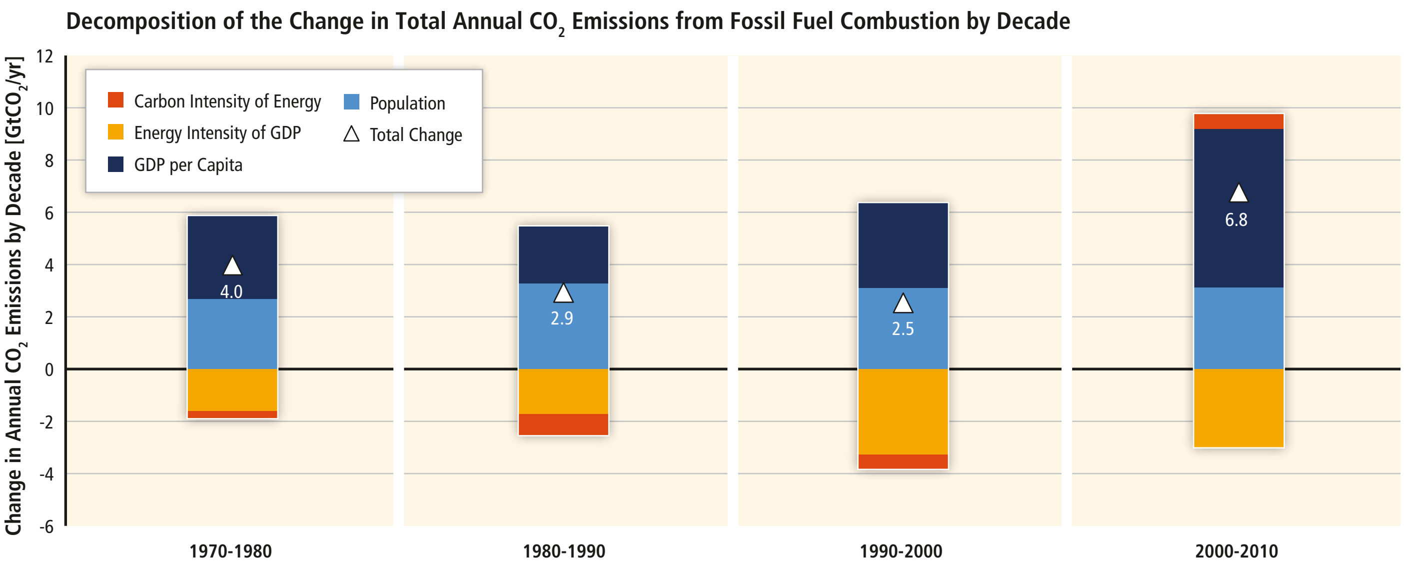

Figure SPM.3 | Decomposition of the change in total annual CO_2 emissions from fossil fuel combustion by decade and four driving factors: population, income (GDP) per capita, energy intensity of GDP and carbon intensity of energy. The bar segments show the changes associated with each factor alone, holding the respective other factors constant. Total emissions changes are indicated by a triangle. The change in emissions over each decade is measured in gigatonnes of CO_2 per year [$GtCO_2$/yr]; income is converted into common units using purchasing power parities. [Figure 1.7]

SPM

SPM.4 Mitigation pathways and measures in the context of sustainable development

SPM.4.1 Long-term mitigation pathways

There are multiple scenarios with a range of technological and behavioral options, with different characteristics and implications for sustainable development, that are consistent with different levels of mitigation. For this assessment, about 900 mitigation scenarios have been collected in a database based on published integrated models.[14] This range spans atmospheric concentration levels in 2100 from 430 ppm CO_2eq to above 720 ppm CO_2eq, which is comparable to the 2100 forcing levels between RCP 2.6 and RCP 6.0. Scenarios outside this range were also assessed including some scenarios with concentrations in 2100 below 430 ppm CO_2eq (for a discussion of these scenarios see below). The mitigation scenarios involve a wide range of technological, socioeconomic, and institutional trajectories, but uncertainties and model limitations exist and developments outside this range are possible (Figure SPM.4, upper panel). [6.1, 6.2, 6.3, TS.3.1, Box TS.6]

Mitigation scenarios in which it is *likely* that the temperature change caused by anthropogenic GHG emissions can be kept to less than 2 °C relative to pre-industrial levels are characterized by atmospheric concentrations in 2100 of about 450 ppm CO_2eq (*high confidence*). Mitigation scenarios reaching concentration levels of about 500 ppm CO_2eq by 2100 are *more likely than not* to limit temperature change to less than 2 °C relative to pre-industrial levels, unless they temporarily 'overshoot' concentration levels of roughly 530 ppm CO_2eq before 2100, in which case they are *about as likely as not* to achieve that goal.[15] Scenarios that reach 530 to 650 ppm CO_2eq concentrations by 2100 are *more unlikely than likely* to keep temperature change below 2 °C relative to pre-industrial levels. Scenarios that exceed about 650 ppm CO_2eq by 2100 are *unlikely* to limit temperature change to below 2 °C relative to pre-industrial levels. Mitigation scenarios in which temperature increase is *more likely than not* to be less than 1.5 °C relative to pre-industrial levels by 2100 are characterized by concentrations in 2100 of below 430 ppm CO_2eq. Temperature peaks during the century and then declines in these scenarios. Probability statements regarding other levels of temperature change can be made with reference to Table SPM.1. [6.3, Box TS.6]

Scenarios reaching atmospheric concentration levels of about 450 ppm CO_2eq by 2100 (consistent with a *likely* chance to keep temperature change below 2 °C relative to pre-industrial levels) include substantial cuts in anthropogenic GHG emissions by mid-century through large-scale changes in energy systems and potentially land use (*high confidence*). Scenarios reaching these concentrations by 2100 are characterized by lower global GHG emissions in 2050 than in 2010, 40 % to 70 % lower globally,[16] and emissions levels near zero $GtCO_2$eq or below in

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[14] The long-term scenarios assessed in WGIII were generated primarily by large-scale, integrated models that project many key characteristics of mitigation pathways to mid-century and beyond. These models link many important human systems (e.g., energy, agriculture and land use, economy) with physical processes associated with climate change (e.g., the carbon cycle). The models approximate cost-effective solutions that minimize the aggregate economic costs of achieving mitigation outcomes, unless they are specifically constrained to behave otherwise. They are simplified, stylized representations of highly-complex, real-world processes, and the scenarios they produce are based on uncertain projections about key events and drivers over often century-long timescales. Simplifications and differences in assumptions are the reason why output generated from different models, or versions of the same model, can differ, and projections from all models can differ considerably from the reality that unfolds. [Box TS.7, 6.2]

[15] Mitigation scenarios, including those reaching 2100 concentrations as high as or higher than about 550 ppm CO_2eq, can temporarily 'overshoot' atmospheric CO_2eq concentration levels before descending to lower levels later. Such concentration overshoot involves less mitigation in the near term with more rapid and deeper emissions reductions in the long run. Overshoot increases the probability of exceeding any given temperature goal. [6.3, Table SPM.1]

[16] This range differs from the range provided for a similar concentration category in AR4 (50 %–85 % lower than 2000 for CO_2 only). Reasons for this difference include that this report has assessed a substantially larger number of scenarios than in AR4 and looks at all GHGs. In addition, a large proportion of the new scenarios include Carbon Dioxide Removal (CDR) technologies (see below). Other factors include the use of 2100 concentration levels instead of stabilization levels and the shift in reference year from 2000 to 2010. Scenarios with higher emissions in 2050 are characterized by a greater reliance on CDR technologies beyond mid-century.

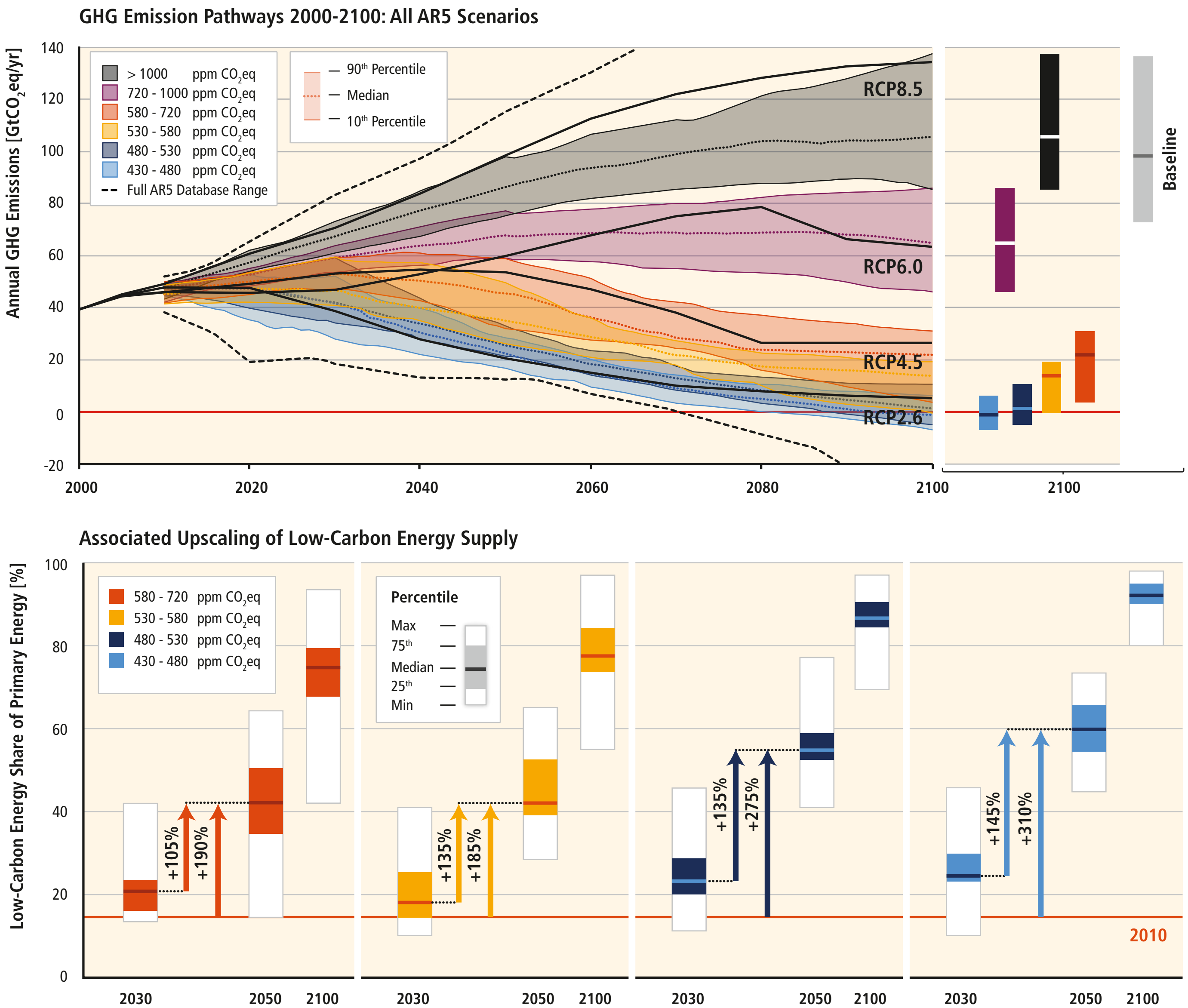

Figure SPM.4 | Pathways of global GHG emissions ($GtCO_2eq/yr$) in baseline and mitigation scenarios for different long-term concentration levels (upper panel) [Figure 6.7] and associated upscaling requirements of low-carbon energy (% of primary energy) for 2030, 2050 and 2100 compared to 2010 levels in mitigation scenarios (lower panel) [Figure 7.16]. The lower panel excludes scenarios with limited technology availability and exogenous carbon price trajectories. For definitions of CO_2-equivalent emissions and CO_2-equivalent concentrations see the WGIII AR5 Glossary.

2100. In scenarios reaching about 500 ppm CO_2eq by 2100, 2050 emissions levels are 25 % to 55 % lower than in 2010 globally. In scenarios reaching about 550 ppm CO_2eq, emissions in 2050 are from 5 % above 2010 levels to 45 % below 2010 levels globally (Table SPM.1). At the global level, scenarios reaching about 450 ppm CO_2eq are also characterized by more rapid improvements in energy efficiency and a tripling to nearly a quadrupling of the share of zero- and low-carbon energy supply from renewables, nuclear energy and fossil energy with carbon dioxide capture and storage (CCS), or bioenergy with CCS (BECCS) by the year 2050 (Figure SPM.4, lower panel). These scenarios describe a wide range of changes in land use, reflecting different assumptions about the scale of bioenergy production, afforestation, and reduced deforestation. All of these emissions, energy, and land-use changes vary across regions.[17] Scenarios reaching higher concentrations include similar changes, but on a slower timescale. On the other hand, scenarios reaching lower concentrations require these changes on a faster timescale. [6.3, 7.11]

Mitigation scenarios reaching about 450 ppm CO_2eq in 2100 typically involve temporary overshoot of atmospheric concentrations, as do many scenarios reaching about 500 ppm to about 550 ppm CO_2eq in 2100. Depending on the level of the overshoot, overshoot scenarios typically rely on the availability and widespread deployment of BECCS and afforestation in the second half of the century. The availability and scale of these and other Carbon Dioxide Removal (CDR) technologies and methods are uncertain and CDR technologies and methods are, to varying degrees, associated with challenges and risks (*high confidence*) (see Section SPM.4.2).[18] CDR is also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive. There is uncertainty about the potential for large-scale deployment of BECCS, large-scale afforestation, and other CDR technologies and methods. [2.6, 6.3, 6.9.1, Figure 6.7, 7.11, 11.13]

Estimated global GHG emissions levels in 2020 based on the Cancún Pledges are not consistent with cost-effective long-term mitigation trajectories that are at least *about as likely as not* to limit temperature change to 2 °C relative to pre-industrial levels (2100 concentrations of about 450 to about 500 ppm CO_2eq), but they do not preclude the option to meet that goal (*high confidence*). Meeting this goal would require further substantial reductions beyond 2020. The Cancún Pledges are broadly consistent with cost-effective scenarios that are *likely* to keep temperature change below 3 °C relative to preindustrial levels. [6.4, 13.13, Figure TS.11]

Delaying mitigation efforts beyond those in place today through 2030 is estimated to substantially increase the difficulty of the transition to low longer-term emissions levels and narrow the range of options consistent with maintaining temperature change below 2 °C relative to pre-industrial levels (*high confidence*). Cost-effective mitigation scenarios that make it at least *about as likely as not* that temperature change will remain below 2 °C relative to pre-industrial levels (2100 concentrations of about 450 to about 500 ppm CO_2eq) are typically characterized by annual GHG emissions in 2030 of roughly between 30 $GtCO_2$eq and 50 $GtCO_2$eq (Figure SPM.5, left panel). Scenarios with annual GHG emissions above 55 $GtCO_2$eq in 2030 are characterized by substantially higher rates of emissions reductions from 2030 to 2050 (Figure SPM.5, middle panel); much more rapid scale-up of low-carbon energy over this period (Figure SPM.5, right panel); a larger reliance on CDR technologies in the long-term; and higher transitional and long-term economic impacts (Table SPM.2, orange segment). Due to these increased mitigation challenges, many models with annual 2030 GHG emissions higher than 55 $GtCO_2$eq could not produce scenarios reaching atmospheric concentration levels that make it *about as likely as not* that temperature change will remain below 2 °C relative to pre-industrial levels. [6.4, 7.11, Figures TS.11, TS.13]

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17 At the national level, change is considered most effective when it reflects country and local visions and approaches to achieving sustainable development according to national circumstances and priorities. [6.4, 11.8.4, WGII SPM]

18 According to WGI, CDR methods have biogeochemical and technological limitations to their potential on the global scale. There is insufficient knowledge to quantify how much CO_2 emissions could be partially offset by CDR on a century timescale. CDR methods carry side-effects and long-term consequences on a global scale. [WGI SPM.E.8]

Table SPM.1 | Key characteristics of the scenarios collected and assessed for WGIII AR5. For all parameters, the 10th to 90th percentile of the scenarios is shown.[1, 2] [Table 6.3]

CO_2eq Concentrations in 2100 [ppm CO_2eq] Category label (concentration range)[9]	Subcategories	Relative position of the RCPs[5]	Cumulative CO_2 emissions[3] [GtCO_2]		Change in CO_2eq emissions compared to 2010 in [%][4]		Temperature change (relative to 1850–1900)[5, 6]				
			2011–2050	2011–2100	2050	2100	2100 Temperature change [°C][7]	Likelihood of staying below temperature level over the 21st century[8]			
								1.5 °C	2.0 °C	3.0 °C	4.0 °C
< 430	Only a limited number of individual model studies have explored levels below 430 ppm CO_2eq										
450 (430–480)	Total range[1, 10]	RCP2.6	550–1300	630–1180	−72 to −41	−118 to −78	1.5–1.7 (1.0–2.8)	*More unlikely than likely*	*Likely*	*Likely*	*Likely*
500 (480–530)	No overshoot of 530 ppm CO_2eq		860–1180	960–1430	−57 to −42	−107 to −73	1.7–1.9 (1.2–2.9)	*Unlikely*	*More likely than not*		
	Overshoot of 530 ppm CO_2eq		1130–1530	990–1550	−55 to −25	−114 to −90	1.8–2.0 (1.2–3.3)		*About as likely as not*		
550 (530–580)	No overshoot of 580 ppm CO_2eq		1070–1460	1240–2240	−47 to −19	−81 to −59	2.0–2.2 (1.4–3.6)		*More unlikely than likely*[12]		
	Overshoot of 580 ppm CO_2eq		1420–1750	1170–2100	−16 to 7	−183 to −86	2.1–2.3 (1.4–3.6)				
(580–650)	Total range	RCP4.5	1260–1640	1870–2440	−38 to 24	−134 to −50	2.3–2.6 (1.5–4.2)				
(650–720)	Total range		1310–1750	2570–3340	−11 to 17	−54 to −21	2.6–2.9 (1.8–4.5)		*Unlikely*	*More likely than not*	
(720–1000)	Total range	RCP6.0	1570–1940	3620–4990	18 to 54	−7 to 72	3.1–3.7 (2.1–5.8)	*Unlikely*[11]		*More unlikely than likely*	
>1000	Total range	RCP8.5	1840–2310	5350–7010	52 to 95	74 to 178	4.1–4.8 (2.8–7.8)		*Unlikely*[11]	*Unlikely*	*More unlikely than likely*

1 The 'total range' for the 430–480 ppm CO_2eq scenarios corresponds to the range of the 10th–90th percentile of the subcategory of these scenarios shown in Table 6.3.

2 Baseline scenarios (see SPM.3) fall into the >1000 and 720–1000 ppm CO_2eq categories. The latter category also includes mitigation scenarios. The baseline scenarios in the latter category reach a temperature change of 2.5–5.8 °C above preindustrial in 2100. Together with the baseline scenarios in the >1000 ppm CO_2eq category, this leads to an overall 2100 temperature range of 2.5–7.8 °C (range based on median climate response: 3.7–4.8 °C) for baseline scenarios across both concentration categories.

3 For comparison of the cumulative CO_2 emissions estimates assessed here with those presented in WGI, an amount of 515 [445–585] GtC (1890 [1630–2150] GtCO_2), was already emitted by 2011 since 1870 [Section WGI 12.5]. Note that cumulative emissions are presented here for different periods of time (2011–2050 and 2011–2100) while cumulative emissions in WGI are presented as total compatible emissions for the RCPs (2012–2100) or for total compatible emissions for remaining below a given temperature target with a given likelihood [WGI Table SPM.3, WGI SPM.E.8].

4 The global 2010 emissions are 31 % above the 1990 emissions (consistent with the historic GHG emission estimates presented in this report). CO_2eq emissions include the basket of Kyoto gases (CO_2, CH_4, N_2O as well as F-gases).

5 The assessment in WGIII involves a large number of scenarios published in the scientific literature and is thus not limited to the RCPs. To evaluate the CO_2eq concentration and climate implications of these scenarios, the MAGICC model was used in a probabilistic mode (see Annex II). For a comparison between MAGICC model results and the outcomes of the models used in WGI, see Sections WGI 12.4.1.2 and WGI 12.4.8 and 6.3.2.6. Reasons for differences with WGI SPM Table.2 include the difference in reference year (1986–2005 vs. 1850–1900 here), difference in reporting year (2081–2100 vs 2100 here), set-up of simulation (CMIP5 concentration driven versus MAGICC emission-driven here), and the wider set of scenarios (RCPs versus the full set of scenarios in the WGIII AR5 scenario database here).

6 Temperature change is reported for the year 2100, which is not directly comparable to the equilibrium warming reported in WGIII AR4 [Table 3.5, Chapter 3]. For the 2100 temperature estimates, the transient climate response (TCR) is the most relevant system property. The assumed 90 % range of the TCR for MAGICC is 1.2–2.6 °C (median 1.8 °C). This compares to the 90 % range of TCR between 1.2–2.4 °C for CMIP5 [WGI 9.7] and an assessed *likely* range of 1–2.5 °C from multiple lines of evidence reported in the WGI AR5 [Box 12.2 in Section 12.5].

7 Temperature change in 2100 is provided for a median estimate of the MAGICC calculations, which illustrates differences between the emissions pathways of the scenarios in each category. The range of temperature change in the parentheses includes in addition the carbon cycle and climate system uncertainties as represented by the MAGICC model [see 6.3.2.6 for further details]. The temperature data compared to the 1850–1900 reference year was calculated by taking all projected warming relative to 1986–2005, and adding 0.61 °C for 1986–2005 compared to 1850–1900, based on HadCRUT4 [see WGI Table SPM.2].

8 The assessment in this table is based on the probabilities calculated for the full ensemble of scenarios in WGIII using MAGICC and the assessment in WGI of the uncertainty of the temperature projections not covered by climate models. The statements are therefore consistent with the statements in WGI, which are based on the CMIP5 runs of the RCPs and the assessed uncertainties. Hence, the likelihood statements reflect different lines of evidence from both WGs. This WGI method was also applied for scenarios with intermediate concentration levels where no CMIP5 runs are available. The likelihood statements are indicative only [6.3], and follow broadly the terms used by the WGI SPM for temperature projections: *likely* 66–100 %, *more likely than not* >50–100 %, *about as likely as not* 33–66 %, and *unlikely* 0–33 %. In addition the term *more unlikely than likely* 0–<50 % is used.

9 The CO_2-equivalent concentration includes the forcing of all GHGs including halogenated gases and tropospheric ozone, as well as aerosols and albedo change (calculated on the basis of the total forcing from a simple carbon cycle/climate model, MAGICC).

10 The vast majority of scenarios in this category overshoot the category boundary of 480 ppm CO_2eq concentrations.

11 For scenarios in this category no CMIP5 run [WGI Chapter 12, Table 12.3] as well as no MAGICC realization [6.3] stays below the respective temperature level. Still, an *unlikely* assignment is given to reflect uncertainties that might not be reflected by the current climate models.

12 Scenarios in the 580–650 ppm CO_2eq category include both overshoot scenarios and scenarios that do not exceed the concentration level at the high end of the category (like RCP4.5). The latter type of scenarios, in general, have an assessed probability of *more unlikely than likely* to stay below the 2 °C temperature level, while the former are mostly assessed to have an *unlikely* probability of staying below this level.

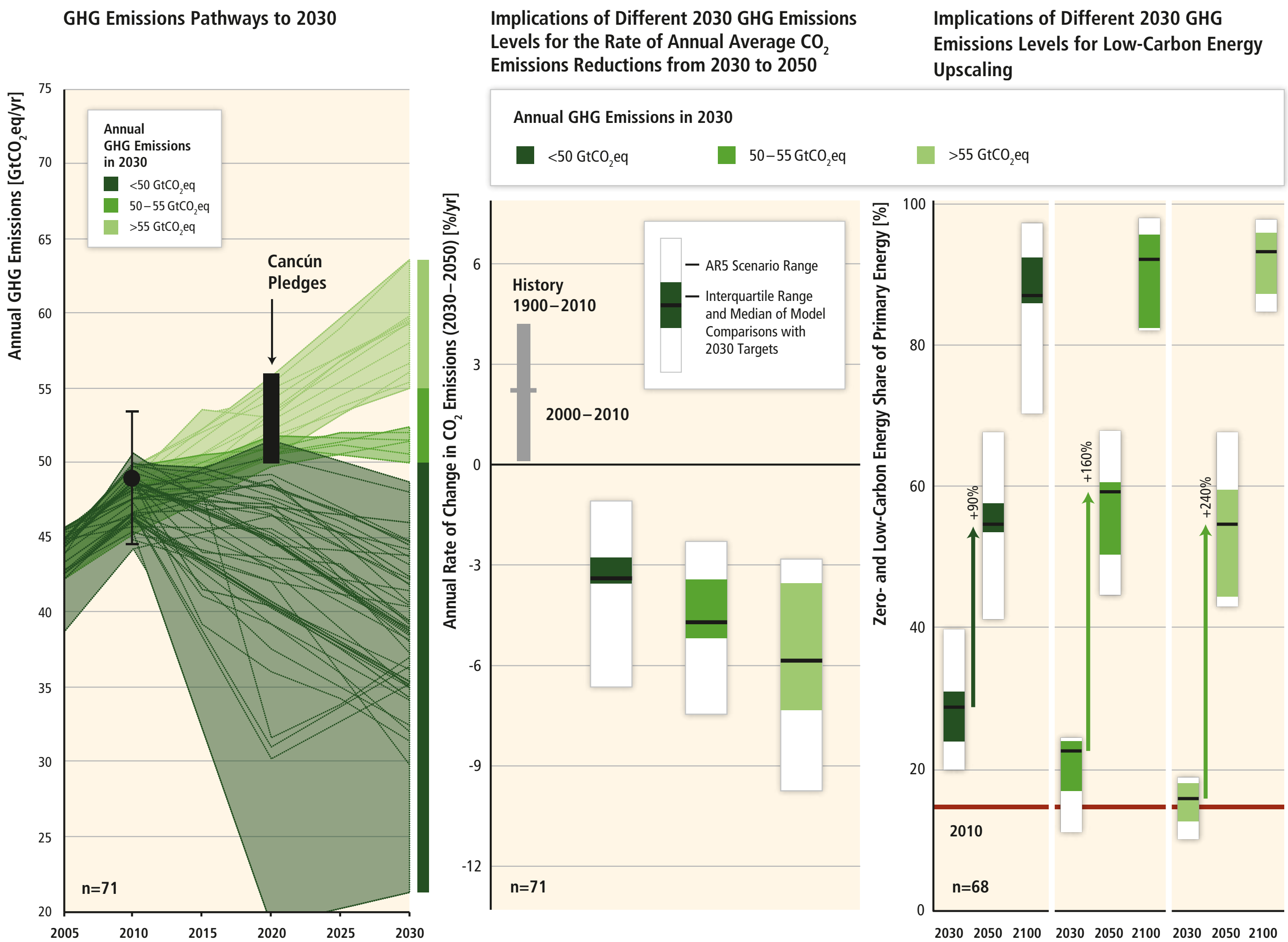

Figure SPM.5 | The implications of different 2030 GHG emissions levels (left panel) for the rate of CO_2 emissions reductions from 2030 to 2050 (middle panel) and low-carbon energy upscaling from 2030 to 2050 and 2100 (right panel) in mitigation scenarios reaching about 450 to about 500 (430–530) ppm CO_2eq concentrations by 2100. The scenarios are grouped according to different emissions levels by 2030 (coloured in different shades of green). The left panel shows the pathways of GHG emissions (GtCO_2eq/yr) leading to these 2030 levels. The black bar shows the estimated uncertainty range of GHG emissions implied by the Cancún Pledges. The middle panel denotes the average annual CO_2 emissions reduction rates for the period 2030–2050. It compares the median and interquartile range across scenarios from recent intermodel comparisons with explicit 2030 interim goals to the range of scenarios in the Scenario Database for WGIII AR5. Annual rates of historical emissions change between 1900–2010 (sustained over a period of 20 years) and average annual emissions change between 2000–2010 are shown in grey. The arrows in the right panel show the magnitude of zero and low-carbon energy supply up-scaling from 2030 to 2050 subject to different 2030 GHG emissions levels. Zero- and low-carbon energy supply includes renewables, nuclear energy, fossil energy with carbon dioxide capture and storage (CCS), and bioenergy with CCS (BECCS). Note: Only scenarios that apply the full, unconstrained mitigation technology portfolio of the underlying models (default technology assumption) are shown. Scenarios with large net negative global emissions (>20 GtCO_2/yr), scenarios with exogenous carbon price assumptions, and scenarios with 2010 emissions significantly outside the historical range are excluded. The right-hand panel includes only 68 scenarios, because three of the 71 scenarios shown in the figure do not report some subcategories for primary energy that are required to calculate the share of zero- and low-carbon energy. [Figures 6.32 and 7.16; 13.13.1.3]

Table SPM.2 | Global mitigation costs in cost-effective scenarios[1] and estimated cost increases due to assumed limited availability of specific technologies and delayed additional mitigation. Cost estimates shown in this table do not consider the benefits of reduced climate change as well as co-benefits and adverse side-effects of mitigation. The yellow columns show consumption losses in the years 2030, 2050, and 2100 and annualized consumption growth reductions over the century in cost-effective scenarios relative to a baseline development without climate policy. The grey columns show the percentage increase in discounted costs[2] over the century, relative to cost-effective scenarios, in scenarios in which technology is constrained relative to default technology assumptions.[3] The orange columns show the increase in mitigation costs over the periods 2030–2050 and 2050–2100, relative to scenarios with immediate mitigation, due to delayed additional mitigation through 2030.[4] These scenarios with delayed additional mitigation are grouped by emission levels of less or more than 55 $GtCO_2eq$ in 2030, and two concentration ranges in 2100 (430–530 ppm CO_2eq and 530–650 ppm CO_2eq). In all figures, the median of the scenario set is shown without parentheses, the range between the 16th and 84th percentile of the scenario set is shown in the parentheses, and the number of scenarios in the set is shown in square brackets.[5] [Figures TS.12, TS.13, 6.21, 6.24, 6.25, Annex II.10]

	Consumption losses in cost-effective scenarios[1]				Increase in total discounted mitigation costs in scenarios with limited availability of technologies				Increase in medium- and long-term mitigation costs due to delayed additional mitigation until 2030			
	[% reduction in consumption relative to baseline]			[percentage point reduction in annualized consumption growth rate]	[% increase in total discounted mitigation costs (2015–2100) relative to default technology assumptions]				[% increase in mitigation costs relative to immediate mitigation]			
									≤55 $GtCO_2eq$		>55 $GtCO_2eq$	
2100 Concentration [ppm CO_2eq]	2030	2050	2100	2010–2100	No CCS	Nuclear phase out	Limited Solar/Wind	Limited Bioenergy	2030–2050	2050–2100	2030–2050	2050–2100
450 (430–480)	1.7 (1.0–3.7) [N: 14]	3.4 (2.1–6.2)	4.8 (2.9–11.4)	0.06 (0.04–0.14)	138 (29–297) [N: 4]	7 (4–18) [N: 8]	6 (2–29) [N: 8]	64 (44–78) [N: 8]	28 (14–50) [N: 34]	15 (5–59)	44 (2–78) [N: 29]	37 (16–82)
500 (480–530)	1.7 (0.6–2.1) [N: 32]	2.7 (1.5–4.2)	4.7 (2.4–10.6)	0.06 (0.03–0.13)	N/A	N/A	N/A	N/A				
550 (530–580)	0.6 (0.2–1.3) [N: 46]	1.7 (1.2–3.3)	3.8 (1.2–7.3)	0.04 (0.01–0.09)	39 (18–78) [N: 11]	13 (2–23) [N: 10]	8 (5–15) [N: 10]	18 (4–66) [N: 12]	3 (−5–16) [N: 14]	4 (−4–11)	15 (3–32) [N: 10]	16 (5–24)
580–650	0.3 (0–0.9) [N: 16]	1.3 (0.5–2.0)	2.3 (1.2–4.4)	0.03 (0.01–0.05)	N/A	N/A	N/A	N/A				

1 Cost-effective scenarios assume immediate mitigation in all countries and a single global carbon price, and impose no additional limitations on technology relative to the models' default technology assumptions.

2 Percentage increase of net present value of consumption losses in percent of baseline consumption (for scenarios from general equilibrium models) and abatement costs in percent of baseline GDP (for scenarios from partial equilibrium models) for the period 2015–2100, discounted at 5 % per year.

3 No CCS: CCS is not included in these scenarios. Nuclear phase out: No addition of nuclear power plants beyond those under construction, and operation of existing plants until the end of their lifetime. Limited Solar/Wind: a maximum of 20 % global electricity generation from solar and wind power in any year of these scenarios. Limited Bioenergy: a maximum of 100 EJ/yr modern bioenergy supply globally (modern bioenergy used for heat, power, combinations, and industry was around 18 EJ/yr in 2008 [11.13.5]).

4 Percentage increase of total undiscounted mitigation costs for the periods 2030–2050 and 2050–2100.

5 The range is determined by the central scenarios encompassing the 16th and 84th percentile of the scenario set. Only scenarios with a time horizon until 2100 are included. Some models that are included in the cost ranges for concentration levels above 530 ppm CO_2eq in 2100 could not produce associated scenarios for concentration levels below 530 ppm CO_2eq in 2100 with assumptions about limited availability of technologies and/or delayed additional mitigation.

Estimates of the aggregate economic costs of mitigation vary widely and are highly sensitive to model design and assumptions as well as the specification of scenarios, including the characterization of technologies and the timing of mitigation (*high confidence*). Scenarios in which all countries of the world begin mitigation immediately, there is a single global carbon price, and all key technologies are available, have been used as a cost-effective benchmark for estimating macroeconomic mitigation costs (Table SPM.2, yellow segments). Under these assumptions, mitigation scenarios that reach atmospheric concentrations of about 450 ppm CO_2eq by 2100 entail losses in global consumption—not including benefits of reduced climate change as well as co-benefits and adverse side-effects of mitigation[19]—of 1 % to 4 % (median: 1.7 %) in 2030, 2 % to 6 % (median: 3.4 %) in 2050, and 3 % to 11 % (median: 4.8 %) in 2100 relative to consumption in baseline scenarios that grows anywhere from 300 % to more than 900 % over the century. These numbers

19 The total economic effect at different temperature levels would include mitigation costs, co-benefits of mitigation, adverse side-effects of mitigation, adaptation costs and climate damages. Mitigation cost and climate damage estimates at any given temperature level cannot be compared to evaluate the costs and benefits of mitigation. Rather, the consideration of economic costs and benefits of mitigation should include the reduction of climate damages relative to the case of unabated climate change.

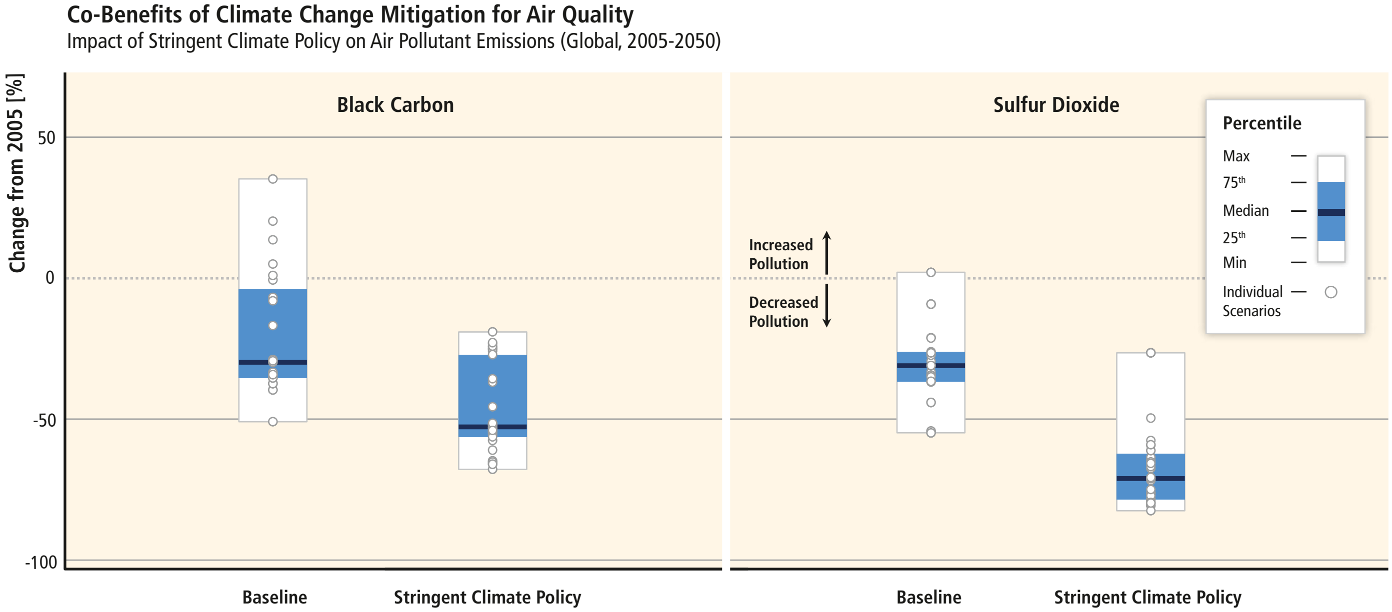

Figure SPM.6 | Air pollutant emission levels for black carbon (BC) and sulfur dioxide (SO_2) in 2050 relative to 2005 (0=2005 levels). Baseline scenarios without additional efforts to reduce GHG emissions beyond those in place today are compared to scenarios with stringent mitigation policies, which are consistent with reaching about 450 to about 500 (430–530) ppm CO_2eq concentrations by 2100. [Figure 6.33]

correspond to an annualized reduction of consumption growth by 0.04 to 0.14 (median: 0.06) percentage points over the century relative to annualized consumption growth in the baseline that is between 1.6 % and 3 % per year. Estimates at the high end of these cost ranges are from models that are relatively inflexible to achieve the deep emissions reductions required in the long run to meet these goals and/or include assumptions about market imperfections that would raise costs. Under the absence or limited availability of technologies, mitigation costs can increase substantially depending on the technology considered (Table SPM.2, grey segment). Delaying additional mitigation further increases mitigation costs in the medium- to long-term (Table SPM.2, orange segment). Many models could not achieve atmospheric concentration levels of about 450 ppm CO_2eq by 2100 if additional mitigation is considerably delayed or under limited availability of key technologies, such as bioenergy, CCS, and their combination (BECCS). [6.3]

Only a limited number of studies have explored scenarios that are *more likely than not* to bring temperature change back to below 1.5 °C by 2100 relative to pre-industrial levels; these scenarios bring atmospheric concentrations to below 430 ppm CO_2eq by 2100 (*high confidence*). Assessing this goal is currently difficult because no multi-model studies have explored these scenarios. Scenarios associated with the limited number of published studies exploring this goal are characterized by (1) immediate mitigation action; (2) the rapid upscaling of the full portfolio of mitigation technologies; and (3) development along a low-energy demand trajectory.[20] [6.3, 7.11]

Mitigation scenarios reaching about 450 to about 500 ppm CO_2eq by 2100 show reduced costs for achieving air quality and energy security objectives, with significant co-benefits for human health, ecosystem impacts, and sufficiency of resources and resilience of the energy system; these scenarios did not quantify other co-benefits or adverse side-effects (*medium confidence*). These mitigation scenarios show improvements in terms of the sufficiency of resources to meet national energy demand as well as the resilience of energy supply, resulting in energy systems that are less vulnerable to price volatility and supply disruptions. The benefits from reduced impacts to

[20] In these scenarios, the cumulative CO_2 emissions range between 680 and 800 $GtCO_2$ for the period 2011–2050 and between 90 and 310 $GtCO_2$ for the period 2011–2100. Global CO_2eq emissions in 2050 are between 70 and 95 % below 2010 emissions, and they are between 110 and 120 % below 2010 emissions in 2100.

health and ecosystems associated with major cuts in air pollutant emissions (Figure SPM.6) are particularly high where currently legislated and planned air pollution controls are weak. There is a wide range of co-benefits and adverse side-effects for additional objectives other than air quality and energy security. Overall, the potential for co-benefits of energy end-use measures outweighs the potential for adverse side-effects, whereas the evidence suggests this may not be the case for all energy supply and AFOLU measures. [WGIII 4.8, 5.7, 6.3.6, 6.6, 7.9, 8.7, 9.7, 10.8, 11.7, 11.13.6, 12.8, Figure TS.14, Table 6.7, Tables TS.3–TS.7; WGII 11.9]

There is a wide range of possible adverse side-effects as well as co-benefits and spillovers from climate policy that have not been well-quantified (*high confidence*). Whether or not side-effects materialize, and to what extent side-effects materialize, will be case- and site-specific, as they will depend on local circumstances and the scale, scope, and pace of implementation. Important examples include biodiversity conservation, water availability, food security, income distribution, efficiency of the taxation system, labour supply and employment, urban sprawl, and the sustainability of the growth of developing countries. [Box TS.11]

Mitigation efforts and associated costs vary between countries in mitigation scenarios. The distribution of costs across countries can differ from the distribution of the actions themselves (*high confidence*). In globally cost-effective scenarios, the majority of mitigation efforts takes place in countries with the highest future emissions in baseline scenarios. Some studies exploring particular effort-sharing frameworks, under the assumption of a global carbon market, have estimated substantial global financial flows associated with mitigation for scenarios leading to 2100 atmospheric concentrations of about 450 to about 550 ppm CO_2eq. [4.6, 6.3.6, 13.4.2.4; Box 3.5; Table 6.4; Figures 6.9, 6.27, 6.28, 6.29]

Mitigation policy could devalue fossil fuel assets and reduce revenues for fossil fuel exporters, but differences between regions and fuels exist (*high confidence*). Most mitigation scenarios are associated with reduced revenues from coal and oil trade for major exporters (*high confidence*). The effect of mitigation on natural gas export revenues is more uncertain, with some studies showing possible benefits for export revenues in the medium term until about 2050 (*medium confidence*). The availability of CCS would reduce the adverse effect of mitigation on the value of fossil fuel assets (*medium confidence*). [6.3.6, 6.6, 14.4.2]

SPM.4.2 Sectoral and cross-sectoral mitigation pathways and measures

SPM.4.2.1 Cross-sectoral mitigation pathways and measures

In baseline scenarios, GHG emissions are projected to grow in all sectors, except for net CO_2 emissions in the AFOLU sector[21] (*robust evidence, medium agreement*). Energy supply sector emissions are expected to continue to be the major source of GHG emissions, ultimately accounting for the significant increases in indirect emissions from electricity use in the buildings and industry sectors. In baseline scenarios, while non-CO_2 GHG agricultural emissions are projected to increase, net CO_2 emissions from the AFOLU sector decline over time, with some models projecting a net sink towards the end of the century (Figure SPM.7).[22] [6.3.1.4, 6.8, Figure TS.15]

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21 Net AFOLU CO_2 emissions include emissions and removals of CO_2 from the AFOLU sector, including land under forestry and, in some assessments, CO_2 sinks in agricultural soils.

22 A majority of the Earth System Models assessed in WGI project a continued land carbon uptake under all RCPs through to 2100, but some models simulate a land carbon loss due to the combined effect of climate change and land-use change. [WGI SPM.E.7, WGI 6.4]

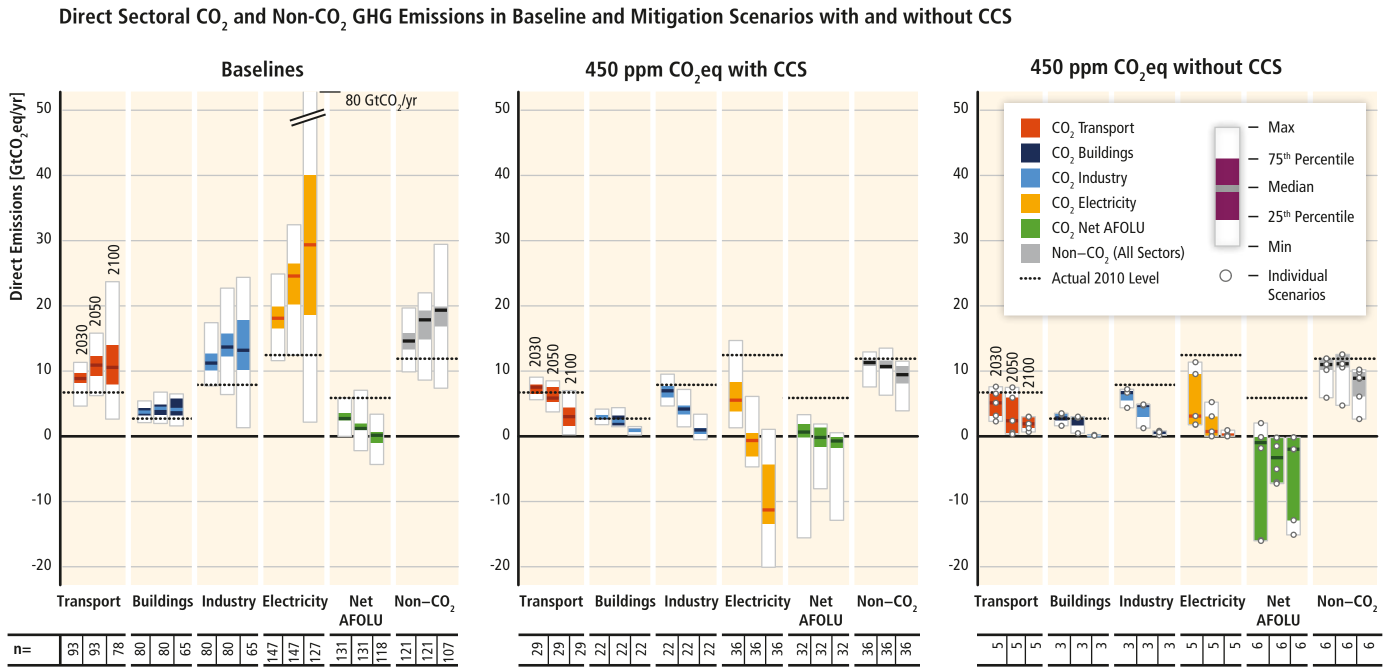

Figure SPM.7 | Direct emissions of CO_2 by sector and total non-CO_2 GHGs (Kyoto gases) across sectors in baseline (left panel) and mitigation scenarios that reach around 450 (430–480) ppm CO_2eq with CCS (middle panel) and without CCS (right panel). The numbers at the bottom of the graphs refer to the number of scenarios included in the range which differs across sectors and time due to different sectoral resolution and time horizon of models. Note that many models cannot reach about 450 ppm CO_2eq concentration by 2100 in the absence of CCS, resulting in a low number of scenarios for the right panel. [Figures 6.34 and 6.35]

Infrastructure developments and long-lived products that lock societies into GHG-intensive emissions pathways may be difficult or very costly to change, reinforcing the importance of early action for ambitious mitigation (*robust evidence, high agreement*). This lock-in risk is compounded by the lifetime of the infrastructure, by the difference in emissions associated with alternatives, and the magnitude of the investment cost. As a result, lock-in related to infrastructure and spatial planning is the most difficult to reduce. However, materials, products and infrastructure with long lifetimes and low lifecycle emissions can facilitate a transition to low-emission pathways while also reducing emissions through lower levels of material use. [5.6.3, 6.3.6.4, 9.4, 10.4, 12.3, 12.4]

There are strong interdependencies in mitigation scenarios between the pace of introducing mitigation measures in energy supply and energy end-use and developments in the AFOLU sector (*high confidence*). The distribution of the mitigation effort across sectors is strongly influenced by the availability and performance of BECCS and large scale afforestation (Figure SPM.7). This is particularly the case in scenarios reaching CO_2eq concentrations of about 450 ppm by 2100. Well-designed systemic and cross-sectoral mitigation strategies are more cost-effective in cutting emissions than a focus on individual technologies and sectors. At the energy system level these include reductions in the GHG emission intensity of the energy supply sector, a switch to low-carbon energy carriers (including low-carbon electricity) and reductions in energy demand in the end-use sectors without compromising development (Figure SPM.8). [6.3.5, 6.4, 6.8, 7.11, Table TS.2]

Mitigation scenarios reaching around 450 ppm CO_2eq concentrations by 2100 show large-scale global changes in the energy supply sector (*robust evidence, high agreement*). In these selected scenarios, global CO_2 emissions from the energy supply sector are projected to decline over the next decades and are characterized by reductions of 90 % or more below 2010 levels between 2040 and 2070. Emissions in many of these scenarios are projected to decline to below zero thereafter. [6.3.4, 6.8, 7.1, 7.11]

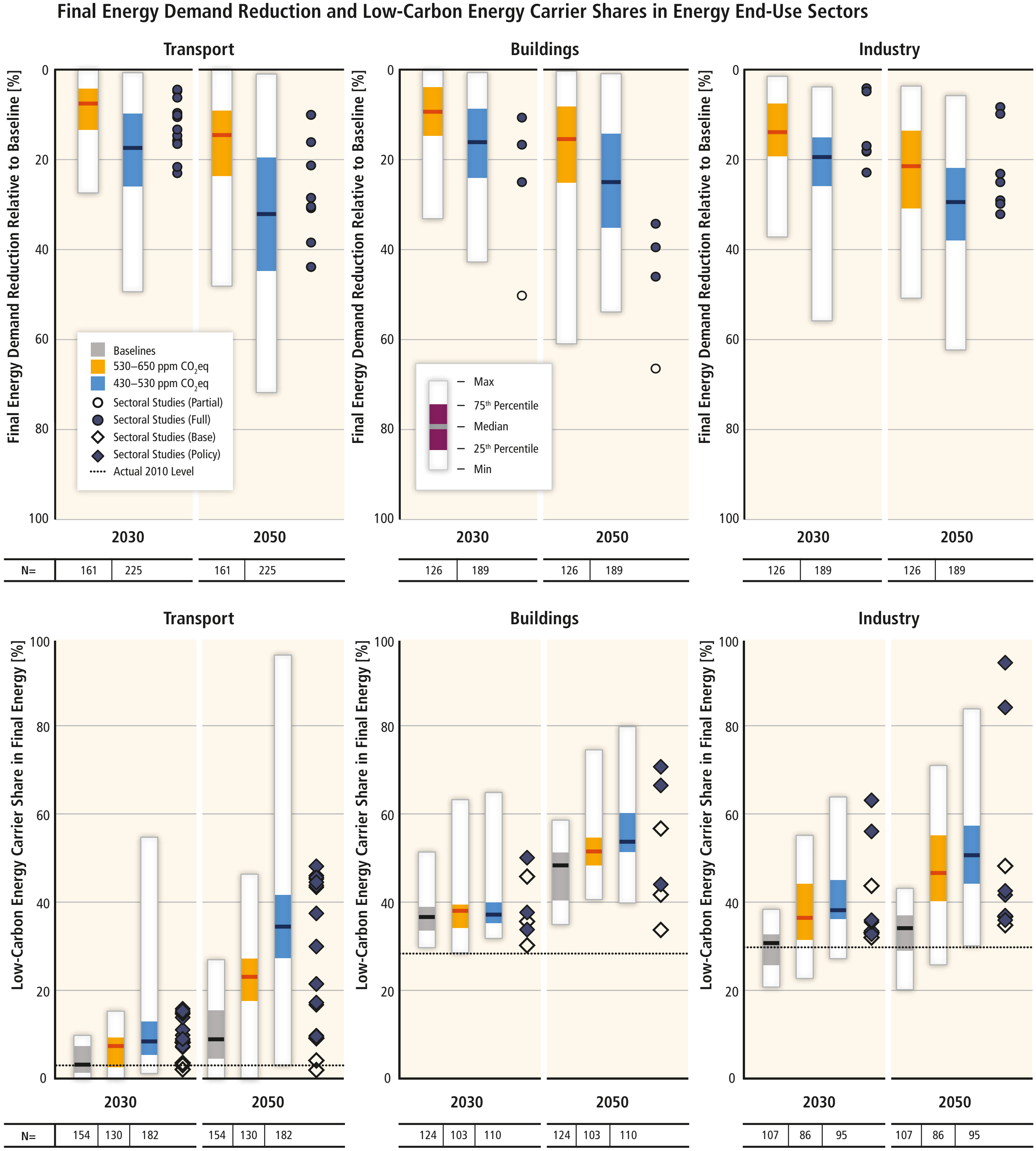

Figure SPM.8 | Final energy demand reduction relative to baseline (upper row) and low-carbon energy carrier shares in final energy (lower row) in the transport, buildings, and industry sectors by 2030 and 2050 in scenarios from two different CO_2eq concentration categories compared to sectoral studies assessed in Chapters 8–10. The demand reductions shown by these scenarios do not compromise development. Low-carbon energy carriers include electricity, hydrogen and liquid biofuels in transport, electricity in buildings and electricity, heat, hydrogen and bioenergy in industry. The numbers at the bottom of the graphs refer to the number of scenarios included in the ranges which differ across sectors and time due to different sectoral resolution and time horizon of models. [Figures 6.37 and 6.38]

Efficiency enhancements and behavioural changes, in order to reduce energy demand compared to baseline scenarios without compromising development, are a key mitigation strategy in scenarios reaching atmospheric CO_2eq concentrations of about 450 to about 500 ppm by 2100 (*robust evidence, high agreement*). Near-term reductions in energy demand are an important element of cost-effective mitigation strategies, provide more flexibility for reducing carbon intensity in the energy supply sector, hedge against related supply-side risks, avoid lock-in to carbon-intensive infrastructures, and are associated with important co-benefits. Both integrated and sectoral studies provide similar estimates for energy demand reductions in the transport, buildings and industry sectors for 2030 and 2050 (Figure SPM.8). [6.3.4, 6.6, 6.8, 7.11, 8.9, 9.8, 10.10]

Behaviour, lifestyle and culture have a considerable influence on energy use and associated emissions, with high mitigation potential in some sectors, in particular when complementing technological and structural change[23] (*medium evidence, medium agreement*). Emissions can be substantially lowered through changes in consumption patterns (e.g., mobility demand and mode, energy use in households, choice of longer-lasting products) and dietary change and reduction in food wastes. A number of options including monetary and non-monetary incentives as well as information measures may facilitate behavioural changes. [6.8, 7.9, 8.3.5, 8.9, 9.2, 9.3, 9.10, Box 10.2, 10.4, 11.4, 12.4, 12.6, 12.7, 15.3, 15.5, Table TS.2]

SPM.4.2.2 Energy supply

In the baseline scenarios assessed in AR5, direct CO_2 emissions from the energy supply sector are projected to almost double or even triple by 2050 compared to the level of 14.4 $GtCO_2$/year in 2010, unless energy intensity improvements can be significantly accelerated beyond the historical development (*medium evidence, medium agreement*). In the last decade, the main contributors to emission growth were a growing energy demand and an increase of the share of coal in the global fuel mix. The availability of fossil fuels alone will not be sufficient to limit CO_2eq concentration to levels such as 450 ppm, 550 ppm, or 650 ppm. (Figure SPM.7) [6.3.4, 7.2, 7.3, Figures 6.15, TS.15]

Decarbonizing (i.e. reducing the carbon intensity of) electricity generation is a key component of cost-effective mitigation strategies in achieving low-stabilization levels (430–530 ppm CO_2eq); in most integrated modelling scenarios, decarbonization happens more rapidly in electricity generation than in the industry, buildings, and transport sectors (*medium evidence, high agreement*) (Figure SPM.7). In the majority of low-stabilization scenarios, the share of low-carbon electricity supply (comprising renewable energy (RE), nuclear and CCS) increases from the current share of approximately 30 % to more than 80 % by 2050, and fossil fuel power generation without CCS is phased out almost entirely by 2100 (Figure SPM. 7). [6.8, 7.11, Figures 7.14, TS.18]

Since AR4, many RE technologies have demonstrated substantial performance improvements and cost reductions, and a growing number of RE technologies have achieved a level of maturity to enable deployment at significant scale (*robust evidence, high agreement*). Regarding electricity generation alone, RE accounted for just over half of the new electricity-generating capacity added globally in 2012, led by growth in wind, hydro and solar power. However, many RE technologies still need direct and/or indirect support, if their market shares are to be significantly increased; RE technology policies have been successful in driving recent growth of RE. Challenges for integrating RE into energy systems and the associated costs vary by RE technology, regional circumstances, and the characteristics of the existing background energy system (*medium evidence, medium agreement*). [7.5.3, 7.6.1, 7.8.2, 7.12, Table 7.1]

Nuclear energy is a mature low-GHG emission source of baseload power, but its share of global electricity generation has been declining (since 1993). Nuclear energy could make an increasing contribution to low-carbon energy supply, but a variety of barriers and risks exist (*robust evidence, high agreement*). Those include:

[23] Structural changes refer to systems transformations whereby some components are either replaced or potentially substituted by other components (see WGIII AR5 Glossary).

operational risks, and the associated concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapon proliferation concerns, and adverse public opinion (*robust evidence, high agreement*). New fuel cycles and reactor technologies addressing some of these issues are being investigated and progress in research and development has been made concerning safety and waste disposal. [7.5.4, 7.8, 7.9, 7.12, Figure TS.19]

GHG emissions from energy supply can be reduced significantly by replacing current world average coal-fired power plants with modern, highly efficient natural gas combined-cycle power plants or combined heat and power plants, provided that natural gas is available and the fugitive emissions associated with extraction and supply are low or mitigated (*robust evidence, high agreement*). In mitigation scenarios reaching about 450 ppm CO_2eq concentrations by 2100, natural gas power generation without CCS acts as a bridge technology, with deployment increasing before peaking and falling to below current levels by 2050 and declining further in the second half of the century (*robust evidence, high agreement*). [7.5.1, 7.8, 7.9, 7.11, 7.12]

Carbon dioxide capture and storage (CCS) technologies could reduce the lifecycle GHG emissions of fossil fuel power plants (*medium evidence, medium agreement*). While all components of integrated CCS systems exist and are in use today by the fossil fuel extraction and refining industry, CCS has not yet been applied at scale to a large, operational commercial fossil fuel power plant. CCS power plants could be seen in the market if this is incentivized by regulation and/or if they become competitive with their unabated counterparts, for instance, if the additional investment and operational costs, caused in part by efficiency reductions, are compensated by sufficiently high carbon prices (or direct financial support). For the large-scale future deployment of CCS, well-defined regulations concerning short- and long-term responsibilities for storage are needed as well as economic incentives. Barriers to large-scale deployment of CCS technologies include concerns about the operational safety and long-term integrity of CO_2 storage as well as transport risks. There is, however, a growing body of literature on how to ensure the integrity of CO_2 wells, on the potential consequences of a pressure build-up within a geologic formation caused by CO_2 storage (such as induced seismicity), and on the potential human health and environmental impacts from CO_2 that migrates out of the primary injection zone (*limited evidence, medium agreement*). [7.5.5., 7.8, 7.9, 7.11, 7.12, 11.13]

Combining bioenergy with CCS (BECCS) offers the prospect of energy supply with large-scale net negative emissions which plays an important role in many low-stabilization scenarios, while it entails challenges and risks (*limited evidence, medium agreement*). These challenges and risks include those associated with the upstream large-scale provision of the biomass that is used in the CCS facility as well as those associated with the CCS technology itself. [7.5.5, 7.9, 11.13]

SPM.4.2.3 Energy end-use sectors

Transport

The transport sector accounted for 27 % of final energy use and 6.7 $GtCO_2$ direct emissions in 2010, with baseline CO_2 emissions projected to approximately double by 2050 (*medium evidence, medium agreement*). This growth in CO_2 emissions from increasing global passenger and freight activity could partly offset future mitigation measures that include fuel carbon and energy intensity improvements, infrastructure development, behavioural change and comprehensive policy implementation (*high confidence*). Overall, reductions in total transport CO_2 emissions of 15–40 % compared to baseline growth could be achieved in 2050 (*medium evidence, medium agreement*). (Figure SPM.7) [6.8, 8.1, 8.2, 8.9, 8.10]

Technical and behavioural mitigation measures for all transport modes, plus new infrastructure and urban redevelopment investments, could reduce final energy demand in 2050 by around 40 % below the baseline, with the mitigation potential assessed to be higher than reported in the AR4 (*robust evidence, medium agreement*). Projected energy efficiency and vehicle performance improvements range from 30–50 % in 2030 relative to 2010 depending on transport mode and vehicle type (*medium evidence, medium agreement*). Integrated urban planning, transit-oriented development, more compact urban form that supports cycling and walking, can all lead to modal shifts as can, in the longer term, urban redevelopment and investments in new infrastructure such as high-speed rail systems that reduce short-haul air travel demand (*medium evidence, medium agreement*). Such mitigation measures are challenging, have uncertain outcomes, and could reduce transport GHG emissions by 20–50 % in 2050 compared to baseline (*limited evidence, low agreement*). (Figure SPM.8 upper panel) [8.2, 8.3, 8.4, 8.5, 8.6, 8.7, 8.8, 8.9, 12.4, 12.5]

Strategies to reduce the carbon intensities of fuel and the rate of reducing carbon intensity are constrained by challenges associated with energy storage and the relatively low energy density of low-carbon transport fuels (*medium confidence*). Integrated and sectoral studies broadly agree that opportunities for switching to low-carbon fuels exist in the near term and will grow over time. Methane-based fuels are already increasing their share for road vehicles and waterborne craft. Electricity produced from low-carbon sources has near-term potential for electric rail and short- to medium-term potential as electric buses, light-duty and 2-wheel road vehicles are deployed. Hydrogen fuels from low-carbon sources constitute longer-term options. Commercially available liquid and gaseous biofuels already provide co-benefits together with mitigation options that can be increased by technology advances. Reducing transport emissions of particulate matter (including black carbon), tropospheric ozone and aerosol precursors (including NO_x) can have human health and mitigation co-benefits in the short term (*medium evidence, medium agreement*). [8.2, 8.3, 11.13, Figure TS.20, right panel]

The cost-effectiveness of different carbon reduction measures in the transport sector varies significantly with vehicle type and transport mode (*high confidence*). The levelized costs of conserved carbon can be very low or negative for many short-term behavioural measures and efficiency improvements for light- and heavy-duty road vehicles and waterborne craft. In 2030, for some electric vehicles, aircraft and possibly high-speed rail, levelized costs could be more than USD100/tCO_2 avoided (*limited evidence, medium agreement*). [8.6, 8.8, 8.9, Figures TS.21, TS.22]

Regional differences influence the choice of transport mitigation options (*high confidence*). Institutional, legal, financial and cultural barriers constrain low-carbon technology uptake and behavioural change. Established infrastructure may limit the options for modal shift and lead to a greater reliance on advanced vehicle technologies; a slowing of growth in light-duty vehicle demand is already evident in some OECD countries. For all economies, especially those with high rates of urban growth, investment in public transport systems and low-carbon infrastructure can avoid lock-in to carbon-intensive modes. Prioritizing infrastructure for pedestrians and integrating non-motorized and transit services can create economic and social co-benefits in all regions (*medium evidence, medium agreement*). [8.4, 8.8, 8.9, 14.3, Table 8.3]

Mitigation strategies, when associated with non-climate policies at all government levels, can help decouple transport GHG emissions from economic growth in all regions (*medium confidence*). These strategies can help reduce travel demand, incentivise freight businesses to reduce the carbon intensity of their logistical systems and induce modal shifts, as well as provide co-benefits including improved access and mobility, better health and safety, greater energy security, and cost and time savings (*medium evidence, high agreement*). [8.7, 8.10]

Buildings

In 2010, the buildings sector[24] accounted for around 32 % final energy use and 8.8 $GtCO_2$ emissions, including direct and indirect emissions, with energy demand projected to approximately double and CO_2 emissions to increase by 50–150 % by mid-century in baseline scenarios (*medium evidence, medium agreement*). This energy demand growth results from improvements in wealth, lifestyle change, access to modern energy services and adequate housing, and urbanisation. There are significant lock-in risks associated with the long lifespans of buildings and related infrastructure, and these are especially important in regions with high construction rates (*robust evidence, high agreement*). (Figure SPM.7) [9.4]

[24] The buildings sector covers the residential, commercial, public and services sectors; emissions from construction are accounted for in the industry sector.

Recent advances in technologies, know-how and policies provide opportunities to stabilize or reduce global buildings sector energy use by mid-century (*robust evidence, high agreement*). For new buildings, the adoption of very low energy building codes is important and has progressed substantially since AR4. Retrofits form a key part of the mitigation strategy in countries with established building stocks, and reductions of heating/cooling energy use by 50–90 % in individual buildings have been achieved. Recent large improvements in performance and costs make very low energy construction and retrofits economically attractive, sometimes even at net negative costs. [9.3]

Lifestyle, culture and behaviour significantly influence energy consumption in buildings (*limited evidence, high agreement*). A three- to five-fold difference in energy use has been shown for provision of similar building-related energy service levels in buildings. For developed countries, scenarios indicate that lifestyle and behavioural changes could reduce energy demand by up to 20 % in the short term and by up to 50 % of present levels by mid-century. In developing countries, integrating elements of traditional lifestyles into building practices and architecture could facilitate the provision of high levels of energy services with much lower energy inputs than baseline. [9.3]

Most mitigation options for buildings have considerable and diverse co-benefits in addition to energy cost savings (*robust evidence, high agreement*). These include improvements in energy security, health (such as from cleaner wood-burning cookstoves), environmental outcomes, workplace productivity, fuel poverty reductions and net employment gains. Studies which have monetized co-benefits often find that these exceed energy cost savings and possibly climate benefits (*medium evidence, medium agreement*). [9.6, 9.7, 3.6.3]

Strong barriers, such as split incentives (e.g., tenants and builders), fragmented markets and inadequate access to information and financing, hinder the market-based uptake of cost-effective opportunities. Barriers can be overcome by policy interventions addressing all stages of the building and appliance lifecycles (*robust evidence, high agreement*). [9.8, 9.10, 16, Box 3.10]

The development of portfolios of energy efficiency policies and their implementation has advanced considerably since AR4. Building codes and appliance standards, if well designed and implemented, have been among the most environmentally and cost-effective instruments for emission reductions (*robust evidence, high agreement*). In some developed countries they have contributed to a stabilization of, or reduction in, total energy demand for buildings. Substantially strengthening these codes, adopting them in further jurisdictions, and extending them to more building and appliance types, will be a key factor in reaching ambitious climate goals. [9.10, 2.6.5.3]

Industry

In 2010, the industry sector accounted for around 28 % of final energy use, and 13 $GtCO_2$ emissions, including direct and indirect emissions as well as process emissions, with emissions projected to increase by 50–150 % by 2050 in the baseline scenarios assessed in AR5, unless energy efficiency improvements are accelerated significantly (*medium evidence, medium agreement*). Emissions from industry accounted for just over 30 % of global GHG emissions in 2010 and are currently greater than emissions from either the buildings or transport end-use sectors. (Figures SPM.2, SPM.7) [10.3]

The energy intensity of the industry sector could be directly reduced by about 25 % compared to the current level through the wide-scale upgrading, replacement and deployment of best available technologies, particularly in countries where these are not in use and in non-energy intensive industries (*high agreement, robust evidence*). Additional energy intensity reductions of about 20 % may potentially be realized through innovation (*limited evidence, medium agreement*). Barriers to implementing energy efficiency relate largely to initial investment costs and lack of information. Information programmes are a prevalent approach for promoting energy efficiency, followed by economic instruments, regulatory approaches and voluntary actions. [10.7, 10.9, 10.11]

Improvements in GHG emission efficiency and in the efficiency of material use, recycling and re-use of materials and products, and overall reductions in product demand (e.g., through a more intensive use of products) and service demand could, in addition to energy efficiency, help reduce GHG emissions below the baseline level in the industry sector (*medium evidence, high agreement*). Many emission-reducing options are cost-effective, profitable and associated with multiple co-benefits (better environmental compliance, health benefits etc.). In the long term, a shift to low-carbon electricity, new industrial processes, radical product innovations (e.g., alternatives to cement), or CCS (e.g., to mitigate process emissions) could contribute to significant GHG emission reductions. Lack of policy and experiences in material and product service efficiency are major barriers. [10.4, 10.7, 10.8, 10.11]

CO_2 emissions dominate GHG emissions from industry, but there are also substantial mitigation opportunities for non-CO_2 gases (*robust evidence, high agreement*). CH_4, N_2O and fluorinated gases from industry accounted for emissions of 0.9 $GtCO_2eq$ in 2010. Key mitigation opportunities include, e.g., the reduction of hydrofluorocarbon emissions by process optimization and refrigerant recovery, recycling and substitution, although there are barriers. [Tables 10.2, 10.7]

Systemic approaches and collaborative activities across companies and sectors can reduce energy and material consumption and thus GHG emissions (*robust evidence, high agreement*). The application of cross-cutting technologies (e.g., efficient motors) and measures (e.g., reducing air or steam leaks) in both large energy intensive industries and small and medium enterprises can improve process performance and plant efficiency cost-effectively. Cooperation across companies (e.g., in industrial parks) and sectors could include the sharing of infrastructure, information, and waste heat utilization. [10.4, 10.5]

Important options for mitigation in waste management are waste reduction, followed by re-use, recycling and energy recovery (*robust evidence, high agreement*). Waste and wastewater accounted for 1.5 $GtCO_2eq$ in 2010. As the share of recycled or reused material is still low (e.g., globally, around 20 % of municipal solid waste is recycled), waste treatment technologies and recovering energy to reduce demand for fossil fuels can result in significant direct emission reductions from waste disposal. [10.4, 10.14]

SPM.4.2.4 Agriculture, Forestry and Other Land Use (AFOLU)

The AFOLU sector accounts for about a quarter (~10–12 $GtCO_2eq/yr$) of net anthropogenic GHG emissions mainly from deforestation, agricultural emissions from soil and nutrient management and livestock (*medium evidence, high agreement*). Most recent estimates indicate a decline in AFOLU CO_2 fluxes, largely due to decreasing deforestation rates and increased afforestation. However, the uncertainty in historical net AFOLU emissions is larger than for other sectors, and additional uncertainties in projected baseline net AFOLU emissions exist. Nonetheless, in the future, net annual baseline CO_2 emissions from AFOLU are projected to decline, with net emissions potentially less than half the 2010 level by 2050 and the possibility of the AFOLU sectors becoming a net CO_2 sink before the end of century (*medium evidence, high agreement*). (Figure SPM. 7) [6.3.1.4, 11.2, Figure 6.5]

AFOLU plays a central role for food security and sustainable development. The most cost-effective mitigation options in forestry are afforestation, sustainable forest management and reducing deforestation, with large differences in their relative importance across regions. In agriculture, the most cost-effective mitigation options are cropland management, grazing land management, and restoration of organic soils (*medium evidence, high agreement*). The economic mitigation potential of supply-side measures is estimated to be 7.2 to 11 $GtCO_2eq/year$[25] in 2030 for mitigation efforts consistent with carbon prices[26] up to 100 USD/tCO_2eq, about a third of which can be achieved at a <20 USD/tCO_2eq (*medium evidence, medium agreement*). There are potential barriers to

[25] Full range of all studies: 0.49–11 $GtCO_2eq/year$

[26] In many models that are used to assess the economic costs of mitigation, carbon price is used as a proxy to represent the level of effort in mitigation policies (see WGIII AR5 Glossary).

implementation of available mitigation options [11.7, 11.8]. Demand-side measures, such as changes in diet and reductions of losses in the food supply chain, have a significant, but uncertain, potential to reduce GHG emissions from food production (*medium evidence, medium agreement*). Estimates vary from roughly 0.76–8.6 $GtCO_2eq/yr$ by 2050 (*limited evidence, medium agreement*). [11.4, 11.6, Figure 11.14]

Policies governing agricultural practices and forest conservation and management are more effective when involving both mitigation and adaptation. Some mitigation options in the AFOLU sector (such as soil and forest carbon stocks) may be vulnerable to climate change (*medium evidence, high agreement*). When implemented sustainably, activities to reduce emissions from deforestation and forest degradation (REDD+[27] is an example designed to be sustainable) are cost-effective policy options for mitigating climate change, with potential economic, social and other environmental and adaptation co-benefits (e.g., conservation of biodiversity and water resources, and reducing soil erosion) (*limited evidence, medium agreement*). [11.3.2, 11.10]

Bioenergy can play a critical role for mitigation, but there are issues to consider, such as the sustainability of practices and the efficiency of bioenergy systems (*robust evidence, medium agreement*) [11.4.4, Box 11.5, 11.13.6, 11.13.7]. Barriers to large-scale deployment of bioenergy include concerns about GHG emissions from land, food security, water resources, biodiversity conservation and livelihoods. The scientific debate about the overall climate impact related to land-use competition effects of specific bioenergy pathways remains unresolved (*robust evidence, high agreement*). [11.4.4, 11.13] Bioenergy technologies are diverse and span a wide range of options and technology pathways. Evidence suggests that options with low lifecycle emissions (e.g., sugar cane, Miscanthus, fast growing tree species, and sustainable use of biomass residues), some already available, can reduce GHG emissions; outcomes are site-specific and rely on efficient integrated 'biomass-to-bioenergy systems', and sustainable land-use management and governance. In some regions, specific bioenergy options, such as improved cookstoves, and small-scale biogas and biopower production, could reduce GHG emissions and improve livelihoods and health in the context of sustainable development (*medium evidence, medium agreement*). [11.13]

SPM.4.2.5 Human settlements, infrastructure and spatial planning

Urbanization is a global trend and is associated with increases in income, and higher urban incomes are correlated with higher consumption of energy and GHG emissions (*medium evidence, high agreement*). As of 2011, more than 52 % of the global population lives in urban areas. In 2006, urban areas accounted for 67–76 % of energy use and 71–76 % of energy-related CO_2 emissions. By 2050, the urban population is expected to increase to 5.6–7.1 billion, or 64–69 % of world population. Cities in non-Annex I countries generally have higher levels of energy use compared to the national average, whereas cities in Annex I countries generally have lower energy use per capita than national averages (*medium evidence, medium agreement*). [12.2, 12.3]

The next two decades present a window of opportunity for mitigation in urban areas, as a large portion of the world's urban areas will be developed during this period (*limited evidence, high agreement*). Accounting for trends in declining population densities, and continued economic and population growth, urban land cover is projected to expand by 56–310 % between 2000 and 2030. [12.2, 12.3, 12.4, 12.8]

Mitigation options in urban areas vary by urbanization trajectories and are expected to be most effective when policy instruments are bundled (*robust evidence, high agreement*). Infrastructure and urban form are strongly interlinked, and lock-in patterns of land use, transport choice, housing, and behaviour. Effective mitigation strategies involve packages of mutually reinforcing policies, including co-locating high residential with high employment densities,

[27] See WGIII AR5 Glossary.

achieving high diversity and integration of land uses, increasing accessibility and investing in public transport and other demand management measures. [8.4, 12.3, 12.4, 12.5, 12.6]

The largest mitigation opportunities with respect to human settlements are in rapidly urbanizing areas where urban form and infrastructure are not locked in, but where there are often limited governance, technical, financial, and institutional capacities (*robust evidence, high agreement*). The bulk of urban growth is expected in small- to medium-size cities in developing countries. The feasibility of spatial planning instruments for climate change mitigation is highly dependent on a city's financial and governance capability. [12.6, 12.7]

Thousands of cities are undertaking climate action plans, but their aggregate impact on urban emissions is uncertain (*robust evidence, high agreement*). There has been little systematic assessment on their implementation, the extent to which emission reduction targets are being achieved, or emissions reduced. Current climate action plans focus largely on energy efficiency. Fewer climate action plans consider land-use planning strategies and cross-sectoral measures to reduce sprawl and promote transit-oriented development[28]. [12.6, 12.7, 12.9]

Successful implementation of urban-scale climate change mitigation strategies can provide co-benefits (*robust evidence, high agreement*). Urban areas throughout the world continue to struggle with challenges, including ensuring access to energy, limiting air and water pollution, and maintaining employment opportunities and competitiveness. Action on urban-scale mitigation often depends on the ability to relate climate change mitigation efforts to local co-benefits (*robust evidence, high agreement*). [12.5, 12.6, 12.7, 12.8]

SPM.5 Mitigation policies and institutions

SPM.5.1 Sectoral and national policies

Substantial reductions in emissions would require large changes in investment patterns. Mitigation scenarios in which policies stabilize atmospheric concentrations (without overshoot) in the range from 430 to 530 ppm CO_2eq by 2100 lead to substantial shifts in annual investment flows during the period 2010–2029 compared to baseline scenarios (Figure SPM.9). Over the next two decades (2010 to 2029), annual investment in conventional fossil fuel technologies associated with the electricity supply sector is projected to decline by about 30 (2–166) billion USD (median: −20 % compared to 2010) while annual investment in low-carbon electricity supply (i.e., renewables, nuclear and electricity generation with CCS) is projected to rise by about 147 (31–360) billion USD (median: +100 % compared to 2010) (*limited evidence, medium agreement*). For comparison, global total annual investment in the energy system is presently about 1200 billion USD. In addition, annual incremental energy efficiency investments in transport, buildings and industry is projected to increase by about 336 (1–641) billion USD (*limited evidence, medium agreement*), frequently involving modernization of existing equipment. [13.11, 16.2.2]

There is no widely agreed definition of what constitutes climate finance, but estimates of the financial flows associated with climate change mitigation and adaptation are available. Published assessments of all current annual financial flows whose expected effect is to reduce net GHG emissions and/or to enhance resilience to climate change and climate variability show 343 to 385 billion USD per year globally (*medium confidence*) [Box TS.14]. Most of this goes to mitigation. Out of this, total public climate finance that flowed to developing countries is estimated to be between 35 and 49 billion USD/yr in 2011 and 2012 (*medium confidence*). Estimates of international private climate

[28] See WGIII AR5 Glossary.

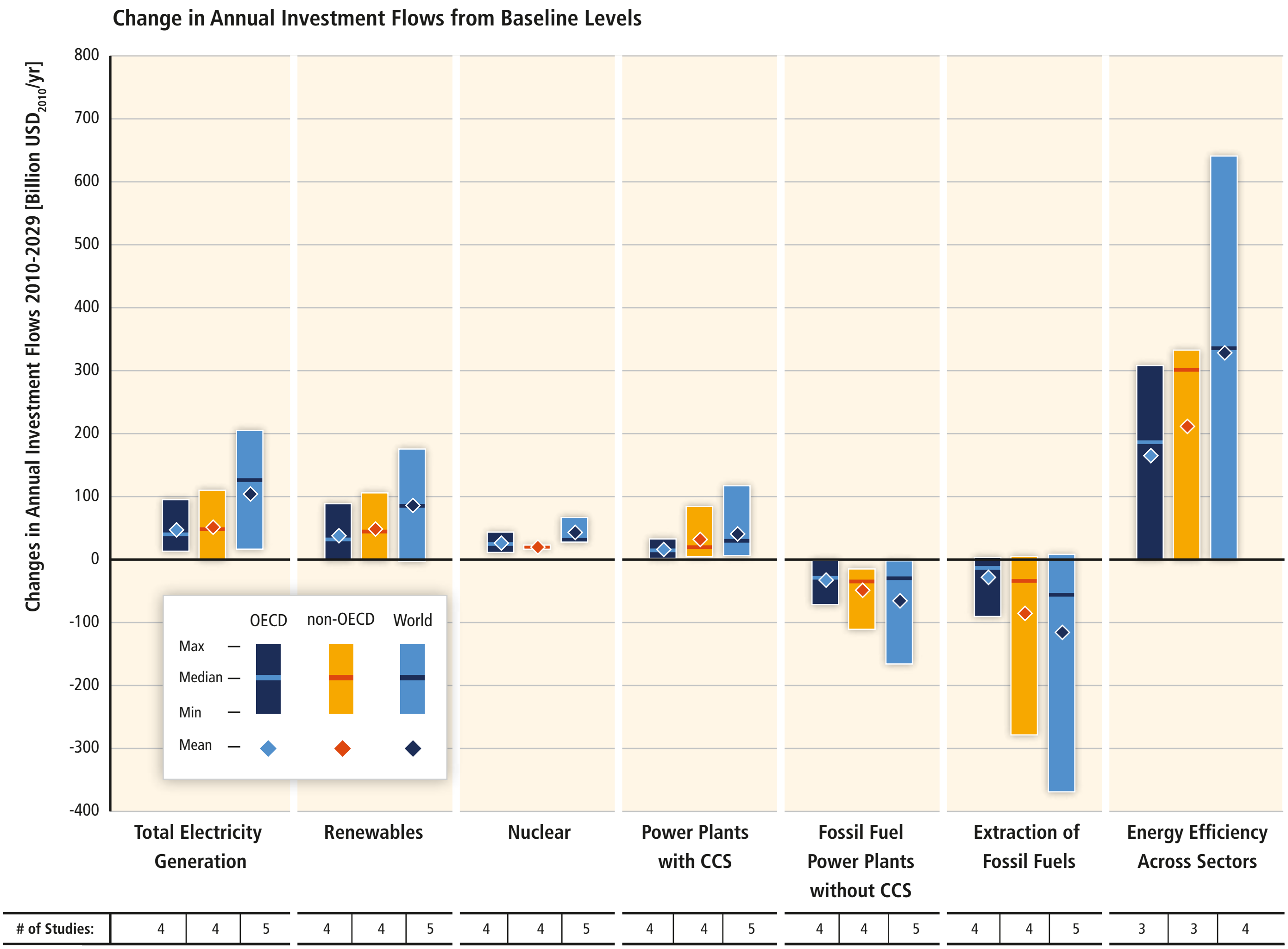

Figure SPM.9 | Change in annual investment flows from the average baseline level over the next two decades (2010–2029) for mitigation scenarios that stabilize concentrations within the range of approximately 430–530 ppm CO_2eq by 2100. Investment changes are based on a limited number of model studies and model comparisons. Total electricity generation (leftmost column) is the sum of renewables, nuclear, power plants with CCS and fossil fuel power plants without CCS. The vertical bars indicate the range between minimum and maximum estimate; the horizontal bar indicates the median. Proximity to this median value does not imply higher likelihood because of the different degree of aggregation of model results, the low number of studies available and different assumptions in the different studies considered. The numbers in the bottom row show the total number of studies in the literature used for the assessment. This underscores that investment needs are still an evolving area of research that relatively few studies have examined. [Figure 16.3]

finance flowing to developing countries range from 10 to 72 billion USD/yr including foreign direct investment as equity and loans in the range of 10 to 37 billion USD/yr over the period of 2008–2011 (*medium confidence*). [16.2.2]

There has been a considerable increase in national and sub-national mitigation plans and strategies since AR4. In 2012, 67 % of global GHG emissions were subject to national legislation or strategies versus 45 % in 2007. However, there has not yet been a substantial deviation in global emissions from the past trend [Figure 1.3c]. These plans and strategies are in their early stages of development and implementation in many countries, making it difficult to assess their aggregate impact on future global emissions (*medium evidence, high agreement*). [14.3.4, 14.3.5, 15.1, 15.2]

Since AR4, there has been an increased focus on policies designed to integrate multiple objectives, increase co-benefits and reduce adverse side-effects (*high confidence*). Governments often explicitly reference co-benefits in climate and sectoral plans and strategies. The scientific literature has sought to assess the size of co-benefits (see Section SPM.4.1) and the greater political feasibility and durability of policies that have large co-benefits and small adverse side-effects. [4.8, 5.7, 6.6, 13.2, 15.2] Despite the growing attention in policymaking and the scientific literature since AR4, the analytical and empirical underpinnings for understanding many of the interactive effects are under-developed [1.2, 3.6.3, 4.2, 4.8, 5.7, 6.6].

Sector-specific policies have been more widely used than economy-wide policies (*medium evidence, high agreement*). Although most economic theory suggests that economy-wide policies for the singular objective of mitigation would be more cost-effective than sector-specific policies, since AR4 a growing number of studies has demonstrated that administrative and political barriers may make economy-wide policies harder to design and implement than sector-specific policies. The latter may be better suited to address barriers or market failures specific to certain sectors, and may be bundled in packages of complementary policies. [6.3.6.5, 8.10, 9.10, 10.10, 15.2, 15.5, 15.8, 15.9]

Regulatory approaches and information measures are widely used, and are often environmentally effective (*medium evidence, medium agreement*). Examples of regulatory approaches include energy efficiency standards; examples of information programmes include labelling programmes that can help consumers make better-informed decisions. While such approaches have often been found to have a net social benefit, the scientific literature is divided on the extent to which such policies can be implemented with negative private costs to firms and individuals. [Box 3.10, 15.5.5, 15.5.6] There is general agreement that rebound effects exist, whereby higher efficiency can lead to lower energy prices and greater consumption, but there is *low agreement* in the literature on the magnitude [3.9.5, 5.7.2, 14.4.2, 15.5.4].

Since AR4, cap and trade systems for GHGs have been established in a number of countries and regions. Their short-run environmental effect has been limited as a result of loose caps or caps that have not proved to be constraining (*limited evidence, medium agreement*). This was related to factors such as the financial and economic crisis that reduced energy demand, new energy sources, interactions with other policies, and regulatory uncertainty. In principle, a cap and trade system can achieve mitigation in a cost-effective way; its implementation depends on national circumstances. Though earlier programmes relied almost exclusively on grandfathering (free allocation of permits), auctioning permits is increasingly applied. If allowances are auctioned, revenues can be used to address other investments with a high social return, and/or reduce the tax and debt burden. [14.4.2, 15.5.3]

In some countries, tax-based policies specifically aimed at reducing GHG emissions—alongside technology and other policies—have helped to weaken the link between GHG emissions and GDP (*high confidence*). In a large group of countries, fuel taxes (although not necessarily designed for the purpose of mitigation) have effects that are akin to sectoral carbon taxes [Table 15.2]. The demand reduction in transport fuel associated with a 1 % price increase is 0.6 % to 0.8 % in the long run, although the short-run response is much smaller [15.5.2]. In some countries revenues are used to reduce other taxes and/or to provide transfers to low-income groups. This illustrates the general principle that mitigation policies that raise government revenue generally have lower social costs than approaches which do not. While it has previously been assumed that fuel taxes in the transport sector are regressive, there have been a number of other studies since AR4 that have shown them to be progressive, particularly in developing countries (*medium evidence, medium agreement*). [3.6.3, 14.4.2, 15.5.2]

The reduction of subsidies for GHG-related activities in various sectors can achieve emission reductions, depending on the social and economic context (*high confidence*). While subsidies can affect emissions in many sectors, most of the recent literature has focused on subsidies for fossil fuels. Since AR4 a small but growing literature based on economy-wide models has projected that complete removal of subsidies for fossil fuels in all countries could result in reductions in global aggregate emissions by mid-century (*medium evidence, medium agreement*) [7.12, 13.13, 14.3.2, 15.5.2]. Studies vary in methodology, the type and definition of subsidies and the time frame for phase out considered. In particular, the studies assess the impacts of complete removal of all fossil fuel subsidies without seeking to assess which subsidies are wasteful and inefficient, keeping in mind national circumstances. Although political economy barriers are substantial, some countries have reformed their tax and budget systems to reduce fuel subsidies. To help reduce possible adverse effects on lower-income groups who often spend a large fraction of their income on energy services, many governments have utilized lump-sum cash transfers or other mechanisms targeted on the poor. [15.5.2]

Interactions between or among mitigation policies may be synergistic or may have no additive effect on reducing emissions (*medium evidence, high agreement*). For instance, a carbon tax can have an additive environmental effect to policies such as subsidies for the supply of RE. By contrast, if a cap and trade system has a binding cap (sufficiently stringent to affect emission-related decisions), then other policies such as RE subsidies have no further impact on reducing emissions within the time period that the cap applies (although they may affect costs and possibly the viability of more stringent future targets) (*medium evidence, high agreement*). In either case, additional policies may be needed to address market failures relating to innovation and technology diffusion. [15.7]

Some mitigation policies raise the prices for some energy services and could hamper the ability of societies to expand access to modern energy services to underserved populations (*low confidence*). **These potential adverse side-effects can be avoided with the adoption of complementary policies** (*medium confidence*). Most notably, about 1.3 billion people worldwide do not have access to electricity and about 3 billion are dependent on traditional solid fuels for cooking and heating with severe adverse effects on health, ecosystems and development. Providing access to modern energy services is an important sustainable development objective. The costs of achieving nearly universal access to electricity and clean fuels for cooking and heating are projected to be between 72 and 95 billion USD per year until 2030 with minimal effects on GHG emissions (*limited evidence, medium agreement*). A transition away from the use of traditional biomass[29] and the more efficient combustion of solid fuels reduce air pollutant emissions, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and black carbon (BC), and thus yield large health benefits (*high confidence*). [4.3, 6.6, 7.9, 9.3, 9.7, 11.13.6, 16.8]

Technology policy complements other mitigation policies (*high confidence*). Technology policy includes technology-push (e.g., publicly funded R&D) and demand-pull (e.g., governmental procurement programmes). Such policies address market failures related to innovation and technology diffusion. [3.11, 15.6] Technology support policies have promoted substantial innovation and diffusion of new technologies, but the cost-effectiveness of such policies is often difficult to assess [2.6.5, 7.12, 9.10]. Nevertheless, program evaluation data can provide empirical evidence on the relative effectiveness of different policies and can assist with policy design [15.6.5].

In many countries, the private sector plays central roles in the processes that lead to emissions as well as to mitigation. Within appropriate enabling environments, the private sector, along with the public sector, can play an important role in financing mitigation (*medium evidence, high agreement*). The share of total mitigation finance from the private sector, acknowledging data limitations, is estimated to be on average between two-thirds and three-fourths on the global level (2010–2012) (*limited evidence, medium agreement*). In many countries, public finance interventions by governments and national and international development banks encourage climate investments by the private sector [16.2.1] and provide finance where private sector investment is limited. The quality of a country's enabling environment includes the effectiveness of its institutions, regulations and guidelines regarding the private sector, security of property rights, credibility of policies and other factors that have a substantial impact on whether private firms invest in new technologies and infrastructures [16.3]. Dedicated policy instruments, for example, credit insurance, power purchase agreements and feed-in tariffs, concessional finance or rebates, provide an incentive for investment by lowering risks for private actors [16.4].

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[29] See WGIII AR5 Glossary.

SPM.5.2 International cooperation

The United Nations Framework Convention on Climate Change (UNFCCC) is the main multilateral forum focused on addressing climate change, with nearly universal participation. Other institutions organized at different levels of governance have resulted in diversifying international climate change cooperation. [13.3.1, 13.4.1.4, 13.5]

Existing and proposed international climate change cooperation arrangements vary in their focus and degree of centralization and coordination. They span: multilateral agreements, harmonized national policies and decentralized but coordinated national policies, as well as regional and regionally-coordinated policies. [Figure TS.38, 13.4.1, 13.13.2, 14.4]

The Kyoto Protocol offers lessons towards achieving the ultimate objective of the UNFCCC, particularly with respect to participation, implementation, flexibility mechanisms, and environmental effectiveness (*medium evidence, low agreement*). [5.3.3, 13.3.4, 13.7.2, 13.13.1.1, 13.13.1.2, 14.3.7.1, Table TS.9]

UNFCCC activities since 2007 have led to an increasing number of institutions and other arrangements for international climate change cooperation. [13.5.1.1, 13.13.1.3, 16.2.1]

Policy linkages among regional, national, and sub-national climate policies offer potential climate change mitigation and adaptation benefits (*medium evidence, medium agreement*). Linkages can be established between national policies, various instruments, and through regional cooperation. [13.3.1, 13.5.3, 13.6, 13.7, 13.13.2.3, 14.4, Figure 13.4]

Various regional initiatives between the national and global scales are either being developed or implemented, but their impact on global mitigation has been limited to date (*medium confidence*). Many climate policies can be more effective if implemented across geographical regions. [13.13, 13.6, 14.4, 14.5]

Technical Summary

TS

Technical Summary

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TS.1 Introduction and framing

'Mitigation', in the context of climate change, is a human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs). One of the central messages from Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) is that the consequences of unchecked climate change for humans and natural ecosystems are already apparent and increasing. The most vulnerable systems are already experiencing adverse effects. Past GHG emissions have already put the planet on a track for substantial further changes in climate, and while there are many uncertainties in factors such as the sensitivity of the climate system many scenarios lead to substantial climate impacts, including direct harms to human and ecological well-being that exceed the ability of those systems to adapt fully.

Because mitigation is intended to reduce the harmful effects of climate change, it is part of a broader policy framework that also includes adaptation to climate impacts. Mitigation, together with adaptation to climate change, contributes to the objective expressed in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) to stabilize "greenhouse gas concentrations in the atmosphere at a level to prevent dangerous anthropogenic interference with the climate system […] within a time frame sufficient to allow ecosystems to adapt […] to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner". However, Article 2 is hard to interpret, as concepts such as 'dangerous' and 'sustainable' have different meanings in different decision contexts (see Box TS.1).[1] Moreover, natural science is unable to predict precisely the response of the climate system to rising GHG

[1] Boxes throughout this summary provide background information on main research concepts and methods that were used to generate insight.

Box TS.1 | Many disciplines aid decision making on climate change

Something is dangerous if it leads to a significant risk of considerable harm. Judging whether human interference in the climate system is dangerous therefore divides into two tasks. One is to estimate the risk in material terms: what the material consequences of human interference might be and how likely they are. The other is to set a value on the risk: to judge how harmful it will be.

The first is a task for natural science, but the second is not [Section 3.1]. As the Synthesis Report of AR4 states, "Determining what constitutes 'dangerous anthropogenic interference with the climate system' in relation to Article 2 of the UNFCCC involves value judgements". Judgements of value (valuations) are called for, not just here, but at almost every turn in decision making about climate change [3.2]. For example, setting a target for mitigation involves judging the value of losses to people's well-being in the future, and comparing it with the value of benefits enjoyed now. Choosing whether to site wind turbines on land or at sea requires a judgement of the value of landscape in comparison with the extra cost of marine turbines. To estimate the social cost of carbon is to value the harm that GHG emissions do [3.9.4].

Different values often conflict, and they are often hard to weigh against each other. Moreover, they often involve the conflicting interests of different people, and are subject to much debate and disagreement. Decision makers must therefore find ways to mediate among different interests and values, and also among differing viewpoints about values. [3.4, 3.5]

Social sciences and humanities can contribute to this process by improving our understanding of values in ways that are illustrated in the boxes contained in this summary. The sciences of human and social behaviour—among them psychology, political science, sociology, and non-normative branches of economics—investigate the values people have, how they change through time, how they can be influenced by political processes, and how the process of making decisions affects their acceptability. Other disciplines, including ethics (moral philosophy), decision theory, risk analysis, and the normative branch of economics, investigate, analyze, and clarify values themselves [2.5, 3.4, 3.5, 3.6]. These disciplines offer practical ways of measuring some values and trading off conflicting interests. For example, the discipline of public health often measures health by means of 'disability-adjusted life years' [3.4.5]. Economics uses measures of social value that are generally based on monetary valuation but can take account of principles of distributive justice [3.6, 4.2, 4.7, 4.8]. These normative disciplines also offer practical decision-making tools, such as expected utility theory, decision analysis, cost-benefit and cost-effectiveness analysis, and the structured use of expert judgment [2.5, 3.6, 3.7, 3.9].

There is a further element to decision making. People and countries have rights and owe duties towards each other. These are matters of justice, equity, or fairness. They fall within the subject matter of moral and political philosophy, jurisprudence, and economics. For example, some have argued that countries owe restitution for the harms that result from their past GHG emissions, and it has been debated, on jurisprudential and other grounds, whether restitution is owed only for harms that result from negligent or blameworthy GHG emissions. [3.3, 4.6] concentrations nor fully understand the harm it will impose on individuals, societies, and ecosystems. Article 2 requires that societies balance a variety of considerations—some rooted in the impacts of climate change itself and others in the potential costs of mitigation and adaptation. The difficulty of that task is compounded by the need to develop a consensus on fundamental issues such as the level of risk that societies are willing to accept and impose on others, strategies for sharing costs, and how to balance the numerous tradeoffs that arise because mitigation intersects with many other goals of societies. Such issues are inherently value-laden and involve different actors who have varied interests and disparate decision-making power.

The Working Group III (WGIII) contribution to the IPCC's Fifth Assessment Report (AR5) assesses literature on the scientific, technological, environmental, economic and social aspects of mitigation of climate change. It builds upon the WGIII contribution to the IPCC's Fourth Assessment Report (AR4), the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) and previous reports and incorporates subsequent new findings and research. Throughout, the focus is on the implications of its findings for policy, without being prescriptive about the particular policies that governments and other important participants in the policy process should adopt. In light of the IPCC's mandate, authors in WGIII were guided by several principles when assembling this assessment: (1) to be explicit about mitigation options, (2) to be explicit about their costs and about their risks and opportunities vis-à-vis other development priorities, (3) and to be explicit about the underlying criteria, concepts, and methods for evaluating alternative policies.

The remainder of this summary offers the main findings of this report. The degree of certainty in findings, as in the reports of all three IPCC Working Groups, is based on the author teams' evaluations of underlying scientific understanding and is expressed as a qualitative level of confidence (from very low to very high) and, when possible, probabilistically with a quantified likelihood (from exceptionally unlikely to virtually certain). Confidence in the validity of a finding is based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement. Probabilistic estimates of quantified measures of uncertainty in a finding are based on statistical analysis of observations or model results, or both, and expert judgment.[2] Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers. Within paragraphs of this summary, the confidence, evidence, and agreement terms given for a bolded finding apply to subsequent statements in the paragraph, unless additional terms are provided. References in [square brackets] indicate chapters, sections, figures, tables, and boxes where supporting evidence in the underlying report can be found.

This section continues with providing a framing of important concepts and methods that help to contextualize the findings presented in subsequent sections. Section TS.2 presents evidence on past trends in stocks and flows of GHGs and the factors that drive emissions at the global, regional, and sectoral scales including economic growth, technology, or population changes. Section TS.3.1 provides findings from studies that analyze the technological, economic, and institutional requirements of long-term mitigation scenarios. Section TS.3.2 provides details on mitigation measures and policies that are used within and across different economic sectors and human settlements. Section TS.4 summarizes insights on the interactions of mitigation policies between governance levels, economic sectors, and instrument types.

Climate change is a global commons problem that implies the need for international cooperation in tandem with local, national, and regional policies on many distinct matters. Because the GHG emissions of any agent (individual, company, country) affect every other agent, an effective outcome will not be achieved if individual agents advance their interests independently of others. International cooperation can contribute by defining and allocating rights and responsibilities with respect to the atmosphere [Sections 1.2.4, 3.1, 4.2, 13.2.1]. Moreover, research and development (R&D) in support of mitigation is a public good, which means that international cooperation can play a constructive role in the coordinated development and diffusion of technologies [1.4.4, 3.11, 13.9, 14.4.3]. This gives rise to separate needs for cooperation on R&D, opening up of markets, and the creation of incentives to encourage private firms to develop and deploy new technologies and households to adopt them.

International cooperation on climate change involves ethical considerations, including equitable effort-sharing. Countries have contributed differently to the build-up of GHG in the atmosphere, have varying capacities to contribute to mitigation and adaptation, and have different levels of vulnerability to climate impacts. Many less developed countries are exposed to the greatest impacts but have contributed least to the problem. Engaging countries in effective international cooperation may require strategies for sharing the costs and benefits of mitigation in ways that are perceived to be equitable [4.2]. Evidence suggests that perceived fairness can influence the level of cooperation among individuals, and that finding may suggest that processes and outcomes seen as fair will lead to more international cooperation as well [3.10, 13.2.2.4]. Analysis contained in the literature of moral and political philosophy can contribute to resolving ethical questions raised by climate change [3.2, 3.3, 3.4]. These questions include how much overall mitigation is needed to avoid 'dangerous interference with the climate system' (Box

[2] The following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100 % probability, very likely 90–100 %, likely 66–100 %, about as likely as not 33–66 %, unlikely 0–33 %, very unlikely 0–10 %, exceptionally unlikely 0–1 %. Additional terms (more likely than not > 50–100 %, and more unlikely than likely 0 –< 50 %) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*. For more details, please refer to the Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, available at http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.

Box TS.2 | Mitigation brings both market and non-market benefits to humanity

The impacts of mitigation consist in the reduction or elimination of some of the effects of climate change. Mitigation may improve people's livelihood, their health, their access to food or clean water, the amenities of their lives, or the natural environment around them.

Mitigation can improve human well-being through both market and non-market effects. Market effects result from changes in market prices, in people's revenues or net income, or in the quality or availability of market commodities. Non-market effects result from changes in the quality or availability of non-marketed goods such as health, quality of life, culture, environmental quality, natural ecosystems, wildlife, and aesthetic values. Each impact of climate change can generate both market and non-market damages. For example, a heat wave in a rural area may cause heat stress for exposed farm labourers, dry up a wetland that serves as a refuge for migratory birds, or kill some crops and damage others. Avoiding these damages is a benefit of mitigation. [3.9]

Economists often use monetary units to value the damage done by climate change and the benefits of mitigation. The monetized value of a benefit to a person is the amount of income the person would be willing to sacrifice in order to get it, or alternatively the amount she would be willing to accept as adequate compensation for not getting it. The monetized value of a harm is the amount of income she would be willing to sacrifice in order to avoid it, or alternatively the amount she would be willing to accept as adequate compensation for suffering it. Economic measures seek to capture how strongly individuals care about one good or service relative to another, depending on their individual interests, outlook, and economic circumstances. [3.9]

Monetary units can be used in this way to measure costs and benefits that come at different times and to different people. But it cannot be presumed that a dollar to one person at one time can be treated as equivalent to a dollar to a different person or at a different time. Distributional weights may need to be applied between people [3.6.1], and discounting (see Box TS.10) may be appropriate between times. [3.6.2]

TS.1) [3.1], how the effort or cost of mitigating climate change should be shared among countries and between the present and future [3.3, 3.6, 4.6], how to account for such factors as historical responsibility for GHG emissions [3.3, 4.6], and how to choose among alternative policies for mitigation and adaptation [3.4, 3.5, 3.6, 3.7]. Ethical issues of well-being, justice, fairness, and rights are all involved. Ethical analysis can identify the different ethical principles that underlie different viewpoints, and distinguish correct from incorrect ethical reasoning [3.3, 3.4].

Evaluation of mitigation options requires taking into account many different interests, perspectives, and challenges between and within societies. Mitigation engages many different agents, such as governments at different levels—regionally [14.1], nationally and locally [15.1], and through international agreements [13.1]—as well as households, firms, and other non-governmental actors. The interconnections between different levels of decision making and among different actors affect the many goals that become linked with climate policy. Indeed, in many countries the policies that have (or could have) the largest impact on emissions are motivated not solely by concerns surrounding climate change. Of particular importance are the interactions and perceived tensions between mitigation and development [4.1, 14.1]. Development involves many activities, such as enhancing access to modern energy services [7.9.1, 14.3.2, 16.8], the building of infrastructures [12.1], ensuring food security [11.1], and eradicating poverty [4.1]. Many of these activities can lead to higher emissions, if achieved by conventional means. Thus, the relationships between development and mitigation can lead to political and ethical conundrums, especially for developing countries, when mitigation is seen as exacerbating urgent development challenges and adversely affecting the current well-being of their populations [4.1]. These conundrums are examined throughout this report, including in special boxes highlighting the concerns of developing countries.

Economic evaluation can be useful for policy design and be given a foundation in ethics, provided appropriate distributional weights are applied. While the limitations of economics are widely documented [2.4, 3.5], economics nevertheless provides useful tools for assessing the pros and cons of mitigation and adaptation options. Practical tools that can contribute to decision making include cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis, expected utility theory, and methods of decision analysis [2.5, 3.7.2]. Economic valuation (see Box TS.2) can be given a foundation in ethics, provided distributional weights are applied that take proper account of the difference in the value of money to rich and poor people [3.6]. Few empirical applications of economic valuation to climate change have been well-founded in this respect [3.6.1]. The literature provides significant guidance on the social discount rate for consumption (see Box TS.10), which is in effect inter-temporal distributional weighting. It suggests that the social discount rate depends in a well-defined way primarily on the anticipated growth in per capita income and inequality aversion [3.6.2].

Most climate policies intersect with other societal goals, either positively or negatively, creating the possibility of 'co-benefits'

Box TS.3 | Deliberative and intuitive thinking are inputs to effective risk management

When people—from individual voters to key decision makers in firms to senior government policymakers—make choices that involve risk and uncertainty, they rely on deliberative as well intuitive thought processes. Deliberative thinking is characterized by the use of a wide range of formal methods to evaluate alternative choices when probabilities are difficult to specify and/or outcomes are uncertain. They can enable decision makers to compare choices in a systematic manner by taking into account both short and long-term consequences. A strength of these methods is that they help avoid some of the well-known pitfalls of intuitive thinking, such as the tendency of decision makers to favour the status quo. A weakness of these deliberative decision aids is that they are often highly complex and require considerable time and attention.

Most analytically based literature, including reports such as this one, is based on the assumption that individuals undertake deliberative and systematic analyses in comparing options. However, when making mitigation and adaptation choices, people are also likely to engage in intuitive thinking. This kind of thinking has the advantage of requiring less extensive analysis than deliberative thinking. However, relying on one's intuition may not lead one to characterize problems accurately when there is limited past experience. Climate change is a policy challenge in this regard since it involves large numbers of complex actions by many diverse actors, each with their own values, goals, and objectives. Individuals are likely to exhibit well-known patterns of intuitive thinking such as making choices related to risk and uncertainty on the basis of emotional reactions and the use of simplified rules that have been acquired by personal experience. Other tendencies include misjudging probabilities, focusing on short time horizons, and utilizing rules of thumb that selectively attend to subsets of goals and objectives. [2.4]

By recognizing that both deliberative and intuitive modes of decision making are prevalent in the real world, risk management programmes can be developed that achieve their desired impacts. For example, alternative frameworks that do not depend on precise specification of probabilities and outcomes can be considered in designing mitigation and adaptation strategies for climate change. [2.4, 2.5, 2.6]

or 'adverse side-effects'. Since the publication of AR4, a substantial body of literature has emerged looking at how countries that engage in mitigation also address other goals, such as local environmental protection or energy security, as a 'co-benefit' and conversely [1.2.1, 6.6.1, 4.8]. This multi-objective perspective is important because it helps to identify areas where political, administrative, stakeholder, and other support for policies that advance multiple goals will be robust. Moreover, in many societies the presence of multiple objectives may make it easier for governments to sustain the political support needed for mitigation [15.2.3]. Measuring the net effect on social welfare (see Box TS.11) requires examining the interaction between climate policies and pre-existing other policies [3.6.3, 6.3.6.5].

Mitigation efforts generate tradeoffs and synergies with other societal goals that can be evaluated in a sustainable development framework. The many diverse goals that societies value are often called 'sustainable development'. A comprehensive assessment of climate policy therefore involves going beyond a narrow focus on distinct mitigation and adaptation options and their specific co-benefits and adverse side-effects. Instead it entails incorporating climate issues into the design of comprehensive strategies for equitable and sustainable development at regional, national, and local levels [4.2, 4.5]. Maintaining and advancing human well-being, in particular overcoming poverty and reducing inequalities in living standards, while avoiding unsustainable patterns of consumption and production, are fundamental aspects of equitable and sustainable development [4.4, 4.6, 4.8]. Because these aspects are deeply rooted in how societies formulate and implement economic and social policies generally, they are critical to the adoption of effective climate policy.

Variations in goals reflect, in part, the fact that humans perceive risks and opportunities differently. Individuals make their decisions based on different goals and objectives and use a variety of different methods in making choices between alternative options. These choices and their outcomes affect the ability of different societies to cooperate and coordinate. Some groups put greater emphasis on near-term economic development and mitigation costs, while others focus more on the longer-term ramifications of climate change for prosperity. Some are highly risk averse while others are more tolerant of dangers. Some have more resources to adapt to climate change and others have fewer. Some focus on possible catastrophic events while others ignore extreme events as implausible. Some will be relative winners, and some relative losers from particular climate changes. Some have more political power to articulate their preferences and secure their interests and others have less. Since AR4, awareness has grown that such considerations—long the domain of psychology, behavioural economics, political economy, and other disciplines—need to be taken into account in assessing climate policy (see Box TS.3). In addition to the different perceptions of climate change and its risks, a variety of norms can also affect what humans view as acceptable behaviour. Awareness has grown about how such norms spread through social networks and ultimately affect activities, behaviours and lifestyles, and thus development pathways, which can have profound impacts on GHG emissions and mitigation policy. [1.4.2, 2.4, 3.8, 3.10, 4.3]

Box TS.4 | 'Fat tails': unlikely vs. likely outcomes in understanding the value of mitigation

What has become known as the 'fat-tails' problem relates to uncertainty in the climate system and its implications for mitigation and adaptation policies. By assessing the chain of structural uncertainties that affect the climate system, the resulting compound probability distribution of possible economic damage may have a fat right tail. That means that the probability of damage does not decline with increasing temperature as quickly as the consequences rise.

The significance of fat tails can be illustrated for the distribution of temperature that will result from a doubling of atmospheric carbon dioxide (CO_2) (climate sensitivity). IPCC Working Group I (WGI) estimates may be used to calibrate two possible distributions, one fat-tailed and one thin-tailed, that each have a median temperature change of 3 °C and a 15 % probability of a temperature change in excess of 4.5 °C. Although the probability of exceeding 4.5 °C is the same for both distributions, likelihood drops off much more slowly with increasing temperature for the fat-tailed compared to the thin-tailed distribution. For example, the probability of temperatures in excess of 8 °C is nearly ten times greater with the chosen fat-tailed distribution than with the thin-tailed distribution. If temperature changes are characterized by a fat tailed distribution, and events with large impact may occur at higher temperatures, then tail events can dominate the computation of expected damages from climate change.

In developing mitigation and adaptation policies, there is value in recognizing the higher likelihood of tail events and their consequences. In fact, the nature of the probability distribution of temperature change can profoundly change how climate policy is framed and structured. Specifically, fatter tails increase the importance of tail events (such as 8 °C warming). While research attention and much policy discussion have focused on the most likely outcomes, it may be that those in the tail of the probability distribution are more important to consider. [2.5, 3.9.2]

Effective climate policy involves building institutions and capacity for governance. While there is strong evidence that a transition to a sustainable and equitable path is technically feasible, charting an effective and viable course for climate change mitigation is not merely a technical exercise. It will involve myriad and sequential decisions among states and civil society actors. Such a process benefits from the education and empowerment of diverse actors to participate in systems of decision making that are designed and implemented with procedural equity as a deliberate objective. This applies at the national as well as international levels, where effective governance relating to global common resources, in particular, is not yet mature. Any given approach has potential winners and losers. The political feasibility of that approach will depend strongly on the distribution of power, resources, and decision-making authority among the potential winners and losers. In a world characterized by profound disparities, procedurally equitable systems of engagement, decision making and governance may help enable a polity to come to equitable solutions to the sustainable development challenge. [4.3]

Effective risk management of climate change involves considering uncertainties in possible physical impacts as well as human and social responses. Climate change mitigation and adaptation is a risk management challenge that involves many different decision-making levels and policy choices that interact in complex and often unpredictable ways. Risks and uncertainties arise in natural, social, and technological systems. As Box TS.3 explains, effective risk management strategies not only consider people's values, and their intuitive decision processes but utilize formal models and decision aids for systematically addressing issues of risk and uncertainty [2.4, 2.5]. Research on other such complex and uncertainty-laden policy domains suggest the importance of adopting policies and measures that are robust across a variety of criteria and possible outcomes [2.5]. As detailed in Box TS.4, a special challenge arises with the growing evidence that climate change may result in extreme impacts whose trigger points and outcomes are shrouded in high levels of uncertainty [2.5, 3.9.2]. A risk management strategy for climate change will require integrating responses in mitigation with different time horizons, adaptation to an array of climate impacts, and even possible emergency responses such as 'geoengineering' in the face of extreme climate impacts [1.4.2, 3.3.7, 6.9, 13.4.4]. In the face of potential extreme impacts, the ability to quickly offset warming could help limit some of the most extreme climate impacts although deploying these geoengineering systems could create many other risks (see Section TS.3.1.3). One of the central challenges in developing a risk management strategy is to have it adaptive to new information and different governing institutions [2.5].

TS.2 Trends in stocks and flows of greenhouse gases and their drivers

This section summarizes historical GHG emissions trends and their underlying drivers. As in most of the underlying literature, all aggregate GHG emissions estimates are converted to CO_2-equivalents based on Global Warming Potentials with a 100-year time horizon (GWP_{100}) (Box TS.5). The majority of changes in GHG emissions trends that are observed in this section are related to changes in drivers such as eco-

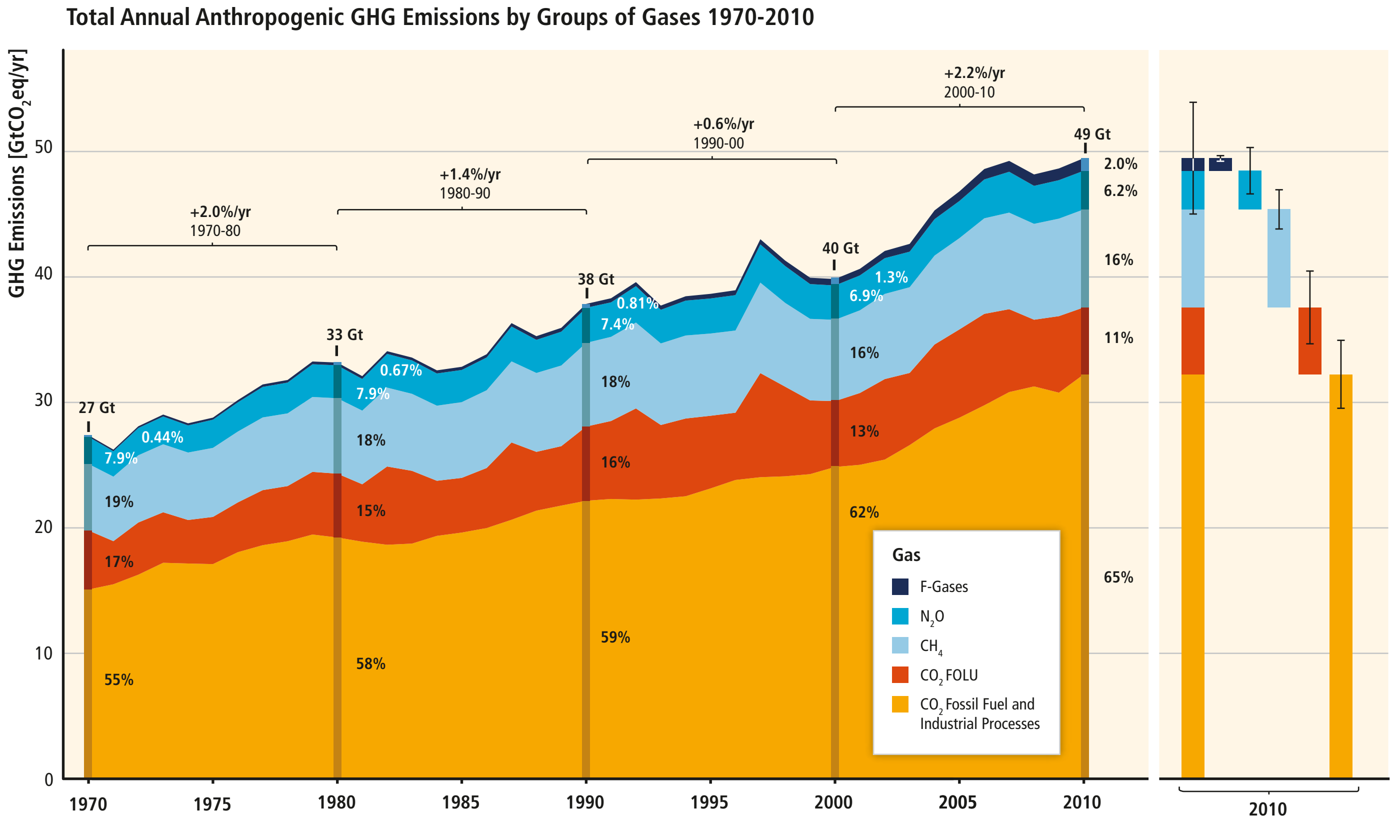

Figure TS.1 | Total annual anthropogenic GHG emissions ($GtCO_2eq/yr$) by groups of gases 1970–2010: carbon dioxide (CO_2) from fossil fuel combustion and industrial processes; CO_2 from Forestry and Other Land Use[4] (FOLU); methane (CH_4); nitrous oxide (N_2O); fluorinated gases[5] covered under the Kyoto Protocol (F-gases). At the right side of the figure, GHG emissions in 2010 are shown again broken down into these components with the associated uncertainties (90 % confidence interval) indicated by the error bars. Total anthropogenic GHG emissions uncertainties are derived from the individual gas estimates as described in Chapter 5 [5.2.3.6]. Emissions are converted into CO_2-equivalents based on Global Warming Potentials with a 100-year time horizon (GWP_{100}) from the IPCC Second Assessment Report (SAR). The emissions data from FOLU represents land-based CO_2 emissions from forest and peat fires and decay that approximate to the net CO_2 flux from FOLU as described in Chapter 11 of this report. Average annual GHG emissions growth rates for the four decades are highlighted with the brackets. The average annual growth rate from 1970 to 2000 is 1.3 %. [Figure 1.3]

nomic growth, technological change, human behaviour, or population growth. But there are also some smaller changes in GHG emissions estimates that are due to refinements in measurement concepts and methods that have happened since AR4. There is a growing body of literature on uncertainties in global GHG emissions data sets. This section tries to make these uncertainties explicit and reports variations in estimates across global data sets wherever possible.

TS.2.1 Greenhouse gas emission trends

Total anthropogenic GHG emissions have risen more rapidly from 2000 to 2010 than in the previous three decades (*high confidence*). Total anthropogenic GHG emissions were the highest in human history from 2000 to 2010 and reached 49 (±4.5) gigatonnes CO_2-equivalents per year ($GtCO_2eq/yr$) in 2010.[3] Current trends are at the high end of levels that had been projected for this last decade. GHG emissions growth has occurred despite the presence of a wide array of multilateral institutions as well as national policies aimed at mitigation. From 2000 to 2010, GHG emissions grew on average by 1.0 $GtCO_2eq$ (2.2 %) per year compared to 0.4 $GtCO_2eq$ (1.3 %) per year over the entire period from 1970 to 2000 (Figure TS.1). The global economic crisis 2007/2008 has only temporarily reduced GHG emissions. [1.3, 5.2, 13.3, 15.2.2, Figure 15.1]

[3] In this summary, uncertainty in historic GHG emissions data is reported using 90 % uncertainty intervals unless otherwise stated. GHG emissions levels are rounded to two significant digits throughout this document; as a consequence, small differences in sums due to rounding may occur.

[4] FOLU (Forestry and Other Land Use)—also referred to as LULUCF (Land Use, Land-Use Change, and Forestry)—is the subset of Agriculture, Forestry, and Other Land Use (AFOLU) emissions and removals of GHGs related to direct human-induced land use, land-use change and forestry activities excluding agricultural emissions (see WGIII AR5 Glossary).

[5] In this report, data on non-CO_2 GHGs, including fluorinated gases, are taken from the EDGAR database (see Annex II.9), which covers substances included in the Kyoto Protocol in its first commitment period.

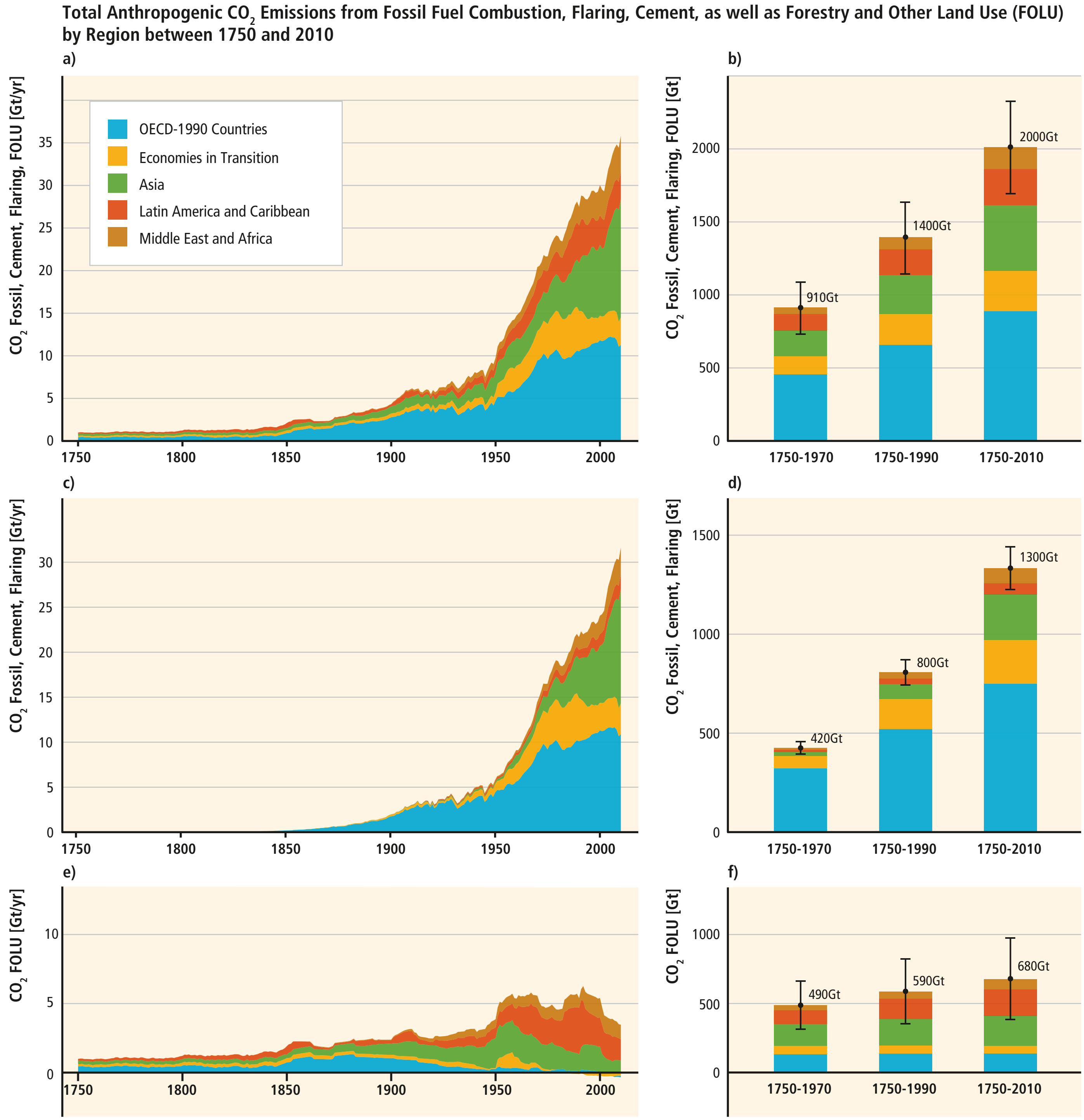

Figure TS.2 | Historical anthropogenic CO_2 emissions from fossil fuel combustion, flaring, cement, and Forestry and Other Land Use (FOLU)[4] in five major world regions: OECD-1990 (blue); Economies in Transition (yellow); Asia (green); Latin America and Caribbean (red); Middle East and Africa (brown). Emissions are reported in gigatonnes of CO_2 per year ($GtCO_2$/yr). Left panels show regional CO_2 emissions 1750–2010 from: (a) the sum of all CO_2 sources (c+e); (c) fossil fuel combustion, flaring, and cement; and (e) FOLU. The right panels report regional contributions to cumulative CO_2 emissions over selected time periods from: (b) the sum of all CO_2 sources (d+f); (d) fossil fuel combustion, flaring and cement; and (f) FOLU. Error bars on panels (b), (d) and (f) give an indication of the uncertainty range (90 % confidence interval). See Annex II.2.2 for definitions of regions. [Figure 5.3]

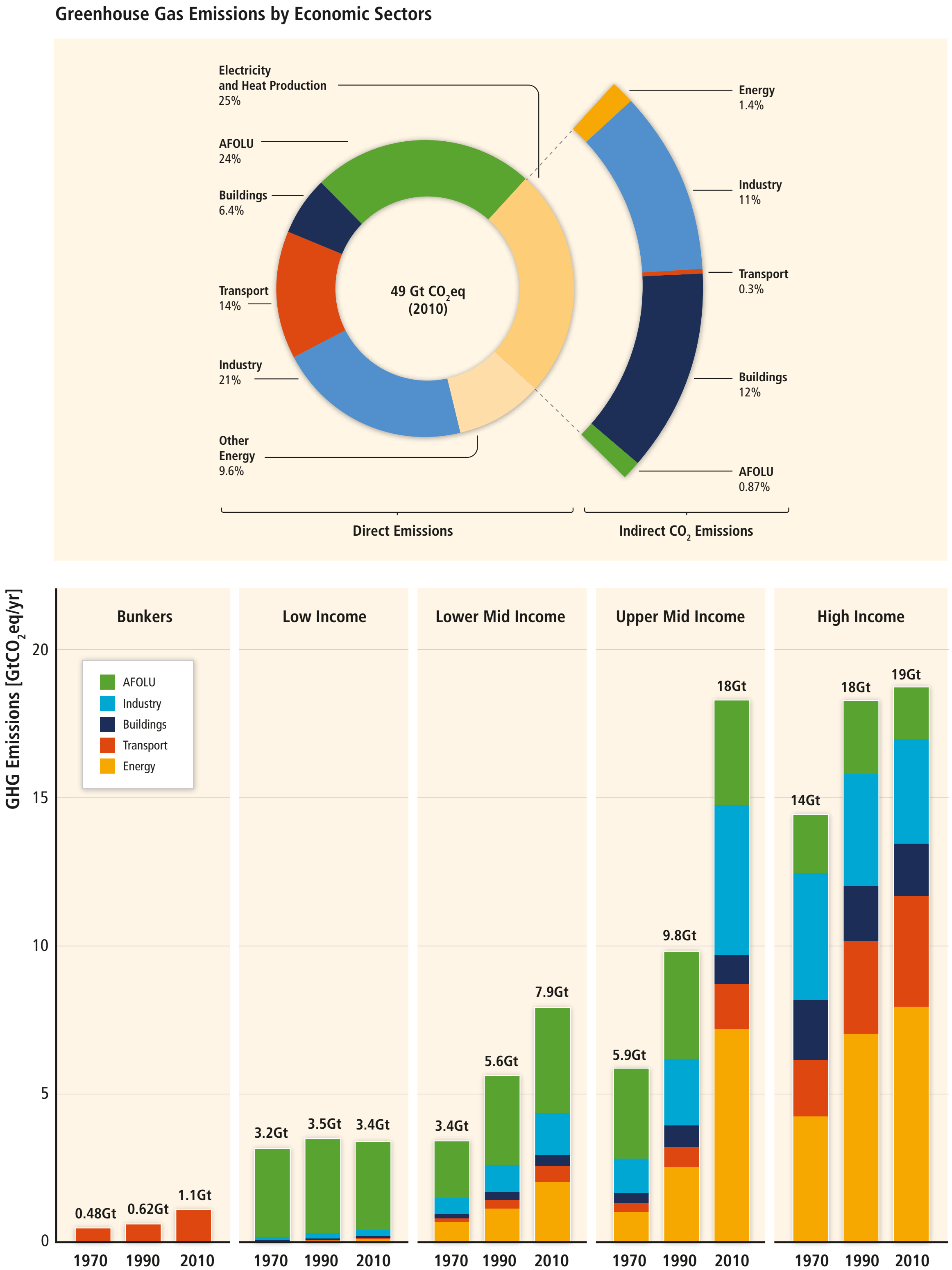

Figure TS.3 | Total anthropogenic GHG emissions ($GtCO_2$ eq/yr) by economic sectors and country income groups. Upper panel: Circle shows direct GHG emission shares (in % of total anthropogenic GHG emissions) of five major economic sectors in 2010. Pull-out shows how indirect CO_2 emission shares (in % of total anthropogenic GHG emissions) from electricity and heat production are attributed to sectors of final energy use. 'Other Energy' refers to all GHG emission sources in the energy sector other than electricity and heat production. Lower panel: Total anthropogenic GHG emissions in 1970, 1990 and 2010 by five major economic sectors and country income groups. 'Bunkers' refer to GHG emissions from international transportation and thus are not, under current accounting systems, allocated to any particular nation's territory. The emissions data from Agriculture, Forestry and Other Land Use (AFOLU) includes land-based CO_2 emissions from forest and peat fires and decay that approximate to the net CO_2 flux from the Forestry and Other Land Use (FOLU) sub-sector as described in Chapter 11 of this report. Emissions are converted into CO_2-equivalents based on Global Warming Potentials with a 100-year time horizon (GWP_{100}) from the IPCC Second Assessment Report (SAR). Assignment of countries to income groups is based on the World Bank income classification in 2013. For details see Annex II.2.3. Sector definitions are provided in Annex II.9.1. [Figure 1.3, Figure 1.6]

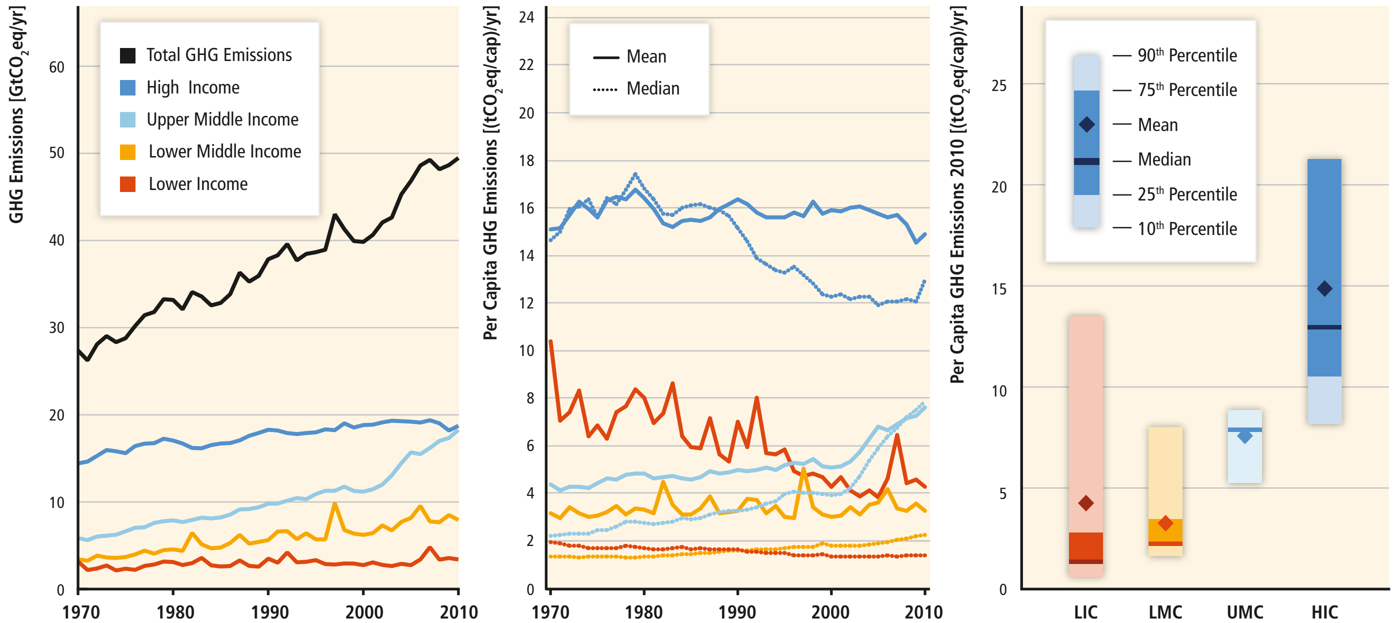

Figure TS.4 | Trends in GHG emissions by country income groups. Left panel: Total annual anthropogenic GHG emissions from 1970 to 2010 ($GtCO_2eq/yr$). Middle panel: Trends in annual per capita mean and median GHG emissions from 1970 to 2010 ($tCO_2eq/cap/yr$). Right panel: Distribution of annual per capita GHG emissions in 2010 of countries within each country income group ($tCO_2/cap/yr$). Mean values show the GHG emissions levels weighed by population. Median values describe GHG emissions levels per capita of the country at the 50th percentile of the distribution within each country income group. Emissions are converted into CO_2-equivalents based on Global Warming Potentials with a 100-year time horizon (GWP_{100}) from the IPCC Second Assessment Report (SAR). Assignment of countries to country income groups is based on the World Bank income classification in 2013. For details see Annex II.2.3. [Figures 1.4, 1.8]

CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78 % to the total GHG emissions increase from 1970 to 2010, with similar percentage contribution for the period 2000–2010 (*high confidence*). Fossil fuel-related CO_2 emissions reached 32 (±2.7) $GtCO_2$/yr in 2010 and grew further by about 3 % between 2010 and 2011 and by about 1–2 % between 2011 and 2012. Since AR4, the shares of the major groups of GHG emissions have remained stable. Of the 49 (±4.5) $GtCO_2eq$/yr in total anthropogenic GHG emissions in 2010, CO_2 remains the major GHG accounting for 76 % (38±3.8 $GtCO_2eq$/yr) of total anthropogenic GHG emissions. 16 % (7.8±1.6 $GtCO_2eq$/yr) come from methane (CH_4), 6.2 % (3.1±1.9 $GtCO_2eq$/yr) from nitrous oxide (N_2O), and 2.0 % (1.0±0.2 $GtCO_2eq$/yr) from fluorinated gases (Figure TS.1).[5] Using the most recent GWP_{100} values from the AR5 [WGI 8.7] global GHG emissions totals would be slightly higher (52 $GtCO_2eq$/yr) and non-CO_2 emission shares would be 20 % for CH_4, 5.0 % for N_2O and 2.2 % for F-gases. Emission shares are sensitive to the choice of emission metric and time horizon, but this has a small influence on global, long-term trends. If a shorter, 20-year time horizon were used, then the share of CO_2 would decline to just over 50 % of total anthropogenic GHG emissions and short-lived gases would rise in relative importance. As detailed in Box TS.5, the choice of emission metric and time horizon involves explicit or implicit value judgements and depends on the purpose of the analysis. [1.2, 3.9, 5.2]

Over the last four decades total cumulative CO_2 emissions have increased by a factor of 2 from about 910 $GtCO_2$ for the period 1750–1970 to about 2000 $GtCO_2$ for 1750–2010 (*high confidence*). In 1970, the cumulative CO_2 emissions from fossil fuel combustion, cement production and flaring since 1750 was 420 (±35) $GtCO_2$; in 2010 that cumulative total had tripled to 1300 (±110) $GtCO_2$ (Figure TS.2). Cumulative CO_2 emissions associated with FOLU[4] since 1750 increased from about 490 (±180) $GtCO_2$ in 1970 to approximately 680 (±300) $GtCO_2$ in 2010. [5.2]

Regional patterns of GHG emissions are shifting along with changes in the world economy (*high confidence*). Since 2000, GHG emissions have been growing in all sectors, except Agriculture, Forestry and Other Land Use (AFOLU)[4] where positive and negative emission changes are reported across different databases and uncertainties in the data are high. More than 75 % of the 10 Gt increase in annual GHG emissions between 2000 and 2010 was emitted in the energy supply (47 %) and industry (30 %) sectors (see Annex II.9.I for sector definitions). 5.9 $GtCO_2eq$ of this sectoral increase occurred in upper-middle income countries,[6] where the most rapid economic development and infrastructure expansion has taken place. GHG emissions growth in the other sectors has been more modest in absolute (0.3–1.1 Gt CO_2eq) as well as in relative terms (3 %–11 %). [1.3, 5.3, Figure 5.18]

[6] When countries are assigned to income groups in this summary, the World Bank income classification for 2013 is used. For details see Annex II.2.3.

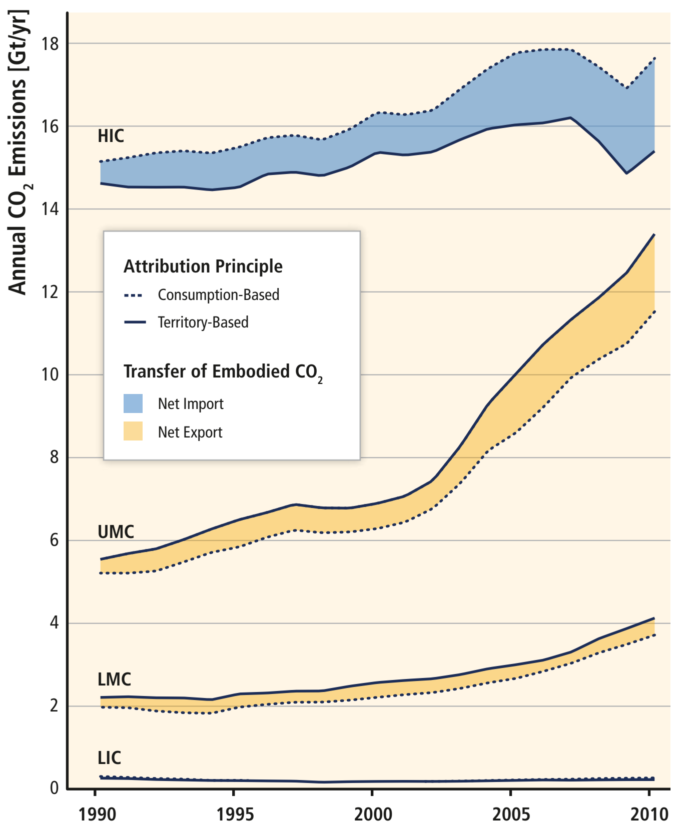

Figure TS.5 | Total annual CO_2 emissions ($GtCO_2$/yr) from fossil fuel combustion for country income groups attributed on the basis of territory (solid line) and final consumption (dotted line). The shaded areas are the net CO_2 trade balances (differences) between each of the four country income groups and the rest of the world. Blue shading indicates that the country income group is a net importer of embodied CO_2 emissions, leading to consumption-based emission estimates that are higher than traditional territorial emission estimates. Orange indicates the reverse situation—the country income group is a net exporter of embodied CO_2 emissions. Assignment of countries to country income groups is based on the World Bank income classification in 2013. For details see Annex II.2.3. [Figure 1.5]

Current GHG emission levels are dominated by contributions from the energy supply, AFOLU, and industry sectors; industry and buildings gain considerably in importance if indirect emissions are accounted for (*robust evidence, high agreement*). Of the 49 (±4.5) $GtCO_2eq$ emissions in 2010, 35 % (17 $GtCO_2eq$) of GHG emissions were released in the energy supply sector, 24 % (12 $GtCO_2eq$, net emissions) in AFOLU, 21 % (10 $GtCO_2eq$) in industry, 14 % (7.0 $GtCO_2eq$) in transport, and 6.4 % (3.2 $GtCO_2eq$) in buildings. When indirect emissions from electricity and heat production are assigned to sectors of final energy use, the shares of the industry and buildings sectors in global GHG emissions grow to 31 % and 19 %,[3] respectively (Figure TS.3 upper panel). [1.3, 7.3, 8.2, 9.2, 10.3, 11.2]

Per capita GHG emissions in 2010 are highly unequal (*high confidence*). In 2010, median per capita GHG emissions (1.4 tCO_2eq/cap/yr) for the group of low-income countries are around nine times lower than median per capita GHG emissions (13 tCO_2eq/cap/yr) of high-income countries (Figure TS.4).[6] For low-income countries, the largest part of GHG emissions comes from AFOLU; for high-income countries, GHG emissions are dominated by sources related to energy supply and industry (Figure TS.3 lower panel). There are substantial variations in per capita GHG emissions within country income groups with emissions at the 90th percentile level more than double those at the 10th percentile level. Median per capita emissions better represent the typical country within a country income group comprised of heterogeneous members than mean per capita emissions. Mean per capita GHG emissions are different from median mainly in low-income countries as individual low-income countries have high per capita emissions due to large CO_2 emissions from land-use change (Figure TS.4, right panel). [1.3, 5.2, 5.3]

A growing share of total anthropogenic CO_2 emissions is released in the manufacture of products that are traded across international borders (*medium evidence, high agreement*). Since AR4, several data sets have quantified the difference between traditional 'territorial' and 'consumption-based' emission estimates that assign all emission released in the global production of goods and services to the country of final consumption (Figure TS.5). A growing share of CO_2 emissions from fossil fuel combustion in middle income countries is released in the production of goods and services exported, notably from upper middle income countries to high income countries. Total annual industrial CO_2 emissions from the non-Annex I group now exceed those of the Annex I group using territorial and consumption-based accounting methods, but per-capita emissions are still markedly higher in the Annex I group. [1.3, 5.3]

Regardless of the perspective taken, the largest share of anthropogenic CO_2 emissions is emitted by a small number of countries (*high confidence*). In 2010, 10 countries accounted for about 70 % of CO_2 emissions from fossil fuel combustion and industrial processes. A similarly small number of countries emit the largest share of consumption-based CO_2 emissions as well as cumulative CO_2 emissions going back to 1750. [1.3]

The upward trend in global fossil fuel related CO_2 emissions is robust across databases and despite uncertainties (*high confidence*). Global CO_2 emissions from fossil fuel combustion are known within 8 % uncertainty. CO_2 emissions related to FOLU have very large uncertainties attached in the order of 50 %. Uncertainty for global emissions of methane (CH_4), nitrous oxide (N_2O), and the fluorinated gases has been estimated as 20 %, 60 %, and 20 %. Combining these values yields an illustrative total global GHG uncertainty estimate of about 10 % (Figure TS.1). Uncertainties can increase at finer spatial scales and for specific sectors. Attributing GHG emissions to the country of final consumption increases uncertainties, but literature on this topic is just emerging. GHG emissions estimates in the AR4 were 5–10 % higher than the estimates reported here, but lie within the estimated uncertainty range.[3] [5.2]

Box TS.5 | Emissions metrics depend on value judgements and contain wide uncertainties

Emission metrics provide 'exchange rates' for measuring the contributions of different GHGs to climate change. Such exchange rates serve a variety of purposes, including apportioning mitigation efforts among several gases and aggregating emissions of a variety of GHGs. However, there is no metric that is both conceptually correct and practical to implement. Because of this, the choice of the appropriate metric depends on the application or policy at issue. [3.9.6]

GHGs differ in their physical characteristics. For example, per unit mass in the atmosphere, methane (CH_4) causes a stronger instantaneous radiative forcing than CO_2, but it remains in the atmosphere for a much shorter time. Thus, the time profiles of climate change brought about by different GHGs are different and consequential. Determining how emissions of different GHGs are compared for mitigation purposes involves comparing the resulting temporal profiles of climate change from each gas and making value judgments about the relative significance to humans of these profiles, which is a process fraught with uncertainty. [3.9.6; WGI 8.7]

A commonly used metric is the Global Warming Potential (GWP). It is defined as the accumulated radiative forcing within a specific time horizon (e.g., 100 years—GWP_{100}), caused by emitting one kilogram of the gas, relative to that of the reference gas CO_2. This metric is used to transform the effects of different GHG emissions to a common scale (CO_2-equivalents).[1] One strength of the GWP is that it can be calculated in a relatively transparent and straightforward manner. However, there are also limitations, including the requirement to use a specific time horizon, the focus on cumulative forcing, and the insensitivity of the metric to the temporal profile of climate effects and its significance to humans. The choice of time horizon is particularly important for short-lived gases, notably methane: when computed with a shorter time horizon for GWP, their share in calculated total warming effect is larger and the mitigation strategy might change as a consequence. [1.2.5]

Many alternative metrics have been proposed in the scientific literature. All of them have advantages and disadvantages, and the choice of metric can make a large difference for the weights given to emissions from particular gases. For instance, methane's GWP_{100} is 28 while its Global Temperature Change Potential (GTP), one alternative metric, is 4 for the same time horizon (AR5 values, see WGI Section 8.7). In terms of aggregate mitigation costs alone, GWP_{100} may perform similarly to other metrics (such as the time-dependent Global Temperature Change Potential or the Global Cost Potential) of reaching a prescribed climate target; however, there may be significant differences in terms of the implied distribution of costs across sectors, regions, and over time. [3.9.6, 6.3.2.5]

An alternative to a single metric for all gases is to adopt a 'multi-basket' approach in which gases are grouped according to their contributions to short and long term climate change. This may solve some problems associated with using a single metric, but the question remains of what relative importance to attach to reducing GHG emissions in the different groups. [3.9.6; WGI 8.7]

[1] In this summary, all quantities of GHG emissions are expressed in CO_2-equivalent (CO_2eq) emissions that are calculated based on GWP_{100}. Unless otherwise stated, GWP values for different gases are taken from IPCC Second Assessment Report (SAR). Although GWP values have been updated several times since, the SAR values are widely used in policy settings, including the Kyoto Protocol, as well as in many national and international emission accounting systems. Modelling studies show that the changes in GWP_{100} values from SAR to AR4 have little impact on the optimal mitigation strategy at the global level. [6.3.2.5, Annex II.9.1]

TS.2.2 Greenhouse gas emission drivers

This section examines the factors that have, historically, been associated with changes in GHG emissions levels. Typically, such analysis is based on a decomposition of total GHG emissions into various components such as growth in the economy (Gross Domestic Product (GDP)/capita), growth in the population (capita), the energy intensity needed per unit of economic output (energy/GDP) and the GHG emissions intensity of that energy (GHGs/energy). As a practical matter, due to data limitations and the fact that most GHG emissions take the form of CO_2 from industry and energy, almost all this research focuses on CO_2 from those sectors.

Globally, economic and population growth continue to be the most important drivers of increases in CO_2 emissions from fossil fuel combustion. The contribution of population growth between 2000 and 2010 remained roughly identical to the previous three decades, while the contribution of economic growth has risen sharply (*high confidence*). Worldwide population increased by 86 % between 1970 and 2010, from 3.7 to 6.9 billion. Over the same period, income as measured through production and/ or consumption per capita has grown by a factor of about two. The exact measurement of global economic growth is difficult because countries use different currencies and converting individual national economic figures into global totals can be done in various ways. With rising population and economic output, emissions of CO_2 from fossil fuel combustion have risen as well. Over the last decade, the importance of economic growth as a driver of global CO_2 emissions has risen sharply while population growth has remained roughly steady. Due to changes in technology, changes in the economic structure and the mix of energy sources as well as changes in other inputs such as capital and labour, the energy intensity of economic output has steadily declined worldwide. This decline has had an offsetting effect on global CO_2 emissions that is nearly of the same magnitude as growth in population (Figure TS.6). There are only a few countries that combine economic growth and decreasing territorial CO_2 emissions over longer periods of time. Such decoupling remains largely atypical, especially when considering consumption-based CO_2 emissions. [1.3, 5.3]

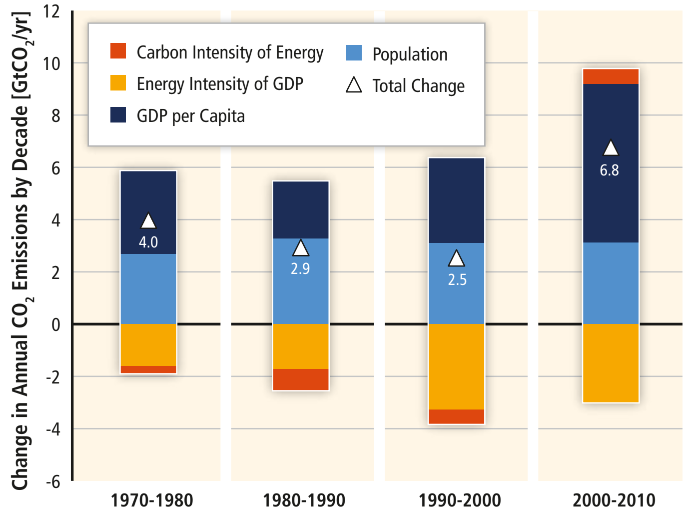

Figure TS.6 | Decomposition of the change in total annual CO_2 emissions from fossil fuel combustion by decade and four driving factors: population, income (GDP) per capita, energy intensity of GDP and carbon intensity of energy. Total emissions changes are indicated by a triangle. The change in emissions over each decade is measured in gigatonnes of CO_2 per year ($GtCO_2$/yr); income is converted into common units using purchasing power parities. [Figure 1.7]

Between 2000 and 2010, increased use of coal relative to other energy sources has reversed a long-standing pattern of gradual decarbonization of the world's energy supply (*high confidence*). Increased use of coal, especially in developing Asia, is exacerbating the burden of energy-related GHG emissions (Figure TS.6). Estimates

Box TS.6 | The use of scenarios in this report

Scenarios of how the future might evolve capture key factors of human development that influence GHG emissions and our ability to respond to climate change. Scenarios cover a range of plausible futures, because human development is determined by a myriad of factors including human decision making. Scenarios can be used to integrate knowledge about the drivers of GHG emissions, mitigation options, climate change, and climate impacts.

One important element of scenarios is the projection of the level of human interference with the climate system. To this end, a set of four 'representative concentration pathways' (RCPs) has been developed. These RCPs reach radiative forcing levels of 2.6, 4.5, 6.0, and 8.5 Watts per square meter (W/m^2) (corresponding to concentrations of 450, 650, 850, and 1370 ppm CO_2eq), respectively, in 2100, covering the range of anthropogenic climate forcing in the 21st century as reported in the literature. The four RCPs are the basis of a new set of climate change projections that have been assessed by WGI AR5. [WGI 6.4, WGI 12.4]

Scenarios of how the future develops without additional and explicit efforts to mitigate climate change ('baseline scenarios') and with the introduction of efforts to limit GHG emissions ('mitigation scenarios'), respectively, generally include socio-economic projections in addition to emission, concentration, and climate change information. WGIII AR5 has assessed the full breadth of baseline and mitigation scenarios in the literature. To this end, it has collected a database of more than 1200 published mitigation and baseline scenarios. In most cases, the underlying socio-economic projections reflect the modelling teams' individual choices about how to conceptualize the future in the absence of climate policy. The baseline scenarios show a wide range of assumptions about economic growth (ranging from threefold to more than eightfold growth in per capita income by 2100), demand for energy (ranging from a 40 % to more than 80 % decline in energy intensity by 2100) and other factors, in particular the carbon intensity of energy. Assumptions about population are an exception: the vast majority of scenarios focus on the low to medium population range of nine to 10 billion people by 2100. Although the range of emissions pathways across baseline scenarios in the literature is broad, it may not represent the full potential range of possibilities (Figure TS.7). [6.3.1]

The concentration outcomes of the baseline and mitigation scenarios assessed by WGIII AR5 cover the full range of RCPs. However, they provide much more detail at the lower end, with many scenarios aiming at concentration levels in the range of 450, 500, and 550 ppm CO_2eq in 2100. The climate change projections of WGI based on RCPs, and the mitigation scenarios assessed by WGIII AR5 can be related to each other through the climate outcomes they imply. [6.2.1]

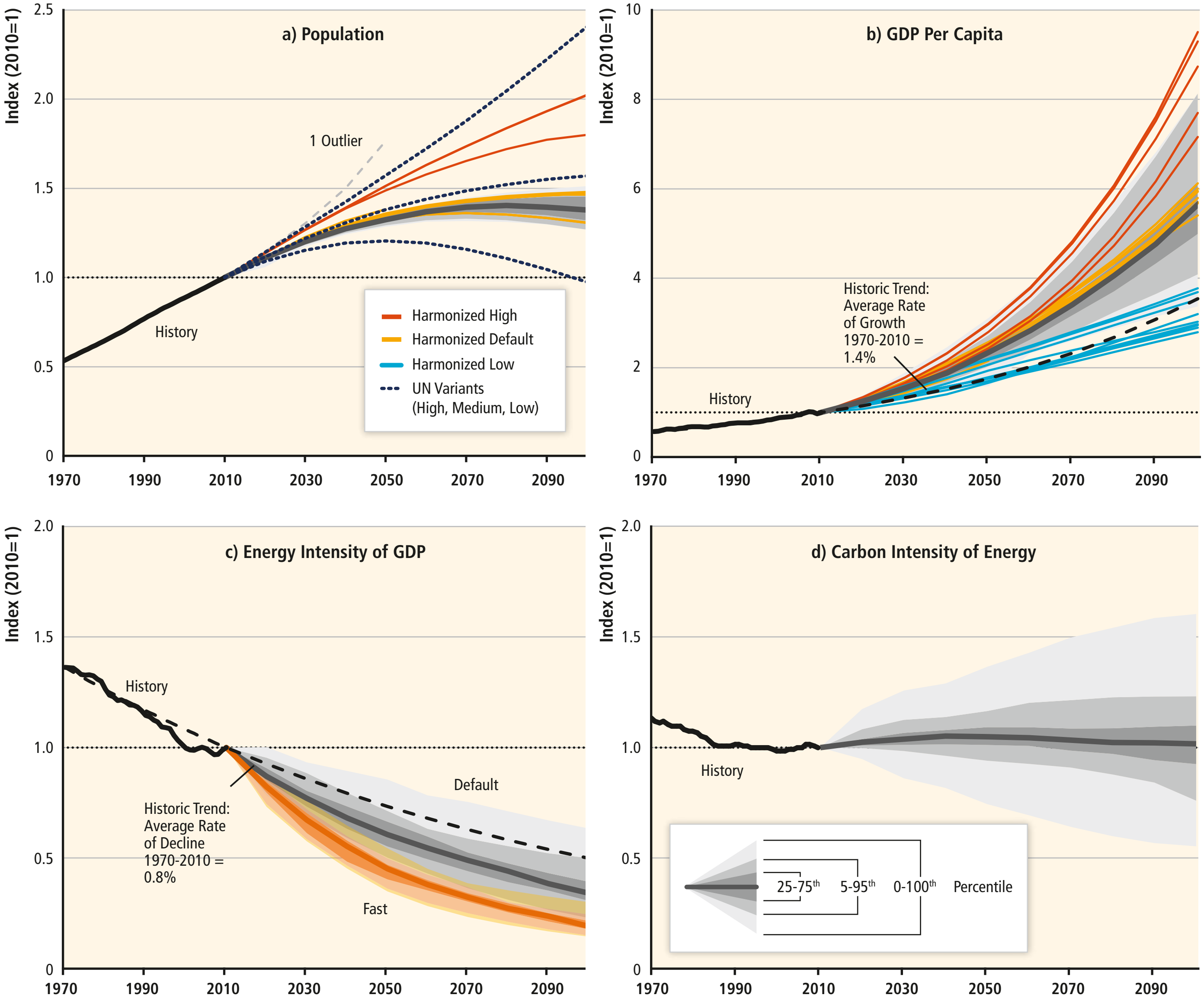

Figure TS.7 | Global baseline projection ranges for four emissions driving factors. Scenarios harmonized with respect to a particular factor are depicted with individual lines. Other scenarios are depicted as a range with median emboldened; shading reflects interquartile range (darkest), 5th–95th percentile range (lighter), and full range (lightest), excluding one indicated outlier in panel a). Scenarios are filtered by model and study for each indicator to include only unique projections. Model projections and historic data are normalized to 1 in 2010. GDP is aggregated using base-year market exchange rates. Energy and carbon intensity are measured with respect to total primary energy. [Figure 6.1]

indicate that coal and unconventional gas and oil resources are large; therefore reducing the carbon intensity of energy may not be primarily driven by fossil resource scarcity, but rather by other driving forces such as changes in technology, values, and socio-political choices. [5.3, 7.2, 7.3, 7.4; SRREN Figure 1.7]

Technological innovations, infrastructural choices, and behaviour affect GHG emissions through productivity growth, energy- and carbon-intensity and consumption patterns (*medium confidence*). Technological innovation improves labour and resource productivity; it can support economic growth both with increasing and with decreasing GHG emissions. The direction and speed of technological change depends on policies. Technology is also central to the choices of infrastructure and spatial organization, such as in cities, which can have long-lasting effects on GHG emissions. In addition, a wide array of attitudes, values, and norms can inform different lifestyles, consumption preferences, and technological choices all of which, in turn, affect patterns of GHG emissions. [5.3, 5.5, 5.6, 12.3]

Without additional efforts to reduce GHG emissions beyond those in place today, emissions growth is expected to persist, driven by growth in global population and economic activities despite improvements in energy supply and end-use technologies (*high confidence*). Atmospheric concentrations in baseline scenarios collected for this assessment (scenarios without explicit additional efforts to reduce GHG emissions) exceed 450 parts per million (ppm) CO_2eq by 2030.[7] They reach CO_2eq concentration levels from 750 to more than 1300 ppm CO_2eq by 2100 and result in projected global mean surface temperature increases in 2100 from 3.7 to 4.8 °C compared to pre-industrial levels[8] (range based on median climate response; the range is 2.5 °C to 7.8 °C when including climate uncertainty, see Table TS.1).[9] The range of 2100 concentrations corresponds roughly to the range of CO_2eq concentrations in the Representative Concentration Pathways (RCP) 6.0 and RCP8.5 pathways (see Box TS.6), with the majority of scenarios falling below the latter. For comparison, the CO_2eq concentration in 2011 has been estimated to be 430 ppm (uncertainty range 340–520 ppm).[10] The literature does not systematically explore the full range of uncertainty surrounding development pathways and possible evolution of key drivers such as population, technology, and resources. Nonetheless, the scenarios strongly suggest that absent any explicit mitigation efforts, cumulative CO_2 emissions since 2010 will exceed 700 $GtCO_2$ by 2030, 1,500 $GtCO_2$ by 2050, and potentially well over 4,000 $GtCO_2$ by 2100. [6.3.1; WGI Figure SPM.5, WGI 8.5, WGI 12.3]

TS.3 Mitigation pathways and measures in the context of sustainable development

This section assesses the literature on mitigation pathways and measures in the context of sustainable development. Section TS 3.1 first examines the anthropogenic GHG emissions trajectories and potential temperature implications of mitigation pathways leading to a range of future atmospheric CO_2eq *concentrations. It then explores the technological, economic, and institutional requirements of these pathways along with their potential co-benefits and adverse side-effects. Section TS 3.2 examines mitigation options by sector and how they may interact across sectors.*

7 These CO_2eq concentrations represent full radiative forcing, including GHGs, halogenated gases, tropospheric ozone, aerosols, mineral dust and albedo change.

8 Based on the longest global surface temperature dataset available, the observed change between the average of the period 1850–1900 and of the AR5 reference period (1986–2005) is 0.61 °C (5–95 % confidence interval: 0.55 to 0.67 °C) [WGI SPM.E], which is used here as an approximation of the change in global mean surface temperature since pre-industrial times, referred to as the period before 1750.

9 Provided estimates reflect the 10th to the 90th percentile of baseline scenarios collected for this assessment. The climate uncertainty reflects the 5th to 95th percentile of climate model calculations described in Table TS.1 for each scenario.

10 This is based on the assessment of total anthropogenic radiative forcing for 2011 relative to 1750 in WGI AR5, i.e., 2.3 $W m^{-2}$, uncertainty range 1.1 to 3.3 $W m^{-2}$. [WGI Figure SPM.5, WGI 8.5, WGI 12.3]

TS.3.1 Mitigation pathways

TS.3.1.1 Understanding mitigation pathways in the context of multiple objectives

The world's societies will need to both mitigate and adapt to climate change if it is to effectively avoid harmful climate impacts (*robust evidence, high agreement*). There are demonstrated examples of synergies between mitigation and adaptation [11.5.4, 12.8.1] in which the two strategies are complementary. More generally, the two strategies are related because increasing levels of mitigation imply less future need for adaptation. Although major efforts are now underway to incorporate impacts and adaptation into mitigation scenarios, inherent difficulties associated with quantifying their interdependencies have limited their representation in models used to generate mitigation scenarios assessed in WGIII AR5 (Box TS.7). [2.6.3, 3.7.2.1, 6.3.3]

There is no single pathway to stabilize CO_2eq concentrations at any level; instead, the literature points to a wide range of mitigation pathways that might meet any concentration level (*high confidence*). Choices, whether deliberated or not, will determine which of these pathways is followed. These choices include, among other things, the emissions pathway to bring atmospheric CO_2eq concentrations to a particular level, the degree to which concentrations temporarily exceed (overshoot) the long-term level, the technologies that are deployed to reduce emissions, the degree to which mitigation is coordinated across countries, the policy approaches used to achieve mitigation within and across countries, the treatment of land use, and the manner in which mitigation is meshed with other policy objectives such as sustainable development. A society's development pathway—with its particular socioeconomic, institutional, political, cultural and technological features—enables and constrains the prospects for mitigation. At the national level, change is considered most effective when it reflects country and local visions and approaches to achieving sustainable development according to national circumstances and priorities. [4.2, 6.3–6.8, 11.8]

Mitigation pathways can be distinguished from one another by a range of outcomes or requirements (*high confidence*). Decisions about mitigation pathways can be made by weighing the requirements of different pathways against each other. Although measures of aggregate economic costs and benefits have often been put forward as key decision-making factors, they are far from the only outcomes that matter. Mitigation pathways inherently involve a range of synergies and tradeoffs connected with other policy objectives such as energy and food security, energy access, the distribution of economic impacts, local air quality, other environmental factors associated with different technological solutions, and economic competitiveness (Box TS.11). Many of these fall under the umbrella of sustainable development. In addition, requirements such as the rates of up-scaling of energy technologies or the rates of reductions in GHG emissions may provide important insights into the degree of challenge associated with meeting a particular long-term goal. [4.5, 4.8, 6.3, 6.4, 6.6]

Box TS.7 | Scenarios from integrated models can help to understand how actions affect outcomes in complex systems

The long-term scenarios assessed in this report were generated primarily by large-scale computer models, referred to here as 'integrated models', because they attempt to represent many of the most important interactions among technologies, relevant human systems (e.g., energy, agriculture, the economic system), and associated GHG emissions in a single integrated framework. A subset of these models is referred to as 'integrated assessment models', or IAMs. IAMs include not only an integrated representation of human systems, but also of important physical processes associated with climate change, such as the carbon cycle, and sometimes representations of impacts from climate change. Some IAMs have the capability of endogenously balancing impacts with mitigation costs, though these models tend to be highly aggregated. Although aggregate models with representations of mitigation and damage costs can be very useful, the focus in this assessment is on integrated models with sufficient sectoral and geographic resolution to understand the evolution of key processes such as energy systems or land systems.

Scenarios from integrated models are invaluable to help understand how possible actions or choices might lead to different future outcomes in these complex systems. They provide quantitative, long-term projections (conditional on our current state of knowledge) of many of the most important characteristics of mitigation pathways while accounting for many of the most important interactions between the various relevant human and natural systems. For example, they provide both regional and global information about emissions pathways, energy and land-use transitions, and aggregate economic costs of mitigation.

At the same time, these integrated models have particular characteristics and limitations that should be considered when interpreting their results. Many integrated models are based on the rational choice paradigm for decision making, excluding the consideration of some behavioural factors. The models approximate cost-effective solutions that minimize the aggregate economic costs of achieving mitigation outcomes, unless they are specifically constrained to behave otherwise. Scenarios from these models capture only some of the dimensions of development pathways that are relevant to mitigation options, often only minimally treating issues such as distributional impacts of mitigation actions and consistency with broader development goals. In addition, the models in this assessment do not effectively account for the interactions between mitigation, adaptation, and climate impacts. For these reasons, mitigation has been assessed independently from climate impacts. Finally, and most fundamentally, integrated models are simplified, stylized, numerical approaches for representing enormously complex physical and social systems, and scenarios from these models are based on uncertain projections about key events and drivers over often century-long timescales. Simplifications and differences in assumptions are the reason why output generated from different models—or versions of the same model—can differ, and projections from all models can differ considerably from the reality that unfolds. [3.7, 6.2]

TS.3.1.2 Short- and long-term requirements of mitigation pathways

Mitigation scenarios point to a range of technological and behavioral measures that could allow the world's societies to follow GHG emissions pathways consistent with a range of different levels of mitigation (*high confidence*). As part of this assessment, about 900 mitigation and 300 baseline scenarios have been collected from integrated modelling research groups around the world (Box TS.7). The mitigation scenarios span atmospheric concentration levels in 2100 from 430 ppm CO_2eq to above 720 ppm CO_2eq, which is roughly comparable to the 2100 forcing levels between the RCP2.6 and RCP6.0 scenarios (Figure TS.8, left panel). Scenarios have been constructed to reach mitigation goals under very different assumptions about energy demands, international cooperation, technologies, the contributions of CO_2 and other forcing agents to atmospheric CO_2eq concentrations, and the degree to which concentrations temporarily exceed the long-term goal (concentration overshoot, see Box TS.8). Other scenarios were also assessed, including some scenarios with concentrations in 2100 below 430 ppm CO_2eq (for a discussion of these scenarios see below). [6.3]

Limiting atmospheric peak concentrations over the course of the century—not only reaching long-term concentration levels—is critical for limiting transient temperature change (*high confidence*). Scenarios reaching concentration levels of about 500 ppm CO_2eq by 2100 are *more likely than not* to limit temperature change to less than 2 °C relative to pre-industrial levels, unless they temporarily 'overshoot' concentration levels of roughly 530 ppm CO_2eq before 2100. In this case, they are *about as likely as not* to achieve that goal. The majority of scenarios reaching long-term concentrations of about 450 ppm CO_2eq in 2100 are *likely* to keep temperature change below 2 °C over the course of the century relative to pre-industrial levels (Table TS.1, Box TS.8). Scenarios that reach 530 to 650 ppm CO_2eq concentrations by 2100 are *more unlikely than likely* to keep temperature change below 2 °C relative to pre-industrial levels. Scenarios that exceed about 650 ppm CO_2eq by 2100 are *unlikely* to limit temperature change to below 2 °C relative to pre-industrial levels. Mitigation

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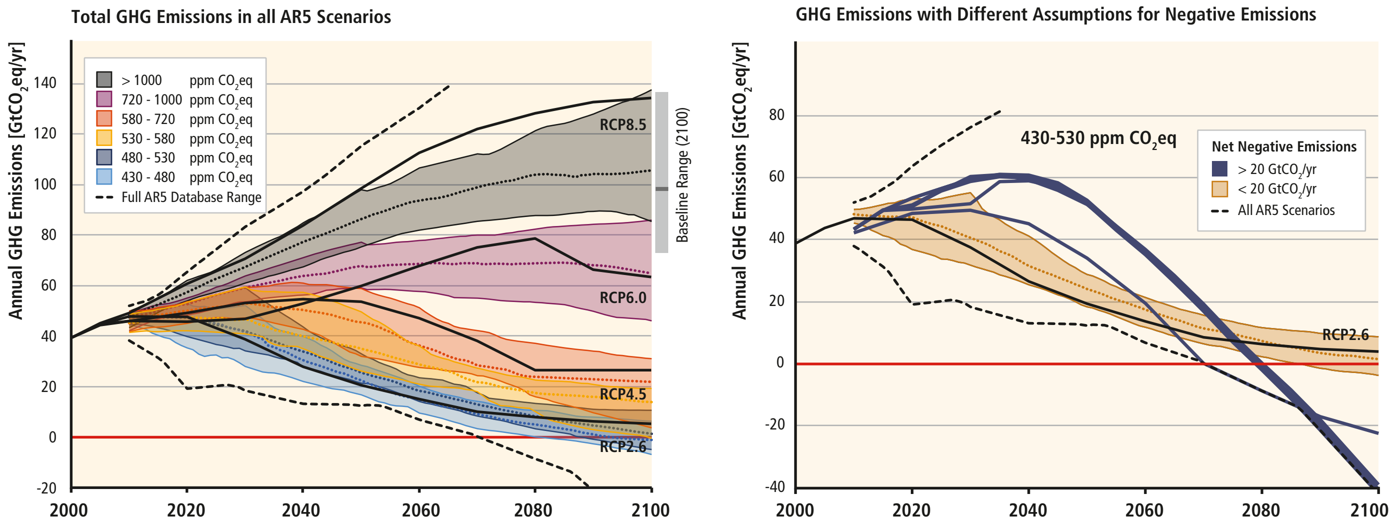

Figure TS.8 | Development of total GHG emissions for different long-term concentration levels (left panel) and for scenarios reaching about 450 to about 500 (430–530) ppm CO_2eq in 2100 with and without net negative CO_2 emissions larger than 20 GtCO_2/yr (right panel). Ranges are given for the 10th–90th percentile of scenarios. [Figure 6.7]

scenarios in which temperature increase is *more likely than not* to be less than 1.5 °C relative to pre-industrial levels by 2100 are characterized by concentrations in 2100 of below 430 ppm CO_2eq. Temperature peaks during the century and then declines in these scenarios. [6.3]

Mitigation scenarios reaching about 450 ppm CO_2eq in 2100 typically involve temporary overshoot of atmospheric concentrations, as do many scenarios reaching about 500 ppm or about 550 ppm CO_2eq in 2100 (*high confidence*). Concentration overshoot means that concentrations peak during the century before descending toward their 2100 levels. Overshoot involves less mitigation in the near term, but it also involves more rapid and deeper emissions reductions in the long run. The vast majority of scenarios reaching about 450 ppm CO_2eq in 2100 involve concentration overshoot, since most models cannot reach the immediate, near-term emissions reductions that would be necessary to avoid overshoot of these concentration levels. Many scenarios have been constructed to reach about 550 ppm CO_2eq by 2100 without overshoot.

Depending on the level of overshoot, many overshoot scenarios rely on the availability and widespread deployment of bioenergy with carbon dioxide capture and storage (BECCS) and/or afforestation in the second half of the century (*high confidence*). These and other carbon dioxide removal (CDR) technologies and methods remove CO_2 from the atmosphere (negative emissions). Scenarios with overshoot of greater than 0.4 W/m^2 (> 35–50 ppm CO_2eq concentration) typically deploy CDR technologies to an extent that net global CO_2 emissions become negative in the second-half of the century (Figure TS.8, right panel). CDR is also prevalent in many scenarios without concentration overshoot to compensate for residual emissions from sectors where mitigation is more expensive. The availability and potential of BECCS, afforestation, and other CDR technologies and methods are uncertain and CDR technologies and methods are, to varying degrees, associated with challenges and risks. There is uncertainty about the potential for large-scale deployment of BECCS, large-scale afforestation, and other CDR technologies and methods. [6.3, 6.9]

Reaching atmospheric concentration levels of about 450 to about 500 ppm CO_2eq by 2100 will require substantial cuts in anthropogenic GHG emissions by mid-century (*high confidence*). Scenarios reaching about 450 ppm CO_2eq by 2100 are associated with GHG emissions reductions of about 40 % to 70 % by 2050 compared to 2010 and emissions levels near zero GtCO_2eq or below in 2100.[11] Scenarios with GHG emissions reductions in 2050 at the lower end of this range are characterized by a greater reliance on CDR technologies beyond mid-century. The majority of scenarios that reach about 500 ppm CO_2eq in 2100 without overshooting roughly 530 ppm CO_2eq at any point during the century are associated with GHG emissions reductions of 40 % to 55 % by 2050 compared to 2010 (Figure TS.8, left panel; Table TS.1). In contrast, in some scenarios in which concentrations rise to well above 530 ppm CO_2eq during the century before descending to concentrations below this level by 2100, emissions rise to as high as 20 % above 2010 levels in 2050. However, these high-overshoot scenarios are characterized by negative global emissions of well over 20 GtCO_2 per year in the second half of the century (Figure TS.8, right panel). Cumulative CO_2

[11] This range differs from the range provided for a similar concentration category in AR4 (50 % to 85 % lower than 2000 for CO_2 only). Reasons for this difference include that this report has assessed a substantially larger number of scenarios than in AR4 and looks at all GHGs. In addition, a large proportion of the new scenarios include Carbon Dioxide Removal (CDR) technologies and associated increases in concentration overshoot. Other factors include the use of 2100 concentration levels instead of stabilization levels and the shift in reference year from 2000 to 2010.

Box TS.8 | Assessment of temperature change in the context of mitigation scenarios

Long-term climate goals have been expressed both in terms of concentrations and temperature. Article 2 of the UNFCCC calls for the need to 'stabilize' concentrations of GHGs. Stabilization of concentrations is generally understood to mean that the CO_2eq concentration reaches a specific level and then remains at that level indefinitely until the global carbon and other cycles come into a new equilibrium. The notion of stabilization does not necessarily preclude the possibility that concentrations might exceed, or 'overshoot' the long-term goal before eventually stabilizing at that goal. The possibility of 'overshoot' has important implications for the required GHG emissions reductions to reach a long-term concentration level. Concentration overshoot involves less mitigation in the near term with more rapid and deeper emissions reductions in the long run.

The temperature response of the concentration pathways assessed in this report focuses on transient temperature change over the course of the century. This is an important difference with WGIII AR4, which focused on the long-term equilibrium temperature response, a state that is reached millennia after the stabilization of concentrations. The temperature outcomes in this report are thus not directly comparable to those presented in the WGIII AR4 assessment. One reason that this assessment focuses on transient temperature response is that it is less uncertain than the equilibrium response and correlates more strongly with GHG emissions in the near and medium term. An additional reason is that the mitigation pathways assessed in WGIII AR5 do not extend beyond 2100 and are primarily designed to reach specific concentration goals for the year 2100. The majority of these pathways do not stabilize concentrations in 2100, which makes the assessment of the equilibrium temperature response ambiguous and dependent on assumptions about post-2100 emissions and concentrations.

Transient temperature goals might be defined in terms of the temperature in a specific year (e.g., 2100), or based on never exceeding a particular level. This report explores the implications of both types of goals. The assessment of temperature goals are complicated by the uncertainty that surrounds our understanding of key physical relationships in the earth system, most notably the relationship between concentrations and temperature. It is not possible to state definitively whether any long-term concentration pathway will limit either transient or equilibrium temperature change to below a specified level. It is only possible to express the temperature implications of particular concentration pathways in probabilistic terms, and such estimates will be dependent on the source of the probability distribution of different climate parameters and the climate model used for analysis. This report employs the MAGICC model and a distribution of climate parameters that results in temperature outcomes with dynamics similar to those from the Earth System Models assessed in WGI AR5. For each emissions scenario, a median transient temperature response is calculated to illustrate the variation of temperature due to different emissions pathways. In addition, a transient temperature range for each scenario is provided, reflecting the climate system uncertainties. Information regarding the full distribution of climate parameters was utilized for estimating the likelihood that the scenarios would limit transient temperature change to below specific levels (Table TS.1). Providing the combination of information about the plausible range of temperature outcomes as well as the likelihood of meeting different targets is of critical importance for policymaking, since it facilitates the assessment of different climate objectives from a risk management perspective. [2.5.7.2, 6.3.2]

emissions between 2011 and 2100 are 630–1180 $GtCO_2$ in scenarios reaching about 450 ppm CO_2eq in 2100; they are 960–1550 $GtCO_2$ in scenarios reaching about 500 ppm CO_2eq in 2100. The variation in cumulative CO_2 emissions across scenarios is due to differences in the contribution of non-CO_2 GHGs and other radiatively active substances as well as the timing of mitigation (Table TS.1). [6.3]

In order to reach atmospheric concentration levels of about 450 to about 500 ppm CO_2eq by 2100, the majority of mitigation relative to baseline emissions over the course of century will occur in the non-Organisation for Economic Co-operation and Development (OECD) countries (*high confidence*). In scenarios that attempt to cost-effectively allocate emissions reductions across countries and over time, the total CO_2eq emissions reductions from baseline emissions in non-OECD countries are greater than in OECD countries. This is, in large part, because baseline emissions from the non-OECD countries are projected to be larger than those from the OECD countries, but it also derives from higher carbon intensities in non-OECD countries and different terms of trade structures. In these scenarios, GHG emissions peak earlier in the OECD countries than in the non-OECD countries. [6.3]

Reaching atmospheric concentration levels of about 450 to about 650 ppm CO_2eq by 2100 will require large-scale changes to global and national energy systems over the coming decades (*high confidence*). Scenarios reaching atmospheric concentrations levels of about 450 to about 500 ppm CO_2eq by 2100 are characterized by a tripling to nearly a quadrupling of the global share of zero- and low-carbon energy supply from renewables, nuclear energy, fossil energy with carbon dioxide capture and storage (CCS), and bioenergy with CCS (BECCS), by the year 2050 relative to 2010 (about 17 %) (Figure TS.10, left panel). The increase in total global low-carbon energy sup-

Table TS.1 | Key characteristics of the scenarios collected and assessed for WGIII AR5. For all parameters, the 10th to 90th percentile of the scenarios is shown.[1,2] [Table 6.3]

CO_2eq Concentrations in 2100 [ppm CO_2eq] Category label (concentration range)[9]	Subcategories	Relative position of the RCPs[5]	Cumulative CO_2 emissions[3] [$GtCO_2$]		Change in CO_2eq emissions compared to 2010 in [%][4]		Temperature change (relative to 1850–1900)[5,6]				
			2011–2050	2011–2100	2050	2100	2100 Temperature change [°C][7]	Likelihood of staying below temperature level over the 21st century[8]			
								1.5 °C	2.0 °C	3.0 °C	4.0 °C
< 430	Only a limited number of individual model studies have explored levels below 430 ppm CO_2eq										
450 (430–480)	Total range[1,10]	RCP2.6	550–1300	630–1180	−72 to −41	−118 to −78	1.5–1.7 (1.0–2.8)	*More unlikely than likely*	*Likely*	*Likely*	*Likely*
500 (480–530)	No overshoot of 530 ppm CO_2eq		860–1180	960–1430	−57 to −42	−107 to −73	1.7–1.9 (1.2–2.9)	*Unlikely*	*More likely than not*		
	Overshoot of 530 ppm CO_2eq		1130–1530	990–1550	−55 to −25	−114 to −90	1.8–2.0 (1.2–3.3)		*About as likely as not*		
550 (530–580)	No overshoot of 580 ppm CO_2eq		1070–1460	1240–2240	−47 to −19	−81 to −59	2.0–2.2 (1.4–3.6)		*More unlikely than likely*[12]		
	Overshoot of 580 ppm CO_2eq		1420–1750	1170–2100	−16 to 7	−183 to −86	2.1–2.3 (1.4–3.6)				
(580–650)	Total range	RCP4.5	1260–1640	1870–2440	−38 to 24	−134 to −50	2.3–2.6 (1.5–4.2)				
(650–720)	Total range		1310–1750	2570–3340	−11 to 17	−54 to −21	2.6–2.9 (1.8–4.5)		*Unlikely*	*More likely than not*	
(720–1000)[2]	Total range	RCP6.0	1570–1940	3620–4990	18 to 54	−7 to 72	3.1–3.7 (2.1–5.8)	*Unlikely*[11]		*More unlikely than likely*	
>1000[2]	Total range	RCP8.5	1840–2310	5350–7010	52 to 95	74 to 178	4.1–4.8 (2.8–7.8)		*Unlikely*[11]	*Unlikely*	*More unlikely than likely*

Notes:

1 The 'total range' for the 430–480 ppm CO_2eq scenarios corresponds to the range of the 10th–90th percentile of the subcategory of these scenarios shown in Table 6.3.

2 Baseline scenarios (see TS.2.2) fall into the >1000 and 720–1000 ppm CO_2eq categories. The latter category also includes mitigation scenarios. The baseline scenarios in the latter category reach a temperature change of 2.5–5.8 °C above preindustrial in 2100. Together with the baseline scenarios in the >1000 ppm CO_2eq category, this leads to an overall 2100 temperature range of 2.5–7.8 °C (range based on median climate response: 3.7–4.8 °C) for baseline scenarios across both concentration categories.

3 For comparison of the cumulative CO_2 emissions estimates assessed here with those presented in WGI AR5, an amount of 515 [445–585] GtC (1890 [1630–2150] $GtCO_2$), was already emitted by 2011 since 1870 [WGI 12.5]. Note that cumulative CO_2 emissions are presented here for different periods of time (2011–2050 and 2011–2100) while cumulative CO_2 emissions in WGI AR5 are presented as total compatible emissions for the RCPs (2012–2100) or for total compatible emissions for remaining below a given temperature target with a given likelihood [WGI Table SPM.3, WGI SPM.E.8].

4 The global 2010 emissions are 31 % above the 1990 emissions (consistent with the historic GHG emissions estimates presented in this report). CO_2eq emissions include the basket of Kyoto gases (CO_2, CH_4, N_2O as well as F-gases).

5 The assessment in WGIII AR5 involves a large number of scenarios published in the scientific literature and is thus not limited to the RCPs. To evaluate the CO_2eq concentration and climate implications of these scenarios, the MAGICC model was used in a probabilistic mode (see Annex II). For a comparison between MAGICC model results and the outcomes of the models used in WGI, see Sections WGI 12.4.1.2, WGI 12.4.8 and 6.3.2.6. Reasons for differences with WGI SPM Table.2 include the difference in reference year (1986–2005 vs. 1850–1900 here), difference in reporting year (2081–2100 vs 2100 here), set-up of simulation (CMIP5 concentration-driven versus MAGICC emission-driven here), and the wider set of scenarios (RCPs versus the full set of scenarios in the WGIII AR5 scenario database here).

6 Temperature change is reported for the year 2100, which is not directly comparable to the equilibrium warming reported in WGIII AR4 [Table 3.5, Chapter 3; see also WGIII AR5 6.3.2]. For the 2100 temperature estimates, the transient climate response (TCR) is the most relevant system property. The assumed 90 % range of the TCR for MAGICC is 1.2–2.6 °C (median 1.8 °C). This compares to the 90 % range of TCR between 1.2–2.4 °C for CMIP5 [WGI 9.7] and an assessed *likely* range of 1–2.5 °C from multiple lines of evidence reported in the WGI AR5 [Box 12.2 in Section 12.5].

7 Temperature change in 2100 is provided for a median estimate of the MAGICC calculations, which illustrates differences between the emissions pathways of the scenarios in each category. The range of temperature change in the parentheses includes in addition the carbon cycle and climate system uncertainties as represented by the MAGICC model [see 6.3.2.6 for further details]. The temperature data compared to the 1850–1900 reference year was calculated by taking all projected warming relative to 1986–2005, and adding 0.61 °C for 1986–2005 compared to 1850–1900, based on HadCRUT4 [see WGI Table SPM.2].

8 The assessment in this table is based on the probabilities calculated for the full ensemble of scenarios in WGIII AR5 using MAGICC and the assessment in WGI AR5 of the uncertainty of the temperature projections not covered by climate models. The statements are therefore consistent with the statements in WGI AR5, which are based on the CMIP5 runs of the RCPs and the assessed uncertainties. Hence, the likelihood statements reflect different lines of evidence from both WGs. This WGI method was also applied for scenarios with intermediate concentration levels where no CMIP5 runs are available. The likelihood statements are indicative only [6.3], and follow broadly the terms used by the WGI AR5 SPM for temperature projections: *likely* 66–100 %, *more likely than not* >50–100 %, *about as likely as not* 33–66 %, and *unlikely* 0–33 %. In addition the term *more unlikely than likely* 0–<50 % is used.

9 The CO_2-equivalent concentration includes the forcing of all GHGs including halogenated gases and tropospheric ozone, as well as aerosols and albedo change (calculated on the basis of the total forcing from a simple carbon cycle/climate model, MAGICC).

10 The vast majority of scenarios in this category overshoot the category boundary of 480 ppm CO_2eq concentrations.

11 For scenarios in this category no CMIP5 run [WGI Chapter 12, Table 12.3] as well as no MAGICC realization [6.3] stays below the respective temperature level. Still, an *unlikely* assignment is given to reflect uncertainties that might not be reflected by the current climate models.

12 Scenarios in the 580–650 ppm CO_2eq category include both overshoot scenarios and scenarios that do not exceed the concentration level at the high end of the category (like RCP4.5). The latter type of scenarios, in general, have an assessed probability of *more unlikely than likely* to stay below the 2 °C temperature level, while the former are mostly assessed to have an *unlikely* probability of staying below this level.

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ply is from three-fold to seven-fold over this same period. Many models could not reach 2100 concentration levels of about 450 ppm CO_2eq if the full suite of low-carbon technologies is not available. Studies indicate a large potential for energy demand reductions, but also indicate that demand reductions on their own would not be sufficient to bring about the reductions needed to reach levels of about 650 ppm CO_2eq or below by 2100. [6.3, 7.11]

Mitigation scenarios indicate a potentially critical role for land-related mitigation measures and that a wide range of alternative land transformations may be consistent with similar concentration levels (*medium confidence*). Land-use dynamics in mitigation scenarios are heavily influenced by the production of bioenergy and the degree to which afforestation is deployed as a negative-emissions, or CDR option. They are, in addition, influenced by forces independent of mitigation such as agricultural productivity improvements and increased demand for food. The range of land-use transformations depicted in mitigation scenarios reflects a wide range of differing assumptions about the evolution of all of these forces. Many scenarios reflect strong increases in the degree of competition for land between food, feed, and energy uses. [6.3, 6.8, 11.4.2]

Delaying mitigation efforts beyond those in place today through 2030 will increase the challenges of, and reduce the options for, limiting atmospheric concentration levels from about 450 to about 500 ppm CO_2eq by the end of the century (*high confidence*). Cost-effective mitigation scenarios leading to atmospheric concentration levels of about 450 to about 500 ppm CO_2eq at the end of the 21st century are typically characterized by annual GHG emissions in 2030 of roughly between 30 $GtCO_2$eq and 50 $GtCO_2$eq. Scenarios with emissions above 55 $GtCO_2$eq in 2030 are characterized by substantially higher rates of emissions reductions from 2030 to 2050 (median emissions reductions of about 6 %/yr as compared to just over 3 %/yr) (Figure TS.9, right panel); much more rapid scale-up of low-carbon energy over this period (more than a tripling compared to a doubling of the low-carbon energy share) (Figure TS.10, right panel);

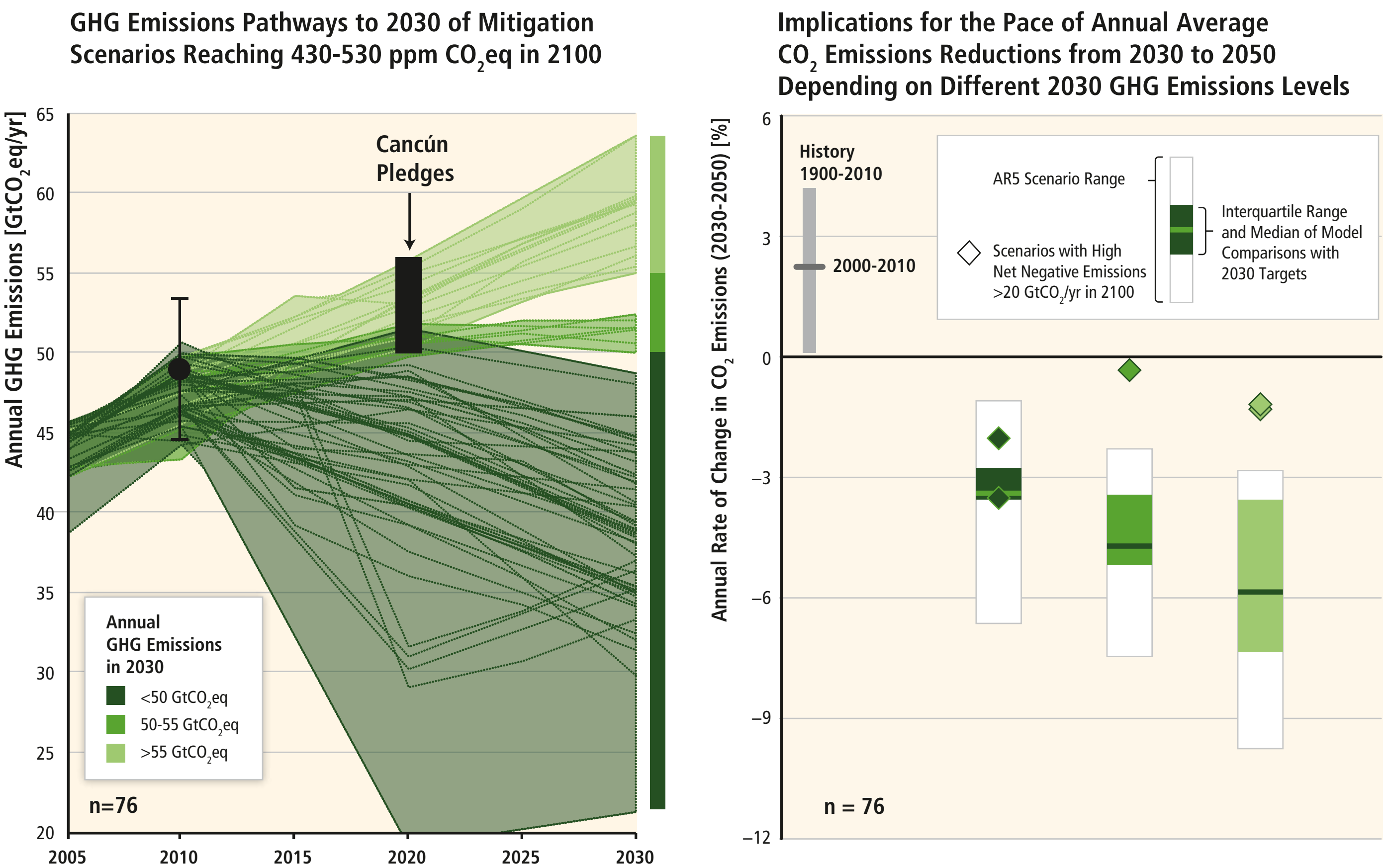

Figure TS.9 | The implications of different 2030 GHG emissions levels for the rate of CO_2 emissions reductions from 2030 to 2050 in mitigation scenarios reaching about 450 to about 500 (430–530) ppm CO_2eq concentrations by 2100. The scenarios are grouped according to different emissions levels by 2030 (coloured in different shades of green). The left panel shows the pathways of GHG emissions ($GtCO_2$eq/yr) leading to these 2030 levels. The black bar shows the estimated uncertainty range of GHG emissions implied by the Cancún Pledges. Black dot with whiskers gives historic GHG emission levels and associated uncertainties in 2010 as reported in Figure TS.1. The right panel denotes the average annual CO_2 emissions reduction rates for the period 2030–2050. It compares the median and interquartile range across scenarios from recent intermodel comparisons with explicit 2030 interim goals to the range of scenarios in the Scenario Database for WGIII AR5. Annual rates of historical emissions change between 1900–2010 (sustained over a period of 20 years) and the average annual emissions change between 2000–2010 are shown in grey. Note: Scenarios with large net negative global emissions (> 20 $GtCO_2$/yr) are not included in the WGIII AR5 scenario range, but rather shown as independent points. Only scenarios that apply the full, unconstrained mitigation technology portfolio of the underlying models (default technology assumption) are shown. Scenarios with exogenous carbon price assumptions or other policies affecting the timing of mitigation (other than 2030 interim targets) as well as scenarios with 2010 emissions significantly outside the historical range are excluded. [Figure 6.32, 13.13.1.3]

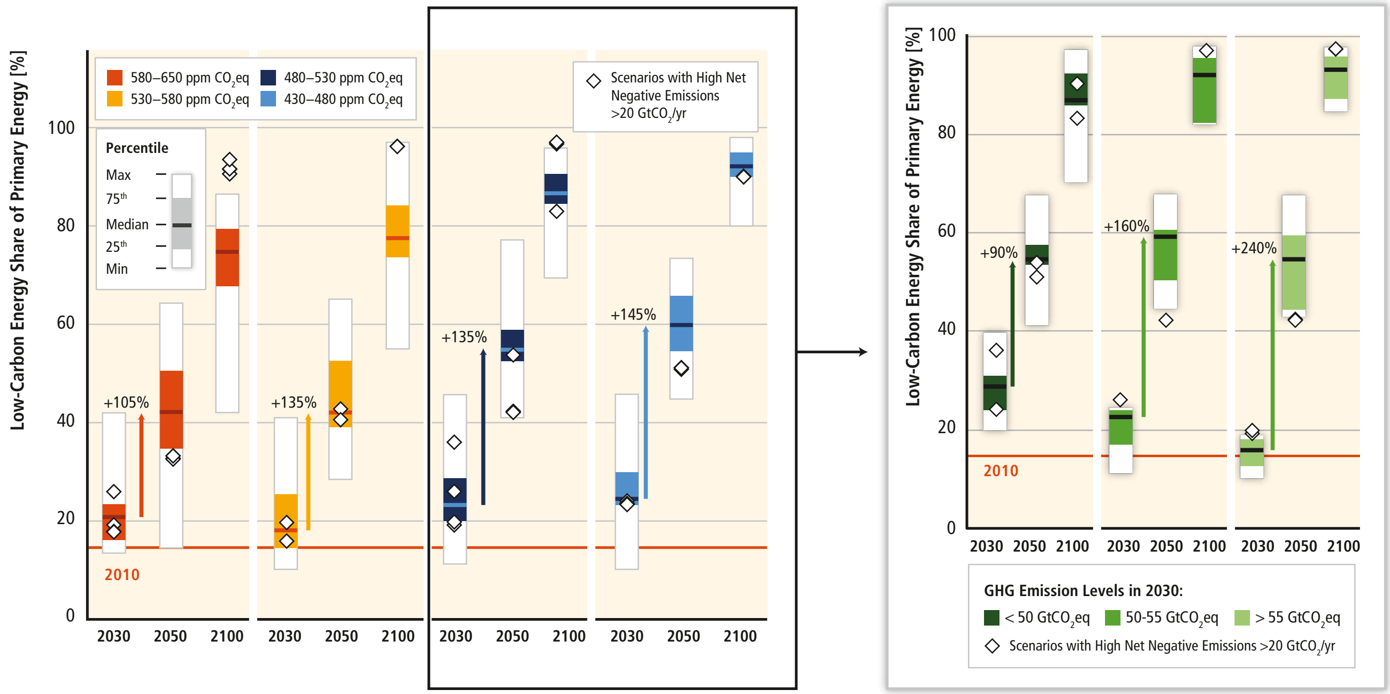

Figure TS.10 | The up-scaling of low-carbon energy in scenarios meeting different 2100 CO_2eq concentration levels (left panel). The right panel shows the rate of up-scaling subject to different 2030 GHG emissions levels in mitigation scenarios reaching about 450 to about 500 (430–530) ppm CO_2eq concentrations by 2100. Colored bars show the interquartile range and white bars indicate the full range across the scenarios, excluding those with large, global net negative CO_2 emissions (> 20 $GtCO_2$/yr). Scenarios with large net negative global emissions are shown as individual points. The arrows indicate the magnitude of zero- and low-carbon energy supply up-scaling from 2030 to 2050. Zero- and low-carbon energy supply includes renewables, nuclear energy, fossil energy with carbon dioxide capture and storage (CCS), and bioenergy with CCS (BECCS). Note: Only scenarios that apply the full, unconstrained mitigation technology portfolio of the underlying models (default technology assumption) are shown. Scenarios with exogenous carbon price assumptions are excluded in both panels. In the right panel, scenarios with policies affecting the timing of mitigation other than 2030 interim targets are also excluded. [Figure 7.16]

a larger reliance on CDR technologies in the long-term (Figure TS.8, right panel); and higher transitional and long term economic impacts (Table TS.2, orange segments, Figure TS.13, right panel). Due to these increased challenges, many models with 2030 GHG emissions in this range could not produce scenarios reaching atmospheric concentrations levels of about 450 to about 500 ppm CO_2eq in 2100. [6.4, 7.11]

Estimated global GHG emissions levels in 2020 based on the Cancún Pledges are not consistent with cost-effective long-term mitigation trajectories that reach atmospheric concentrations levels of about 450 to about 500 ppm CO_2eq by 2100, but they do not preclude the option to meet that goal (*robust evidence, high agreement*). The Cancún Pledges are broadly consistent with cost-effective scenarios reaching about 550 ppm CO_2eq to 650 ppm CO_2eq by 2100. Studies confirm that delaying mitigation through 2030 has a substantially larger influence on the subsequent challenges of mitigation than do delays through 2020 (Figures TS.9, TS.11). [6.4]

Only a limited number of studies have explored scenarios that are *more likely than not* to bring temperature change back to below 1.5 °C by 2100 relative to pre-industrial levels; these scenarios bring atmospheric concentrations to below 430 ppm CO_2eq by 2100 (*high confidence*). Assessing this goal is currently difficult because no multi-model study has explored these scenarios. The limited number of published studies exploring this goal have produced associated scenarios that are characterized by (1) immediate mitigation; (2) the rapid up-scaling of the full portfolio of mitigation technologies; and (3) development along a low-energy demand trajectory.[12] [6.3, 7.11]

TS.3.1.3 Costs, investments and burden sharing

Globally comprehensive and harmonized mitigation actions would result in significant economic benefits compared to fragmented approaches, but would require establishing effective institutions (*high confidence*). Economic analysis of mitigation scenarios demonstrates that globally comprehensive and harmonized mitigation actions achieve mitigation at least aggregate economic cost, since they allow mitigation to be undertaken where and when it is least expensive (see Box TS.7, Box TS.9). Most of these mitigation scenarios assume a global carbon price, which reaches all sectors of the economy. Instruments with limited coverage of GHG emissions reductions among sectors and climate policy regimes with fragmented regional

12 In these scenarios, the cumulative CO_2 emissions range between 680–800 $GtCO_2$ for the period 2011–2050 and between 90–310 $GtCO_2$ for the period 2011–2100. Global CO_2eq emissions in 2050 are between 70–95 % below 2010 emissions, and they are between 110–120 % below 2010 emissions in 2100.

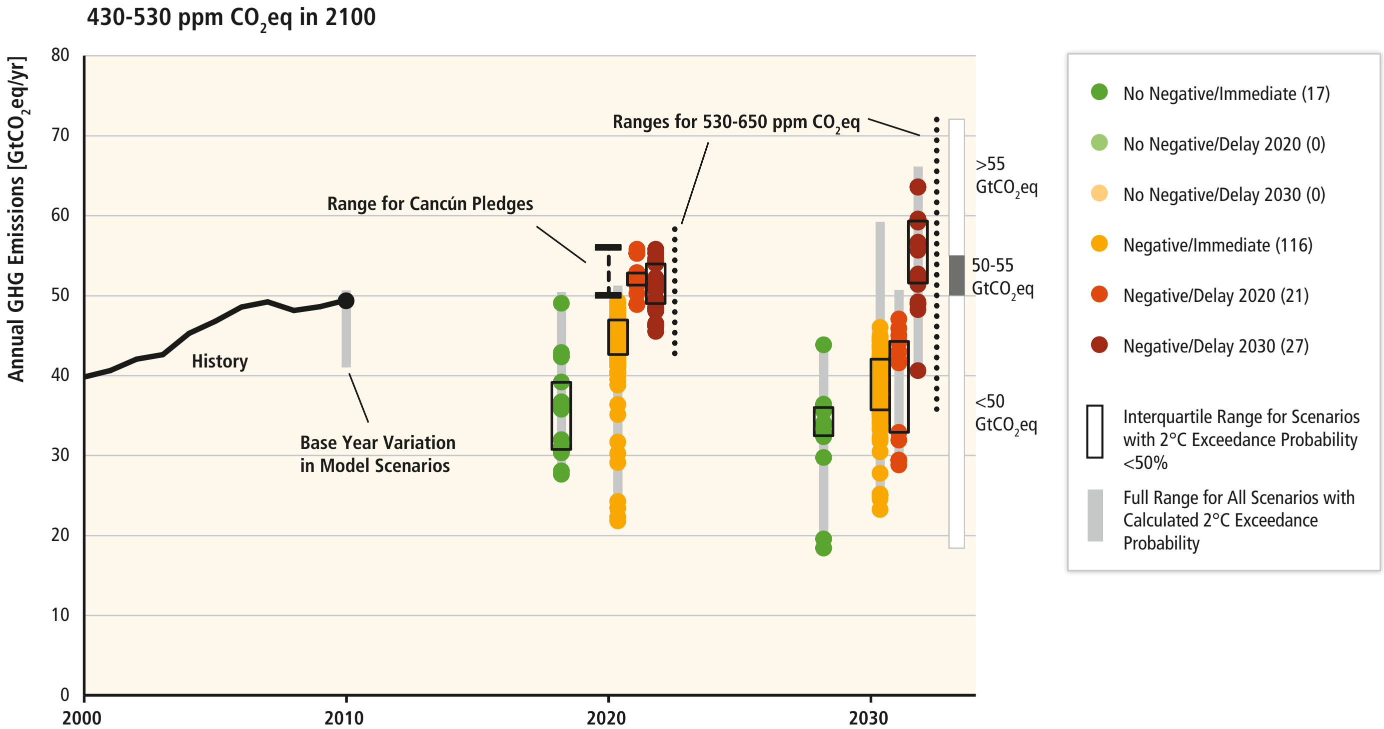

Figure TS.11 | Near-term GHG emissions from mitigation scenarios reaching about 450 to about 500 (430–530) ppm CO_2eq concentrations by 2100. The Figure includes only scenarios for which temperature exceedance probabilities were calculated. Individual model results are indicated with a data point when 2 °C exceedance probability is below 50 % as assessed by a simple carbon cycle/climate model (MAGICC). Colours refer to scenario classification in terms of whether net CO_2 emissions become negative before 2100 (negative vs. no negative) and the timing of international participation in climate mitigation (immediate vs. delay until 2020 vs. delay until 2030). Number of reported individual results is shown in legend. The range of global GHG emissions in 2020 implied by the Cancún Pledges is based on analysis of alternative interpretations of national pledges. Note: In the WGIII AR5 scenario database, only four reported scenarios were produced based on delayed mitigation without net negative emissions while still lying below 530 ppm CO_2eq by 2100. They do not appear in the figure, because the model had insufficient coverage of non-gas species to enable a temperature calculation. Delay in these scenarios extended only to 2020, and their emissions fell in the same range as the 'No Negative/Immediate' category. Delay scenarios include both delayed global mitigation and fragmented action scenarios. [Figure 6.31, 13.13.1.3]

action increase aggregate economic costs. These cost increases are higher at more ambitious levels of mitigation. [6.3.6]

Estimates of the aggregate economic costs of mitigation vary widely, but increase with stringency of mitigation (*high confidence*). Most cost-effective scenarios collected for this assessment that are based on the assumptions that all countries of the world begin mitigation immediately, there is a single global carbon price applied to well-functioning markets, and key technologies are available, estimate that reaching about 450 ppm CO_2eq by 2100 would entail global consumption losses of 1 % to 4 % in 2030 (median: 1.7 %), 2 % to 6 % in 2050 (median: 3.4 %), and 3 % to 11 % in 2100 (median: 4.8 %) relative to consumption in baseline scenarios (those without additional mitigation efforts) that grows anywhere from 300 % to more than 900 % between 2010 and 2100 (baseline consumption growth represents the full range of corresponding baseline scenarios; Figure TS.12; Table TS.2 yellow segments). The consumption losses correspond to an annual average reduction of consumption growth by 0.06 to 0.2 percentage points from 2010 through 2030 (median: 0.09), 0.06 to 0.17 percentage points through 2050 (median: 0.09), and 0.04 to 0.14 percentage points over the century (median: 0.06). These numbers are relative to annual average consumption growth rates in baseline scenarios between 1.9 % and 3.8 % per year through 2050 and between 1.6 % and 3 % per year over the century (Table TS.2, yellow segments). These mitigation cost estimates do not consider the benefits of reduced climate change or co-benefits and adverse side-effects of mitigation (Box TS.9). Costs for maintaining concentrations in the range of 530–650 ppm CO_2eq are estimated to be roughly one-third to two-thirds lower than for associated 430–530 ppm CO_2eq scenarios. Cost estimates from scenarios can vary substantially across regions. Substantially higher cost estimates have been obtained based on assumptions about less idealized policy implementations and limits on technology availability as discussed below. Both higher and lower estimates have been obtained based on interactions with pre-existing distortions, non-climate market failures, or complementary policies. [6.3.6.2]

Delaying mitigation efforts beyond those in place today through 2030 or beyond could substantially increase mitigation costs in the decades that follow and the second half of the century (*high confidence*). Although delays in mitigation by any major emitter will reduce near-term mitigation costs, they will also result in more investment in carbon-intensive infrastructure and then rely on future

Table TS.2 | Global mitigation costs in cost-effective scenarios[1] and estimated cost increases due to assumed limited availability of specific technologies and delayed additional mitigation. Cost estimates shown in this table do not consider the benefits of reduced climate change as well as co-benefits and adverse side-effects of mitigation. The yellow columns show consumption losses (Figure TS.12, right panel) and annualized consumption growth reductions in cost-effective scenarios relative to a baseline development without climate policy. The grey columns show the percentage increase in discounted costs[2] over the century, relative to cost-effective scenarios, in scenarios in which technology is constrained relative to default technology assumptions (Figure TS.13, left panel).[3] The orange columns show the increase in mitigation costs over the periods 2030–2050 and 2050–2100, relative to scenarios with immediate mitigation, due to delayed additional mitigation through 2030 (see Figure TS.13, right panel).[4] These scenarios with delayed additional mitigation are grouped by emission levels of less or more than 55 $GtCO_2eq$ in 2030, and two concentration ranges in 2100 (430–530 ppm CO_2eq and 530–650 ppm CO_2eq). In all figures, the median of the scenario set is shown without parentheses, the range between the 16th and 84th percentile of the scenario set is shown in the parentheses, and the number of scenarios in the set is shown in square brackets.[5] [Figures TS.12, TS.13, 6.21, 6.24, 6.25, Annex II.10]

	Consumption losses in cost-effective scenarios[1]						Increase in total discounted mitigation costs in scenarios with limited availability of technologies				Increase in medium- and long-term mitigation costs due to delayed additional mitigation until 2030			
	[% reduction in consumption relative to baseline]			[percentage point reduction in annualized consumption growth rate]			[% increase in total discounted mitigation costs (2015–2100) relative to default technology assumptions]				[% increase in mitigation costs relative to immediate mitigation]			
											≤55 $GtCO_2eq$		>55 $GtCO_2eq$	
Concentration in 2100 [ppm CO_2eq]	2030	2050	2100	2010–2030	2010–2050	2010–2100	No CCS	Nuclear phase out	Limited Solar/Wind	Limited Bioenergy	2030–2050	2050–2100	2030–2050	2050–2100
450 (430–480)	1.7 (1.0–3.7) [N: 14]	3.4 (2.1–6.2)	4.8 (2.9–11.4)	0.09 (0.06–0.2)	0.09 (0.06–0.17)	0.06 (0.04–0.14)	138 (29–297) [N: 4]	7 (4–18) [N: 8]	6 (2–29) [N: 8]	64 (44–78) [N: 8]	28 (14–50) [N: 34]	15 (5–59)	44 (2–78) [N: 29]	37 (16–82)
500 (480–530)	1.7 (0.6–2.1) [N: 32]	2.7 (1.5–4.2)	4.7 (2.4–10.6)	0.09 (0.03–0.12)	0.07 (0.04–0.12)	0.06 (0.03–0.13)	N/A	N/A	N/A	N/A				
550 (530–580)	0.6 (0.2–1.3) [N: 46]	1.7 (1.2–3.3)	3.8 (1.2–7.3)	0.03 (0.01–0.08)	0.05 (0.03–0.08)	0.04 (0.01–0.09)	39 (18–78) [N: 11]	13 (2–23) [N: 10]	8 (5–15) [N: 10]	18 (4–66) [N: 12]	3 (−5–16) [N: 14]	4 (−4–11)	15 (3–32) [N: 10]	16 (5–24)
580–650	0.3 (0–0.9) [N: 16]	1.3 (0.5–2.0)	2.3 (1.2–4.4)	0.02 (0–0.04)	0.03 (0.01–0.05)	0.03 (0.01–0.05)	N/A	N/A	N/A	N/A				

Notes:

1 Cost-effective scenarios assume immediate mitigation in all countries and a single global carbon price. In this analysis, they also impose no additional limitations on technology relative to the models' default technology assumptions.

2 Percentage increase of net present value of consumption losses in percent of baseline consumption (for scenarios from general equilibrium models) and abatement costs in percent of baseline GDP (for scenarios from partial equilibrium models) for the period 2015–2100, discounted (see Box TS.10) at 5 % per year.

3 No CCS: CCS is not included in these scenarios. Nuclear phase out: No addition of nuclear power plants beyond those under construction, and operation of existing plants until the end of their lifetime. Limited Solar/Wind: a maximum of 20 % global electricity generation from solar and wind power in any year of these scenarios. Limited Bioenergy: a maximum of 100 EJ/yr modern bioenergy supply globally (modern bioenergy used for heat, power, combinations, and industry was around 18 EJ/yr in 2008 [11.13.5]).

4 Percentage increase of total undiscounted mitigation costs for the periods 2030–2050 and 2050–2100.

5 The range is determined by the central scenarios encompassing the 16th and 84th percentile of the scenario set. Only scenarios with a time horizon until 2100 are included. Some models that are included in the cost ranges for concentration levels above 530 ppm CO_2eq in 2100 could not produce associated scenarios for concentration levels below 530 ppm CO_2eq in 2100 with assumptions about limited availability of technologies and/or delayed additional mitigation (see caption of Figure TS.13 for more details).

decision makers to undertake a more rapid, deeper, and costlier future transformation of this infrastructure. Studies have found that aggregate costs, and associated carbon prices, rise more rapidly to higher levels in scenarios with delayed mitigation compared to scenarios where mitigation is undertaken immediately. Recent modelling studies have found that delayed mitigation through 2030 can substantially increase the aggregate costs of meeting 2100 concentrations of about 450 to about 500 ppm CO_2eq, particularly in scenarios with emissions greater than 55 $GtCO_2eq$ in 2030. (Figure TS.13, right panel; Table TS.2, orange segments) [6.3.6.4]

The technological options available for mitigation greatly influence mitigation costs and the challenges of reaching atmospheric concentration levels of about 450 to about 550 ppm CO_2eq by 2100 (*high confidence*). Many models in recent model intercomparisons could not produce scenarios reaching atmospheric concentrations of about 450 ppm CO_2eq by 2100 with broadly pessimistic assumptions about key mitigation technologies. In these studies, the character and availability of CCS and bioenergy were found to have a particularly important influence on the mitigation costs and the challenges of reaching concentration levels in this range. For those models that could produce such scenarios, pessimistic assumptions about these increased discounted global mitigation costs of reaching concentration levels of about 450 and about 550 ppm CO_2eq by the end of the century significantly, with the effect being larger for more stringent mitigation scenarios (Figure TS.13, left panel; Table TS.2, grey segments). The studies also showed that reducing energy demand could potentially decrease mitigation costs significantly. [6.3.6.3]

The distribution of mitigation costs among different countries depends in part on the nature of effort-sharing frameworks and thus need not be the same as the distribution of mitigation efforts. Different effort-sharing frameworks draw upon different ethical principles (*medium confidence*). In cost-effective scenarios reaching concentrations of about 450 to about 550 ppm CO_2eq in 2100, the majority of mitigation investments over the course

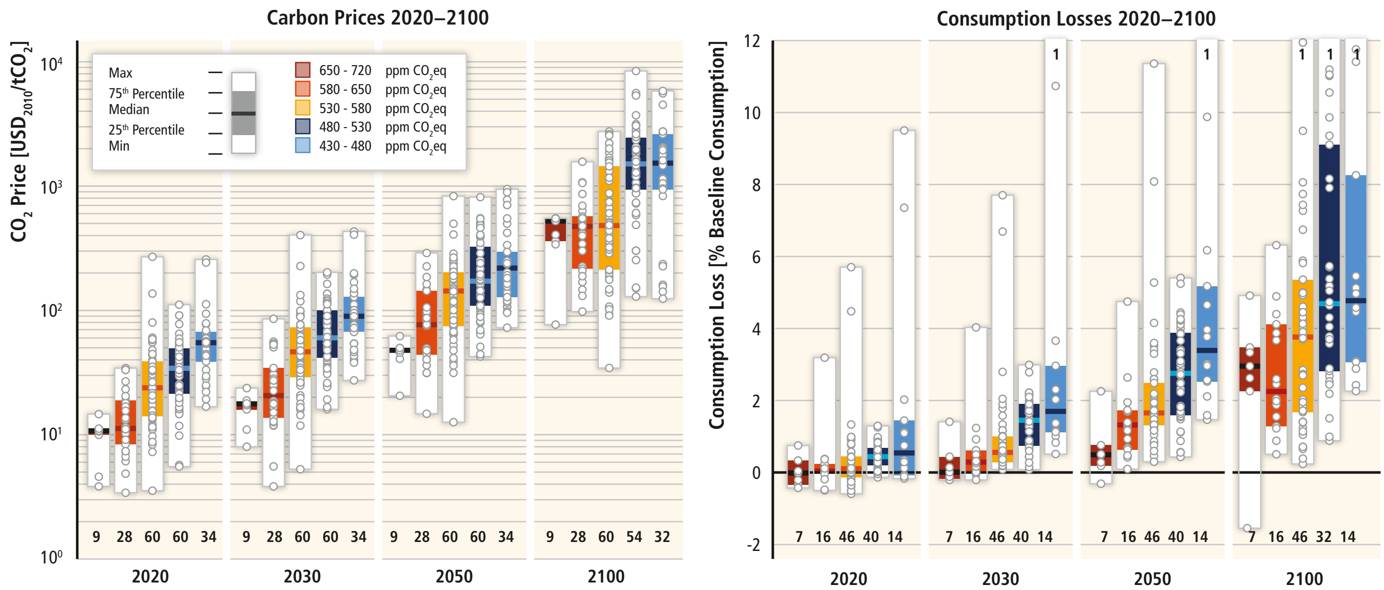

Figure TS.12 | Global carbon prices (left panel) and consumption losses (right panel) over time in cost-effective, idealized implementation scenarios. Consumption losses are expressed as the percentage reduction from consumption in the baseline. The number of scenarios included in the boxplots is indicated at the bottom of the panels. The 2030 numbers also apply to 2020 and 2050. The number of scenarios outside the figure range is noted at the top. Note: The figure shows only scenarios that reported consumption losses (a subset of models with full coverage of the economy) or carbon prices, respectively, to 2050 or 2100. Multiple scenarios from the same model with similar characteristics are only represented by a single scenario in the sample. [Figure 6.21]

Box TS.9 | The meaning of 'mitigation cost' in the context of mitigation scenarios

Mitigation costs represent one component of the change in human welfare from climate change mitigation. Mitigation costs are expressed in monetary terms and generally are estimated against baseline scenarios, which typically involve continued, and sometimes substantial, economic growth and no additional and explicit mitigation efforts [3.9.3, 6.3.6]. Because mitigation cost estimates focus only on direct market effects, they do not take into account the welfare value (if any) of co-benefits or adverse side-effects of mitigation actions (Box TS.11) [3.6.3]. Further, these costs do not capture the benefits of reducing climate impacts through mitigation (Box TS.2).

There are a wide variety of metrics of aggregate mitigation costs used by economists, measured in different ways or at different places in the economy, including changes in GDP, consumption losses, equivalent variation and compensating variation, and loss in consumer and producer surplus. Consumption losses are often used as a metric because they emerge from many integrated models and they directly impact welfare. They can be expressed as a reduction in overall consumption relative to consumption in the corresponding baseline scenario in a given year or as a reduction of the average rate of consumption growth in the corresponding baseline scenario over a given time period.

Mitigation costs need to be distinguished from emissions prices. Emissions prices measure the cost of an additional unit of emissions reduction; that is, the marginal cost. In contrast, mitigation costs usually represent the total costs of all mitigation. In addition, emissions prices can interact with other policies and measures, such as regulatory policies directed at GHG reduction. If mitigation is achieved partly by these other measures, emissions prices may not reflect the actual costs of an additional unit of emissions reductions (depending on how additional emissions reductions are induced).

In general, estimates of global aggregate mitigation costs over the coming century from integrated models are based on largely stylized assumptions about both policy approaches and existing markets and policies, and these assumptions have an important influence on cost estimates. For example, cost-effective idealized implementation scenarios assume a uniform price on CO_2 and other GHGs in every country and sector across the globe, and constitute the least cost approach in the idealized case of largely efficient markets without market failures other than the climate change externality. Most long-term, global scenarios do not account for the interactions between mitigation and pre-existing or new policies, market failures, and distortions. Climate policies can interact with existing policies to increase or reduce the actual cost of climate policies. [3.6.3.3, 6.3.6.5]

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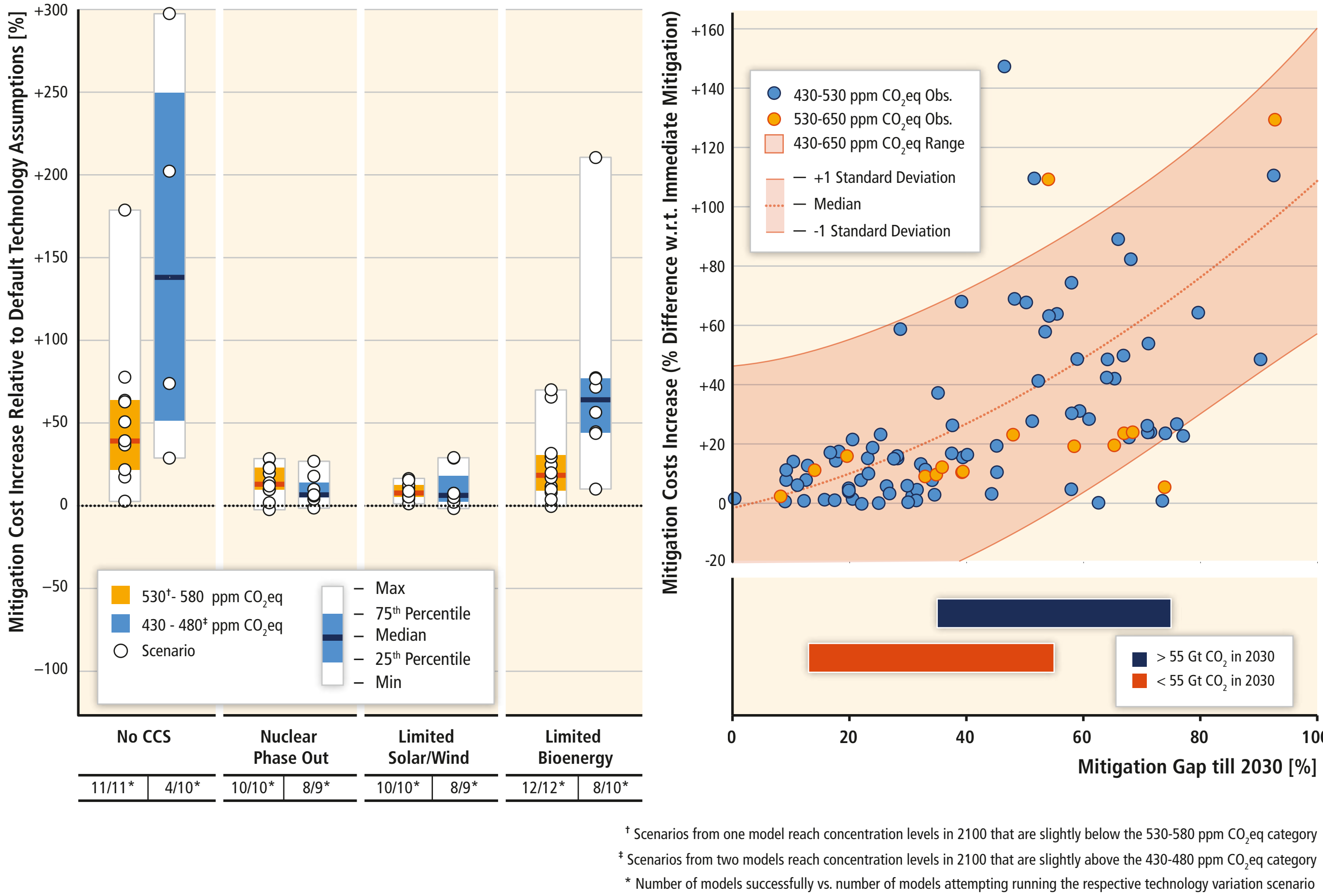


Figure TS.13 | Left panel shows the relative increase in net present value mitigation costs (2015–2100, discounted at 5 % per year) from technology portfolio variations relative to a scenario with default technology assumptions. Scenario names on the horizontal axis indicate the technology variation relative to the default assumptions: No CCS = unavailability of carbon dioxide capture and storage (CCS); Nuclear phase out = No addition of nuclear power plants beyond those under construction; existing plants operated until the end of their lifetime; Limited Solar/Wind = a maximum of 20 % global electricity generation from solar and wind power in any year of these scenarios; Limited Bioenergy = a maximum of 100 exajoules per year (EJ/yr) modern bioenergy supply globally. [Figure 6.24] Right panel shows increase in long-term mitigation costs for the period 2050–2100 (sum over undiscounted costs) as a function of reduced near-term mitigation effort, expressed as the relative change between scenarios implementing mitigation immediately and those that correspond to delayed additional mitigation through 2020 or 2030 (referred to here as 'mitigation gap'). The mitigation gap is defined as the difference in cumulative CO_2 emissions reductions until 2030 between the immediate and delayed additional mitigation scenarios. The bars in the lower right panel indicate the mitigation gap range where 75 % of scenarios with 2030 emissions above (dark blue) and below (red) 55 $GtCO_2$, respectively, are found. Not all model simulations of delayed additional mitigation until 2030 could reach the lower concentration goals of about 450 or 500 (430–530) ppm CO_2eq (for 2030 emissions above 55 $GtCO_2$eq, 29 of 48 attempted simulations could reach the goal; for 2030 emissions below 55 $GtCO_2$eq, 34 of 51 attempted simulations could reach the goal). [Figure 6.25]

of century occur in the non-OECD countries. Some studies exploring particular effort-sharing frameworks, under the assumption of a global carbon market, estimate that the associated financial flows could be in the order of hundred billions of USD per year before mid-century to bring concentrations to between about 450 and about 500 ppm CO_2eq in 2100. Most studies assume efficient mechanisms for international carbon markets, in which case economic theory and empirical research suggest that the choice of effort sharing allocations will not meaningfully affect the globally efficient levels of regional abatement or aggregate global costs. Actual approaches to effort-sharing can deviate from this assumption. [3.3, 6.3.6.6, 13.4.2.4]

Geoengineering denotes two clusters of technologies that are quite distinct: carbon dioxide removal (CDR) and solar radiation management (SRM). Mitigation scenarios assessed in AR5 do not assume any geoengineering options beyond large-scale CDR due to afforestation and BECCS. CDR techniques include afforestation, using bioenergy along with CCS (BECCS), and enhancing uptake of CO_2 by the oceans through iron fertilization or increasing alkalinity. Most terrestrial CDR techniques would require large-scale land-use changes and could involve local and regional risks, while maritime CDR may involve significant transboundary risks for ocean ecosystems, so that its deployment could pose additional challenges for cooperation between countries. With currently known technologies, CDR could not be deployed quickly on a large scale. SRM includes various technologies to offset crudely some of the climatic effects of the build-up of GHGs in the atmosphere. It works by adjusting the planet's heat balance through a small increase in the reflection of incoming sunlight such as by injecting particles or aerosol precursors in the upper atmosphere. SRM has attracted considerable attention, mainly

Box TS.10 | Future goods should be discounted at an appropriate rate

Investments aimed at mitigating climate change will bear fruit far in the future, much of it more than 100 years from now. To decide whether a particular investment is worthwhile, its future benefits need to be weighed against its present costs. In doing this, economists do not normally take a quantity of commodities at one time as equal in value to the same quantity of the same commodities at a different time. They normally give less value to later commodities than to earlier ones. They 'discount' later commodities, that is to say. The rate at which the weight given to future goods diminishes through time is known as the 'discount rate' on commodities.

There are two types of discount rates used for different purposes. The market discount rate reflects the preferences of presently living people between present and future commodities. The social discount rate is used by society to compare benefits of present members of society with those not yet born. Because living people may be impatient, and because future people do not trade in the market, the market may not accurately reflect the value of commodities that will come to future people relative to those that come to present people. So the social discount rate may differ from the market rate.

The chief reason for social discounting (favouring present people over future people) is that commodities have 'diminishing marginal benefit' and per capita income is expected to increase over time. Diminishing marginal benefit means that the value of extra commodities to society declines as people become better off. If economies continue to grow, people who live later in time will on average be better off—possess more commodities—than people who live earlier. The faster the growth and the greater the degree of diminishing marginal benefit, the greater should be the discount rate on commodities. If per capita growth is expected to be negative (as it is in some countries), the social discount rate may be negative.

Some authors have argued, in addition, that the present generation of people should give less weight to later people's well-being just because they are more remote in time. This factor would add to the social discount rate on commodities.

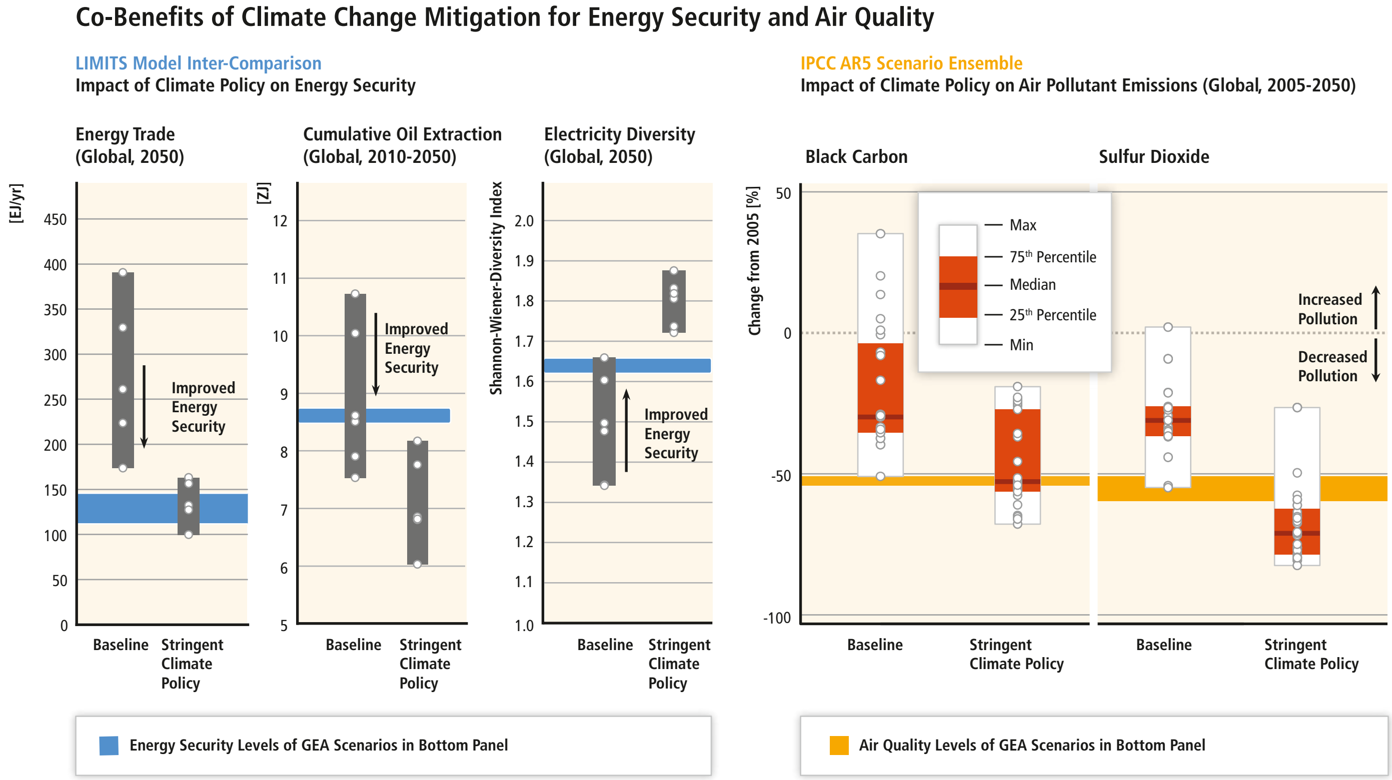
The social discount rate is appropriate for evaluating mitigation projects that are financed by reducing current consumption. If a project is financed partly by 'crowding out' other investments, the benefits of those other investments are lost, and their loss must be counted as an opportunity cost of the mitigation project. If a mitigation project crowds out an exactly equal amount of other investment, then the only issue is whether or not the mitigation investment produces a greater return than the crowded-out investment. This can be tested by evaluating the mitigation investment using a discount rate equal to the return that would have been expected from the crowded out investment. If the market functions well, this will be the market discount rate. [3.6.2]

because of the potential for rapid deployment in case of climate emergency. The suggestion that deployment costs for individual technologies could potentially be low could result in new challenges for international cooperation because nations may be tempted to prematurely deploy unilaterally systems that are perceived to be inexpensive. Consequently, SRM technologies raise questions about costs, risks, governance, and ethical implications of developing and deploying SRM, with special challenges emerging for international institutions, norms and other mechanisms that could coordinate research and restrain testing and deployment. [1.4, 3.3.7, 6.9, 13.4.4]

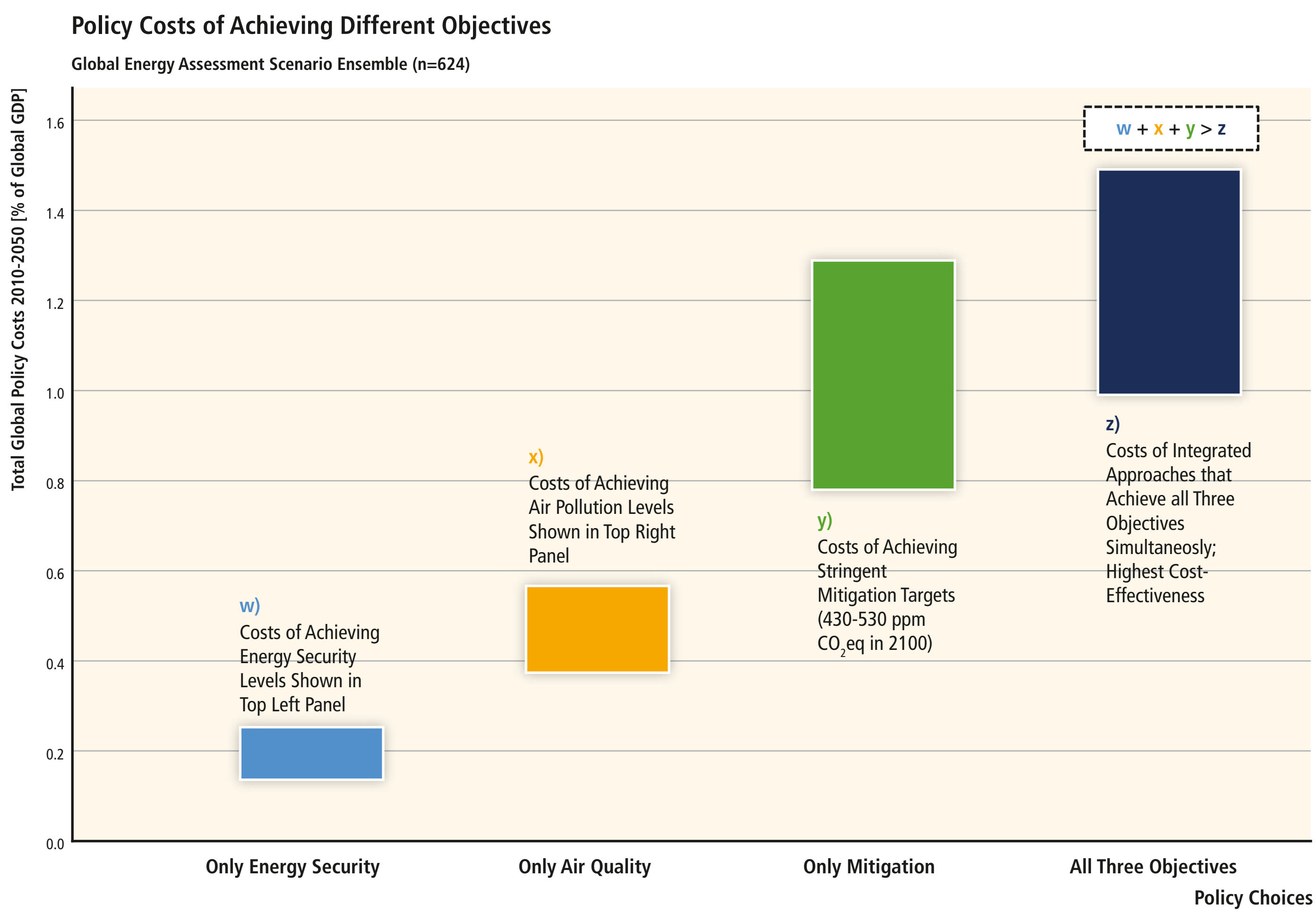
Knowledge about the possible beneficial or harmful effects of SRM is highly preliminary. SRM would have varying impacts on regional climate variables such as temperature and precipitation, and might result in substantial changes in the global hydrological cycle with uncertain regional effects, for example on monsoon precipitation. Non-climate effects could include possible depletion of stratospheric ozone by stratospheric aerosol injections. A few studies have begun to examine climate and non-climate impacts of SRM, but there is very little agreement in the scientific community on the results or on whether the lack of knowledge requires additional research or eventually field testing of SRM-related technologies. [1.4, 3.3.7, 6.9, 13.4.4]

TS.3.1.4 Implications of mitigation pathways for other objectives

Mitigation scenarios reaching about 450 to about 500 ppm CO_2eq by 2100 show reduced costs for achieving energy security and air quality objectives (*medium confidence*) (Figure TS.14, lower panel). The mitigation costs of most of the scenarios in this assessment do not consider the economic implications of the cost reductions for these other objectives (Box TS.9). There is a wide range of co-benefits and adverse side-effects other than air quality and energy security (Tables TS.4–8). The impact of mitigation on the overall costs for achieving many of these other objectives as well as the associated welfare implications are less well understood and have not been assessed thoroughly in the literature (Box TS.11). [3.6.3, 4.8, 6.6]



Co-Benefits of Climate Change Mitigation for Energy Security and Air Quality
LIMITS Model Inter-Comparison
Impact of Climate Policy on Energy Security
IPCC AR5 Scenario Ensemble
Impact of Climate Policy on Air Pollutant Emissions (Global, 2005-2050)
Energy Trade (Global, 2050)
Cumulative Oil Extraction (Global, 2010-2050)
Electricity Diversity (Global, 2050)
Black Carbon
Sulfur Dioxide
[EJ/yr]
[ZJ]
Shannon-Wiener-Diversity Index
Change from 2005 [%]
Improved Energy Security
Max
75th Percentile
Median
25th Percentile
Min
Increased Pollution
Decreased Pollution
Baseline
Stringent Climate Policy
Energy Security Levels of GEA Scenarios in Bottom Panel
Air Quality Levels of GEA Scenarios in Bottom Panel



Policy Costs of Achieving Different Objectives
Global Energy Assessment Scenario Ensemble (n=624)
Total Global Policy Costs 2010-2050 [% of Global GDP]
w + x + y > z
w)
Costs of Achieving Energy Security Levels Shown in Top Left Panel
x)
Costs of Achieving Air Pollution Levels Shown in Top Right Panel
y)
Costs of Achieving Stringent Mitigation Targets (430-530 ppm CO_2eq in 2100)
z)
Costs of Integrated Approaches that Achieve all Three Objectives Simultaneosly; Highest Cost-Effectiveness
Only Energy Security
Only Air Quality
Only Mitigation
All Three Objectives
Policy Choices

⇒

Figure TS.14 | Co-benefits of mitigation for energy security and air quality in scenarios with stringent climate policies reaching about 450 to about 500 (430–530) ppm CO_2eq concentrations in 2100. Upper panels show co-benefits for different security indicators and air pollutant emissions. Lower panel shows related global policy costs of achieving the energy security, air quality, and mitigation objectives, either alone (w, x, y) or simultaneously (z). Integrated approaches that achieve these objectives simultaneously show the highest cost-effectiveness due to synergies (w + x + y > z). Policy costs are given as the increase in total energy system costs relative to a baseline scenario without additional efforts to reduce GHG emissions beyond those in place today. Costs are indicative and do not represent full uncertainty ranges. [Figure 6.33]

Mitigation scenarios reaching about 450 to about 500 ppm CO_2eq by 2100 show co-benefits for energy security objectives, enhancing the sufficiency of resources to meet national energy demand as well as the resilience of the energy system (*medium confidence*). These mitigation scenarios show improvements in terms of the diversity of energy sources and reduction of energy imports, resulting in energy systems that are less vulnerable to price volatility and supply disruptions (Figure TS.14, upper left panel). [6.3.6, 6.6, 7.9, 8.7, 9.7, 10.8, 11.13.6, 12.8]

Mitigation policy could devalue fossil fuel assets and reduce revenues for fossil fuel exporters, but differences between regions and fuels exist (*high confidence*). Most mitigation scenarios are associated with reduced revenues from coal and oil trade for major exporters (*high confidence*). However, a limited number of studies find that mitigation policies could increase the relative competitiveness of conventional oil vis-à-vis more carbon-intensive unconventional oil and 'coal-to-liquids'. The effect of mitigation on natural gas export revenues is more uncertain, with some studies showing possible benefits for export revenues in the medium term until about 2050 (*medium confidence*). The availability of CCS would reduce the adverse effect of mitigation on the value of fossil fuel assets (*medium confidence*). [6.3.6, 6.6, 14.4.2]

Fragmented mitigation policy can provide incentives for emission-intensive economic activity to migrate away from a region that undertakes mitigation (*medium confidence*). Scenario studies have shown that such 'carbon leakage' rates of energy-related emissions are relatively contained, often below 20 % of the emissions reductions. Leakage in land-use emissions could be substantial, though fewer studies have quantified it. While border tax adjustments are seen as enhancing the competitiveness of GHG- and trade-intensive industries within a climate policy regime, they can also entail welfare losses for non-participating, and particularly developing, countries. [5.4, 6.3, 13.8, 14.4]

Mitigation scenarios leading to atmospheric concentration levels of about 450 to about 500 ppm CO_2eq in 2100 are associated with significant co-benefits for air quality and related human health and ecosystem impacts. The benefits from major cuts in air pollutant emissions are particularly high where currently legislated and planned air pollution controls are weak (*high confidence*). Stringent mitigation policies result in co-controls with major cuts in air pollutant emissions significantly below baseline scenarios (Figure TS.14, upper right panel). Co-benefits for health are particularly high in today's developing world. The extent to which air pollution policies, targeting for example black carbon (BC), can mitigate climate change is uncertain. [5.7, 6.3, 6.6, 7.9, 8.7, 9.7, 10.8, 11.7, 11.13.6, 12.8; WGII 11.9]

There is a wide range of possible adverse side-effects as well as co-benefits and spillovers from climate policy that have not been well-quantified (*high confidence*). Whether or not side-effects materialize, and to what extent side-effects materialize, will be case- and site-specific, as they will depend on local circumstances and the scale, scope, and pace of implementation. Important examples include biodiversity conservation, water availability, food security, income distribution, efficiency of the taxation system, labour supply and employment, urban sprawl, and the sustainability of the growth of developing countries. (Box TS.11)

Some mitigation policies raise the prices for some energy services and could hamper the ability of societies to expand access to modern energy services to underserved populations (*low confidence*). **These potential adverse side-effects can be avoided with the adoption of complementary policies** (*medium confidence*). Most notably, about 1.3 billion people worldwide do not have access to electricity and about 3 billion are dependent on traditional solid fuels for cooking and heating with severe adverse effects on health, ecosystems and development. Providing access to modern energy services is an important sustainable development objective. The costs of achieving nearly universal access to electricity and clean fuels for cooking and heating are projected to be between 72 to 95 billion USD per year until 2030 with minimal effects on GHG emissions (*limited evidence, medium agreement*). A transition away from the use of traditional biomass[13] and the more efficient combustion of solid fuels reduce air pollutant emissions, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and black carbon (BC), and thus yield large health benefits (*high confidence*). [4.3, 6.6, 7.9, 9.3, 9.7, 11.13.6, 16.8]

The effect of mitigation on water use depends on technological choices and the portfolio of mitigation measures (*high confidence*). While the switch from fossil energy to renewable energy like photovoltaic (PV) or wind can help reducing water use of the energy system, deployment of other renewables, such as some forms of hydropower, concentrated solar power (CSP), and bioenergy may have adverse effects on water use. [6.6, 7.9, 9.7, 10.8, 11.7, 11.13.6]

[13] Traditional biomass refers to the biomass — fuelwood, charcoal, agricultural residues, and animal dung — used with the so-called traditional technologies such as open fires for cooking, rustic kilns and ovens for small industries (see Glossary).

Box TS.11 | Accounting for the co-benefits and adverse side-effects of mitigation

A government policy or a measure intended to achieve one objective (such as mitigation) will also affect other objectives (such as local air quality). To the extent these side-effects are positive, they can be deemed 'co-benefits'; otherwise they are termed 'adverse side-effects'. In this report, co-benefits and adverse side-effects are measured in non-monetary units. Determining the value of these effects to society is a separate issue. The effects of co-benefits on social welfare are not evaluated in most studies, and one reason is that the value of a co-benefit depends on local circumstances and can be positive, zero, or even negative. For example, the value of the extra tonne of sulfur dioxide (SO_2) reduction that occurs with mitigation depends greatly on the stringency of existing SO_2 control policies: in the case of weak existing SO_2 policy, the value of SO_2 reductions may be large, but in the case of stringent existing SO_2 policy it may be near zero. If SO_2 policy is too stringent, the value of the co-benefit may be negative (assuming SO_2 policy is not adjusted). While climate policy affects non-climate objectives (Tables TS.4–8) other policies also affect climate change outcomes. [3.6.3, 4.8, 6.6, Glossary]

Mitigation can have many potential co-benefits and adverse side-effects, which makes comprehensive analysis difficult. The direct benefits of climate policy include, for example, intended effects on global mean surface temperature, sea level rise, agricultural productivity, biodiversity, and health effects of global warming [WGII TS]. The co-benefits and adverse side-effects of climate policy could include effects on a partly overlapping set of objectives such as local air pollutant emissions reductions and related health and ecosystem impacts, biodiversity conservation, water availability, energy and food security, energy access, income distribution, efficiency of the taxation system, labour supply and employment, urban sprawl, and the sustainability of the growth of developing countries [3.6, 4.8, 6.6, 15.2].

All these side-effects are important, because a comprehensive evaluation of climate policy needs to account for benefits and costs related to other objectives. If overall social welfare is to be determined and quantified, this would require valuation methods and a consideration of pre-existing efforts to attain the many objectives. Valuation is made difficult by factors such as interaction between climate policies and pre-existing non-climate policies, externalities, and non-competitive behaviour. [3.6.3]

Mitigation scenarios and sectoral studies show that overall the potential for co-benefits of energy end-use measures outweigh the potential adverse side-effects, whereas the evidence suggests this may not be the case for all energy supply and AFOLU measures (*high confidence*). (Tables TS.4–8) [4.8, 5.7, 6.6, 7.9, 8.7, 9.7, 10.8, 11.7, 11.13.6, 12.8]

TS.3.2 Sectoral and cross-sectoral mitigation measures

Anthropogenic GHG emissions result from a broad set of human activities, most notably those associated with energy supply and consumption and with the use of land for food production and other purposes. A large proportion of emissions arise in urban areas. Mitigation options can be grouped into three broad sectors: (1) energy supply, (2) energy end-use sectors including transport, buildings, industry, and (3) AFOLU. Emissions from human settlements and infrastructures cut across these different sectors. Many mitigation options are linked. The precise set of mitigation actions taken in any sector will depend on a wide range of factors, including their relative economics, policy structures, normative values, and linkages to other policy objectives. The first section examines issues that cut across the sectors and the following subsections examine the sectors themselves.

TS.3.2.1 Cross-sectoral mitigation pathways and measures

Without new mitigation policies GHG emissions are projected to grow in all sectors, except for net CO_2 emissions in the AFOLU[14] sector (*robust evidence, medium agreement*). Energy supply sector emissions are expected to continue to be the major source of GHG emissions in baseline scenarios, ultimately accounting for the significant increases in indirect emissions from electricity use in the buildings and the industry sectors. Deforestation decreases in most of the baseline scenarios, which leads to a decline in net CO_2 emissions from the AFOLU sector. In some scenarios the AFOLU sector changes from an emission source to a net emission sink towards the end of the century. (Figure TS.15) [6.3.1.4, 6.8]

Infrastructure developments and long-lived products that lock societies into GHG-intensive emissions pathways may be difficult or very costly to change, reinforcing the importance of early action for ambitious mitigation (*robust evidence, high agreement*). This lock-in risk is compounded by the lifetime of the infrastructure, by the difference in emissions associated with alternatives, and

[14] Net AFOLU CO_2 emissions include emissions and removals of CO_2 from the AFOLU sector, including land under forestry and, in some assessments, CO_2 sinks in agricultural soils.

the magnitude of the investment cost. As a result, lock-in related to infrastructure and spatial planning is the most difficult to eliminate, and thus avoiding options that lock high emission patterns in permanently is an important part of mitigation strategies in regions with rapidly developing infrastructure. In mature or established cities, options are constrained by existing urban forms and infrastructure, and limits on the potential for refurbishing or altering them. However, materials, products and infrastructure with long lifetimes and low lifecycle emissions can ensure positive lock-in as well as avoid emissions through dematerialization (i.e., through reducing the total material inputs required to deliver a final service). [5.6.3, 6.3.6.4, 9.4, 10.4, 12.3, 12.4]

Systemic and cross-sectoral approaches to mitigation are expected to be more cost-effective and more effective in cutting emissions than sector-by-sector policies (*medium confidence*). Cost-effective mitigation policies need to employ a system perspective in order to account for inter-dependencies among different economic sectors and to maximize synergistic effects. Stabilizing atmospheric CO_2eq concentrations at any level will ultimately require deep reductions in emissions and fundamental changes to both the end-use and supply-side of the energy system as well as changes in land-use practices and industrial processes. In addition, many low-carbon energy supply technologies (including CCS) and their infrastructural requirements face public acceptance issues limiting their deployment. This applies also to the adoption of new technologies, and structural and behavioural change, in the energy end-use sectors (*robust evidence, high agreement*) [7.9.4, 8.7, 9.3.10, 9.8, 10.8, 11.3, 11.13]. Lack of acceptance may have implications not only for mitigation in that particular sector, but also for wider mitigation efforts.

Integrated models identify three categories of energy system related mitigation measures: the decarbonization of the energy supply sector, final energy demand reductions, and the switch to low-carbon energy carriers, including electricity, in the energy end-use sectors (*robust evidence, high agreement*) [6.3.4, 6.8, 7.11]. The broad range of sectoral mitigation options available mainly relate to achieving reductions in GHG emissions intensity, energy intensity and changes in activity (Table TS.3) [7.5, 8.3, 8.4, 9.3, 10.4, 12.4]. Direct options in AFOLU involve storing carbon in terrestrial systems (for example, through afforestation) and providing bioenergy feedstocks [11.3, 11.13]. Options to reduce non-CO_2 GHG emissions exist across all sectors, but most notably in agriculture, energy supply, and industry.

Demand reductions in the energy end-use sectors, due to, e.g., efficiency enhancement and behavioural change, are a key miti-

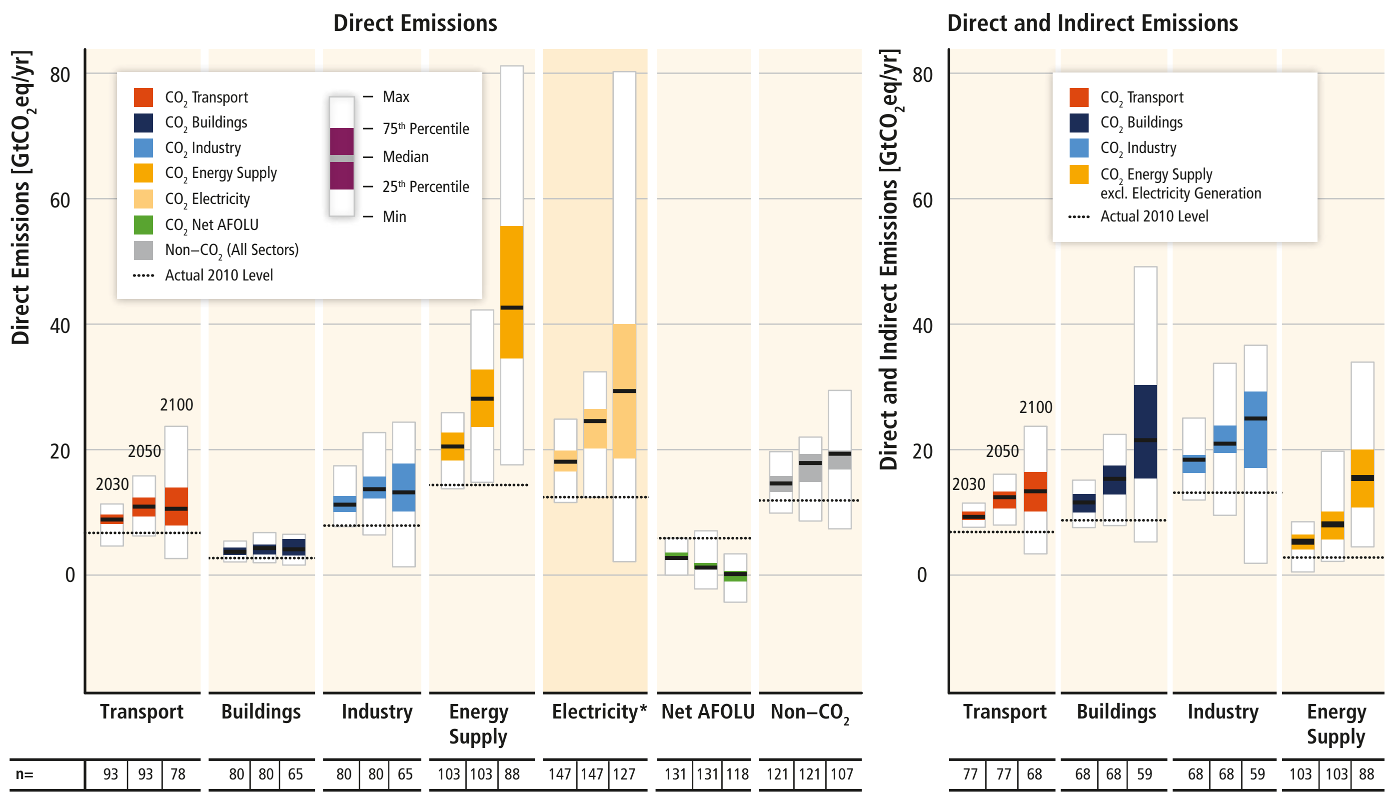
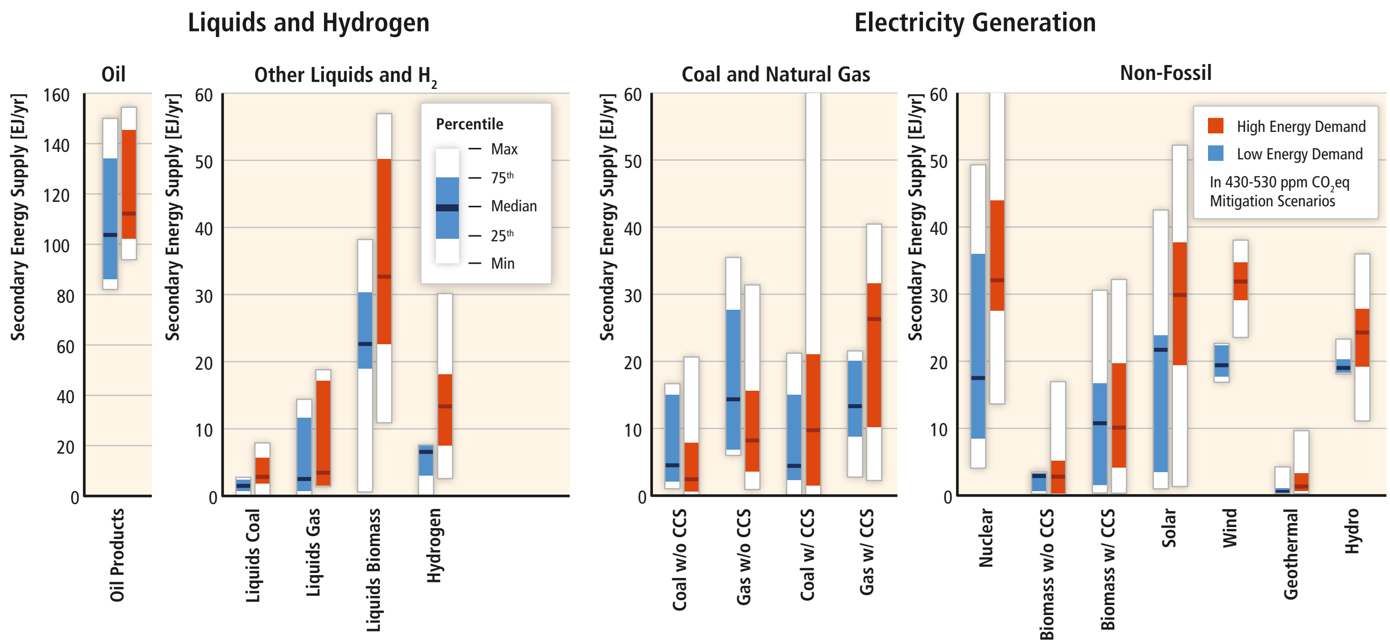


Figure TS.15 | Direct (left panel) and direct and indirect emissions (right panel) of CO_2 and non-CO_2 GHGs across sectors in baseline scenarios. Non-CO_2 GHGs are converted to CO_2-equivalents based on Global Warming Potentials with a 100-year time horizon from the IPCC Second Assessment Report (SAR) (see Box TS.5). Note that in the case of indirect emissions, only electricity generation emissions are allocated from energy supply to end-use sectors. In the left panel electricity sector emissions are shown (Electricity*) in addition to energy supply sector emissions which they are part of, to illustrate their large role on the energy supply side. The numbers at the bottom refer to the number of scenarios included in the ranges that differ across sectors and time due to different sectoral resolutions and time horizons of models. [Figure 6.34]



1	2	3	4
High energy demand scenarios show higher levels of oil supply.	In high energy demand scenarios, alternative liquid and hydrogen technologies are scaled up more rapidly.	High energy demand scenarios show a more rapid up-scaling of CCS technologies but a more rapid phase-out of unabated fossil fuel conversion technologies.	In high energy demand scenarios non-fossil electricity generation technologies are scaled up more rapidly.

Figure TS.16 | Influence of energy demand on the deployment of energy supply technologies in 2050 in mitigation scenarios reaching about 450 to about 500 (430–530) ppm CO_2eq concentrations by 2100. Blue bars for 'low energy demand' show the deployment range of scenarios with limited growth of final energy of < 20 % in 2050 compared to 2010. Red bars show the deployment range of technologies in case of 'high energy demand' (> 20 % growth in 2050 compared to 2010). For each technology, the median, interquartile, and full deployment range is displayed. Notes: Scenarios assuming technology restrictions and scenarios with final energy in the base-year outside ± 5 % of 2010 inventories are excluded. Ranges include results from many different integrated models. Multiple scenario results from the same model were averaged to avoid sampling biases; see Chapter 6 for further details. [Figure 7.11]

gation strategy and affect the scale of the mitigation challenge for the energy supply side (*high confidence*). Limiting energy demand: (1) increases policy choices by maintaining flexibility in the technology portfolio; (2) reduces the required pace for up-scaling low-carbon energy supply technologies and hedges against related supply-side risks (Figure TS.16); (3) avoids lock-in to new, or potentially premature retirement of, carbon-intensive infrastructures; (4) maximizes co-benefits for other policy objectives, since the potential for co-benefits of energy end-use measures outweighs the potential for adverse side-effects which may not be the case for all supply-side measures (see Tables TS.4–8); and (5) increases the cost-effectiveness of the transformation (as compared to mitigation strategies with higher levels of energy demand) (*medium confidence*). However, energy service demand reductions are unlikely in developing countries or for poorer population segments whose energy service levels are low or partially unmet. [6.3.4, 6.6, 7.11, 10.4]

Behaviour, lifestyle, and culture have a considerable influence on energy use and associated emissions, with a high mitigation potential in some sectors, in particular when complementing technological and structural change (*medium evidence, medium agreement*). Emissions can be substantially lowered through: changes in consumption patterns (e.g., mobility demand and mode, energy use in households, choice of longer-lasting products); dietary change and reduction in food wastes; and change of lifestyle (e.g., stabilizing/lowering consumption in some of the most developed countries, sharing economy and other behavioural changes affecting activity) (Table TS.3). [8.1, 8.9, 9.2, 9.3, Box 10.2, 10.4, 11.4, 12.4, 12.6, 12.7]

Evidence from mitigation scenarios indicates that the decarbonization of energy supply is a key requirement for stabilizing atmospheric CO_2eq concentrations below 580 ppm (*robust evidence, high agreement*). In most long-term mitigation scenarios not exceeding 580 ppm CO_2eq by 2100, global energy supply is fully decarbonized at the end of the 21st century with many scenarios relying on a net removal of CO_2 from the atmosphere. However, because existing supply systems are largely reliant on carbon-intensive fossil fuels, energy intensity reductions can equal or outweigh decarbonization of energy supply in the near term. In the buildings and industry sector, for example, efficiency improvements are an important strategy for reducing indirect emissions from electricity generation (Figure TS.15). In the long term, the reduction in electricity generation emissions is accompanied by an increase in the share of electricity in end uses (e.g., for

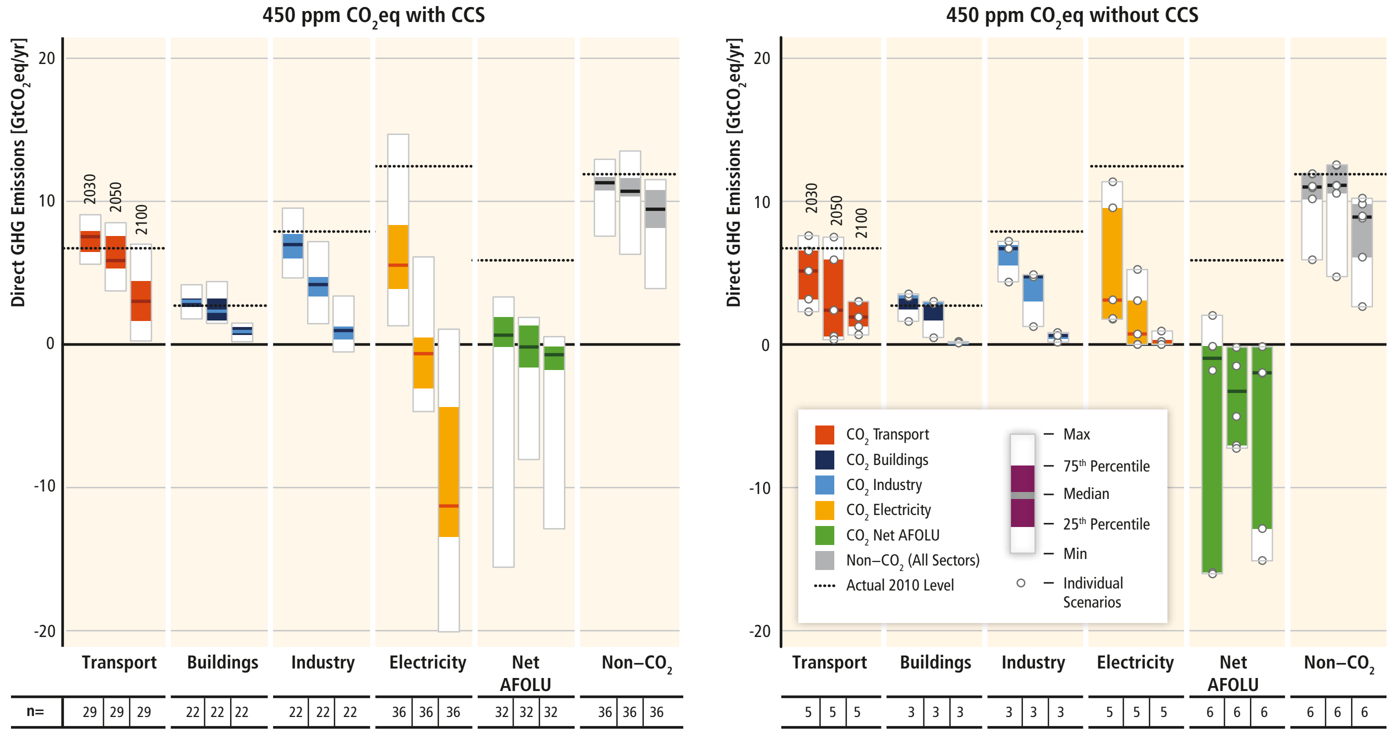


Figure TS.17 | Direct emissions of CO_2 and non-CO_2 GHGs across sectors in mitigation scenarios that reach about 450 (430–480) ppm CO_2eq concentrations in 2100 with using carbon dioxide capture and storage (CCS) (left panel) and without using CCS (right panel). The numbers at the bottom of the graphs refer to the number of scenarios included in the ranges that differ across sectors and time due to different sectoral resolutions and time horizons of models. White dots in the right panel refer to emissions of individual scenarios to give a sense of the spread within the ranges shown due to the small number of scenarios. [Figures 6.35]

space and process heating, and potentially for some modes of transport). Deep emissions reductions in transport are generally the last to emerge in integrated modelling studies because of the limited options to switch to low-carbon energy carriers compared to buildings and industry (Figure TS.17). [6.3.4, 6.8, 8.9, 9.8, 10.10, 7.11, Figure 6.17]

The availability of CDR technologies affects the size of the mitigation challenge for the energy end-use sectors (*robust evidence, high agreement*) [6.8, 7.11]. There are strong interdependencies in mitigation scenarios between the required pace of decarbonization of energy supply and end-use sectors. The more rapid decarbonization of supply generally provides more flexibility for the end-use sectors. However, barriers to decarbonizing the supply side, resulting for example from a limited availability of CCS to achieve negative emissions when combined with bioenergy, require a more rapid and pervasive decarbonisation of the energy end-use sectors in scenarios achieving low-CO_2eq concentration levels (Figure TS.17). The availability of mature large-scale biomass supply for energy, or carbon sequestration technologies in the AFOLU sector also provides flexibility for the development of mitigation technologies in the energy supply and energy end-use sectors [11.3] (*limited evidence, medium agreement*), though there may be adverse impacts on sustainable development.

Spatial planning can contribute to managing the development of new infrastructure and increasing system-wide efficiencies across sectors (*robust evidence, high agreement*). Land use, transport choice, housing, and behaviour are strongly interlinked and shaped by infrastructure and urban form. Spatial and land-use planning, such as mixed-zoning, transport-oriented development, increasing density, and co-locating jobs and homes can contribute to mitigation across sectors by (1) reducing emissions from travel demand for both work and leisure, and enabling non-motorized transport, (2) reducing floor space for housing, and hence (3) reducing overall direct and indirect energy use through efficient infrastructure supply. Compact and in-fill development of urban spaces and intelligent densification can save land for agriculture and bioenergy and preserve land carbon stocks. [8.4, 9.10, 10.5, 11.10, 12.2, 12.3]

Interdependencies exist between adaptation and mitigation at the sectoral level and there are benefits from considering adaptation and mitigation in concert (*medium evidence, high agreement*). Particular mitigation actions can affect sectoral climate vulnerability, both by influencing exposure to impacts and by altering the capacity to adapt to them [8.5, 11.5]. Other interdependencies include climate impacts on mitigation options, such as forest conservation or hydropower production [11.5.5, 7.7], as well as the effects of particular adaptation options, such as heating or cooling of buildings or establishing more diversified cropping systems in agriculture, on GHG emissions and radiative forcing [11.5.4, 9.5]. There is a growing evidence base for such interdependencies in each sector, but there are substantial knowledge gaps that prevent the generation of integrated results at the cross-sectoral level.

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Table TS.3 | Main sectoral mitigation measures categorized by key mitigation strategies (in bold) and associated sectoral indicators (highlighted in yellow) as discussed in Chapters 7–12.

	GHG emissions intensity reduction	Energy intensity reduction by improving technical efficiency	Production and resource efficiency improvement	Structural and systems efficiency improvement	Activity indicator change
Energy [Section 7.5]	*Emissions/ secondary energy output*	*Energy input/ energy output*	*Embodied energy/ energy output*	–	*Final energy use*
	Greater deployment of renewable energy (RE), nuclear energy, and (BE)CCS; fuel switching within the group of fossil fuels; reduction of fugitive (methane) emissions in the fossil fuel chain	Extraction, transport and conversion of fossil fuels; electricity/ heat/ fuel transmission, distribution, and storage; Combined Heat and Power (CHP) or cogeneration (*see Buildings and Human Settlements*)	Energy embodied in manufacturing of energy extraction, conversion, transmission and distribution technologies	Addressing integration needs	Demand from end-use sectors for different energy carriers (*see Transport, Buildings and Industry*)
Transport [8.3]	*Emissions/ final energy*	*Final energy/ transport service*	–	*Shares for each mode*	*Total distance per year*
	Fuel carbon intensity (CO_2eq/megajoule (MJ)): Fuel switching to low-carbon fuels e.g., electricity/hydrogen from low-carbon sources (*see Energy*); specific biofuels in various modes (*see AFOLU*)	**Energy intensity (MJ/passenger-km, tonne-km):** Fuel-efficient engines and vehicle designs; more advanced propulsion systems and designs; use of lighter materials in vehicles	Embodied emissions during vehicle manufacture; material efficiency; and recycling of materials (*see Industry*); infrastructure lifecycle emissions (*see Human Settlements*)	Modal shifts from light-duty vehicles (LDVs) to public transit, cycling/walking, and from aviation and heavy-duty vehicles (HDVs) to rail; eco-driving; improved freight logistics; transport (infrastructure) planning	Journey avoidance; higher occupancy/loading rates; reduced transport demand; urban planning (*see Human Settlements*)
Buildings [9.3]	*Emissions/ final energy*	*Final energy/ useful energy*	*Embodied energy/ operating energy*	*Useful energy/ energy service*	*Energy service demand*
	Fuel carbon intensity (CO_2eq/MJ): Building-integrated RE technologies; fuel switching to low-carbon fuels, e.g., electricity (*see Energy*)	**Device efficiency:** heating/cooling (high-performance boilers, ventilation, air-conditioning, heat pumps); water heating; cooking (advanced biomass stoves); lighting; appliances	Building lifetime; component, equipment, and appliance durability; low(er) energy and emission material choice for construction (*see Industry*)	**Systemic efficiency:** integrated design process; low/zero energy buildings; building automation and controls; urban planning; district heating/cooling and CHP; smart meters/grids; commissioning	Behavioural change (e.g., thermostat setting, appliance use); lifestyle change (e.g., per capita dwelling size, adaptive comfort)
Industry [10.4]	*Emissions/ final energy*	*Final energy/ material production*	*Material input/ product output*	*Product demand/ service demand*	*Service demand*
	Emissions intensity: Process emissions reductions; use of waste (e.g., municipal solid waste (MSW)/sewage sludge in cement kilns) and CCS in industry; HFCs replacement and leak repair; fuel switching among fossil fuels to low-carbon electricity (*see Energy*) or biomass (*see AFOLU*)	**Energy efficiency/ best available technologies:** Efficient steam systems; furnace and boiler systems; electric motor (pumps, fans, air compressor, refrigerators, and material handling) and electronic control systems; (waste) heat exchanges; recycling	**Material efficiency:** Reducing yield losses; manufacturing/construction: process innovations, new design approaches, re-using old material (e.g., structural steel); product design (e.g., light weight car design); fly ash substituting clinker	**Product-service efficiency:** More intensive use of products (e.g., car sharing, using products such as clothing for longer, new and more durable products)	Reduced demand for, e.g., products such as clothing; alternative forms of travel leading to reduced demand for car manufacturing
Human Settlements [12.4]	*Emissions/ final energy*	*Final energy/ useful energy*	*Material input in infrastructure*	*Useful energy/ energy service*	*Service demand per capita*
	Integration of urban renewables; urban-scale fuel switching programmes	Cogeneration, heat cascading, waste to energy	Managed infrastructure supply; reduced primary material input for infrastructure	Compact urban form; increased accessibility; mixed land use	Increasing accessibility: shorter travel time, and more transport mode options

	Supply-side improvements			Demand-side measures
Agriculture, Forestry and Other Land Use (AFOLU) [11.3]	*Emissions/ area or unit product (conserved, restored)*			*Animal/crop product consumption per capita*
	Emissions reduction: of methane (e.g., livestock management) and nitrous oxide (fertilizer and manure management) and prevention of emissions to the atmosphere by conserving existing carbon pools in soils or vegetation (reducing deforestation and forest degradation, fire prevention/control, agroforestry); reduced emissions intensity (GHG/unit product).	**Sequestration:** Increasing the size of existing carbon pools, thereby extracting CO_2 from the atmosphere (e.g., afforestation, reforestation, integrated systems, carbon sequestration in soils)	**Substitution:** of biological products for fossil fuels or energy-intensive products, thereby reducing CO_2 emissions, e.g., biomass co-firing/CHP (*see Energy*), biofuels (*see Transport*), biomass-based stoves, and insulation products (*see Buildings*)	**Demand-side measures:** Reducing losses and wastes of food; changes in human diets towards less emission-intensive products; use of long-lived wood products

TS.3.2.2 Energy supply

The energy supply sector is the largest contributor to global GHG emissions (*robust evidence, high agreement*). Annual GHG emissions from the global energy supply sector grew more rapidly between 2000 and 2010 than in the previous decade; their growth accelerated from 1.7 %/yr from 1990–2000 to 3.1 %/yr from 2000–2010. The main contributors to this trend are an increasing demand for energy services and a growing share of coal in the global fuel mix. The energy supply sector, as defined in this report, comprises all energy extraction, conversion, storage, transmission, and distribution processes that deliver final energy to the end-use sectors (industry, transport, buildings, agriculture and forestry). [7.2, 7.3]

In the baseline scenarios assessed in AR5, direct CO_2 emissions from the energy supply sector increase from 14.4 $GtCO_2$/yr in 2010 to 24–33 $GtCO_2$/yr in 2050 (25–75th percentile; full range 15–42 $GtCO_2$/yr), with most of the baseline scenarios assessed in WGIII AR5 showing a significant increase (*medium evidence, medium agreement*) (Figure TS.15). The lower end of the full range is dominated by scenarios with a focus on energy intensity improvements that go well beyond the observed improvements over the past 40 years. The availability of fossil fuels alone will not be sufficient to limit CO_2eq concentration to levels such as 450 ppm, 550 ppm, or 650 ppm. [6.3.4, 6.8, 7.11, Figure 6.15]

The energy supply sector offers a multitude of options to reduce GHG emissions (*robust evidence, high agreement*). These options include: energy efficiency improvements and fugitive emission reductions in fuel extraction as well as in energy conversion, transmission, and distribution systems; fossil fuel switching; and low-GHG energy supply technologies such as renewable energy (RE), nuclear power, and CCS (Table TS.3). [7.5, 7.8.1, 7.11]

The stabilization of GHG concentrations at low levels requires a fundamental transformation of the energy supply system, including the long-term phase-out of unabated fossil fuel conversion technologies and their substitution by low-GHG alternatives (*robust evidence, high agreement*). Concentrations of CO_2 in the atmosphere can only be stabilized if global (net) CO_2 emissions peak and decline toward zero in the long term. Improving the energy efficiencies of fossil fuel power plants and/or the shift from coal to gas will not by themselves be sufficient to achieve this. Low-GHG energy supply technologies would be necessary if this goal were to be achieved (Figure TS.19). [7.5.1, 7.8.1, 7.11]

Decarbonizing (i.e., reducing the carbon intensity of) electricity generation is a key component of cost-effective mitigation strategies in achieving low-stabilization levels (430–530 ppm CO_2eq); in most integrated modelling scenarios, decarbonization happens more rapidly in electricity generation than in the buildings, transport, and industry sectors (*medium evidence, high agreement*) (Figure TS.17). In the majority of mitigation scenarios reaching about 450 ppm CO_2eq concentrations by 2100, the share of low-carbon electricity supply (comprising RE, nuclear, fossil fuels with CCS, and BECCS) increases from the current share of around 30 % to more than 80 % by 2050, and fossil fuel power generation without CCS is phased out almost entirely by 2100 (Figures TS.17 and TS.18) [7.14].

Since AR4, many RE technologies have demonstrated substantial performance improvements and cost reductions, and a growing number of RE technologies have achieved a level of maturity to enable deployment at significant scale (*robust evidence, high agreement*). Some technologies are already economically competitive in various settings. Levelized costs of PV systems fell most substantially between 2009 and 2012, and a less extreme trend has been observed for many others RE technologies. Regarding electricity generation alone, RE accounted for just over half of the new electricity-generating capacity added globally in 2012, led by growth in wind, hydro, and solar power. Decentralized RE to meet rural energy needs has also increased, including various modern and advanced traditional biomass options as well as small hydropower, PV, and wind. Nevertheless, many RE technologies still need direct support (e.g., feed-in tariffs (FITs), RE quota obligations, and tendering/bidding) and/or indirect support (e.g., sufficiently high carbon prices and the internalization of other externalities), if their market shares are to be significantly increased. RE technology policies have been successful in driving the recent growth of RE. Additional enabling policies are needed to address their integration into future energy systems. (*medium evidence, medium agreement*) (Figure TS.19) [7.5.3, 7.6.1, 7.8.2, 7.12, 11.13]

The use of RE is often associated with co-benefits, including the reduction of air pollution, local employment opportunities, few severe accidents compared to some other energy supply technologies, as well as improved energy access and security (*medium evidence, medium agreement*) (Table TS.4). At the same time, however, some RE technologies can have technology and location-specific adverse side-effects, which can be reduced to a degree through appropriate technology selection, operational adjustments, and siting of facilities. [7.9]

Infrastructure and integration challenges vary by RE technology and the characteristics of the existing energy system (*medium evidence, medium agreement*). Operating experience and studies of medium to high penetrations of RE indicate that integration issues can be managed with various technical and institutional tools. As RE penetrations increase, such issues are more challenging, must be carefully considered in energy supply planning and operations to ensure reliable energy supply, and may result in higher costs. [7.6, 7.8.2]

Nuclear energy is a mature low-GHG emission source of baseload power, but its share of global electricity generation has been declining (since 1993). Nuclear energy could make an increasing contribution to low-carbon energy supply, but a variety of barriers and risks exist (*robust evidence, high agree-*

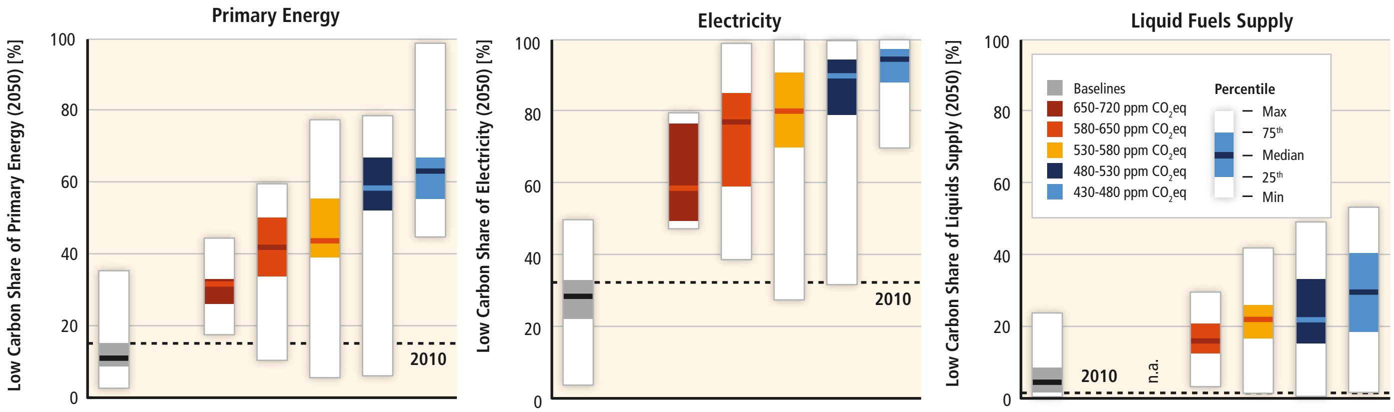

Figure TS.18 | Share of low-carbon energy in total primary energy, electricity and liquid fuels supply sectors for the year 2050. Dashed horizontal lines show the low-carbon share for the year 2010. Low-carbon energy includes nuclear, renewables, fossil fuels with carbon dioxide capture and storage (CCS) and bioenergy with CCS. [Figure 7.14]

ment) (Figure TS.19). Nuclear electricity accounted for 11 % of the world's electricity generation in 2012, down from a high of 17 % in 1993. Pricing the externalities of GHG emissions (carbon pricing) could improve the competitiveness of nuclear power plants. [7.2, 7.5.4, 7.8.1, 7.12]

Barriers and risks associated with an increasing use of nuclear energy include operational risks and the associated safety concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapon proliferation concerns, and adverse public opinion (*robust evidence, high agreement*) (Table TS.4). New fuel cycles and reactor technologies addressing some of these issues are under development and progress has been made concerning safety and waste disposal. Investigation of mitigation scenarios not exceeding 580 ppm CO_2eq has shown that excluding nuclear power from the available portfolio of technologies would result in only a slight increase in mitigation costs compared to the full technology portfolio (Figure TS.13). If other technologies, such as CCS, are constrained the role of nuclear power expands. [6.3.6, 7.5.4, 7.8.2, 7.9, 7.11]

GHG emissions from energy supply can be reduced significantly by replacing current world average coal-fired power plants with modern, highly efficient natural gas combined cycle power plants or combined heat and power (CHP) plants, provided that natural gas is available and the fugitive emissions associated with its extraction and supply are low or mitigated (*robust evidence, high agreement*). In mitigation scenarios reaching about 450 ppm CO_2eq concentrations by 2100, natural gas power generation without CCS typically acts as a bridge technology, with deployment increasing before peaking and falling to below current levels by 2050 and declining further in the second half of the century (*robust evidence, high agreement*). [7.5.1, 7.8, 7.9, 7.11, 7.12]

Carbon dioxide capture and storage (CCS) technologies could reduce the lifecycle GHG emissions of fossil fuel power plants (*medium evidence, medium agreement*). While all components of integrated CCS systems exist and are in use today by the fossil fuel extraction and refining industry, CCS has not yet been applied at scale to a large, commercial fossil fuel power plant. CCS power plants could be seen in the market if they are required for fossil fuel facilities by regulation or if they become competitive with their unabated counterparts, for instance, if the additional investment and operational costs faced by CCS plants, caused in part by efficiency reductions, are compensated by sufficiently high carbon prices (or direct financial support). Beyond economic incentives, well-defined regulations concerning short- and long-term responsibilities for storage are essential for a large-scale future deployment of CCS. [7.5.5]

Barriers to large-scale deployment of CCS technologies include concerns about the operational safety and long-term integrity of CO_2 storage, as well as risks related to transport and the required up-scaling of infrastructure (*limited evidence, medium agreement*) (Table TS.4). There is, however, a growing body of literature on how to ensure the integrity of CO_2 wells, on the potential consequences of a CO_2 pressure build-up within a geologic formation (such as induced seismicity), and on the potential human health and environmental impacts from CO_2 that migrates out of the primary injection zone (*limited evidence, medium agreement*). [7.5.5, 7.9, 7.11]

Combining bioenergy with CCS (BECCS) offers the prospect of energy supply with large-scale net negative emissions, which plays an important role in many low-stabilization scenarios, while it entails challenges and risks (*limited evidence, medium agreement*). Until 2050, bottom-up studies estimate the economic potential to be between 2–10 $GtCO_2$ per year [11.13]. Some mitigation scenarios show higher deployment of BECCS towards the end of the century. Technological challenges and risks include those associated with the upstream provision of the biomass that is used in the CCS facility, as well as those associated with the CCS technology itself. Currently, no large-scale projects have been financed. [6.9, 7.5.5, 7.9, 11.13]

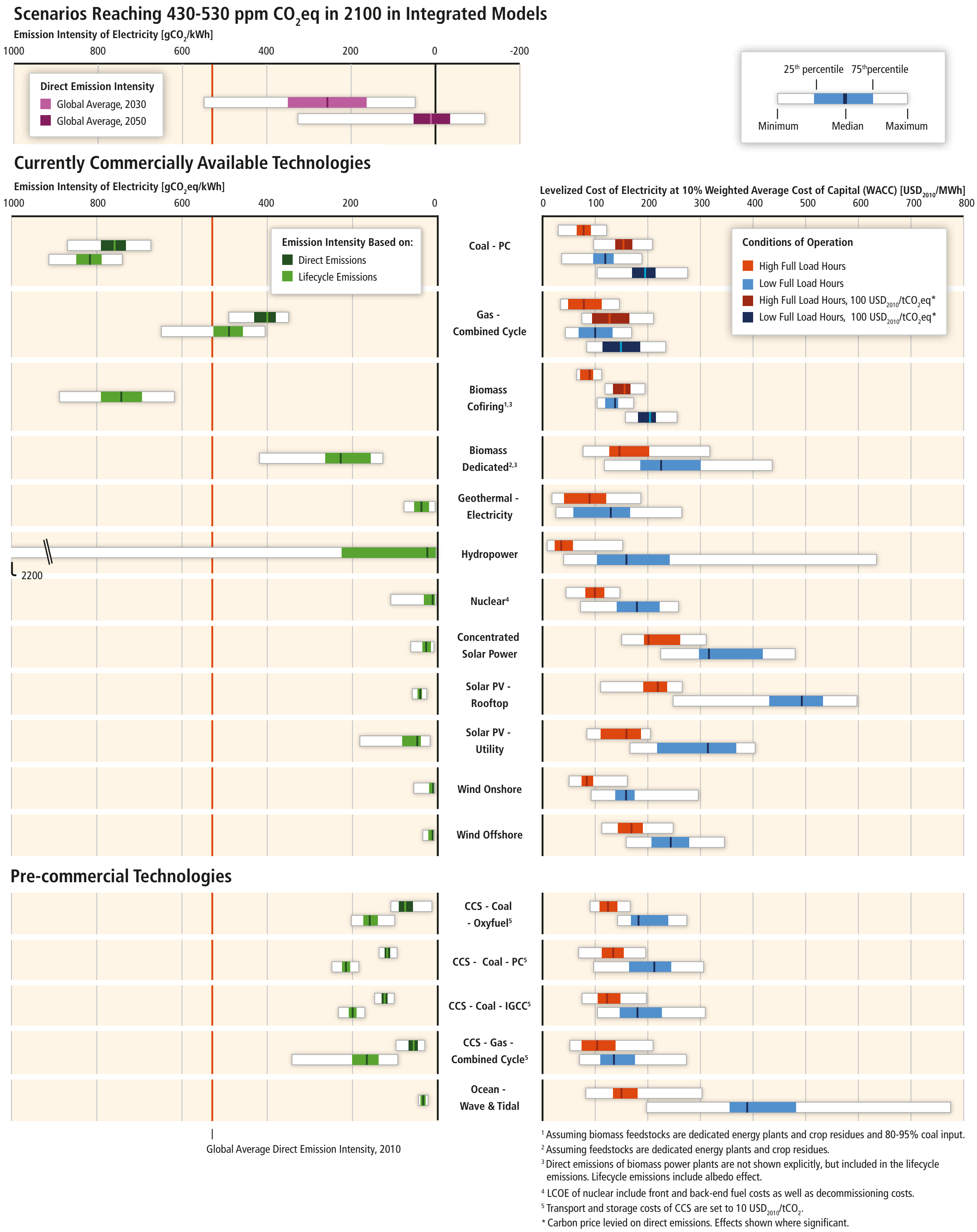

Figure TS.19 | Specific direct and lifecycle emissions (gCO_2eq/ kilowatt hour (kWh)) and levelized cost of electricity (LCOE in USD_{2010}/MWh) for various power-generating technologies (see Annex III.2 for data and assumptions and Annex II.3.1 and II.9.3 for methodological issues). The upper left graph shows global averages of specific direct CO_2 emissions (gCO_2/kWh) of power generation in 2030 and 2050 for the set of about 450 to about 500 (430–530) ppm CO_2eq scenarios that are contained in the WG III AR5 Scenario Database (see Annex II.10). The global average of specific direct CO_2 emissions (gCO_2/kWh) of power generation in 2010 is shown as a vertical line. Note: The inter-comparability of LCOE is limited. For details on general methodological issues and interpretation see Annexes as mentioned above. CCS: CO_2 capture and storage; IGCC: Integrated coal gasification combined cycle; PC: Pulverized hard coal; PV: Photovoltaic; WACC: Weighted average cost of capital. [Figure 7.7]

Table TS.4 | Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the energy supply sector; arrows pointing up/down denote a positive/negative effect on the respective objective or concern; a question mark (**?**) denotes an uncertain net effect. Co-benefits and adverse side-effects depend on local circumstances as well as on the implementation practice, pace, and scale. For possible upstream effects of biomass supply for bioenergy, see Table TS.8. For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see e.g., Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. The uncertainty qualifiers in brackets denote the level of evidence and agreement on the respective effects (see TS.1). Abbreviations for evidence: l=limited, m=medium, r=robust; for agreement: l=low, m=medium, h=high. [Table 7.3]

Energy Supply	Effect on additional objectives/concerns			
	Economic	Social	Environmental	Other
Nuclear replacing coal power	↑ Energy security (reduced exposure to fuel price volatility) (**m**/**m**) ↑ Local employment impact (but uncertain net effect) (**l**/**m**) ↑ Legacy cost of waste and abandoned reactors (**m**/**h**)	Health impact via ↓ Air pollution and coal mining accidents (**m**/**h**) ↑ Nuclear accidents and waste treatment, uranium mining and milling (**m**/**l**) ↑ Safety and waste concerns (**r**/**h**)	Ecosystem impact via ↓ Air pollution (**m**/**h**) and coal mining (**l**/**h**) ↑ Nuclear accidents (**m**/**m**)	Proliferation risk (**m**/**m**)
RE (wind, PV, concentrated solar power (CSP), hydro, geothermal, bioenergy) replacing coal	↑ Energy security (resource sufficiency, diversity in the near/medium term) (**r**/**m**) ↑ Local employment impact (but uncertain net effect) (**m**/**m**) ↑ Irrigation, flood control, navigation, water availability (for multipurpose use of reservoirs and regulated rivers) (**m**/**h**) ↑ Extra measures to match demand (for PV, wind and some CSP) (**r**/**h**)	Health impact via ↓ Air pollution (except bioenergy) (**r**/**h**) ↓ Coal mining accidents (**m**/**h**) ↑ Contribution to (off-grid) energy access (**m**/**l**) ? Project-specific public acceptance concerns (e.g., visibility of wind) (**l**/**m**) ↑ Threat of displacement (for large hydro) (**m**/**h**)	Ecosystem impact via ↓ Air pollution (except bioenergy) (**m**/**h**) ↓ Coal mining (**l**/**h**) ↑ Habitat impact (for some hydro) (**m**/**m**) ↑ Landscape and wildlife impact (for wind) **m**/**m**) ↓ Water use (for wind and PV) (**m**/**m**) ↑ Water use (for bioenergy, CSP, geothermal, and reservoir hydro) (**m**/**h**)	Higher use of critical metals for PV and direct drive wind turbines (**r**/**m**)
Fossil CCS replacing coal	↑↑ Preservation vs. lock-in of human and physical capital in the fossil industry (**m**/**m**)	Health impact via ↑ Risk of CO_2 leakage (**m**/**m**) ↑ Upstream supply-chain activities (**m**/**h**) ↑ Safety concerns (CO_2 storage and transport) (**m**/**h**)	↑ Ecosystem impact via upstream supply-chain activities (**m**/**m**) ↑ Water use (**m**/**h**)	Long-term monitoring of CO_2 storage (**m**/**h**)
BECCS replacing coal	*See fossil CCS where applicable. For possible upstream effect of biomass supply, see Table TS.8.*			
Methane leakage prevention, capture or treatment	↑ Energy security (potential to use gas in some cases) (**l**/**h**)	↓ Health impact via reduced air pollution (**m**/**m**) ↑ Occupational safety at coal mines (**m**/**m**)	↓ Ecosystem impact via reduced air pollution (**l**/**m**)	

TS.3.2.3 Transport

Since AR4, emissions in the global transport sector have grown in spite of more efficient vehicles (road, rail, watercraft, and aircraft) and policies being adopted (*robust evidence, high agreement*). Road transport dominates overall emissions but aviation could play an increasingly important role in total CO_2 emissions in the future. [8.1, 8.3, 8.4]

The global transport sector accounted for 27% of final energy use and 6.7 $GtCO_2$ direct emissions in 2010, with baseline CO_2 emissions projected to increase to 9.3–12 $GtCO_2$/yr in 2050 (25–75th percentile; full range 6.2–16 $GtCO_2$/yr); most of the baseline scenarios assessed in WGIII AR5 foresee a significant increase (*medium evidence/medium agreement*) (Figure TS.15). Without aggressive and sustained mitigation policies being implemented, transport sector emissions could increase faster than in the other energy end-use sectors and could lead to more than a doubling of CO_2 emissions by 2050. [6.8, 8.9, 8.10]

While the continuing growth in passenger and freight activity constitutes a challenge for future emission reductions, analyses of both sectoral and integrated studies suggest a higher mitigation potential in the transport sector than reported in the AR4 (*medium evidence, medium agreement*). Transport energy demand per capita in developing and emerging economies is far lower than in OECD countries but is expected to increase at a much faster rate in the next decades due to rising incomes and the development of infrastructure. Baseline scenarios thus show increases in transport energy demand from 2010 out to 2050 and beyond. However, sectoral and integrated mitigation scenarios indicate that energy demand reductions of 10–45 % are possible by 2050 relative to baseline (Figure TS.20, left panel) (*medium evidence, medium agreement*). [6.8.4, 8.9.1, 8.9.4, 8.12, Figure 8.9.4]

A combination of low-carbon fuels, the uptake of improved vehicle and engine performance technologies, behavioural change leading to avoided journeys and modal shifts, investments in related infrastructure and changes in the built environment, together offer a high mitigation potential (*high confidence*) [8.3, 8.8]. Direct (tank-to-wheel) GHG emissions from passenger and freight transport can be reduced by:

- using fuels with lower carbon intensities (CO_2eq/ megajoule (MJ));
- lowering vehicle energy intensities (MJ/passenger-km or MJ/tonne-km);
- encouraging modal shift to lower-carbon passenger and freight transport systems coupled with investment in infrastructure and compact urban form; and
- avoiding journeys where possible (Table TS.3).

Other short-term mitigation strategies include reducing black carbon (BC), aviation contrails, and nitrogen oxides (NO_x) emissions. [8.4]

Strategies to reduce the carbon intensities of fuel and the rate of reducing carbon intensity are constrained by challenges associated with energy storage and the relatively low energy density of low-carbon transport fuels; integrated and sectoral studies broadly agree that opportunities for fuel switching exist in the short term and will grow over time (*medium evidence, medium agreement*) (Figure TS.20, right panel). Electric, hydrogen, and some biofuel technologies could help reduce the carbon intensity of fuels, but their total mitigation potentials are very uncertain (*medium evidence, medium agreement*). Methane-based fuels are already increasing their share for road vehicles and waterborne craft. Electricity produced from low-carbon sources has near-term potential for electric rail and short- to medium-term potential as electric buses, light-duty and 2-wheel road vehicles are deployed. Hydrogen fuels from low-carbon sources constitute longer-term options. Commercially available liquid and gaseous biofuels already provide co-benefits together with mitigation options that can be increased by technology advances, particularly drop-in biofuels for aircraft. Reducing transport emissions of particulate matter (including BC), tropospheric ozone and aerosol precursors (including NO_x) can have human health and mitigation co-benefits in the short term (*medium evidence, medium agreement*). Up to 2030, the majority of integrated studies expect a continued reliance on liquid and gaseous fuels, supported by an increase in the use of biofuels. During the second half of the century, many integrated studies also show substantial shares of electricity and/or hydrogen to fuel electric and fuel-cell light-duty vehicles (LDVs). [8.2, 8.3, 11.13]

Energy efficiency measures through improved vehicle and engine designs have the largest potential for emissions reduc-

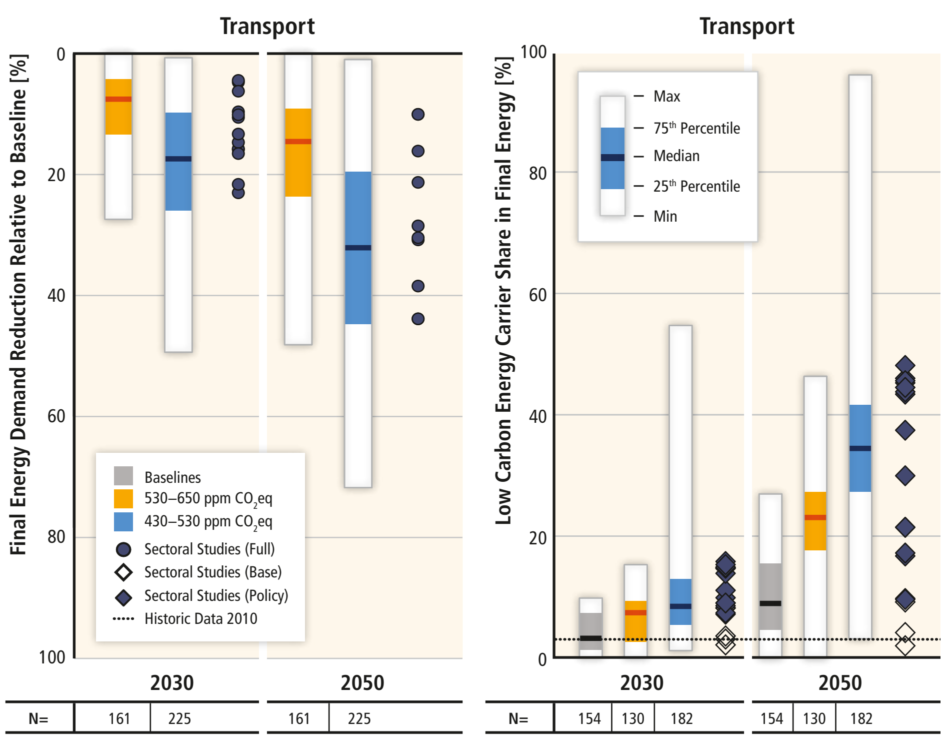

Figure TS.20 | Final energy demand reduction relative to baseline (left panel) and development of final low-carbon energy carrier share in final energy (including electricity, hydrogen, and liquid biofuels; right panel) in transport by 2030 and 2050 in mitigation scenarios from three different CO_2eq concentrations ranges shown in boxplots (see Section 6.3.2) compared to sectoral studies shown in shapes assessed in Chapter 8. Filled circles correspond to sectoral studies with full sectoral coverage. [Figures 6.37 and 6.38]

tions in the short term (*high confidence*). Potential energy efficiency and vehicle performance improvements range from 30–50 % relative to 2010 depending on transport mode and vehicle type (Figures TS.21, TS.22). Realizing this efficiency potential will depend on large investments by vehicle manufacturers, which may require strong incentives and regulatory policies in order to achieve GHG emissions reduction goals (*medium evidence, medium agreement*). [8.3, 8.6, 8.9, 8.10]

Shifts in transport mode and behaviour, impacted by new infrastructure and urban (re)development, can contribute to the reduction of transport emissions (*medium evidence, low agreement*). Over the medium term (up to 2030) to long term (to 2050 and beyond), urban redevelopment and investments in new infrastructure, linked with integrated urban planning, transit-oriented development, and more compact urban form that supports cycling and walking can all lead to modal shifts. Such mitigation measures are challenging, have uncertain outcomes, and could reduce transport GHG emissions by 20–50 % compared to baseline (*limited evidence, low agreement*). Pricing strategies, when supported by public acceptance initiatives and public and non-motorized transport infrastructures, can reduce travel demand, increase the demand for more efficient vehicles (e.g., where fuel economy standards exist) and induce a shift to low-carbon modes (*medium evidence, medium agreement*). While infrastructure investments may appear expensive at the margin, the case for sustainable urban planning and related policies is reinforced when co-benefits, such as improved health, accessibility, and resilience, are accounted for (Table TS.5). Business initiatives to decarbonize freight transport have begun but will need further support from fiscal, regulatory, and advisory policies to encourage shifting from road to low-carbon modes such as rail or waterborne options where feasible, as well as improving logistics (Figure TS.22). [8.4, 8.5, 8.7, 8.8, 8.9, 8.10]

Sectoral and integrated studies agree that substantial, sustained, and directed policy interventions could limit transport emissions to be consistent with low concentration goals, but the societal mitigation costs (USD/tCO_2eq avoided) remain uncertain (Figures TS.21, TS.22, TS.23). There is good potential to reduce emissions from LDVs and long-haul heavy-duty vehicles (HDVs) from both lower energy intensity vehicles and fuel switching, and the levelized costs of conserved carbon (LCCC) for efficiency improvements can be very low and negative (*limited evidence, low agreement*). Rail, buses, two-wheel motorbikes, and waterborne craft for freight already have relatively low emissions so their emissions reduction potential is limited. The mitigation cost of electric vehicles is currently high, especially if using grid electricity with a high emissions factor, but their LCCC are expected to decline by 2030. The emissions intensity of aviation could decline by around 50 % in 2030 but the LCCC, although uncertain, are probably over USD 100/tCO_2eq. While it is expected that mitigation costs will decrease in the future, the magnitude of such reductions is uncertain. (*limited evidence, low agreement*) [8.6, 8.9]

Barriers to decarbonizing transport for all modes differ across regions but can be overcome, in part, through economic incentives (*medium evidence, medium agreement*). Financial, institutional, cultural, and legal barriers constrain low-carbon technology uptake and behavioural change. They include the high investment costs needed to build low-emissions transport systems, the slow turnover of stock and infrastructure, and the limited impact of a carbon price on petroleum fuels that are already heavily taxed. Regional differences are likely due to cost and policy constraints. Oil price trends, price instruments on GHG emissions, and other measures such as road pricing and airport charges can provide strong economic incentives for consumers to adopt mitigation measures. [8.8]

There are regional differences in transport mitigation pathways with major opportunities to shape transport systems and infrastructure around low-carbon options, particularly in developing and emerging countries where most future urban growth will occur (*robust evidence, high agreement*). Possible transformation pathways vary with region and country due to differences in the dynamics of motorization, age and type of vehicle fleets, existing infrastructure, and urban development processes. Prioritizing infrastructure for pedestrians, integrating non-motorized and transit services, and managing excessive road speed for both urban and rural travellers can create economic and social co-benefits in all regions. For all economies, especially those with high rates of urban growth, investments in public transport systems and low-carbon infrastructure can avoid lock-in to carbon-intensive modes. Established infrastructure may limit the options for modal shift and lead to a greater reliance on advanced vehicle technologies; a slowing of growth in LDV demand is already evident in some OECD countries. (*medium evidence, medium agreement*) [8.4, 8.9]

A range of strong and mutually supportive policies will be needed for the transport sector to decarbonize and for the co-benefits to be exploited (*robust evidence, high agreement*). Transport mitigation strategies associated with broader non-climate policies at all government levels can usually target several objectives simultaneously to give lower travel costs, improved access and mobility, better health, greater energy security, improved safety, and increased time savings. Activity reduction measures have the largest potential to realize co-benefits. Realizing the co-benefits depends on the regional context in terms of economic, social, and political feasibility as well as having access to appropriate and cost-effective advanced technologies (Table TS.5). (*medium evidence, high agreement*) Since rebound effects can reduce the CO_2 benefits of efficiency improvements and undermine a particular policy, a balanced package of policies, including pricing initiatives, could help to achieve stable price signals, avoid unintended outcomes, and improve access, mobility, productivity, safety, and health (*medium evidence, medium agreement*). [8.4, 8.7, 8.10]

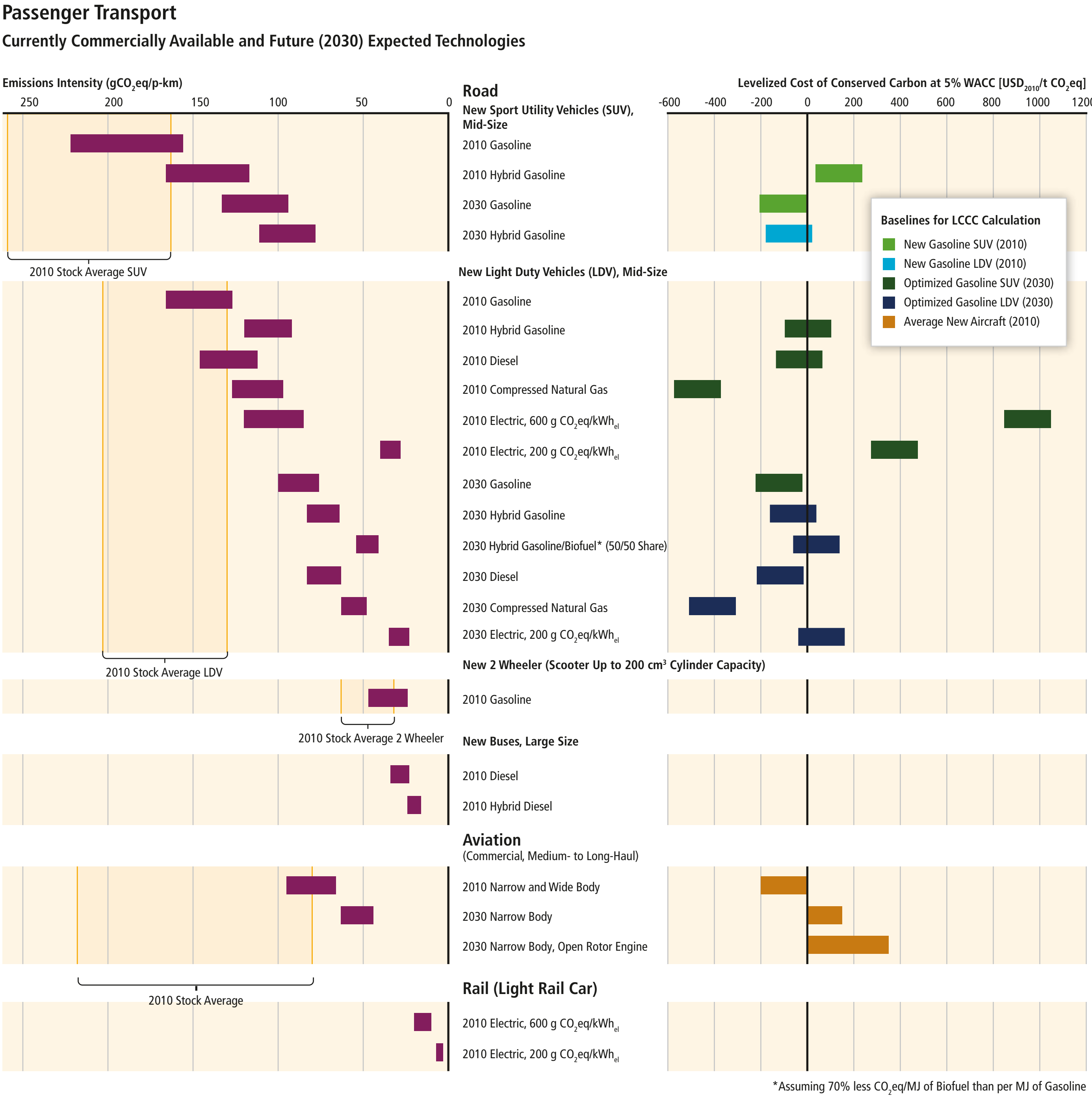

Figure TS.21 | Indicative emissions intensity (tCO_2eq/p-km) and levelized costs of conserved carbon (LCCC in USD_{2010}/tCO_2eq saved) of selected passenger transport technologies. Variations in emissions intensities stem from variation in vehicle efficiencies and occupancy rates. Estimated LCCC for passenger road transport options are point estimates ±100 USD_{2010}/tCO_2eq based on central estimates of input parameters that are very sensitive to assumptions (e.g., specific improvement in vehicle fuel economy to 2030, specific biofuel CO_2eq intensity, vehicle costs, fuel prices). They are derived relative to different baselines (see legend for colour coding) and need to be interpreted accordingly. Estimates for 2030 are based on projections from recent studies, but remain inherently uncertain. LCCC for aviation are taken directly from the literature. Table 8.3 provides additional context (see Annex III.3 for data and assumptions on emissions intensities and cost calculations and Annex II.3.1 for methodological issues on levelized cost metrics). WACC: Weighted average cost of capital. [Table 8.3]

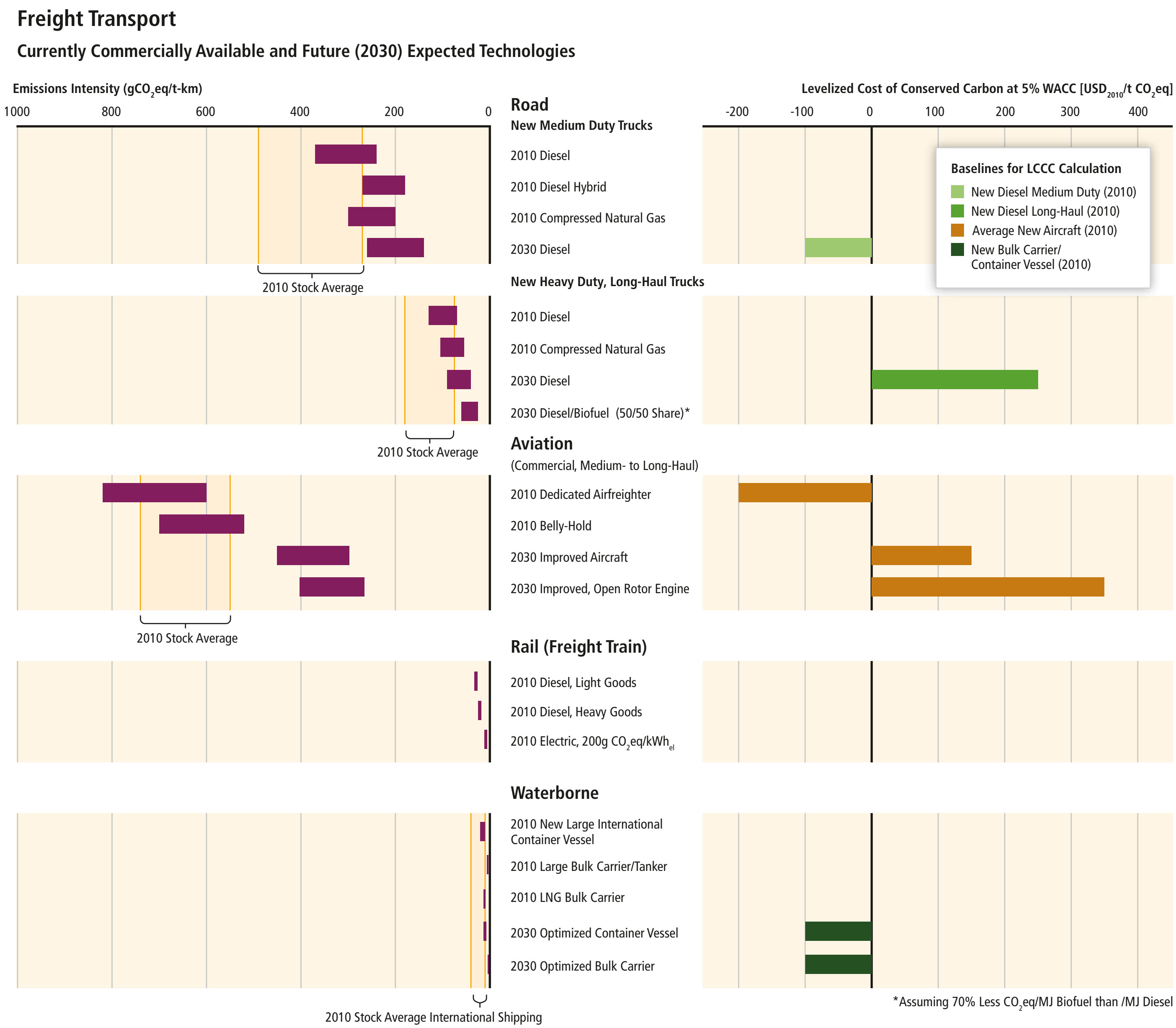

Figure TS.22 | Indicative emissions intensity (tCO_2eq/t-km) and levelized costs of conserved carbon (LCCC in USD_{2010}/tCO_2eq saved) of selected freight transport technologies. Variations in emissions intensities largely stem from variation in vehicle efficiencies and load rates. Levelized costs of conserved carbon are taken directly from the literature and are very sensitive to assumptions (e.g., specific improvement in vehicle fuel economy to 2030, specific biofuel CO_2eq intensity, vehicle costs, and fuel prices). They are expressed relative to current baseline technologies (see legend for colour coding) and need to be interpreted accordingly. Estimates for 2030 are based on projections from recent studies but remain inherently uncertain. Table 8.3 provides additional context (see Annex III.3 for data and assumptions on emissions intensities and cost calculations and Annex II.3.1 for methodological issues on levelized cost metrics). LNG: Liquefied natural gas; WACC: Weighted average cost of capital. [Table 8.3]

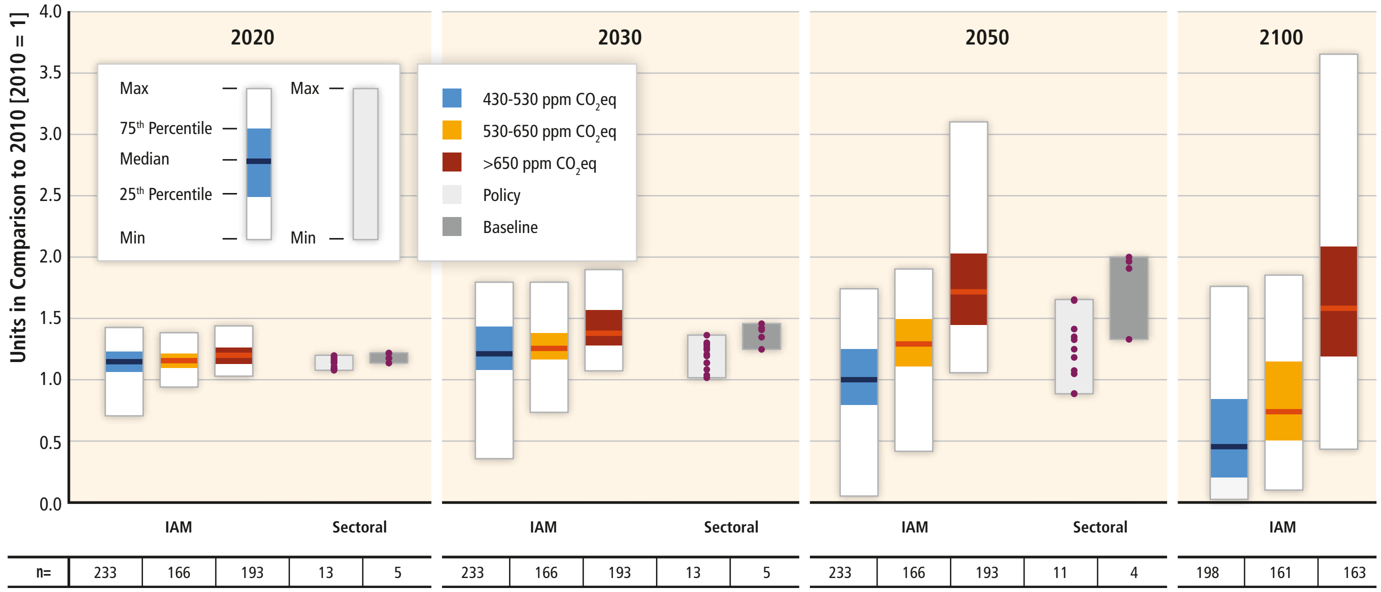

Figure TS.23 | Direct global CO_2 emissions from all passenger and freight transport are indexed relative to 2010 values for each scenario with integrated model studies grouped by CO_2eq concentration levels by 2100, and sectoral studies grouped by baseline and policy categories. [Figure 8.9]

Table TS.5 | Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the transport sector; arrows pointing up/down denote a positive/negative effect on the respective objective or concern; a question mark (**?**) denotes an uncertain net effect. Co-benefits and adverse side-effects depend on local circumstances as well as on implementation practice, pace and scale. For possible upstream effects of low-carbon electricity, see Table TS.4. For possible upstream effects of biomass supply, see Table TS.8. For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see e.g., Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. The uncertainty qualifiers in brackets denote the level of evidence and agreement on the respective effects (see TS.1). Abbreviations for evidence: l = limited, m = medium, r = robust; for agreement: l = low, m = medium, h = high. [Table 8.4]

Transport	Effect on additional objectives/concerns		
	Economic	**Social**	**Environmental**
Reduction of fuel carbon intensity: electricity, hydrogen (H_2), compressed natural gas (CNG), biofuels, and other fuels	↑ Energy security (diversification, reduced oil dependence and exposure to oil price volatility) (**m/m**) ↑ Technological spillovers (e.g., battery technologies for consumer electronics) (**l/l**)	Health impact via urban air pollution by ? CNG, biofuels: net effect unclear (**m/l**) ↓ Electricity, H_2: reducing most pollutants (**r/h**) ↑ Shift to diesel: potentially increasing pollution (**l/m**) ↓ Health impact via reduced noise (electricity and fuel cell LDVs) (**l/m**) ↓ Road safety (silent electric LDVs at low speed) (**l/l**)	Ecosystem impact of electricity and hydrogen via ↓ Urban air pollution (**m/m**) ↑ Material use (unsustainable resource mining) (**l/l**) ? Ecosystem impact of biofuels: *see AFOLU*
Reduction of energy intensity	↑ Energy security (reduced oil dependence and exposure to oil price volatility) (**m/m**)	↓ Health impact via reduced urban air pollution (**r/h**) ↑ Road safety (via increased crash-worthiness) (**m/m**)	↓ Ecosystem and biodiversity impact via reduced urban air pollution (**m/h**)
Compact urban form and improved transport infrastructure **Modal shift**	↑ Energy security (reduced oil dependence and exposure to oil price volatility) (**m/m**) ↑ Productivity (reduced urban congestion and travel times, affordable and accessible transport) (**m/h**) ? Employment opportunities in the public transport sector vs. car manufacturing (**l/m**)	Health impact for non-motorized modes via ↓ Increased physical activity (**r/h**) ↑ Potentially higher exposure to air pollution (**r/h**) ↓ Noise (modal shift and travel reduction) (**r/h**) ↑ Equitable mobility access to employment opportunities, particularly in developing countries (**r/h**) ↑ Road safety (via modal shift and/or infrastructure for pedestrians and cyclists) (**r/h**)	Ecosystem impact via ↓ Urban air pollution (**r/h**) ↓ Land-use competition (**m/m**)
Journey distance reduction and avoidance	↑ Energy security (reduced oil dependence and exposure to oil price volatility) (**r/h**) ↑ Productivity (reduced urban congestion, travel times, walking) (**r/h**)	↓ Health impact (for non-motorized transport modes) (**r/h**)	Ecosystem impact via ↓ Urban air pollution (**r/h**) ↑ New/shorter shipping routes (**r/h**) ↓ Land-use competition from transport infrastructure (**r/h**)

TS.3.2.4 Buildings

GHG emissions from the buildings sector[15] have more than doubled since 1970, accounting for 19 % of global GHG emissions in 2010, including indirect emissions from electricity generation. The share rises to 25 % if AFOLU emissions are excluded from the total. The buildings sector also accounted for 32 % of total global final energy use, approximately one-third of black carbon emissions, and an eighth to a third of F-gases, with significant uncertainty (*medium evidence, medium agreement*). (Figure TS.3) [9.2]

Direct and indirect CO_2 emissions from buildings are projected to increase from 8.8 $GtCO_2$/yr in 2010 to 13–17 $GtCO_2$/yr in 2050 (25–75th percentile; full range 7.9–22 $GtCO_2$/yr) in baseline scenarios; most of the baseline scenarios assessed in WGIII AR5 show a significant increase (*medium evidence, medium agreement*) (Figure TS.15) [6.8]. The lower end of the full range is dominated by scenarios with a focus on energy intensity improvements that go well beyond the observed improvements over the past 40 years. Without further policies, final energy use of the buildings sector may grow from approximately 120 exajoules per year (EJ/yr) in 2010 to 270 EJ/yr in 2050 [9.9].

Significant lock-in risks arise from the long lifespans of buildings and related infrastructure (*robust evidence, high agreement*). If only currently planned policies are implemented, the final energy use in buildings that could be locked-in by 2050, compared to a scenario where today's best practice buildings become the standard in newly built structures and retrofits, is equivalent to approximately 80 % of the final energy use of the buildings sector in 2005. [9.4]

Improvements in wealth, lifestyle change, the provision of access to modern energy services and adequate housing, and urbanization will drive the increases in building energy demand (*robust evidence, high agreement*). The manner in which those without access to adequate housing (about 0.8 billion people), modern energy carriers, and sufficient levels of energy services including clean cooking and heating (about 3 billion people) meet these needs will influence the development of building-related emissions. In addition, migration to cities, decreasing household size, increasing levels of wealth, and lifestyle changes, including increasing dwelling size and number and use of appliances, all contribute to considerable increases in building energy services demand. The substantial amount of new construction taking place in developing countries represents both a risk and opportunity from a mitigation perspective. [9.2, 9.4, 9.9]

Recent advances in technologies, know-how, and policies in the buildings sector, however, make it feasible that the global total sector final energy use stabilizes or even declines by mid-century (*robust evidence, medium agreement*). Recent advances in technology, design practices and know-how, coupled with behavioural changes, can achieve a two to ten-fold reduction in energy requirements of individual new buildings and a two to four-fold reduction for individual existing buildings largely cost-effectively or sometimes even at net negative costs (see Box TS.12) (*robust evidence, high agreement*). [9.6]

Advances since AR4 include the widespread demonstration worldwide of very low, or net zero energy buildings both in new construction and retrofits (*robust evidence, high agreement*). In some jurisdictions, these have already gained important market shares with, for instance, over 25 million m^2 of building floorspace in Europe complying with the 'Passivehouse' standard in 2012. However, zero energy/carbon buildings may not always be the most cost-optimal solution, nor even be feasible in certain building types and locations. [9.3]

High-performance retrofits are key mitigation strategies in countries with existing building stocks, as buildings are very long-lived and a large fraction of 2050 developed country buildings already exists (*robust evidence, high agreement*). Reductions of heating/cooling energy use by 50–90 % have been achieved using best practices. Strong evidence shows that very low-energy construction and retrofits can be economically attractive. [9.3]

With ambitious policies it is possible to keep global building energy use constant or significantly reduce it by mid-century compared to baseline scenarios which anticipate an increase of more than two-fold (*medium evidence, medium agreement*) (Figure TS.24). Detailed building sector studies indicate a larger energy savings potential by 2050 than do integrated studies. The former indicate a potential of up to 70 % of the baseline for heating and cooling only, and around 35–45 % for the whole sector. In general, deeper reductions are possible in thermal energy uses than in other energy services mainly relying on electricity. With respect to additional fuel switching as compared to baseline, both sectoral and integrated studies find modest opportunities. In general, both sectoral and integrated studies indicate that electricity will supply a growing share of building energy demand over the long term, especially if heating demand decreases due to a combination of efficiency gains, better architecture, and climate change. [6.8.4, 9.8.2, Figure 9.19]

The history of energy efficiency programmes in buildings shows that 25–30 % efficiency improvements have been available at costs substantially lower than those of marginal energy supply (*robust evidence, high agreement*). Technological progress enables the potential for cost-effective energy efficiency improvements to be maintained, despite continuously improving standards. There has been substantial progress in the adoption of voluntary and mandatory standards since AR4, including ambitious building codes and targets, voluntary construction standards, and appliance standards. At the same time, in both new and retrofitted buildings, as well as in appliances and information, communication and media technology equipment, there have been notable performance and cost improvements. Large

[15] The buildings sector covers the residential, commercial, public and services sectors; emissions from construction are accounted for in the industry sector.

Box TS.12 | Negative private mitigation costs

A persistent issue in the analysis of mitigation options and costs is whether there are mitigation opportunities that are privately beneficial—generating private benefits that more than offset the costs of implementation—but which consumers and firms do not voluntarily undertake. There is some evidence of unrealized mitigation opportunities that would have negative private cost. Possible examples include investments in vehicles [8.1], lighting and heating technology in homes and commercial buildings [9.3], as well as industrial processes [10.1].

Examples of negative private costs imply that firms and individuals do not take opportunities to save money. This might be explained in a number of ways. One is that status-quo bias can inhibit the switch to new technologies or products [2.4, 3.10.1]. Another is that firms and individuals may focus on short-term goals and discount future costs and benefits sharply; consumers have been shown to do this when choosing energy conservation measures or investing in energy-efficient technologies [2.4.3, 2.6.5.3, 3.10.1]. Risk aversion and ambiguity aversion may also account for this behaviour when outcomes are uncertain [2.4.3, 3.10.1]. Other possible explanations include: insufficient information on opportunities to conserve energy; asymmetric information—for example, landlords may be unable to convey the value of energy efficiency improvements to renters; split incentives, where one party pays for an investment but another party reaps the benefits; and imperfect credit markets, which make it difficult or expensive to obtain finance for energy savings [3.10.1, 16.4].

Some engineering studies show a large potential for negative-cost mitigation. The extent to which such negative-cost opportunities can actually be realized remains a matter of contention in the literature. Empirical evidence is mixed. [Box 3.10]

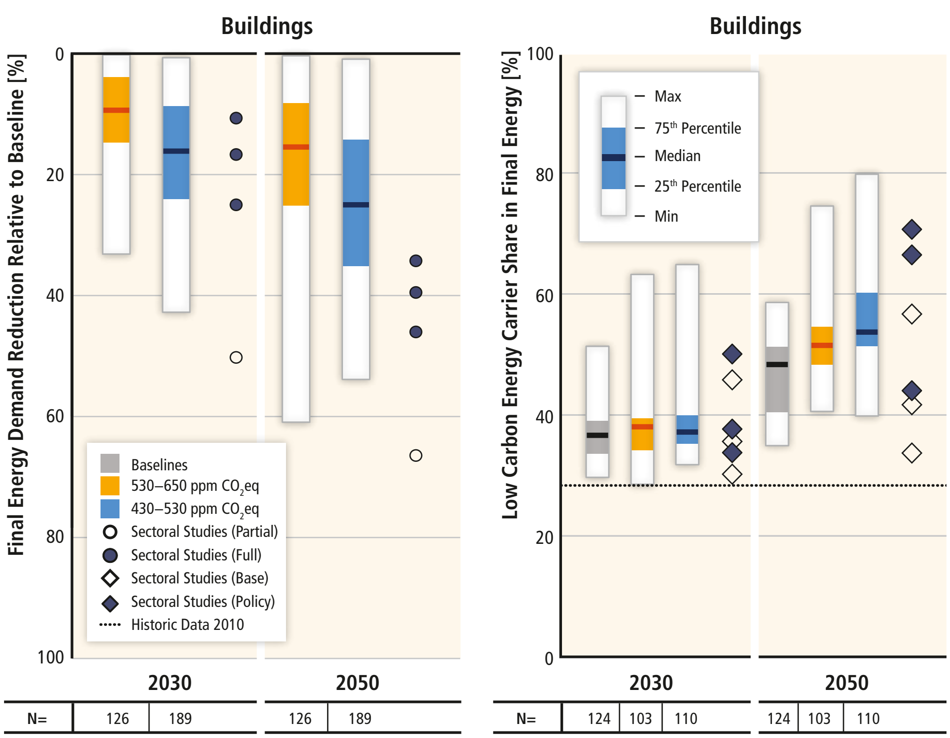

Figure TS.24 | Final energy demand reduction relative to baseline (left panel) and development of final low-carbon energy carrier share in final energy (from electricity; right panel) in buildings by 2030 and 2050 in mitigation scenarios from three different CO_2eq concentrations ranges shown in boxplots (see Section 6.3.2) compared to sectoral studies shown in shapes assessed in Chapter 9. Filled circles correspond to sectoral studies with full sectoral coverage while empty circles correspond to studies with only partial sectoral coverage (e.g., heating and cooling). [Figures 6.37 and 6.38]

reductions in thermal energy use in buildings are possible at costs lower than those of marginal energy supply, with the most cost-effective options including very high-performance new commercial buildings; the same holds for efficiency improvements in some appliances and cooking equipment. [9.5, 9.6, 9.9]

Lifestyle, culture, and other behavioural changes may lead to further large reductions in building and appliance energy requirements beyond those achievable through technologies and architecture. A three- to five-fold difference in energy use has been shown for provision of similar building-related energy

service levels in buildings. (*limited evidence, high agreement*) For developed countries, scenarios indicate that lifestyle and behavioural changes could reduce energy demand by up to 20 % in the short term and by up to 50 % of present levels by mid-century (*medium evidence, medium agreement*). There is a high risk that emerging countries follow the same path as developed economies in terms of building-related architecture, lifestyle, and behaviour. But the literature suggests that alternative development pathways exist that provide high levels of building services at much lower energy inputs, incorporating strategies such as learning from traditional lifestyles, architecture, and construction techniques. [9.3]

Most mitigation options in the building sector have considerable and diverse co-benefits (*robust evidence, high agreement*). These include, but are not limited to: energy security; less need for energy subsidies; health and environmental benefits (due to reduced indoor and outdoor air pollution); productivity and net employment gains; the alleviation of fuel poverty; reduced energy expenditures; increased value for building infrastructure; and improved comfort and services. (Table TS.6) [9.6, 9.7]

Especially strong barriers in this sector hinder the market-based uptake of cost-effective technologies and practices; as a consequence, programmes and regulation are more effective than pricing instruments alone (*robust evidence, high agreement*). Barriers include imperfect information and lack of awareness, principal/agent problems and other split incentives, transaction costs, lack of access to financing, insufficient training in all construction-related trades, and cognitive/behavioural barriers. In developing countries, the large informal sector, energy subsidies, corruption, high implicit discount rates, and insufficient service levels are further barriers. Therefore, market forces alone are not expected to achieve the necessary transformation without external stimuli. Policy intervention addressing all stages of the building and appliance lifecycle and use, plus new business and financial models, are essential. [9.8, 9.10]

A large portfolio of building-specific energy efficiency policies was already highlighted in AR4, but further considerable advances in available instruments and their implementation have occurred since (*robust evidence, high agreement*). Evidence shows that many building energy efficiency policies worldwide have

Table TS.6 | Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the buildings sector; arrows pointing up/down denote a positive/negative effect on the respective objective or concern. Co-benefits and adverse side-effects depend on local circumstances as well as on implementation practice, pace and scale. For possible upstream effects of fuel switching and RE, see Tables TS.4 and TS.8. For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see e.g., Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. The uncertainty qualifiers in brackets denote the level of evidence and agreement on the respective effects (see TS.1). Abbreviations for evidence: l = limited, m = medium, r = robust; for agreement: l = low, m = medium, h = high. [Table 9.7]

Buildings	Effect on additional objectives/concerns			
	Economic	Social	Environmental	Other
Fuel switching, RES incorporation, green roofs, and other measures reducing GHG emissions intensity	↑ Energy security (**m/h**) ↑ Employment impact (**m/m**) ↑ Lower need for energy subsidies (**l/l**) ↑ Asset values of buildings (**l/m**)	Fuel poverty (residential) via ↓ Energy demand (**m/h**) ↑ Energy cost (**l/m**) ↓ Energy access (for higher energy cost) (**l/m**) ↑ Productive time for women/children (for replaced traditional cookstoves) (**m/h**)	Health impact in residential buildings via ↓ Outdoor air pollution (**r/h**) ↓ Indoor air pollution (in developing countries) (**r/h**) ↓ Fuel poverty (**r/h**) ↓ Ecosystem impact (less outdoor air pollution) (**r/h**) ↑ Urban biodiversity (for green roofs) (**m/m**)	Reduced Urban Heat Island (UHI) effect (**l/m**)
Retrofits of existing buildings (e.g., cool roof, passive solar, etc.) **Exemplary new buildings** **Efficient equipment**	↑ Energy security (**m/h**) ↑ Employment impact (**m/m**) ↑ Productivity (for commercial buildings) (**m/h**) ↑ Lower need for energy subsidies (**l/l**) ↑ Asset values of buildings (**l/m**) ↑ Disaster resilience (**l/m**)	↓ Fuel poverty (for retrofits and efficient equipment) (**m/h**) ↓ Energy access (higher cost for housing due to the investments needed) (**l/m**) ↑ Thermal comfort (for retrofits and exemplary new buildings) (**m/h**) ↑ Productive time for women and children (for replaced traditional cookstoves) (**m/h**)	Health impact via ↓ Outdoor air pollution (**r/h**) ↓ Indoor air pollution (for efficient cookstoves) (**r/h**) ↓ Improved indoor environmental conditions (**m/h**) ↓ Fuel poverty (**r/h**) ↓ Insufficient ventilation (**m/m**) ↓ Ecosystem impact (less outdoor air pollution) (**r/h**) ↓ Water consumption and sewage production (**l/l**)	Reduced UHI effect (for retrofits and new exemplary buildings) (**l/m**)
Behavioural changes reducing energy demand	↑ Energy security (**m/h**) ↑ Lower need for energy subsidies (**l/l**)		↓ Health impact via less outdoor air pollution (**r/h**) and improved indoor environmental conditions (**m/h**) ↓ Ecosystem impact (less outdoor air pollution) (**r/h**)	

already been saving GHG emissions at large negative costs. Among the most environmentally and cost-effective policies are regulatory instruments such as building and appliance energy performance standards and labels, as well as public leadership programmes and procurement policies. Progress in building codes and appliance standards in some developed countries over the last decade have contributed to stabilizing or even reducing total building energy use, despite growth in population, wealth, and corresponding energy service level demands. Developing countries have also been adopting different effective policies, most notably appliance standards. However, in order to reach ambitious climate goals, these standards need to be substantially strengthened and adopted in further jurisdictions, and to other building and appliance types. Due to larger capital requirements, financing instruments are essential both in developed and developing countries to achieve deep reductions in energy use. [9.10]

TS.3.2.5 Industry

In 2010, the industry sector accounted for around 28 % of final energy use, and direct and indirect GHG emissions (the latter being associated with electricity consumption) are larger than the emissions from either the buildings or transport end-use sectors and represent just over 30 % of global GHG emissions in 2010 (the share rises to 40 % if AFOLU emissions are excluded from the total) (*high confidence*). Despite the declining share of industry in global GDP, global industry and waste/wastewater GHG emissions grew from 10 $GtCO_2eq$ in 1990 to 13 $GtCO_2eq$ in 2005 and to 15 $GtCO_2eq$ in 2010 (of which waste/wastewater accounted for 1.4 $GtCO_2eq$). [10.3]

Carbon dioxide emissions from industry, including direct and indirect emissions as well as process emissions, are projected to increase from 13 $GtCO_2$/yr in 2010 to 20–24 $GtCO_2$/yr in 2050 (25–75th percentile; full range 9.5–34 $GtCO_2$/yr) in baseline scenarios; most of the baseline scenarios assessed in WGIII AR5 show a significant increase (*medium evidence, medium agreement*) (Figure TS.15) [6.8]. The lower end of the full range is dominated by scenarios with a focus on energy intensity improvements that go well beyond the observed improvements over the past 40 years.

The wide-scale upgrading, replacement and deployment of best available technologies, particularly in countries where these are not in practice, and in non-energy intensive industries, could directly reduce the energy intensity of the industry sector by about 25 % compared to the current level (*robust evidence, high agreement*). Despite long-standing attention to energy efficiency in industry, many options for improved energy efficiency still remain. Through innovation, additional reductions of about 20 % in energy intensity may potentially be realized (*limited evidence, medium agree-*

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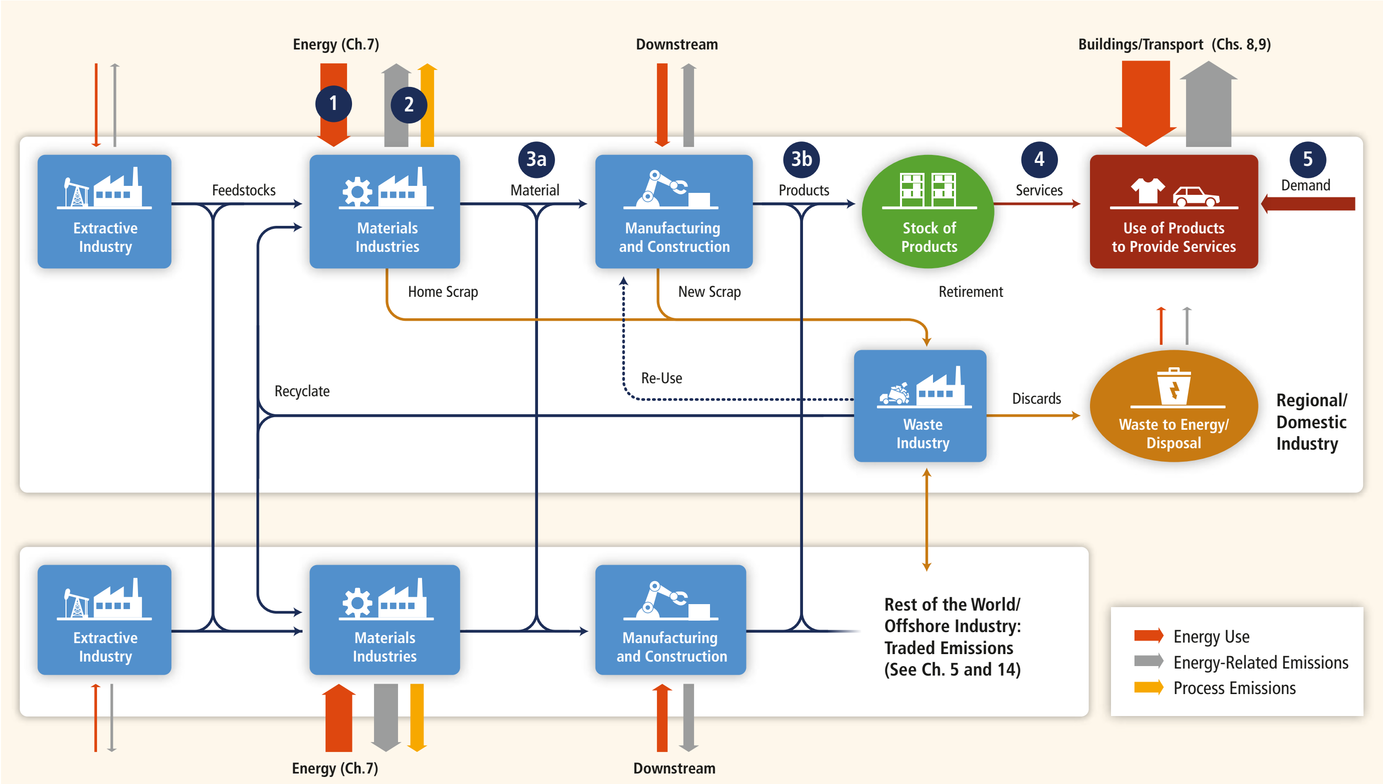


Figure TS.25 | A schematic illustration of industrial activity over the supply chain. Options for mitigation in the industry sector are indicated by the circled numbers: (1) energy efficiency; (2) emissions efficiency; (3a) material efficiency in manufacturing; (3b) material efficiency in product design; (4) product-service efficiency; (5) service demand reduction. [Figure 10.2] *ment*). Barriers to implementing energy efficiency relate largely to the initial investment costs and lack of information. Information programmes are a prevalent approach for promoting energy efficiency, followed by economic instruments, regulatory approaches, and voluntary actions. [10.4, 10.7, 10.9, 10.11]

An absolute reduction in emissions from the industry sector will require deployment of a broad set of mitigation options that go beyond energy efficiency measures (*medium evidence, high agreement*) [10.4, 10.7]. In the context of continued overall growth in industrial demand, substantial reductions from the sector will require parallel efforts to increase emissions efficiency (e.g., through fuel and feedstock switching or CCS); material use efficiency (e.g., less scrap, new product design); recycling and re-use of materials and products; product-service efficiency (e.g., more intensive use of products through car sharing, longer life for products); radical product innovations (e.g., alternatives to cement); as well as service demand reductions. Lack of policy and experiences in material and product-service efficiency are major barriers. (Table TS.3, Figure TS.25) [10.4, 10.7, 10.11]

While detailed industry sector studies tend to be more conservative than integrated studies, both identify possible industrial final energy demand savings of around 30 % by 2050 in mitigation scenarios not exceeding 650 ppm CO_2eq by 2100 relative to baseline scenarios (*medium evidence, medium agreement*) (Figure TS.26). Integrated models in general treat the industry sector in a more aggregated fashion and mostly do not explicitly provide detailed sub-sectoral material flows, options for reducing material demand, and price-induced inter-input substitution possibilities. Due to the heterogeneous character of the industry sector, a coherent comparison between sectoral and integrated studies remains difficult. [6.8.4, 10.4, 10.7, 10.10.1, Figure 10.14]

Mitigation in the industry sector can also be achieved by reducing material and fossil fuel demand by enhanced waste use, which concomitantly reduces direct GHG emissions from waste disposal (*robust evidence, high agreement*). The hierarchy of waste management places waste reduction at the top, followed by re-use, recycling, and energy recovery. As the share of recycled or reused material is still low, applying waste treatment technologies and recovering energy to reduce demand for fossil fuels can result in direct emission reductions from waste disposal. Globally, only about 20 % of municipal solid waste (MSW) is recycled and about 14 % is treated with energy recovery while the rest is deposited in open dumpsites or landfills. About 47 % of wastewater produced in the domestic and manufacturing sectors is still untreated. The largest cost range is for reducing GHG emissions from landfilling through the treatment of waste by anaerobic digestion. The costs range from negative (see Box TS.12) to very high. Advanced wastewater treatment technologies may enhance GHG emissions reduction in wastewater treatment but they are clustered among the higher cost options (*medium evidence, medium agreement*). (Figure TS.29) [10.4, 10.14]

Figure TS.26 | Final energy demand reduction relative to baseline (left panel) and development of final low-carbon energy carrier share in final energy (including electricity, heat, hydrogen, and bioenergy; right panel) in industry by 2030 and 2050 in mitigation scenarios from three different CO_2eq concentration ranges shown in boxplots (see Section 6.3.2) compared to sectoral studies shown in shapes assessed in Chapter 10. Filled circles correspond to sectoral studies with full sectoral coverage. [Figures 6.37 and 6.38]

Figure TS.27 | Indicative CO_2 emission intensities for cement (upper panel) and steel (lower panel) production, as well as indicative levelized cost of conserved carbon (LCCC) shown for various production practices/technologies and for 450 ppm CO_2eq scenarios of a limited selection of integrated models (for data and methodology, see Annex III). DRI: Direct reduced iron; EAF: Electric arc furnace. [Figures 10.7, 10.8]

Waste policy and regulation have largely influenced material consumption, but few policies have specifically pursued material efficiency or product-service efficiency (*robust evidence, high agreement*) [10.11]. Barriers to improving material efficiency include lack of human and institutional capacities to encourage management decisions and public participation. Also, there is a lack of experience and often there are no clear incentives either for suppliers or consumers to address improvements in material or product-service efficiency, or to reduce product demand. [10.9]

CO_2 emissions dominate GHG emissions from industry, but there are also substantial mitigation opportunities for non-CO_2 gases

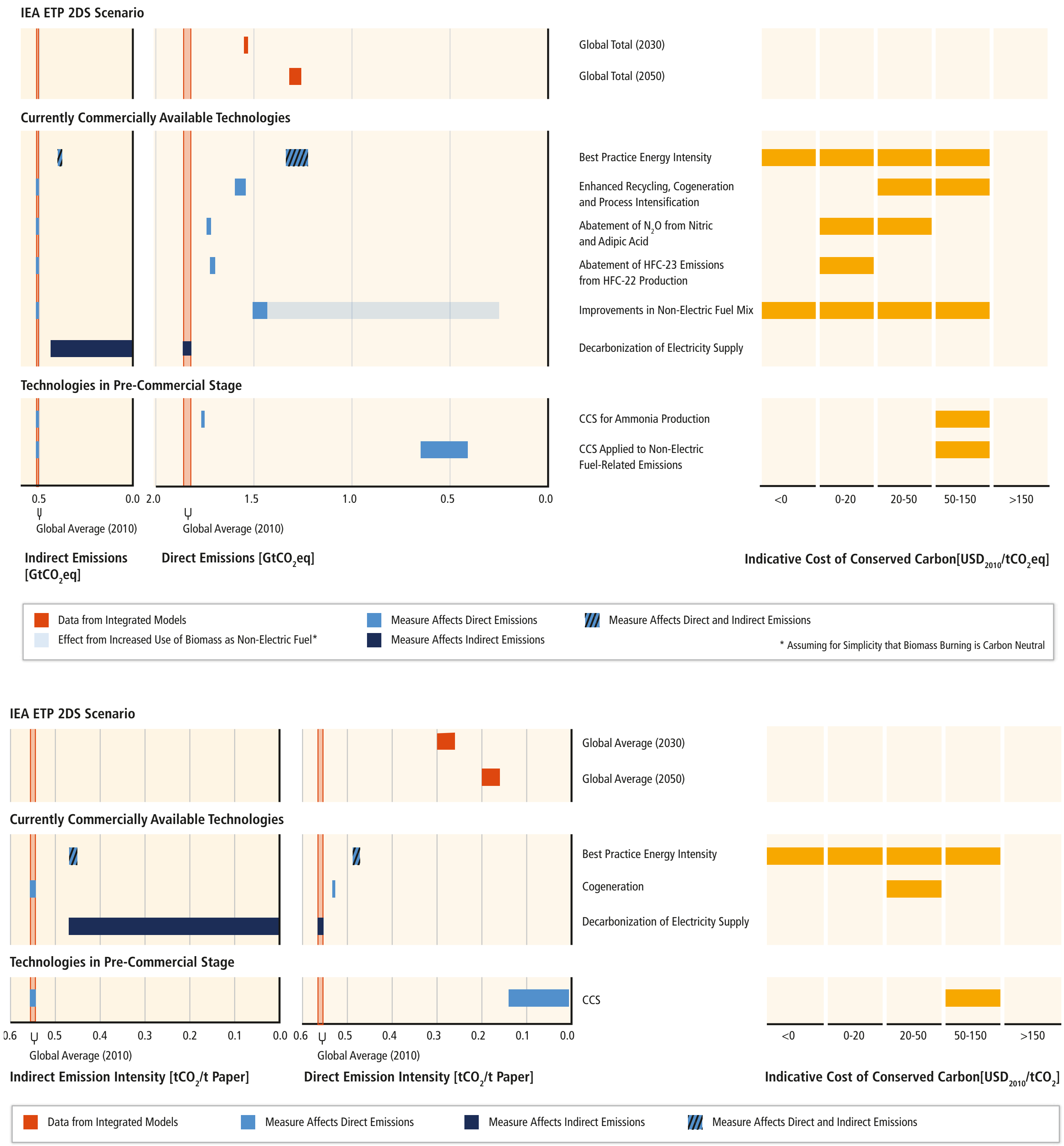


Figure TS.28 | Indicative global CO_2eq emissions for chemicals production (upper panel) and indicative global CO_2 emission intensities for paper production (lower panel) as well as indicative levelized cost of conserved carbon (LCCC) shown for various production practices/technologies and for 450 ppm CO_2eq scenarios of a limited selection of integrated models (for data and methodology, see Annex III). [Figures 10.9, 10.10]

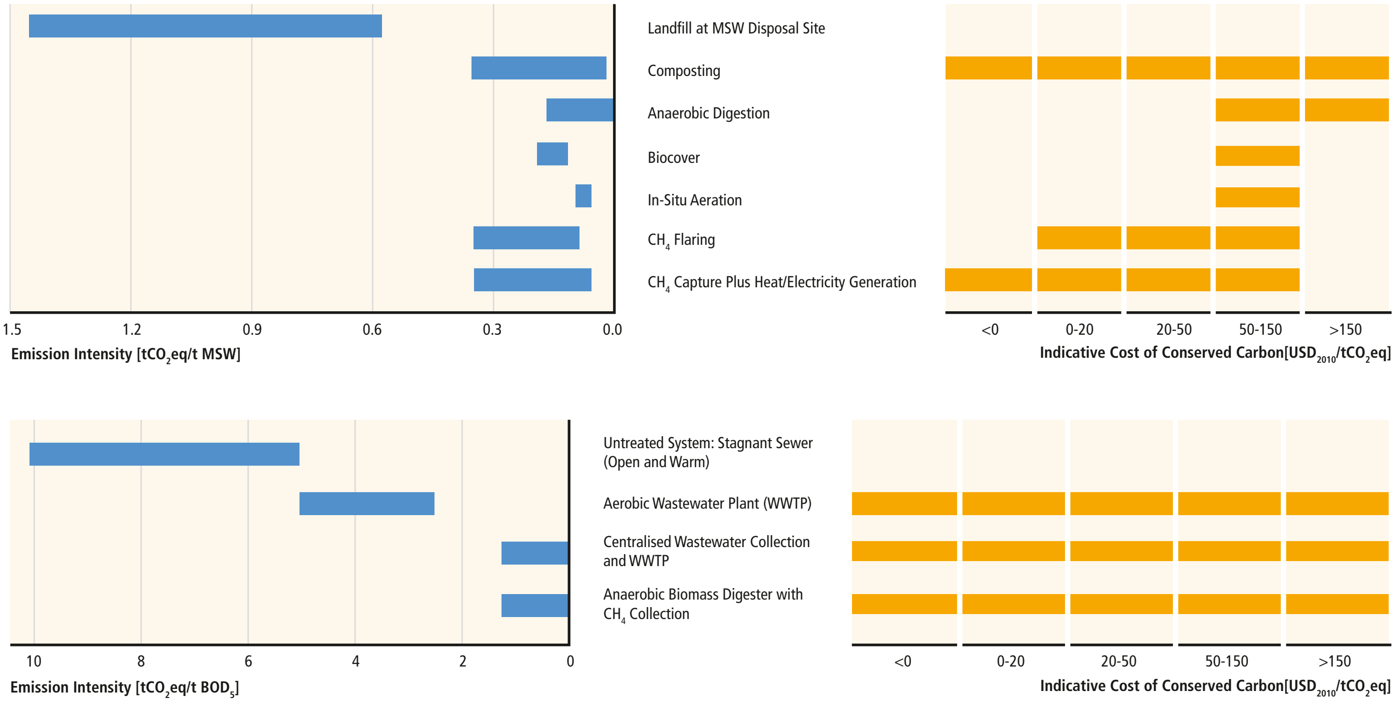


Figure TS.29 | Indicative CO_2eq emission intensities for waste (upper panel) and wastewater (lower panel) of various practices as well as indicative levelized cost of conserved carbon (for data and methodology, see Annex III). MSW: Municipal solid waste. [Figures 10.19 and 10.20]

(*robust evidence, high agreement*). Methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (F-gases) from industry accounted for emissions of 0.9 $GtCO_2eq$ in 2010. Key mitigation opportunities comprise, e.g., reduction of hydrofluorocarbon (HFC) emissions by leak repair, refrigerant recovery and recycling, and proper disposal and replacement by alternative refrigerants (ammonia, HC, CO_2). N_2O emissions from adipic and nitric acid production can be reduced through the implementation of thermal destruction and secondary catalysts. The reduction of non-CO_2 GHGs also faces numerous barriers. Lack of awareness, lack of economic incentives and lack of commercially available technologies (e.g., for HFC recycling and incineration) are typical examples. [Table 10.2, 10.7]

Systemic approaches and collaborative activities across companies (large energy-intensive industries and Small and Medium Enterprises (SMEs)) and sectors can help to reduce GHG emissions (*robust evidence, high agreement*). Cross-cutting technologies such as efficient motors, and cross-cutting measures such as reducing air or steam leaks, help to optimize performance of industrial processes and improve plant efficiency very often cost-effectively with both energy savings and emissions benefits. Industrial clusters also help to realize mitigation, particularly from SMEs. [10.4] Cooperation and cross-sectoral collaboration at different levels—for example, sharing of infrastructure, information, waste heat, cooling, etc.—may provide further mitigation potential in certain regions/industry types [10.5].

Several emission-reducing options in the industrial sector are cost-effective and profitable (*medium evidence, medium agreement*). While options in cost ranges of 0–20 and 20–50 USD/tCO_2eq and even below 0 USD/tCO_2eq exist, achieving near-zero emissions intensity levels in the industry sector would require the additional realization of long-term step-change options (e.g., CCS), which are associated with higher levelized costs of conserved carbon (LCCC) in the range of 50–150 USD/tCO_2eq. Similar cost estimates for implementing material efficiency, product-service efficiency, and service demand reduction strategies are not available. With regard to long-term options, some sector-specific measures allow for significant reductions in specific GHG emissions but may not be applicable at scale, e.g., scrap-based iron and steel production. Decarbonized electricity can play an important role in some subsectors (e.g., chemicals, pulp and paper, and aluminium), but will have limited impact in others (e.g., cement, iron and steel, waste). In general, mitigation costs vary regionally and depend on site-specific conditions. (Figures TS.27, TS.28, TS.29) [10.7]

Mitigation measures are often associated with co-benefits (*robust evidence, high agreement*). Co-benefits include enhanced competitiveness through cost-reductions, new business opportunities, better environmental compliance, health benefits through better local air and water quality and better work conditions, and reduced waste, all of which provide multiple indirect private and social benefits (Table TS.7). [10.8]

There is no single policy that can address the full range of mitigation measures available for industry and overcome associated barriers. Unless barriers to mitigation in industry are resolved, the pace and extent of mitigation in industry will be limited and even profitable measures will remain untapped (*robust evidence, high agreement*). [10.9, 10.11]

Table TS.7 | Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the industry sector; arrows pointing up/down denote a positive/negative effect on the respective objective or concern. Co-benefits and adverse side-effects depend on local circumstances as well as on the implementation practice, pace and scale. For possible upstream effects of low-carbon energy supply (includes CCS), see Table TS.4. For possible upstream effects of biomass supply, see Table TS.8. For an assessment of macroeconomic, cross-sectoral, effects associated with mitigation policies (e. g., on energy prices, consumption, growth, and trade), see e. g., Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. The uncertainty qualifiers in brackets denote the level of evidence and agreement on the respective effects (see TS.1). Abbreviations for evidence: l = limited, m = medium, r = robust; for agreement: l = low, m = medium, h = high. [Table 10.5]

Industry	Effect on additional objectives/concerns		
	Economic	**Social**	**Environmental**
CO_2 and non-CO_2 GHG emissions intensity reduction	↑ Competitiveness and productivity **(m/h)**	↓ Health impact via reduced local air pollution and better work conditions (for perfluorocarbons from aluminium) **(m/m)**	↓ Ecosystem impact via reduced local air pollution and reduced water pollution **(m/m)** ↑ Water conservation **(l/m)**
Technical energy efficiency improvements via new processes and technologies	↑ Energy security (via lower energy intensity) **(m/m)** ↑ Employment impact **(l/l)** ↑ Competitiveness and productivity **(m/h)** ↑ Technological spillovers in developing countries (due to supply chain linkages) **(l/l)**	↓ Health impact via reduced local pollution **(l/m)** ↑ New business opportunities **(m/m)** ↑ Water availability and quality **(l/l)** ↑ Safety, working conditions and job satisfaction **(m/m)**	Ecosystem impact via: ↓ Fossil fuel extraction **(l/l)** ↓ Local pollution and waste **(m/m)**
Material efficiency of goods, recycling	↓ National sales tax revenue in medium term **(l/l)** ↑ Employment impact in waste recycling market **(l/l)** ↑ Competitiveness in manufacturing **(l/l)** ↑ New infrastructure for industrial clusters **(l/l)**	↓ Health impacts and safety concerns **(l/m)** ↑ New business opportunities **(m/m)** ↓ Local conflicts (reduced resource extraction) **(l/m)**	↓ Ecosystem impact via reduced local air and water pollution and waste material disposal **(m/m)** ↓ Use of raw/virgin materials and natural resources implying reduced unsustainable resource mining **(l/l)**
Product demand reductions	↓ National sales tax revenue in medium term **(l/l)**	↑ Wellbeing via diverse lifestyle choices **(l/l)**	↓ Post-consumption waste **(l/l)**

TS.3.2.6 Agriculture, Forestry and Other Land Use (AFOLU)

Since AR4, GHG emissions from the AFOLU sector have stabilized but the share of total anthropogenic GHG emissions has decreased (*robust evidence, high agreement*). The average annual total GHG flux from the AFOLU sector was 10–12 $GtCO_2eq$ in 2000–2010, with global emissions of 5.0–5.8 $GtCO_2eq/yr$ from agriculture on average and around 4.3–5.5 $GtCO_2eq/yr$ from forestry and other land uses. Non-CO_2 emissions derive largely from agriculture, dominated by N_2O emissions from agricultural soils and CH_4 emissions from livestock enteric fermentation, manure management, and emissions from rice paddies, totalling 5.0–5.8 $GtCO_2eq/yr$ in 2010 (*robust evidence, high agreement*). Over recent years, most estimates of FOLU CO_2 fluxes indicate a decline in emissions, largely due to decreasing deforestation rates and increased afforestation (*limited evidence, medium agreement*). The absolute levels of emissions from deforestation and degradation have fallen from 1990 to 2010 (*robust evidence, high agreement*). Over the same time period, total emissions for high-income countries decreased while those of low-income countries increased. In general, AFOLU emissions from high-income countries are dominated by agriculture activities while those from low-income countries are dominated by deforestation and degradation. [Figure 1.3, 11.2]

Net annual baseline CO_2 emissions from AFOLU are projected to decline over time with net emissions potentially less than half of the 2010 level by 2050, and the possibility of the AFOLU sector becoming a net sink before the end of century. However, the uncertainty in historical net AFOLU emissions is larger than for other sectors, and additional uncertainties in projected baseline net AFOLU emissions exist. (*medium evidence, high agreement*) (Figure TS.15) [6.3.1.4, 6.8, Figure 6.5] As in AR4, most projections suggest declining annual net CO_2 emissions in the long run. In part, this is driven by technological change, as well as projected declining rates of agriculture area expansion related to the expected slowing in population growth. However, unlike AR4, none of the more recent scenarios projects growth in the near-term. There is also a somewhat larger range of variation later in the century, with some models projecting a stronger net sink starting in 2050 (*limited evidence, medium agreement*). There are few reported projections of baseline global land-related N_2O and CH_4 emissions and they indicate an increase over time. Cumulatively, land CH_4 emissions are projected to be 44–53 % of total CH_4 emissions through 2030, and 41–59 % through 2100, and land N_2O emissions 85–89 % and 85–90 %, respectively (*limited evidence, medium agreement*). [11.9]

Opportunities for mitigation in the AFOLU sector include supply- and demand-side mitigation options (*robust evidence, high agreement*). Supply-side measures involve reducing emissions arising from land-use change, in particular reducing deforestation, and land and livestock management, increasing carbon stocks by sequestration in soils and biomass, or the substitution of fossil fuels by biomass for energy production (Table TS.3). Further new supply-side technologies not assessed in AR4, such as biochar or wood products for energy-intensive building materials, could contribute to the mitigation potential of the AFOLU sector, but there are still few studies upon which to make robust estimates. Demand-side measures include dietary change and waste reduction in the food supply chain. Increasing forestry and agricultural production without a commensurate increase in emissions (i.e., one component of sustainable intensification; Figure TS.30) also reduces emissions intensity (i.e., the GHG emissions per unit of product), a mitigation mechanism largely unreported for AFOLU in AR4, which could reduce absolute emissions as long as production volumes do not increase. [11.3, 11.4]

Among supply-side measures, the most cost-effective forestry options are afforestation, sustainable forest management and reducing deforestation, with large differences in their relative importance across regions; in agriculture, low carbon prices[16] (20 USD/tCO_2eq) favour cropland and grazing land management and high carbon prices (100 USD/tCO_2eq) favour restoration of organic soils (*medium evidence, medium agreement*). When considering only studies that cover both forestry and agriculture and include agricultural soil carbon sequestration, the economic mitigation potential in the AFOLU sector is estimated to be 7.18 to 10.6 (full range of all studies: 0.49–10.6) GtCO_2eq/yr in 2030 for mitigation efforts consistent with carbon prices up to 100 USD/ tCO_2eq, about a third of which can be achieved at < 20 USD/ tCO_2eq (*medium evidence, medium agreement*). The range of global estimates at a given carbon price partly reflects uncertainty surrounding AFOLU mitigation potentials in the literature and the land-use assumptions of the scenarios considered. The ranges of estimates also reflect differences in the GHGs and options considered in the studies. A comparison of estimates of economic mitigation potential in the AFOLU sector published since AR4 is shown in Figure TS.31. [11.6]

[16] In many models that are used to assess the economic costs of mitigation, carbon price is used as a proxy to represent the level of effort in mitigation policies (see Glossary).

While demand-side measures are under-researched, changes in diet, reductions of losses in the food supply chain, and other measures have a significant, but uncertain, potential to reduce GHG emissions from food production (0.76–8.55 GtCO_2eq/yr by 2050) (Figure TS.31) (*limited evidence, medium agreement*). Barriers to implementation are substantial, and include concerns about jeopardizing health and well-being, and cultural and societal resistance to behavioural change. However, in countries with a high consumption of animal protein, co-benefits are reflected in positive health impacts resulting from changes in diet (*robust evidence, high agreement*). [11.4.3, 11.6, 11.7, 11.9]

The mitigation potential of AFOLU is highly dependent on broader factors related to land-use policy and patterns (*medium evidence, high agreement*). The many possible uses of land can compete or work in synergy. The main barriers to mitigation are institutional (lack of tenure and poor governance), accessibility to financing mechanisms, availability of land and water, and poverty. On the other hand, AFOLU mitigation options can promote innovation, and many technological supply-side mitigation options also increase agricultural and silvicultural efficiency, and can reduce climate vulnerability by improving resilience. Multifunctional systems that allow the delivery of multiple services from land have the capacity to deliver to many policy goals in addition to mitigation, such as improving land tenure, the governance of natural resources, and equity [11.8] (*limited evidence, high agreement*). Recent frameworks, such as those for assessing environmental or ecosystem services, could provide tools for valuing the multiple synergies and tradeoffs that may arise from mitigation actions (Table TS.8) (*medium evidence, medium agreement*). [11.7, 11.8]

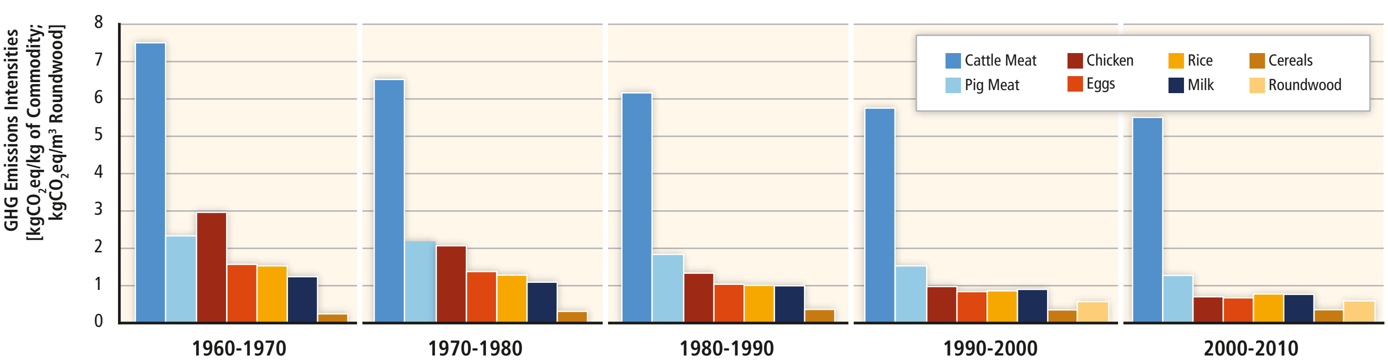


Figure TS.30 | GHG emissions intensities of selected major AFOLU commodities for decades 1960s–2000s. (1) Cattle meat, defined as GHG (enteric fermentation + manure management of cattle, dairy and non-dairy)/meat produced; (2) pig meat, defined as GHG (enteric fermentation + manure management of swine, market and breeding)/meat produced; (3) chicken meat, defined as GHG (manure management of chickens)/meat produced; (4) milk, defined as GHG (enteric fermentation + manure management of cattle, dairy)/milk produced; (5) eggs, defined as GHG (manure management of chickens, layers)/egg produced; (6) rice, defined as GHG (rice cultivation)/rice produced; (7) cereals, defined as GHG (synthetic fertilizers)/cereals produced; (8) wood, defined as GHG (carbon loss from harvest)/roundwood produced. [Figure 11.15]

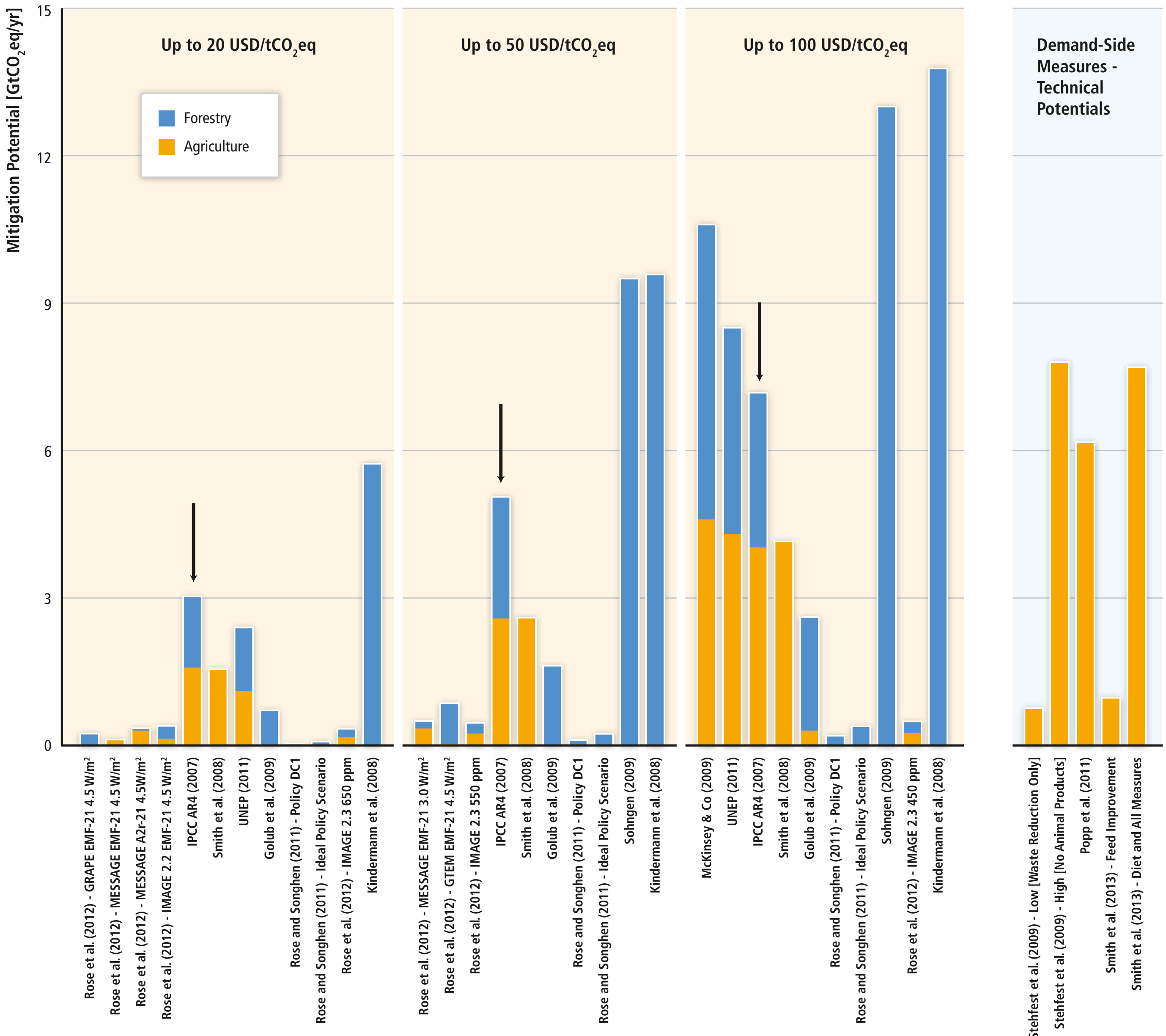


Figure TS.31 | Estimates of economic mitigation potentials in the AFOLU sector published since AR4 (AR4 estimates shown for comparison, denoted by black arrows), including bottom-up, sectoral studies, and top-down, multi-sector studies. Supply-side mitigation potentials are estimated for around 2030, ranging from 2025 to 2035, and are for agriculture, forestry or both sectors combined. Studies are aggregated for potentials up to ~20 USD/tCO_2eq (actual range 1.64–21.45), up to ~50 USD/tCO_2eq (actual range 31.39–50.00), and up to ~100 USD/tCO_2eq (actual range 70.0–120.91). Demand-side measures (shown on the right hand side of the figure) are for ~2050 and are not assessed at a specific carbon price, and should be regarded as technical potentials. Smith et al. (2013) values are the mean of the range. Not all studies consider the same measures or the same GHGs. [11.6.2, Figure 11.14]

Policies governing practices in agriculture as well as forest conservation and management need to account for the needs of both mitigation and adaptation (*medium evidence, high agreement*). Some mitigation options in the AFOLU sector (such as soil and forest carbon stocks) may be vulnerable to climate change. Economic incentives (e.g., special credit lines for low-carbon agriculture, sustainable agriculture and forestry practices, tradable credits, payment for ecosystem services) and regulatory approaches (e.g., enforcement of environmental law to protect forest carbon stocks by reducing deforestation, set-aside policies, air and water pollution control reducing nitrate load and N_2O emissions) have been effective in different cases. Investments in research, development, and diffusion (e.g., increase of resource use-efficiency (fertilizers), livestock improvement, better forestry management practices) could result in synergies between adaptation and mitigation. Successful cases of deforestation reduction in different regions are found to combine different policies such as land planning, regulatory approaches and economic incentives (*limited evidence, high agreement*). [11.3.2, 11.10, 15.11]

Table TS.8 | Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the AFOLU sector; arrows pointing up/down denote a positive/negative effect on the respective objective or concern. These effects depend on the specific context (including bio-physic, institutional and socio-economic aspects) as well as on the scale of implementation. For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see e.g., Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. The uncertainty qualifiers in brackets denote the level of evidence and agreement on the respective effects (see TS.1). Abbreviations for evidence: l = limited, m = medium, r = robust; for agreement: l = low, m = medium, h = high. [Tables 11.9 and 11.12]

AFOLU	Effect on additional objectives/concerns			
	Economic	Social	Environmental	Institutional
Supply side: Forestry, land-based agriculture, livestock, integrated systems, and bioenergy (**marked by ***) **Demand side:** Reduced losses in the food supply chain, changes in human diets, changes in demand for wood and forestry products	* Employment impact via ↑ Entrepreneurship development (**m/h**) ↓ Use of less labour-intensive technologies in agriculture (**m/m**) ↑* Diversification of income sources and access to markets (**r/h**) ↑* Additional income to (sustainable) landscape management (**m/h**) ↑* Income concentration (**m/m**) ↑* Energy security (resource sufficiency) (**m/h**) ↑ Innovative financing mechanisms for sustainable resource management (**m/h**) ↑ Technology innovation and transfer (**m/m**)	↑* Food-crops production through integrated systems and sustainable agriculture intensification (**r/m**) ↓* Food production (locally) due to large-scale monocultures of non-food crops (**r/l**) ↑ Cultural habitats and recreational areas via (sustainable) forest management and conservation (**m/m**) ↑* Human health and animal welfare e.g., through less pesticides, reduced burning practices, and practices like agroforestry and silvo-pastoral systems (**m/h**) ↓* Human health when using burning practices (in agriculture or bioenergy) (**m/m**) * Gender, intra- and inter-generational equity via ↑ Participation and fair benefit sharing (**r/h**) ↑ Concentration of benefits (**m/m**)	Provision of ecosystem services via ↑ Ecosystem conservation and sustainable management as well as sustainable agriculture (**r/h**) ↓* Large scale monocultures (**r/h**) ↑* Land-use competition (**r/m**) ↑ Soil quality (**r/h**) ↓ Erosion (**r/h**) ↑ Ecosystem resilience (**m/h**) ↑ Albedo and evaporation (**r/h**)	↑↓* Tenure and use rights at the local level (for indigenous people and local communities) especially when implementing activities in natural forests (**r/h**) ↑↓ Access to participative mechanisms for land management decisions (**r/h**) ↑ Enforcement of existing policies for sustainable resource management (**r/h**)

Reducing Emissions from Deforestation and Forest Degradation (REDD+)[17] can be a very cost-effective policy option for mitigating climate change, if implemented in a sustainable manner (*limited evidence, medium agreement*). REDD+ includes: reducing emissions from deforestation and forest degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks. It could supply a large share of global abatement of emissions from the AFOLU sector, especially through reducing deforestation in tropical regions, with potential economic, social and other environmental co-benefits. To assure these co-benefits, the implementation of national REDD+ strategies would need to consider financing mechanisms to local stakeholders, safeguards (such as land rights, conservation of biodiversity and other natural resources), and the appropriate scale and institutional capacity for monitoring and verification. [11.10]

Bioenergy can play a critical role for mitigation, but there are issues to consider, such as the sustainability of practices and the efficiency of bioenergy systems (*robust evidence, medium agreement*) [11.4.4, Box 11.5, 11.13.6, 11.13.7]. Barriers to large-scale deployment of bioenergy include concerns about GHG emissions from land, food security, water resources, biodiversity conservation and livelihoods. The scientific debate about the overall climate impact related to land-use competition effects of specific bioenergy pathways remains unresolved (*robust evidence, high agreement*). [11.4.4, 11.13] Bioenergy technologies are diverse and span a wide range of options and technology pathways. Evidence suggests that options with low lifecycle emissions (e.g., sugar cane, Miscanthus, fast growing tree species, and sustainable use of biomass residues), some already available, can reduce GHG emissions; outcomes are site-specific and rely on efficient integrated 'biomass-to-bioenergy systems', and sustainable land-use management and governance. In some regions, specific bioenergy options, such as improved cookstoves, and small-scale biogas and biopower production, could reduce GHG emissions and improve livelihoods and health in the context of sustainable development (*medium evidence, medium agreement*). [11.13]

[17] UN Programme on Reducing Emissions from Deforestation and Forest Degradation in developing countries, including conservation, sustainable management of forests and enhancement of forest carbon stocks.

TS.3.2.7 Human settlements, infrastructure, and spatial planning

Urbanization is a global trend transforming human settlements, societies, and energy use (*robust evidence, high agreement*). In 1900, when the global population was 1.6 billion, only 13 % of the population, or some 200 million, lived in urban areas. As of 2011, more than 52 % of the world's population—roughly 3.6 billion—lives in urban areas. By 2050, the urban population is expected to increase to 5.6–7.1 billion, or 64–69 % of the world population. [12.2]

Urban areas account for more than half of global primary energy use and energy-related CO_2 emissions (*medium evidence, high agreement*). The exact share of urban energy and GHG emissions varies with emission accounting frameworks and definitions. Taking account of direct and indirect emissions, urban areas account for 67–76 % of global energy use (central estimate) and 71–76 % of global energy-related CO_2 emissions. Taking account of direct emissions only, the urban share of emissions is 44 % (Figure TS.32). [12.2, 12.3]

No single factor explains variations in per-capita emissions across cities, and there are significant differences in per capita GHG emissions between cities within a single country (*robust evidence, high agreement*). Urban GHG emissions are influenced by a variety of physical, economic and social factors, development levels, and urbanization histories specific to each city. Key influences on urban GHG emissions include income, population dynamics, urban form, locational factors, economic structure, and market failures. Per capita final energy use and CO_2 emissions in cities of Annex I countries tend to be lower than national averages, in cities of non-Annex I countries they tend to be higher. [12.3]

The majority of infrastructure and urban areas have yet to be built (*limited evidence, high agreement*). Accounting for trends in declining population densities, and continued economic and population growth, urban land cover is projected to expand by 56–310 % between 2000 and 2030. If the global population increases to 9.3 billion by 2050 and developing countries expand their built environment and infrastructure to current global average levels using available technology of today, the production of infrastructure materials alone would generate about 470 $GtCO_2$ emissions. Currently, average per capita CO_2 emissions embodied in the infrastructure of industrialized countries is five times larger than those in developing countries. [12.2, 12.3]

Infrastructure and urban form are strongly interlinked, and lock in patterns of land use, transport choice, housing, and behaviour (*medium evidence, high agreement*). Urban form and infrastructure shape long-term land-use management, influence individual transport choice, housing, and behaviour, and affect the system-wide efficiency of a city. Once in place, urban form and infrastructure are difficult to change (Figure TS.33). [12.2, 12.3, 12.4]

Mitigation options in urban areas vary by urbanization trajectories and are expected to be most effective when policy instruments are bundled (*robust evidence, high agreement*). For rapidly developing cities, options include shaping their urbanization and infrastructure development towards more sustainable and low-carbon pathways. In mature or established cities, options are constrained by existing urban forms and infrastructure and the potential for refurbishing existing systems and infrastructures. Key mitigation strategies include co-locating high residential with high employment densities,

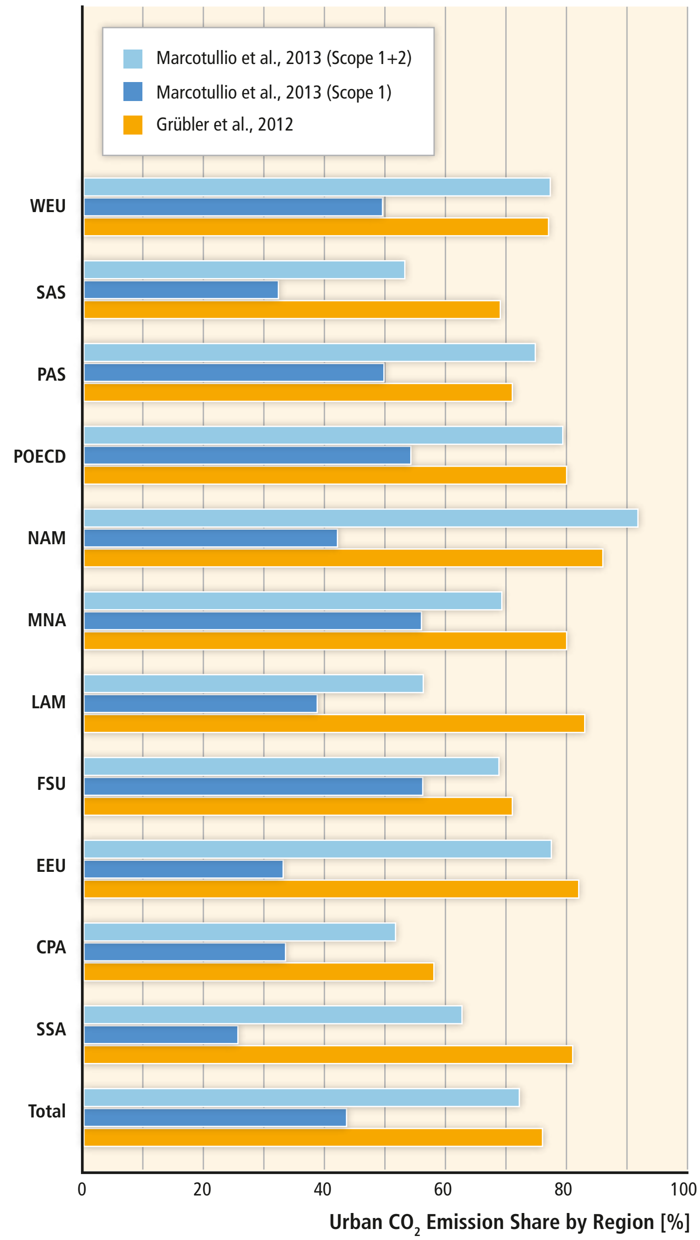


Figure TS.32 | Estimated shares of direct (Scope 1) and indirect urban CO_2 emissions in total emissions across world regions ($GtCO_2$). Indirect emissions (Scope 2) allocate emissions from thermal power plants to urban areas. CPA: Centrally Planned Asia and China; EEU: Central and Eastern Europe; FSU: Former Soviet Union; LAM: Latin America and Caribbean; MNA: Middle East and North Africa; NAM: North America; PAS: South-East Asia and Pacific; POECD: Pacific OECD; SAS: South Asia; SSA: Sub Saharan Africa; WEU: Western Europe. [12.2.2, Figure 12.4]

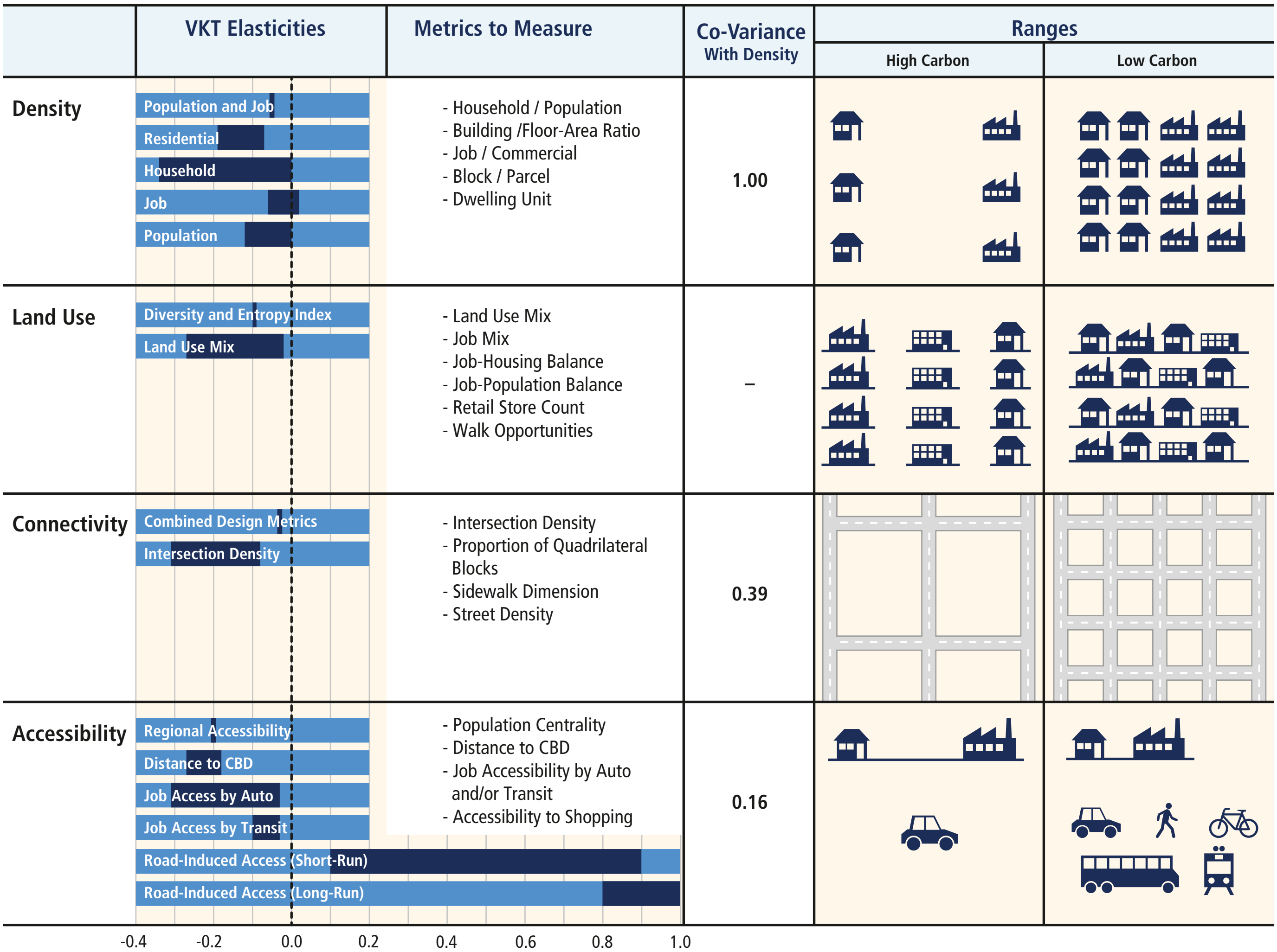


Figure TS.33 | Four key aspects of urban form and structure (density, land-use mix, connectivity, and accessibility), their vehicle kilometers travelled (VKT) elasticities, commonly used metrics, and stylized graphics. The dark blue row segments under the VKT elasticities column provide the range of elasticities for the studies included. CBD: Central business district. [Figure 12.14]

achieving high diversity and integration of land uses, increasing accessibility and investing in public transit and other supportive demand-management measures (Figure TS.33). Bundling these strategies can reduce emissions in the short term and generate even higher emissions savings in the long term. [12.4, 12.5]

The largest opportunities for future urban GHG emissions reduction might be in rapidly urbanizing countries where urban form and infrastructure are not locked-in but where there are often limited governance, technical, financial, and institutional capacities (*robust evidence, high agreement*). The bulk of future infrastructure and urban growth is expected in small- to medium-size cities in developing countries, where these capacities can be limited or weak. [12.4, 12.5, 12.6, 12.7]

Thousands of cities are undertaking climate action plans, but their aggregate impact on urban emissions is uncertain (*robust evidence, high agreement*). Local governments and institutions possess unique opportunities to engage in urban mitigation activities and local mitigation efforts have expanded rapidly. However, little systematic assessment exists regarding the overall extent to which cities are implementing mitigation policies and emissions reduction targets are being achieved, or emissions reduced. Climate action plans include a range of measures across sectors, largely focused on energy efficiency rather than broader land-use planning strategies and cross-sectoral measures to reduce sprawl and promote transit-oriented development (Figure TS.34). [12.6, 12.7, 12.9]

The feasibility of spatial planning instruments for climate change mitigation is highly dependent on a city's financial and governance capability (*robust evidence, high agreement*). Drivers of urban GHG emissions are interrelated and can be addressed by a number of regulatory, management, and market-based instruments. Many of these instruments are applicable to cities in both developed and developing countries, but the degree to which they can be implemented varies. In addition, each instrument varies in its potential to generate public revenues or require government expenditures, and the administrative scale at which it can be applied (Figure TS.35). A bun-

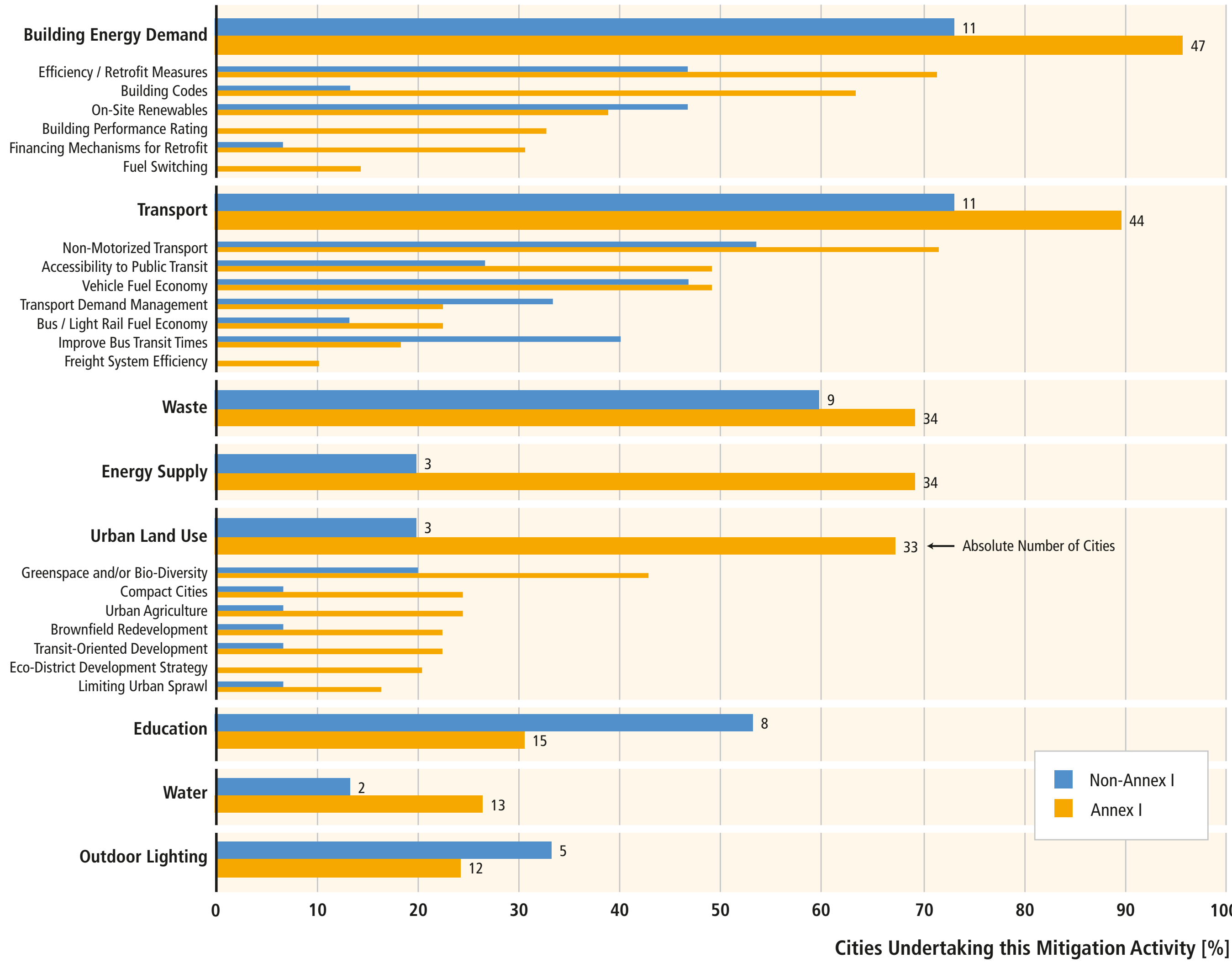


Figure TS.34 | Common mitigation measures in Climate Action Plans. [Figure 12.22]

dling of instruments and a high level of coordination across institutions can increase the likelihood of achieving emissions reductions and avoiding unintended outcomes. [12.6, 12.7]

For designing and implementing climate policies effectively, institutional arrangements, governance mechanisms, and financial resources should be aligned with the goals of reducing urban GHG emissions (*high confidence*). These goals will reflect the specific challenges facing individual cities and local governments. The following have been identified as key factors: (1) institutional arrangements that facilitate the integration of mitigation with other high-priority urban agendas; (2) a multilevel governance context that empowers cities to promote urban transformations; (3) spatial planning competencies and political will to support integrated land-use and transportation planning; and (4) sufficient financial flows and incentives to adequately support mitigation strategies. [12.6, 12.7]

Successful implementation of urban climate change mitigation strategies can provide co-benefits (*robust evidence, high agreement*). Urban areas throughout the world continue to struggle with challenges, including ensuring access to energy, limiting air and water pollution, and maintaining employment opportunities and competitiveness. Action on urban-scale mitigation often depends on the ability to relate climate change mitigation efforts to local co-benefits. The co-benefits of local climate change mitigation can include public savings, air quality and associated health benefits, and productivity increases in urban centres, providing additional motivation for undertaking mitigation activities. [12.5, 12.6, 12.7, 12.8]

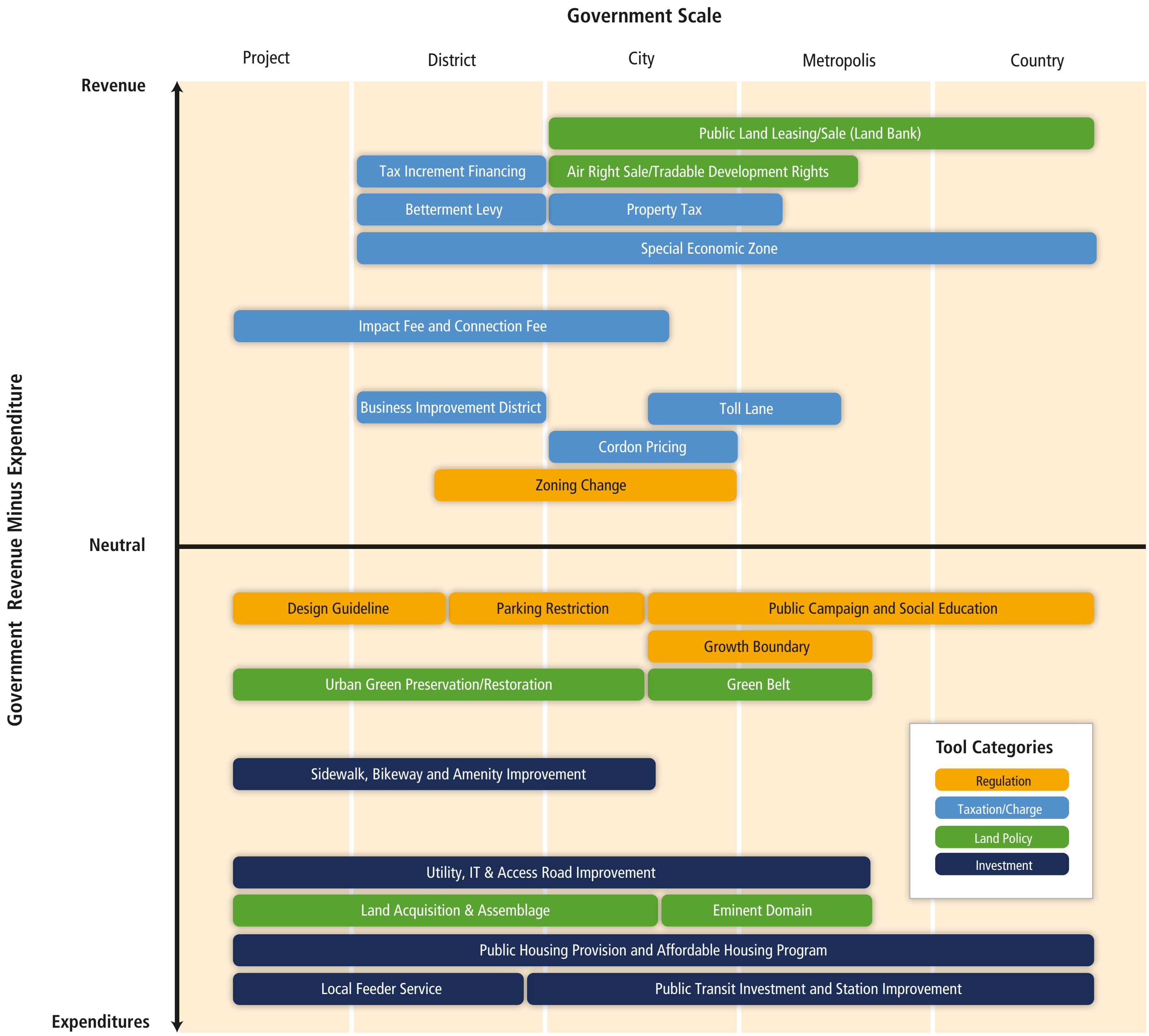


Figure TS.35 | Key spatial planning tools and effects on government revenues and expenditures across administrative scales. Figure shows four key spatial planning tools (coded in colours) and the scale of governance at which they are administered (x-axis) as well as how much public revenue or expenditure the government generates by implementing each instrument (y-axis). [Figure 12.20]

TS.4 Mitigation policies and institutions

The previous section shows that since AR4 the scholarship on mitigation pathways has begun to consider in much more detail how a variety of real-world considerations—such as institutional and political constraints, uncertainty associated with climate change risks, the availability of technologies and other factors—affect the kinds of policies and measures that are adopted. Those factors have important implications for the design, cost, and effectiveness of mitigation action. This section focuses on how governments and other actors in the private and public sectors design, implement, and evaluate mitigation policies. It considers the 'normative' scientific research on how policies should be designed to meet particular criteria. It also considers research on how policies are actually designed and implemented a field known as 'positive' analysis. The discussion first characterizes fundamental conceptual issues, and then presents a summary of the main findings from WGIII AR5 on local, national, and sectoral policies. Much of the practical policy effort since AR4 has occurred in these contexts. From there the summary looks at ever-higher levels of aggregation, ultimately ending at the global level and cross-cutting investment and finance issues.

TS.4.1 Policy design, behaviour and political economy

There are multiple criteria for evaluating policies. Policies are frequently assessed according to four criteria [3.7.1, 13.2.2, 15.4.1]:

- Environmental effectiveness—whether policies achieve intended goals in reducing emissions or other pressures on the environment or in improving measured environmental quality.
- Economic effectiveness—the impact of policies on the overall economy. This criterion includes the concept of economic efficiency, the principle of maximizing net economic benefits. Economic welfare also includes the concept of cost-effectiveness, the principle of attaining a given level of environmental performance at lowest aggregate cost.
- Distributional and social impacts—also known as 'distributional equity,' this criterion concerns the allocation of costs and benefits of policies to different groups and sectors within and across economies over time. It includes, often, a special focus on impacts on the least well-off members of societies within countries and around the world.
- Institutional and political feasibility—whether policies can be implemented in light of available institutional capacity, the political constraints that governments face, and other factors that are essential to making a policy viable.

All criteria can be applied with regard to the immediate 'static' impacts of policies and from a long-run 'dynamic' perspective that accounts for the many adjustments in the economic, social and political systems. Criteria may be mutually reinforcing, but there may also be conflicts or tradeoffs among them. Policies designed for maximum environmental effectiveness or economic performance may fare less well on other criteria, for example. Such tradeoffs arise at multiple levels of governing systems. For example, it may be necessary to design international agreements with flexibility so that it is feasible for a large number of diverse countries to accept them, but excessive flexibility may undermine incentives to invest in cost-effective long-term solutions.

Policymakers make use of many different policy instruments at the same time. Theory can provide some guidance on the normative advantages and disadvantages of alternative policy instruments in light of the criteria discussed above. The range of different policy instruments includes [3.8, 15.3]:

- Economic incentives, such as taxes, tradable allowances, fines, and subsidies
- Direct regulatory approaches, such as technology or performance standards
- Information programmes, such as labelling and energy audits
- Government provision, for example of new technologies or in state enterprises
- Voluntary actions, initiated by governments, firms, and non-governmental organizations (NGOs)

Since AR4, the inventory of research on these different instruments has grown, mostly with reference to experiences with policies adopted within particular sectors and countries as well as the many interactions between policies. One implication of that research has been that international agreements that aim to coordinate across countries reflect the practicalities on the particular policy choices of national governments and other jurisdictions.

The diversity in policy goals and instruments highlights differences in how sectors and countries are organized economically and politically as well as the multi-level nature of mitigation. Since AR4, one theme of research in this area has been that the success of mitigation measures depends in part on the presence of institutions capable of designing and implementing regulatory policies and the willingness of respective publics to accept these policies. Many policies have effects, sometimes unanticipated, across multiple jurisdictions—across cities, regions and countries—because the economic effects of policies and the technological options are not contained within a single jurisdiction. [13.2.2.3, 14.1.3, 15.2, 15.9]

Interactions between policy instruments can be welfare-enhancing or welfare-degrading. The chances of welfare-enhancing interactions are particularly high when policy instruments address multiple different market failures—for example, a subsidy or other policy instrument aimed at boosting investment in R&D on less emission-intensive technologies can complement policies aimed at controlling emissions, as can regulatory intervention to support efficient improvement of end-use energy efficiency. By contrast, welfare-degrading interactions are particularly likely when policies are designed to achieve identical goals. Narrowly targeted policies such as support for deployment (rather than R&D) of particular energy technologies that exist in tandem with broader economy-wide policies aimed at reducing emissions (for example, a cap-and-trade emissions scheme) can have the effect of shifting the mitigation effort to particular sectors of the economy in ways that typically result in higher overall costs. [3.8.6, 15.7, 15.8]

There are a growing number of countries devising policies for adaptation, as well as mitigation, and there may be benefits to considering the two within a common policy framework (*medium evidence, low agreement*). However, there are divergent views on whether adding adaptation to mitigation measures in the policy portfolio encourages or discourages participation in international cooperation [1.4.5, 13.3.3]. It is recognized that an integrated approach can be valuable, as there exist both synergies and tradeoffs [16.6].

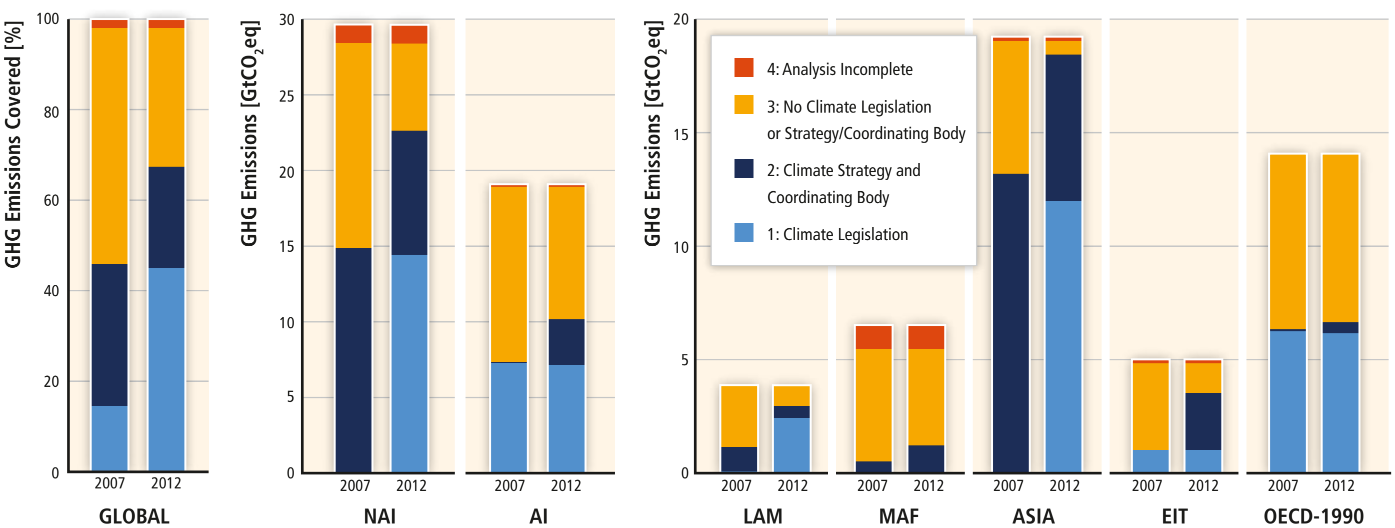
Traditionally, policy design, implementation, and evaluation has focused on governments as central designers and implementers of policies, but new studies have emerged on government acting in a coordinating role (*medium confidence*). In these cases, governments themselves seek to advance voluntary approaches, especially when traditional forms of regulation are thought to be inadequate or the best choices of policy instruments and goals is not yet apparent. Examples include voluntary schemes that allow individuals and firms to purchase emission credits that offset the emissions associated with their own activities such as flying and driving. Since AR4, a substantial new literature has emerged to examine these schemes from positive and normative perspectives. [13.12, 15.5.7]

The successful implementation of policy depends on many factors associated with human and institutional behaviour (*very high confidence*). One of the challenges in designing effective instruments is that the activities that a policy is intended to affect—such as the choice of energy technologies and carriers and a wide array of agricultural and forestry practices—are also influenced by social norms, decision-making rules, behavioural biases, and institutional processes [2.4, 3.10]. There are examples of policy instruments made more effective by taking these factors into account, such as in the case of financing mechanisms for household investments in energy efficiency and renewable energy that eliminate the need for up-front investment [2.4, 2.6.5.3]. Additionally, the norms that guide acceptable practices could have profound impacts on the baselines against which policy interventions are evaluated, either magnifying or reducing the required level of policy intervention [1.2.4, 4.3, 6.5.2].

Climate policy can encourage investment that may otherwise be suboptimal because of market imperfections (*very high confidence*). Many of the options for energy efficiency as well as low-carbon energy provision require high up-front investment that is often magnified by high-risk premiums associated with investments in new technologies. The relevant risks include those associated with future market conditions, regulatory actions, public acceptance, and technology cost and performance. Dedicated financial instruments exist to lower these risks for private actors—for example, credit insurance, feed-in tariffs (FITs), concessional finance, or rebates [16.4]. The design of other mitigation policies can also incorporate elements to help reduce risks, such as a cap-and-trade regime that includes price floors and ceilings [2.6.5, 15.5, 15.6].

TS.4.2 Sectoral and national policies

There has been a considerable increase in national and sub-national mitigation plans and strategies since AR4 (Figure TS.36). These plans and strategies are in their early stages of development and implementation in many countries, making it difficult to assess whether and how they will result in appropriate institutional and policy change, and therefore, their impact on future GHG emissions. However, to date these policies, taken together, have not yet achieved a substantial deviation in GHG emissions from the past trend. Theories of institutional change suggest they might play a role in shaping incentives, political contexts, and policy paradigms in a way that encourages



	GLOBAL 2007	GLOBAL 2012	NAI 2007	NAI 2012	AI 2007	AI 2012
1	7 (15%)	22 (44%)	0 (0%)	14 (49%)	7 (38%)	7 (38%)
2	15 (30%)	11 (23%)	15 (50%)	8 (28%)	0 (0%)	3 (16%)
3	25 (52%)	15 (30%)	14 (46%)	6 (19%)	12 (61%)	9 (46%)
4	1 (3%)	1 (3%)	1 (4%)	1 (4%)	0 (1%)	0 (1%)

	LAM 2007	LAM 2012	MAF 2007	MAF 2012	ASIA 2007	ASIA 2012	EIT 2007	EIT 2012	OECD-1990 2007	OECD-1990 2012
1	0 (2%)	2 (63%)	0 (0%)	0 (0%)	0 (0%)	12 (62%)	1 (20%)	1 (20%)	6 (44%)	6 (44%)
2	1 (28%)	1 (13%)	1 (8%)	1 (19%)	13 (69%)	6 (34%)	0 (0%)	3 (50%)	0 (0%)	0 (3%)
3	3 (70%)	1 (23%)	5 (76%)	4 (65%)	6 (30%)	1 (3%)	4 (76%)	1 (26%)	8 (55%)	7 (53%)
4	0 (0%)	0 (0%)	1 (16%)	1 (16%)	0 (1%)	0 (1%)	0 (3%)	0 (3%)	0 (0%)	0 (0%)

Figure TS.36 | National climate legislation and strategies in 2007 and 2012. Regions include NAI (Non Annex I countries—developing countries), AI (Annex I countries—developed countries), LAM (Latin America), MAF (Middle East and Africa), ASIA (Asia), EIT (Economies in Transition), OECD-1990; see Annex II.2 for more details. In this figure, climate legislation is defined as mitigation-focused legislation that goes beyond sectoral action alone. Climate strategy is defined as a non-legislative plan or framework aimed at mitigation that encompasses more than a small number of sectors, and that includes a coordinating body charged with implementation. International pledges are not included, nor are sub-national plans and strategies. The panel shows proportion of GHG emissions covered. [Figure 15.1]

GHG emissions reductions in the future [15.1, 15.2]. However, many baseline scenarios (i.e., those without additional mitigation policies) show concentrations that exceed 1000 ppm CO_2eq by 2100, which is far from a concentration with a *likely* probability of maintaining temperature increases below 2 °C this century. Mitigation scenarios suggest that a wide range of environmentally effective policies could be enacted that would be consistent with such goals [6.3]. In practice, climate strategies and the policies that result are influenced by political economy factors, sectoral considerations, and the potential for realizing co-benefits. In many countries, mitigation policies have also been actively pursued at state and local levels. [15.2, 15.5, 15.8]

Since AR4, there is growing political and analytical attention to co-benefits and adverse side-effects of climate policy on other objectives and vice versa that has resulted in an increased focus on policies designed to integrate multiple objectives (*high confidence*). Co-benefits are often explicitly referenced in climate and sectoral plans and strategies and often enable enhanced political support [15.2]. However, the analytical and empirical underpinnings for many of these interactive effects, and particularly for the associated welfare impacts, are under-developed [1.2, 3.6.3, 4.2, 4.8, 6.6]. The scope for co-benefits is greater in low-income countries, where complementary policies for other objectives, such as air quality, are often weak [5.7, 6.6, 15.2].

The design of institutions affects the choice and feasibility of policy options as well as the sustainable financing of mitigation measures. Institutions designed to encourage participation by representatives of new industries and technologies can facilitate transitions to low-GHG emissions pathways [15.2, 15.6]. Policies vary in the extent to which they require new institutional capabilities to be implemented. Carbon taxation, in most settings, can rely mainly on existing tax infrastructure and is administratively easier to implement than many other alternatives such as cap-and-trade systems [15.5]. The extent of institutional innovation required for policies can be a factor in instrument choice, especially in developing countries.

Sector-specific policies have been more widely used than economy-wide, market-based policies (*medium evidence, high agreement*). Although economic theory suggests that market-based, economy-wide policies for the singular objective of mitigation would generally be more cost-effective than sector-specific policies, political economy considerations often make economy-wide policies harder to design and implement than sector-specific policies [15.2.3, 15.2.6, 15.5.1]. In some countries, emission trading and taxes have been enacted to address the market externalities associated with GHG emissions, and have contributed to the fulfilment of sector-specific GHG reduction goals (*medium evidence, medium agreement*) [7.12]. In the longer term, GHG pricing can support the adoption of low-GHG energy technologies. Even if economy-wide policies were implemented, sector-specific policies may be needed to overcome sectoral market failures. For example, building codes can require energy-efficient investments where private investments would otherwise not exist [9.10]. In transport, pricing policies that raise the cost of carbon-intensive forms of private transport are more effective when backed by public investment in viable alternatives [8.10]. Table TS.9 presents a range of sector-specific policies that have been implemented in practice. [15.1, 15.2, 15.5, 15.8, 15.9]

Carbon taxes have been implemented in some countries and—alongside technology and other policies—have contributed to decoupling of emissions from GDP (*high confidence*). Differentiation by sector, which is quite common, reduces cost-effectiveness that arises from the changes in production methods, consumption patterns, lifestyle shifts, and technology development, but it may increase political feasibility, or be preferred for reasons of competitiveness or distributional equity. In some countries, high carbon and fuel taxes have been made politically feasible by refunding revenues or by lowering other taxes in an environmental fiscal reform. Mitigation policies that raise government revenue (e.g., auctioned emission allowances under a cap-and-trade system or emission taxes) generally have lower social costs than approaches that do not, but this depends on how the revenue is used [3.6.3]. [15.2, 15.5.2, 15.5.3]

Fuel taxes are an example of a sector-specific policy and are often originally put in place for objectives such as revenue—they are not necessarily designed for the purpose of mitigation (*high confidence*). In Europe, where fuel taxes are highest, they have contributed to reductions in carbon emissions from the transport sector of roughly 50 % for this group of countries. The short-run response to higher fuel prices is often small, but long-run price elasticities are quite high, or roughly −0.6 to −0.8. This means that in the long run, 10 % higher fuel prices correlate with 7 % reduction in fuel use and emissions. In the transport sector, taxes have the advantage of being progressive or neutral in most countries and strongly progressive in low-income countries. [15.5.2]

Cap-and-trade systems for GHG emissions are being established in a growing number of countries and regions. Their environmental effect has so far been limited because caps have either been loose or have not yet been binding (*limited evidence, medium agreement*). There appears to have been a tradeoff between the political feasibility and environmental effectiveness of these programmes, as well as between political feasibility and distributional equity in the allocation of permits. Greater environmental effectiveness through a tighter cap may be combined with a price ceiling that improves political feasibility. [14.4.2, 15.5.3]

Different factors reduced the price of European Union Emissions Trading System (EU ETS) allowances below anticipated levels, thereby slowing investment in mitigation (*high confidence*). While the European Union demonstrated that a cross-border cap-and-trade system can work, the low price of EU ETS allowances in recent years provided insufficient incentives for significant additional investment in mitigation. The low price is related to unexpected depth and duration of the economic recession, uncertainty about the long-term reduction targets for GHG emissions, import of credits from the Clean Development Mechanism (CDM), and the interaction with other policy instruments,

Table TS.9 | Sector policy instruments. The table brings together evidence on mitigation policy instruments discussed in Chapters 7 to 12. [Table 15.2]

Policy Instruments	Energy [7.12]	Transport [8.10]	Buildings [9.10]	Industry [10.11]	AFOLU [11.10]	Human Settlements and Infrastructure
Economic Instruments—Taxes (Carbon taxes may be economy-wide)	• Carbon taxes	• Fuel taxes • Congestion charges, vehicle registration fees, road tolls • Vehicle taxes	• Carbon and/or energy taxes (either sectoral or economy wide)	• Carbon tax or energy tax • Waste disposal taxes or charges	• Fertilizer or Nitrogen taxes to reduce nitrous oxide	• Sprawl taxes, Impact fees, exactions, split-rate property taxes, tax increment finance, betterment taxes, congestion charges
Economic Instruments—Tradable Allowances (May be economy-wide)	• Emissions trading (e.g., EU ETS) • Emission credits under CDM • Tradable Green Certificates	• Fuel and vehicle standards	• Tradable certificates for energy efficiency improvements (white certificates)	• Emissions trading • Emission credit under CDM • Tradable Green Certificates	• Emission credits under the Kyoto Protocol's Clean Development Mechanism (CDM) • Compliance schemes outside Kyoto protocol (national schemes) • Voluntary carbon markets	• Urban-scale Cap and Trade
Economic Instruments—Subsidies	• Fossil fuel subsidy removal • Feed-in-tariffs for renewable energy • Capital subsidies and insurance for 1st generation Carbon Dioxide Capture and Storage (CCS)	• Biofuel subsidies • Vehicle purchase subsidies • Feebates	• Subsidies or Tax exemptions for investment in efficient buildings, retrofits and products • Subsidized loans	• Subsidies (e.g., for energy audits) • Fiscal incentives (e.g., for fuel switching)	• Credit lines for low carbon agriculture, sustainable forestry.	• Special Improvement or Redevelopment Districts
Regulatory Approaches	• Efficiency or environmental performance standards • Renewable Portfolio standards for renewable energy • Equitable access to electricity grid • Legal status of long term CO_2 storage	• Fuel economy performance standards • Fuel quality standards • GHG emission performance standards • Regulatory restrictions to encourage modal shifts (road to rail) • Restriction on use of vehicles in certain areas • Environmental capacity constraints on airports • Urban planning and zoning restrictions	• Building codes and standards • Equipment and appliance standards • Mandates for energy retailers to assist customers invest in energy efficiency	• Energy efficiency standards for equipment • Energy management systems (also voluntary) • Voluntary agreements (where bound by regulation) • Labelling and public procurement regulations	• National policies to support REDD+ including monitoring, reporting and verification • Forest law to reduce deforestation • Air and water pollution control GHG precursors • Land-use planning and governance	• Mixed use zoning • Development restrictions • Affordable housing mandates • Site access controls • Transfer development rights • Design codes • Building codes • Street codes • Design standards
Information Programmes		• Fuel labelling • Vehicle efficiency labelling	• Energy audits • Labelling programmes • Energy advice programmes	• Energy audits • Benchmarking • Brokerage for industrial cooperation	• Certification schemes for sustainable forest practices • Information policies to support REDD+ including monitoring, reporting and verification	
Government Provision of Public Goods or Services	• Research and development • Infrastructure expansion (district heating/cooling or common carrier)	• Investment in transit and human powered transport • Investment in alternative fuel infrastructure • Low emission vehicle procurement	• Public procurement of efficient buildings and appliances	• Training and education • Brokerage for industrial cooperation	• Protection of national, state, and local forests. • Investment in improvement and diffusion of innovative technologies in agriculture and forestry	• Provision of utility infrastructure such as electricity distribution, district heating/cooling and wastewater connections, etc. • Park improvements • Trail improvements • Urban rail
Voluntary Actions			• Labelling programmes for efficient buildings • Product eco-labelling	• Voluntary agreements on energy targets or adoption of energy management systems, or resource efficiency	• Promotion of sustainability by developing standards and educational campaigns	

particularly related to the expansion of renewable energy as well as regulation on energy efficiency. It has proven to be politically difficult to address this problem by removing GHG emission permits temporarily, tightening the cap, or providing a long-term mitigation goal. [14.4.2]

Adding a mitigation policy to another may not necessarily enhance mitigation. For instance, if a cap-and-trade system has a sufficiently stringent cap then other policies such as renewable subsidies have no further impact on total GHG emissions (although they may affect costs and possibly the viability of more stringent future targets). If the cap is loose relative to other policies, it becomes ineffective. This is an example of a negative interaction between policy instruments. Since other policies cannot be 'added on' to a cap-and-trade system, if it is to meet any particular target, a sufficiently low cap is necessary. A carbon tax, on the other hand, can have an additive environmental effect to policies such as subsidies to renewables. [15.7]

Reduction of subsidies to fossil energy can achieve significant emission reductions at negative social cost (*very high confidence*). Although political economy barriers are substantial, many countries have reformed their tax and budget systems to reduce fuel subsidies that actually accrue to the relatively wealthy, and utilized lump-sum cash transfers or other mechanisms that are more targeted to the poor. [15.5.3]

Direct regulatory approaches and information measures are widely used, and are often environmentally effective, though debate remains on the extent of their environmental impacts and cost-effectiveness (*medium confidence*). Examples of regulatory approaches include energy efficiency standards; examples of information programmes include labelling programmes that can help consumers make better-informed decisions. While such approaches often work at a net social benefit, the scientific literature is divided on whether such policies are implemented with negative private costs (see Box TS.12) to firms and individuals [3.9.3, 15.5.5, 15.5.6]. Since AR4 there has been continued investigation into the 'rebound' effects (see Box TS.13) that arise when higher efficiency leads to lower energy costs and greater consumption. There is general agreement that such rebound effects exist, but there is low agreement in the literature on the magnitude [3.9.5, 5.7.2, 15.5.4].

There is a distinct role for technology policy as a complement to other mitigation policies (*high confidence*). Properly implemented technology policies reduce the cost of achieving a given environmental target. Technology policy will be most effective when technology-push policies (e.g., publicly funded R&D) and demand-pull policies (e.g., governmental procurement programmes or performance regulations) are used in a complementary fashion. While technology-push and demand-pull policies are necessary, they are unlikely to be sufficient without complementary framework conditions. Managing social challenges of technology policy change may require innovations in policy and institutional design, including building integrated policies that make complementary use of market incentives, authority, and norms (*medium confidence*). Since AR4, a large number of countries and subnational jurisdictions have introduced support policies for renewable

Box TS.13 | The rebound effect can reduce energy savings from technological improvement

Technological improvements in energy efficiency (EE) have direct effects on energy consumption and thus GHG emissions, but can cause other changes in consumption, production, and prices that will, in turn, affect GHG emissions. These changes are generally called 'rebound' or 'takeback' because in most cases they reduce the net energy or emissions reduction associated with the efficiency improvement. The size of EE rebound is controversial, with some research papers suggesting little or no rebound and others concluding that it offsets most or all reductions from EE policies [3.9.5, 5.7.2].

Total EE rebound can be broken down into three distinct parts: substitution-effect, income-effect, and economy-wide effect [3.9.5]. In end-use consumption, substitution-effect rebound, or 'direct rebound' assumes that a consumer will make more use of a device if it becomes more energy efficient because it will be cheaper to use. Income-effect rebound or 'indirect rebound', arises if the improvement in EE makes the consumer wealthier and leads her to consume additional products that require energy. Economy-wide rebound refers to impacts beyond the behaviour of the entity benefiting directly from the EE improvement, such as the impact of EE on the price of energy.

Analogous rebound effects for EE improvements in production are substitution towards an input with improved energy efficiency, and substitution among products by consumers when an EE improvement changes the relative prices of goods, as well as an income effect when an EE improvement lowers production costs and creates greater wealth.

Rebound is sometimes confused with the concept of carbon leakage, which often describes the incentive for emissions-intensive economic activity to migrate away from a region that restricts GHGs (or other pollutants) towards areas with fewer or no restrictions on such emissions [5.4.1, 14.4]. Energy efficiency rebound can occur regardless of the geographic scope of the adopted policy. As with leakage, however, the potential for significant rebound illustrates the importance of considering the full equilibrium effects of a mitigation policy [3.9.5, 15.5.4].

energy such as feed-in tariffs and renewable portfolio standards. These have promoted substantial diffusion and innovation of new energy technologies such as wind turbines and photovoltaic panels, but have raised questions about their economic efficiency, and introduced challenges for grid and market integration. [2.6.5, 7.12, 15.6.5]

Worldwide investment in research in support of mitigation is small relative to overall public research spending (*medium confidence*). The effectiveness of research support will be greatest if it is increased slowly and steadily rather than dramatically or erratically. It is important that data collection for program evaluation is built into technology policy programmes, because there is limited empirical evidence on the relative effectiveness of different mechanisms for supporting the invention, innovation and diffusion of new technologies. [15.6.2, 15.6.5]

Government planning and provision can facilitate shifts to less energy- and GHG-intensive infrastructure and lifestyles (*high confidence*). This applies particularly when there are indivisibilities in the provision of infrastructure as in the energy sector [7.6] (e.g., for electricity transmission and distribution or district heating networks); in the transport sector [8.4] (e.g., for non-motorized or public transport); and in urban planning [12.5]. The provision of adequate infrastructure is important for behavioural change [15.5.6].

Successful voluntary agreements on mitigation between governments and industries are characterized by a strong institutional framework with capable industrial associations (*medium confidence*). The strengths of voluntary agreements are speed and flexibility in phasing measures, and facilitation of barrier removal activities for energy efficiency and low-emission technologies. Regulatory threats, even though the threats are not always explicit, are also an important factor for firms to be motivated. There are few environmental impacts without a proper institutional framework. [15.5.7]

TS.4.3 Development and regional cooperation

Regional cooperation offers substantial opportunities for mitigation due to geographic proximity, shared infrastructure and policy frameworks, trade, and cross-border investment that would be difficult for countries to implement in isolation (*high confidence*). Examples of possible regional cooperation policies include regionally-linked development of renewable energy power pools, networks of natural gas supply infrastructure, and coordinated policies on forestry. [14.1]

At the same time, there is a mismatch between opportunities and capacities to undertake mitigation (*medium confidence*). The regions with the greatest potential to leapfrog to low-carbon development trajectories are the poorest developing regions where there are few lock-in effects in terms of modern energy systems and urbanization patterns. However, these regions also have the lowest financial, technological, and institutional capacities to embark on such low-carbon development paths (Figure TS.37) and their cost of waiting is high due to unmet energy and development needs. Emerging economies already have more lock-in effects but their rapid build-up of modern energy systems and urban settlements still offers substantial opportunities for low-carbon development. Their capacity to reorient themselves to low-carbon development strategies is higher, but also faces constraints in terms of finance, technology, and the high cost of delaying the installation of new energy capacity. Lastly, industrialized economies have the largest lock-in effects, but the highest capacities to reorient their energy, transport, and urbanizations systems towards low-carbon development. [14.1.3, 14.3.2]

Regional cooperation has, to date, only had a limited (positive) impact on mitigation (*medium evidence, high agreement*). Nonetheless, regional cooperation could play an enhanced role in promoting mitigation in the future, particularly if it explicitly incorporates mitigation objectives in trade, infrastructure and energy policies and promotes direct mitigation action at the regional level. [14.4.2, 14.5]

Most literature suggests that climate-specific regional cooperation agreements in areas of policy have not played an important role in addressing mitigation challenges to date (*medium confidence*). This is largely related to the low level of regional integration and associated willingness to transfer sovereignty to supra-national regional bodies to enforce binding agreements on mitigation. [14.4.2, 14.4.3]

Climate-specific regional cooperation using binding regulation-based approaches in areas of deep integration, such as EU directives on energy efficiency, renewable energy, and biofuels, have had some impact on mitigation objectives (*medium confidence*). Nonetheless, theoretical models and past experience suggest that there is substantial potential to increase the role of climate-specific regional cooperation agreements and associated instruments, including economic instruments and regulatory instruments. In this context it is important to consider carbon leakage of such regional initiatives and ways to address it. [14.4.2, 14.4.1]

In addition, non-climate-related modes of regional cooperation could have significant implications for mitigation, even if mitigation objectives are not a component (*medium confidence*). Regional cooperation with non-climate-related objectives but possible mitigation implications, such as trade agreements, cooperation on technology, and cooperation on infrastructure and energy, has to date also had negligible impacts on mitigation. Modest impacts have been found on the level of GHG emissions of members of regional preferential trade areas if these agreements are accompanied with environmental agreements. Creating synergies between adaptation and mitigation can increase the cost-effectiveness of climate change actions. Linking electricity and gas grids at the regional level has also had a modest impact on mitigation as it facilitated greater use of low-carbon and renewable technologies; there is substantial further mitigation potential in such arrangements. [14.4.2]

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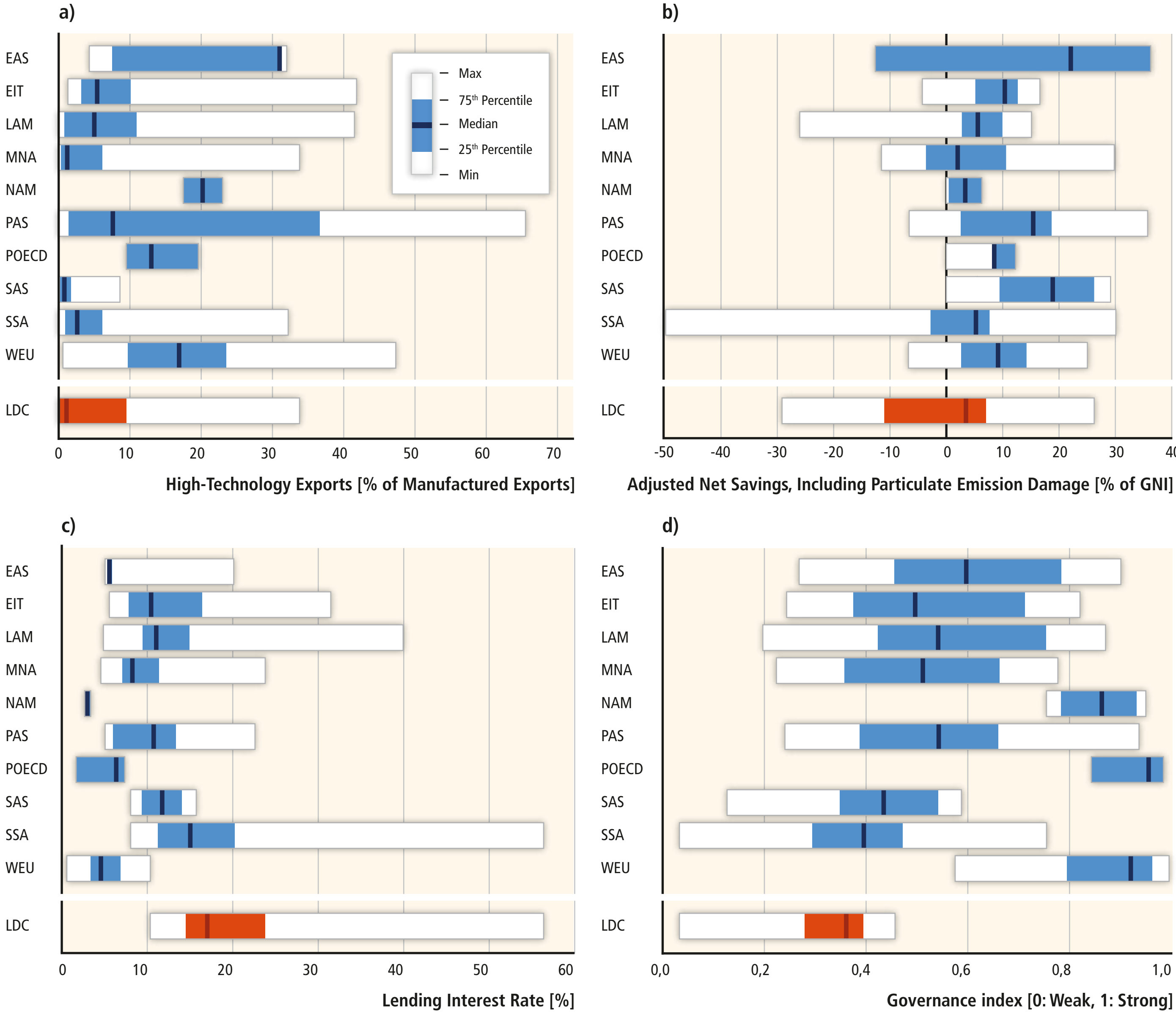
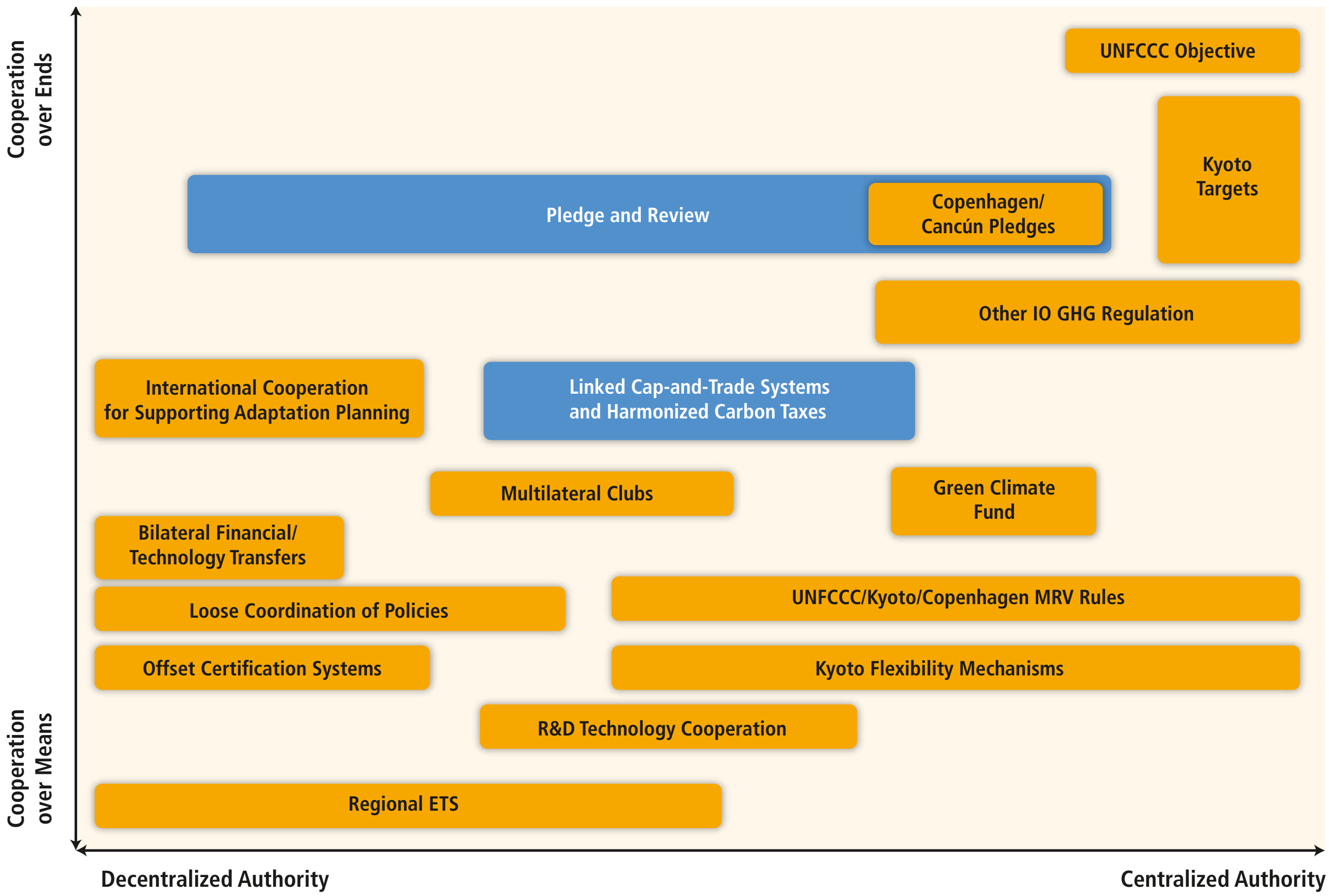


Figure TS.37 | Economic and governance indicators affecting regional capacities to embrace mitigation policies. Regions include EAS (East Asia), EIT (Economies in Transition), LAM (Latin America and Caribbean), MNA (Middle East and North Africa), NAM (North America), POECD (Pacific Organisation for Economic Co-operation and Development (OECD)-1990 members), PAS (South East Asia and Pacific), SAS (South Asia), SSA (sub-Saharan Africa), WEU (Western Europe), LDC (least-developed countries). Statistics refer to the year 2010 or the most recent year available. Note: The lending interest rate refers to the average interest rate charged by banks to private sector clients for short- to medium-term financing needs. The governance index is a composite measure of governance indicators compiled from various sources, rescaled to a scale of 0 to 1, with 0 representing weakest governance and 1 representing strongest governance. [Figure 14.2]

TS.4.4 International cooperation

Climate change mitigation is a global commons problem that requires international cooperation, but since AR4, scholarship has emerged that emphasizes a more complex and multi-faceted view of climate policy (*very high confidence*). Two characteristics of climate change necessitate international cooperation: climate change is a global commons problem, and it is characterized by a high degree of heterogeneity in the origins of GHG emissions, mitigation opportunities, climate impacts, and capacity for mitigation and adaptation [13.2.1.1]. Policymaking efforts to date have primarily focused on international cooperation as a task centrally focused on the coordination of national policies that would be adopted with the goal of mitigation. More recent policy developments suggest that there is a more complicated set of relationships between national, regional, and global policymaking, based on a multiplicity of goals, a recognition of policy co-benefits, and barriers to technological innovation and diffusion [1.2, 6.6, 15.2]. A major challenge is assessing whether decentralized policy action is consistent with and can lead to total mitigation efforts that are effective, equitable, and efficient [6.1.2.1, 13.13].



Loose coordination of policies: examples include transnational city networks and Nationally Appropriate Mitigation Actions (NAMAs); R&D technology cooperation: examples include the Major Economies Forum on Energy and Climate (MEF), Global Methane Initiative (GMI), or Renewable Energy and Energy Efficiency Partnership (REEEP); Other international organization (IO) GHG regulation: examples include the Montreal Protocol, International Civil Aviation Organization (ICAO), International Maritime Organization (IMO).

Figure TS.38 | Alternative forms of international cooperation. The figure represents a compilation of existing and possible forms of international cooperation, based upon a survey of published research, but is not intended to be exhaustive of existing or potential policy architectures, nor is it intended to be prescriptive. Examples in orange are existing agreements. Examples in blue are structures for agreements proposed in the literature. The width of individual boxes indicates the range of possible degrees of centralization for a particular agreement. The degree of centralization indicates the authority an agreement confers on an international institution, not the process of negotiating the agreement. [Figure 13.2]

International cooperation on climate change has become more institutionally diverse over the past decade (*very high confidence*). Perceptions of fairness can facilitate cooperation by increasing the legitimacy of an agreement [3.10, 13.2.2.4]. UNFCCC remains a primary international forum for climate negotiations, but other institutions have emerged at multiple scales, namely: global, regional, national, and local [13.3.1, 13.4.1.4, 13.5]. This institutional diversity arises in part from the growing inclusion of climate change issues in other policy arenas (e.g., sustainable development, international trade, and human rights). These and other linkages create opportunities, potential co-benefits, or harms that have not yet been thoroughly examined. Issue linkage also creates the possibility for countries to experiment with different forums of cooperation ('forum shopping'), which may increase negotiation costs and potentially distract from or dilute the performance of international cooperation toward climate goals. [13.3, 13.4, 13.5] Finally, there has been an emergence of new transnational climate-related institutions not centred on sovereign states (e.g., public-private partnerships, private sector governance initiatives, transnational NGO programmes, and city level initiatives) [13.3.1, 13.12].

Existing and proposed international climate agreements vary in the degree to which their authority is centralized. As illustrated in Figure TS.38, the range of centralized formalization spans strong multilateral agreements (such as the Kyoto Protocol targets), harmonized national policies (such as the Copenhagen/Cancún pledges), and decentralized but coordinated national policies (such as planned linkages of national and sub-national emissions trading schemes) [13.4.1, 13.4.3]. Four other design elements of international agreements have particular relevance: legal bindingness, goals and targets, flexible mechanisms, and equitable methods for effort-shar-

Table TS.10 | Summary of performance assessments of existing and proposed forms of cooperation. Forms of cooperation are evaluated along the four evaluation criteria described in Sections 3.7.1 and 13.2.2. [Table 13.3]

	Mode of International Cooperation		**Assessment Criteria**			
			Environmental Effectiveness	**Aggregate Economic Performance**	**Distributional Impacts**	**Institutional Feasibility**
Existing Cooperation [13.13.1]	**UNFCCC**		Aggregate GHG emissions in Annex I countries declined by 6.0 to 9.2 % below 1990 levels by 2000, a larger reduction than the apparent 'aim' of returning to 1990 levels by 2000.	Authorized joint fulfilment of commitments, multi-gas approach, sources and sinks, and domestic policy choice. Cost and benefit estimates depend on baseline, discount rate, participation, leakage, co-benefits, adverse effects, and other factors.	Commitments distinguish between Annex I (industrialized) and non-Annex I countries. Principle of 'common but differentiated responsibility.' Commitment to 'equitable and appropriate contributions by each [party].'	Ratified (or equivalent) by 195 countries and regional organizations. Compliance depends on national communications.
	The Kyoto Protocol (KP)		Aggregate emissions in Annex I countries were reduced by 8.5 to 13.6 % below 1990 levels by 2011, more than the first commitment period (CP1) collective reduction target of 5.2 %. Reductions occurred mainly in EITs; emissions; increased in some others. Incomplete participation in CP1 (even lower in CP2).	Cost-effectiveness improved by flexible mechanisms (Joint Implementation (JI), CDM, International Emissions Trading (IET)) and domestic policy choice. Cost and benefit estimates depend on baseline, discount rate, participation, leakage, co-benefits, adverse effects, and other factors.	Commitments distinguish between developed and developing countries, but dichotomous distinction correlates only partly (and decreasingly) with historical emissions trends and with changing economic circumstances. Intertemporal equity affected by short-term actions.	Ratified (or equivalent) by 192 countries and regional organizations, but took 7 years to enter into force. Compliance depends on national communications, plus KP compliance system. Later added approaches to enhance measurement, reporting, and verification (MRV).
	The Kyoto Mechanisms		About 1.4 billion tCO_2eq credits under the CDM, 0.8 billion under JI, and 0.2 billion under IET (through July 2013). Additionality of CDM projects remains an issue but regulatory reform underway.	CDM mobilized low cost options, particularly industrial gases, reducing costs. Underperformance of some project types. Some evidence that technology is transferred to non-Annex I countries.	Limited direct investment from Annex I countries. Domestic investment dominates, leading to concentration of CDM projects in few countries. Limited contributions to local sustainable development.	Helped enable political feasibility of Kyoto Protocol. Has multi-layered governance. Largest carbon markets to date. Has built institutional capacity in developing countries.
	Further Agreements under the UNFCCC		Pledges to limit emissions made by all major emitters under Cancun Agreements. Unlikely sufficient to limit temperature change to 2 °C. Depends on treatment of measures beyond current pledges for mitigation and finance. Durban Platform calls for new agreement by 2015, to take effect in 2020, engaging all parties.	Efficiency not assessed. Cost-effectiveness might be improved by market-based policy instruments, inclusion of forestry sector, commitments by more nations than Annex I countries (as envisioned in Durban Platform).	Depends on sources of financing, particularly for actions of developing countries.	Cancún Conference of the Parties (COP) decision; 97 countries made pledges of emission reduction targets or actions for 2020.
	Agreements outside the UNFCCC	**G8, G20, Major Economies Forum on Energy and Climate (MEF)**	G8 and MEF have recommended emission reduction by all major emitters. G20 may spur GHG reductions by phasing out of fossil fuel subsidies.	Action by all major emitters may reduce leakage and improve cost-effectiveness, if implemented using flexible mechanisms. Potential efficiency gains through subsidy removal. Too early to assess economic performance empirically.	Has not mobilized climate finance. Removing fuel subsidies would be progressive but have negative effects on oil-exporting countries and on those with very low incomes unless other help for the poorest is provided.	Lower participation of countries than UNFCCC, yet covers 70 % of global emissions. Opens possibility for forum-shopping, based on issue preferences.
		Montreal Protocol on Ozone-Depleting Substances (ODS)	Spurred emission reductions through ODS phaseouts approximately 5 times the magnitude of Kyoto CP1 targets. Contribution may be negated by high-GWP substitutes, though efforts to phase out HFCs are growing.	Cost-effectiveness supported by multi-gas approach. Some countries used market-based mechanisms to implement domestically.	Later compliance period for phaseouts by developing countries. Montreal Protocol Fund provided finance to developing countries.	Universal participation. but the timing of required actions vary for developed and developing countries
		Voluntary Carbon Market	Covers 0.13 billion tCO_2eq, but certification remains an issue	Credit prices are heterogeneous, indicating market inefficiencies	[No literature cited.]	Fragmented and non-transparent market.

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	Mode of International Cooperation		Assessment Criteria			
			Environmental Effectiveness	**Aggregate Economic Performance**	**Distributional Impacts**	**Institutional Feasibility**
Proposed Cooperation [13.13.2]	**Proposed architectures**	**Strong multilateralism**	Tradeoff between ambition (deep) and participation (broad).	More cost-effectivewith greater reliance on market mechanisms.	Multilateralism facilitates integrating distributional impacts into negotiations and may apply equity-based criteria as outlined in Ch. 4	Depends on number of parties; degree of ambition
		Harmonized national policies	Depends on net aggregate change in ambition across countries resulting from harmonization.	More cost-effectivewith greater reliance on market mechanisms.	Depends on specific national policies	Depends on similarity of national policies; more similar may support harmonization but domestic circumstances may vary. National enforcement.
		Decentralized architectures, coordinated national policies	Effectiveness depends on quality of standards and credits across countries	Often (though not necessarily) refers to linkage of national cap-and-trade systems, in which case cost effective.	Depends on specific national policies	Depends on similarity of national policies. National enforcement.
	Effort (burden) sharing arrangements		Refer to Sections 4.6.2 for discussion of the principles on which effort (burden) sharing arrangements may be based, and Section 6.3.6.6 for quantitative evaluation.			

ing [13.4.2]. Existing and proposed modes of international cooperation are assessed in Table TS.10. [13.13]

The UNFCCC is currently the only international climate policy venue with broad legitimacy, due in part to its virtually universal membership (*high confidence*). The UNFCCC continues to evolve institutions and systems for governance of climate change. [13.2.2.4, 13.3.1, 13.4.1.4, 13.5]

Incentives for international cooperation can interact with other policies (*medium confidence*). Interactions between proposed and existing policies, which may be counterproductive, inconsequential, or beneficial, are difficult to predict, and have been understudied in the literature [13.2, 13.13, 15.7.4]. The game-theoretic literature on climate change agreements finds that self-enforcing agreements engage and maintain participation and compliance. Self-enforcement can be derived from national benefits due to direct climate benefits, co-benefits of mitigation on other national objectives, technology transfer, and climate finance. [13.3.2]

Decreasing uncertainty concerning the costs and benefits of mitigation can reduce the willingness of states to make commitments in forums of international cooperation (*medium confidence*). In some cases, the reduction of uncertainty concerning the costs and benefits of mitigation can make international agreements less effective by creating a disincentive for states to participate [13.3.3, 2.6.4.1]. A second dimension of uncertainty, that concerning whether the policies states implement will in fact achieve desired outcomes, can lessen the willingness of states to agree to commitments regarding those outcomes [2.6.3].

International cooperation can stimulate public and private investment and the adoption of economic incentives and direct regulations that promote technological innovation (*medium confidence*). Technology policy can help lower mitigation costs, thereby increasing incentives for participation and compliance with international cooperative efforts, particularly in the long run. Equity issues can be affected by domestic intellectual property rights regimes, which can alter the rate of both technology transfer and the development of new technologies. [13.3, 13.9]

In the absence of—or as a complement to—a binding, international agreement on climate change, policy linkages between and among existing and nascent international, regional, national, and sub-national climate policies offer potential climate change mitigation and adaptation benefits (*medium confidence*). Direct and indirect linkages between and among sub-national, national, and regional carbon markets are being pursued to improve market efficiency. Linkage between carbon markets can be stimulated by competition between and among public and private governance regimes, accountability measures, and the desire to learn from policy experiments. Yet integrating climate policies raises a number of concerns about the performance of a system of linked legal rules and economic activities. [13.3.1, 13.5.3, 13.13.2.3] Prominent examples of linkages are among national and regional climate initiatives (e.g., planned linkage between the EU ETS and the Australian Emission Trading Scheme, international offsets planned for recognition by a number of jurisdictions), and national and regional climate initiatives with the Kyoto Protocol (e.g., the EU ETS is linked to international carbon markets through the project-based Kyoto Mechanisms) [13.6, 13.7, Figure 13.4, 14.4.2].

International trade can promote or discourage international cooperation on climate change (*high confidence*). Developing constructive relationships between international trade and climate agreements involves considering how existing trade policies and rules can be modified to be more climate-friendly; whether border adjustment measures or other trade measures can be effective in meeting the goals of international climate policy, including participation in and compliance with climate agreements; or whether the UNFCCC, World Trade Organization (WTO), a hybrid of the two, or a new institution is the best forum for a trade-and-climate architecture. [13.8]

The Montreal Protocol, aimed at protecting the stratospheric ozone layer, achieved reductions in global GHG emissions (*very high confidence*). The Montreal Protocol set limits on emissions of ozone-depleting gases that are also potent GHGs, such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). Substitutes for those ozone-depleting gases (such as hydrofluorocarbons (HFCs), which are not ozone-depleting) may also be potent GHGs. Lessons learned from the Montreal Protocol, for example about the effect of financial and technological transfers on broadening participation in an international environmental agreement, could be of value to the design of future international climate change agreements (see Table TS.10). [13.3.3, 13.3.4, 13.13.1.4]

The Kyoto Protocol was the first binding step toward implementing the principles and goals provided by the UNFCCC, but it has had limited effects on global GHG emissions because some countries did not ratify the Protocol, some Parties did not meet their commitments, and its commitments applied to only a portion of the global economy (*medium evidence, low agreement*). The Parties collectively surpassed their collective emission reduction target in the first commitment period, but the Protocol credited emissions reductions that would have occurred even in its absence. The Kyoto Protocol does not directly influence the emissions of non-Annex I countries, which have grown rapidly over the past decade. [5.2, 13.13.1.1]

The flexible mechanisms under the Protocol have cost-saving potential, but their environmental effectiveness is less clear (*medium confidence*). The CDM, one of the Protocol's flexible mechanisms, created a market for GHG emissions offsets from developing countries, generating credits equivalent to nearly 1.4 $GtCO_2eq$ as of October 2013. The CDM's environmental effectiveness has been mixed due to concerns about the limited additionality of projects, the validity of baselines, the possibility of emissions leakage, and recent credit price decreases. Its distributional impact has been unequal due to the concentration of projects in a limited number of countries. The Protocol's other flexible mechanisms, Joint Implementation (JI) and International Emissions Trading (IET), have been undertaken both by governments and private market participants, but have raised concerns related to government sales of emission units. (Table TS.10) [13.7.2, 13.13.1.2, 14.3.7.1]

Recent UNFCCC negotiations have sought to include more ambitious contributions from the countries with commitments under the Kyoto Protocol, mitigation contributions from a broader set of countries, and new finance and technology mechanisms. Under the 2010 Cancún Agreement, developed countries formalized voluntary pledges of quantified, economy-wide GHG emission reduction targets and some developing countries formalized voluntary pledges to mitigation actions. The distributional impact of the agreement will depend in part on the magnitude and sources of financing, although the scientific literature on this point is limited, because financing mechanisms are evolving more rapidly than respective scientific assessments (*limited evidence, low agreement*). Under the 2011 Durban Platform for Enhanced Action, delegates agreed to craft a future legal regime that would be 'applicable to all Parties […] under the Convention' and would include substantial new financial support and technology arrangements to benefit developing countries, but the delegates did not specify means for achieving those ends. [13.5.1.1, 13.13.1.3, 16.2.1]

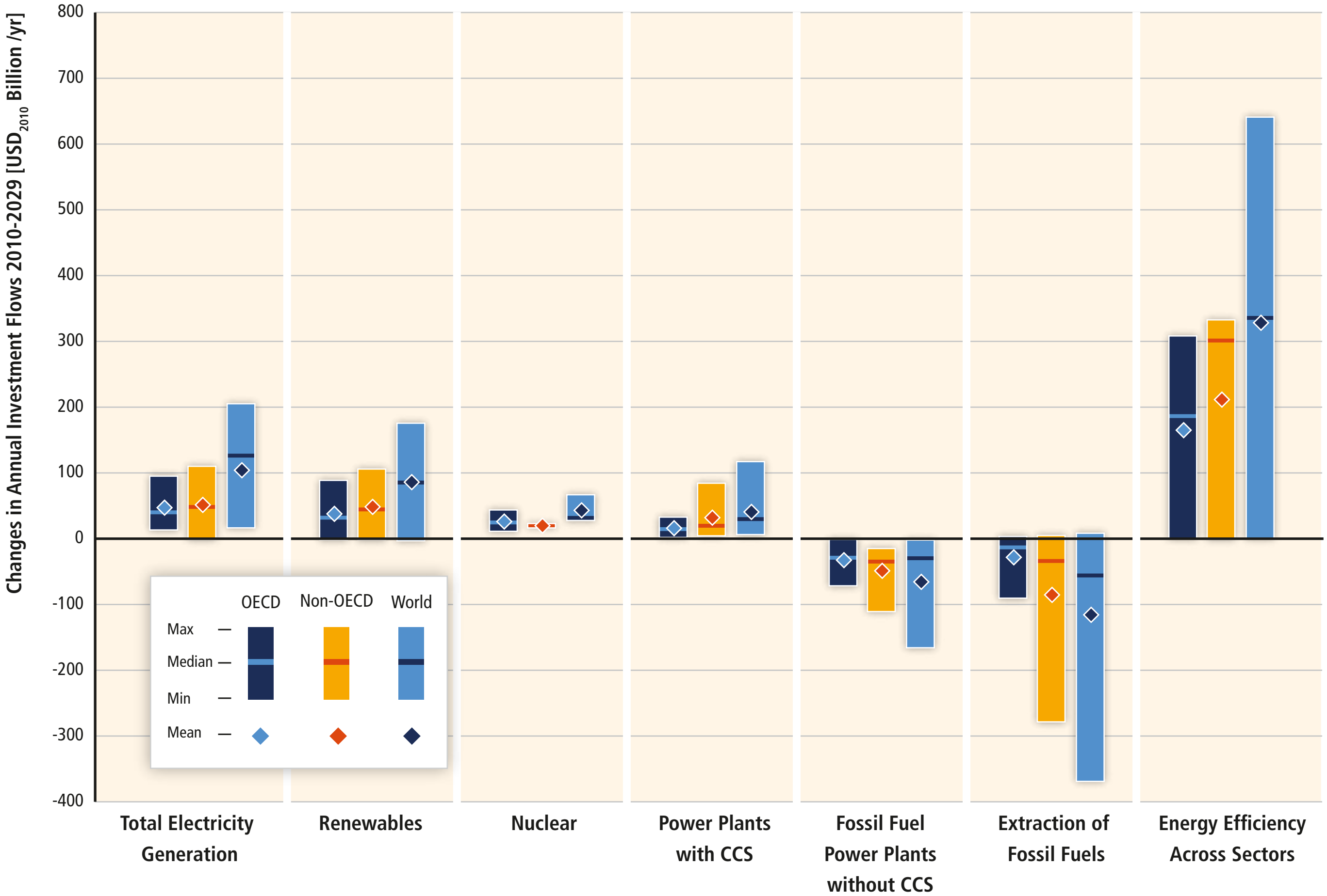
TS.4.5 Investment and finance

A transformation to a low-carbon economy implies new patterns of investment. A limited number of studies have examined the investment needs for different mitigation scenarios. Information is largely limited to energy use with global total annual investment in the energy sector at about 1200 billion USD. Mitigation scenarios that reach atmospheric CO_2eq concentrations in the range from 430 to 530 ppm CO_2eq by 2100 (without overshoot) show substantial shifts in annual investment flows during the period 2010–2029 if compared to baseline scenarios (Figure TS.39): annual investment in the existing technologies associated with the energy supply sector (e.g., conventional fossil fuelled power plants and fossil fuel extraction) would decline by 30 (2 to 166) billion USD per year (median: –20 % compared to 2010) (*limited evidence, medium agreement*). Investment in low-emissions generation technologies (renewables, nuclear, and power plants with CCS) would increase by 147 (31 to 360) billion USD per year (median: +100 % compared to 2010) during the same period (*limited evidence, medium agreement*) in combination with an increase by 336 (1 to 641) billion USD in energy efficiency investments in the building, transport and industry sectors (*limited evidence, medium agreement*). Higher energy efficiency and the shift to low-emission generation technologies contribute to a reduction in the demand for fossil fuels, thus causing a decline in investment in fossil fuel extraction, transformation and transportation. Scenarios suggest that average annual reduction of investment in fossil fuel extraction in 2010–2029 would be 116 (–8 to 369) billion USD (*limited evidence, medium agreement*). Such spillover effects could yield adverse effects on the revenues of countries that export fossil fuels. Mitigation scenarios also reduce deforestation against current deforestation trends by 50 % reduction with an investment of 21 to 35 billion USD per year (*low confidence*). [16.2.2]

Estimates of total climate finance range from 343 to 385 billion USD per year between 2010 and 2012 (*medium confidence*). The range is based on 2010, 2011, and 2012 data. Climate finance was almost evenly invested in developed and developing countries. Around 95 % of the total was invested in mitigation (*medium confidence*). The figures reflect the total financial flow for the underlying investments, *not the incremental investment*, i.e., the portion attributed to the mitigation/adaptation cost increment (see Box TS.14). In general, quantitative data on climate finance are limited, relate to different concepts, and are incomplete. [16.2.1.1]

Depending on definitions and approaches, climate finance flows to developing countries are estimated to range from 39 to 120 billion USD per year during the period 2009 to 2012 (*medium confidence*). The range covers public and private flows for mitigation and adaptation. Public climate finance was 35 to 49 billion USD (2011/2012 USD) (*medium confidence*). Most public climate finance provided to developing countries flows through bilateral and multilateral institutions usually as concessional loans and grants. Under the UNFCCC, climate finance is funding provided to developing countries by Annex II Parties and averaged nearly 10 billion USD per year from 2005 to 2010 (*medium confidence*). Between 2010 and 2012, the 'fast start finance' provided by some developed countries amounted to over 10 billion USD per year (*medium confidence*). Estimates of international private climate finance flowing to developing countries range from 10 to 72 billion USD (2009/2010 USD) per year, including foreign direct investment as equity and loans in the range of 10 to 37 billion USD (2010 USD and 2008 USD) per year over the period of 2008–2011 (*medium confidence*). Figure TS.40 provides an overview of climate finance, outlining sources and managers of capital, financial instruments, project owners, and projects. [16.2.1.1]

Within appropriate enabling environments, the private sector, along with the public sector, can play an important role in financing mitigation*.* The private sector contribution to total climate finance is estimated at an average of 267 billion USD (74 %) per year in the period 2010 to 2011 and at 224 billion USD (62 %) per year in the



# of Studies:	4	4	5	4	4	5	4	4	5	4	4	5	4	4	5	4	4	5	3	3	4

Figure TS.39 | Change of average annual investment flows in mitigation scenarios (2010–2029). Investment changes are calculated by a limited number of model studies and model comparisons for mitigation scenarios that reach concentrations within the range of 430–530 ppm CO_2eq by 2100 compared to respective average baseline investments. The vertical bars indicate the range between minimum and maximum estimate of investment changes; the horizontal bar indicates the median of model results. Proximity to this median value does not imply higher likelihood because of the different degree of aggregation of model results, low number of studies available and different assumptions in the different studies considered. The numbers in the bottom row show the total number of studies assessed. [Figure 16.3]

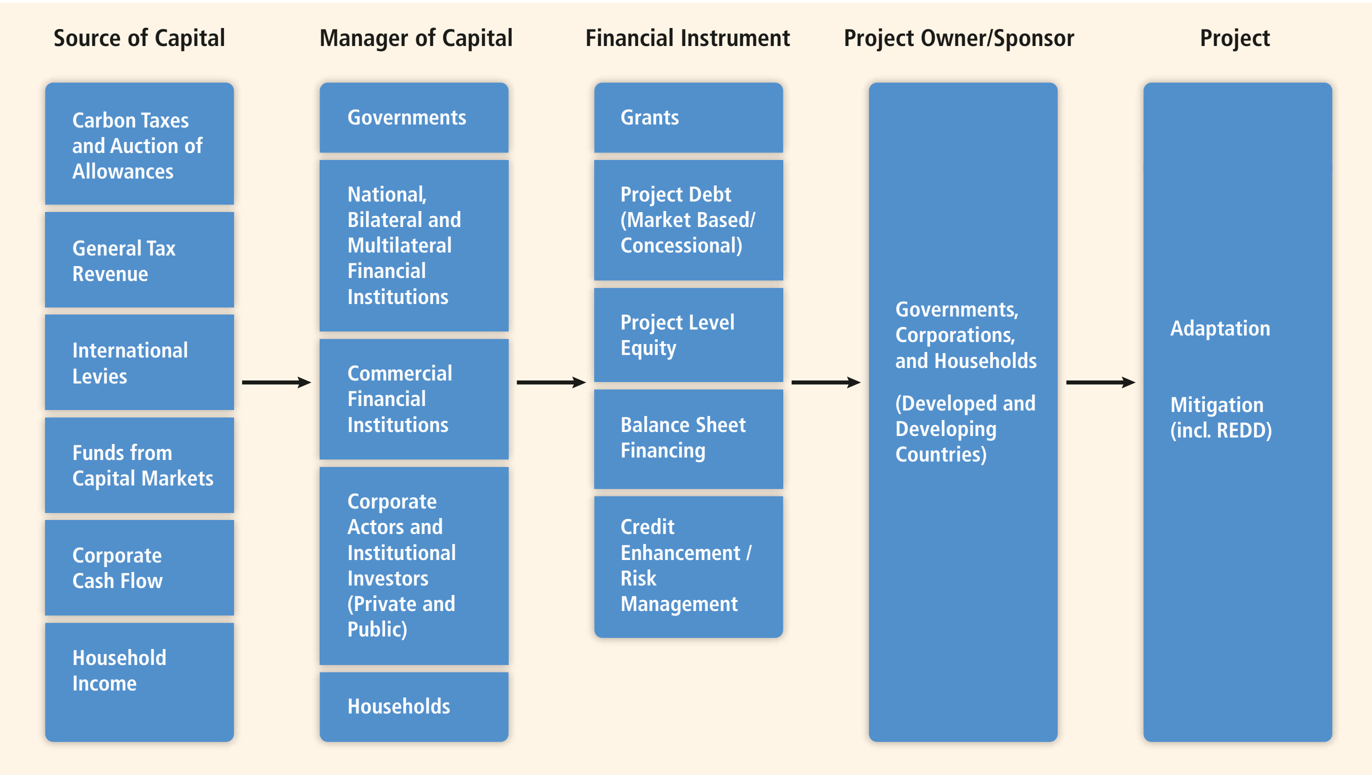


Figure TS.40 | Types of climate finance flows. 'Capital' includes all relevant financial flows. The size of the boxes is not related to the magnitude of the financial flow. [Figure 16.1]

Box TS.14 | There are no agreed definitions of ´climate investment´ and 'climate finance'

'*Total climate finance*' includes all financial flows whose expected effect is to reduce net GHG emissions and/or to enhance resilience to the impacts of climate variability and the projected climate change. This covers private and public funds, domestic and international flows, expenditures for mitigation and adaptation, and adaptation to current climate variability as well as future climate change. It covers the full value of the financial flow rather than the share associated with the climate change benefit. The share associated with the climate change benefit is the incremental cost. The '*total climate finance flowing to developing countries*' is the amount of the total climate finance invested in developing countries that comes from developed countries. This covers private and public funds for mitigation and adaptation. '*Public climate finance provided to developing countries*' is the finance provided by developed countries´ governments and bilateral institutions as well as multilateral institutions for mitigation and adaptation activities in developing countries. '*Private climate finance flowing to developing countries*' is finance and investment by private actors in/from developed countries for mitigation and adaptation activities in developing countries. Under the UNFCCC, climate finance is not well-defined. Annex II Parties provide and mobilize funding for climate-related activities in developing countries.

The '*incremental investment*' is the extra capital required for the initial investment for a mitigation or adaptation project in comparison to a reference project. Incremental investment for mitigation and adaptation projects is not regularly estimated and reported, but estimates are available from models. The '*incremental cost*' reflects the cost of capital of the incremental investment and the change of operating and maintenance costs for a mitigation or adaptation project in comparison to a reference project. It can be calculated as the difference of the net present values of the two projects. Many mitigation measures have higher investment costs and lower operating and maintenance costs than the measures displaced so incremental cost tends to be lower than the incremental investment. Values depend on the incremental investment as well as projected operating costs, including fossil fuel prices, and the discount rate. The '*macroeconomic cost of mitigation policy*' is the reduction of aggregate consumption or GDP induced by the reallocation of investments and expenditures induced by climate policy (see Box TS.9). These costs do not account for the benefit of reducing anthropogenic climate change and should thus be assessed against the economic benefit of avoided climate change impacts. [16.1] period 2011 to 2012 (*limited evidence, medium agreement*) [16.2.1]. In a range of countries, a large share of private sector climate investment relies on low-interest and long-term loans as well as risk guarantees provided by public sector institutions to cover the incremental costs and risks of many mitigation investments. The quality of a country's enabling environment—including the effectiveness of its institutions, regulations and guidelines regarding the private sector, security of property rights, credibility of policies, and other factors—has a substantial impact on whether private firms invest in new technologies and infrastructure [16.3]. By the end of 2012, the 20 largest emitting developed and developing countries with lower risk country grades for private sector investments produced 70 % of global energy related CO_2 emissions (*low confidence*). This makes them attractive for international private sector investment in low-carbon technologies. In many other countries, including most least-developed countries, low-carbon investment will often have to rely mainly on domestic sources or international public finance. [16.4.2]

A main barrier to the deployment of low-carbon technologies is a low risk-adjusted rate of return on investment vis-à-vis high-carbon alternatives (*high confidence*). Public policies and support instruments can address this either by altering the average rates of return for different investment options, or by creating mechanisms to lessen the risks that private investors face [15.12, 16.3]. Carbon pricing mechanisms (carbon taxes, cap-and-trade systems), as well as renewable energy premiums, FITs, RPSs, investment grants, soft loans and credit insurance can move risk-return profiles into the required direction [16.4]. For some instruments, the presence of substantial uncertainty about their future levels (e.g., the future size of a carbon tax relative to differences in investment and operating costs) can lead to a lessening of the effectiveness and/or efficiency of the instrument. Instruments that create a fixed or immediate incentive to invest in low-emission technologies, such as investment grants, soft loans, or FITs, do not appear to suffer from this problem. [2.6.5]

Chapters

1

Introductory Chapter

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Executive Summary

Since the first Intergovernmental Panel on Climate Change (IPCC) assessment report (FAR) (IPCC, 1990a), the quantity and depth of scientific research on climate change mitigation has grown enormously. In tandem with scholarship on this issue, the last two decades have seen relatively active efforts around the world to design and adopt policies that control ('mitigate') the emissions of pollutants that affect the climate. The effects of those emissions are felt globally; mitigation thus involves managing the global commons and requires a measure of international coordination among nations. But the actual policies that lead to mitigation arise at the local and national levels as well as internationally. Those policies have included, among others, market-based approaches such as emission trading systems along with regulation and voluntary initiatives; they encompass many diverse economic development strategies that countries have adopted with the goal of promoting human welfare and jobs while also achieving other goals such as mitigating emissions of climate pollutants. These policies also include other efforts to address market failures, such as public investments in research and development (R&D) needed to increase the public good of knowledge about new less emission-intensive technologies and practices. International diplomacy—leading to agreements such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol as well as various complementary initiatives such as the commitments pledged at the Copenhagen and Cancun Conferences of the Parties—has played a substantial role in focusing attention on mitigation of greenhouse gases (GHGs).

The field of scientific research in this area has evolved in parallel with actual policy experience allowing, in theory, insights from each domain to inform the other. Since the 4th assessment report (AR4) of IPCC (2007a; b) there have been numerous important developments in both the science and practical policy experience related to mitigation. There is growing insight into how climate change mitigation policies interact with other important social goals from the local to the national and international levels. There is also growing practical experience and scholarly research concerning a wide array of policy instruments. Scholars have developed much more sophisticated information on how public opinion influences the design and stringency of climate change mitigation policies.

Meanwhile, events in the world have had a large impact on how scientific researchers have seen the scale of the mitigation challenge and its practical policy outcomes. For example, a worldwide economic recession beginning around 2008 has affected patterns of emissions and investment in the world economy and in many countries has affected political priorities on matters related to climate change mitigation.

The present chapter identifies six conclusions. Where appropriate, we indicate not only the major findings but also our confidence in the finding and the level of supporting evidence. (For an overview of the language on agreement and confidence see Mastrandrea et al. (2011).

First, since AR4, annual global GHG emissions have continued to grow and reached 49.5 billion tonnes (giga tonnes or Gt) of carbon dioxide equivalents (CO_2eq) in the year 2010, higher than any level prior to that date, with an uncertainty estimate at ±10 % for the 90 % confidence interval. On a per-capita basis, emissions from industrialized countries that are listed in Annex I of the UNFCCC are on average 2.5 times of those from developing countries. However, since AR4, total emissions from countries not listed in Annex I have overtaken total emissions from the Annex I industrialized countries (see glossary for Annex I countries). Treating the 27 members of the EU as a single country, about ten large countries—from the industrialized and developing worlds—account for 70 % of world emissions. (*robust evidence, high agreement*) [Section 1.3]. The dominant driving forces for anthropogenic emissions include population, the structure of the economy, income and income distribution, policy, patterns of consumption, investment decisions, individual and societal behaviour, the state of technology, availability of energy resources, and land-use change. In nearly all countries it is very likely that the main short-term driver of changes in the level of emissions is the overall state of the economy. In some countries there is also a significant role for climate policies focused on controlling emissions. (*medium evidence, medium agreement*) [1.3]

Second, national governments are addressing climate change in the context of other national priorities, such as energy security and alleviation of poverty. In nearly all countries the most important driving forces for climate policy are not solely the concern about climate change. (*medium evidence, medium agreement*) [1.2 and 1.4]. Studies on policy implementation show that improvements to climate policy programs need to engage these broader national priorities. Despite the variety of existing policy efforts and the existence of the UNFCCC and the Kyoto Protocol, GHG emissions have grown at about twice the rate in the recent decade (2000–2010) than any other decade since 1970. (*robust evidence, high agreement*) [1.3.1]

Third, the current trajectory of global annual and cumulative emissions of GHGs is inconsistent with widely discussed goals of limiting global warming at 1.5 to 2 degrees Celsius above the pre-industrial level (*medium evidence, medium agreement*). [1.2.1.6 and 1.3.3] The ability to link research on mitigation of emissions to actual climate outcomes, such as average temperature, has not substantially changed since AR4 due to a large number of uncertainties in scientific understanding of the physical sensitivity of the climate to the build-up of GHGs discussed in Working Group I of the IPCC (WGI). Those physical uncertainties are multiplied by the many socioeconomic uncertainties that affect how societies would respond to emission control policies (*low evidence, high agreement*). Acknowledging these uncertainties, mitigating emissions along a pathway that would be cost-effective and consistent with likely avoiding warming of more than 2 degrees implies that nearly all governments promptly engage in international cooperation, adopt stringent national and international emission control policies, and deploy rapidly a wide array of low- and zero-emission technologies. Modelling studies that adopt assumptions that are less ideal—for example, with international cooperation that emerges slowly or only restricted availability of some technologies—show that achieving this 2 degree goal is much more costly and requires deployments of technology that are substantially more aggressive than the least-cost strategies (*robust evidence, medium agreement*) [1.3.3]. The assumptions needed to have a likely chance of limiting warming to 2 degrees are very difficult to satisfy in real world conditions (*medium evidence; low agreement*). The tenor of modelling research since AR4 suggests that the goal of stabilizing warming at 1.5 degrees Celsius is so challenging to achieve that relatively few modelling studies have even examined it in requisite detail (*low evidence, medium agreement*) [1.3.3].

Fourth, deep cuts in emissions will require a diverse portfolio of policies, institutions, and technologies as well as changes in human behaviour and consumption patterns (*high evidence; high agreement*). There are many different development trajectories capable of substantially mitigating emissions; the ability to meet those trajectories will be constrained if particular technologies are removed from consideration. It is virtually certain that the most appropriate policies will vary by sector and country, suggesting the need for flexibility rather than a singular set of policy tools. In most countries the actors that are relevant to controlling emissions aren't just national governments. Many diverse actors participate in climate policy from the local to the global levels—including a wide array of nongovernmental organizations representing different environmental, social, business and other interests. (*robust evidence, medium agreement*) [1.4]

Fifth, policies to mitigate emissions are extremely complex and arise in the context of many different forms of uncertainty. While there has been much public attention to uncertainties in the underlying science of climate change—a topic addressed in detail in the WGI and II reports—profound uncertainties arise in the socioeconomic factors addressed here in WGIII. Those uncertainties include the development and deployment of technologies, prices for major primary energy sources, average rates of economic growth and the distribution of benefits and costs within societies, emission patterns, and a wide array of institutional factors such as whether and how countries cooperate effectively at the international level. In general, these uncertainties and complexities multiply those already identified in climate science by WGI and WGII. The pervasive complexities and uncertainties suggest that there is a need to emphasize policy strategies that are robust over many criteria, adaptive to new information, and able to respond to unexpected events. (*medium evidence, medium agreement*) [1.2].

Sixth, there are many important knowledge gaps that additional research could address. This report points to at least two of them. First is that the scholarship has developed increasingly sophisticated techniques for assessing risks, but so far those risk management techniques have not spread into widespread use in actual mitigation strategies. Risk management requires drawing attention to the interactions between mitigation and other kinds of policy responses such as adaptation to climate change; they require more sophisticated understanding of how humans perceive risk and respond to different kinds of risks. And such strategies require preparing for possible extreme climate risks that may implicate the use of geoengineering technologies as a last resort in response to climate emergencies (*limited evidence, low agreement*). Second, the community of analysts studying mitigation has just begun the process of examining how mitigation costs and feasibility are affected by 'real world' assumptions such as possible limited availability of certain technologies. Improving this line of research could radically improve the utility of studies on mitigation and will require integration of insights from a wide array of social science disciplines, including economics, psychology, political science, sociology and others.

1.1 Introduction

Working Group III (WGIII) of the Intergovernmental Panel on Climate Change (IPCC) is charged with assessing scientific research related to the mitigation of climate change. 'Mitigation' is the effort to control the human sources of climate change and their cumulative impacts, notably the emission of greenhouse gases (GHGs) and other pollutants, such as black carbon particles, that also affect the planet's energy balance. Mitigation also includes efforts to enhance the processes that remove GHGs from the atmosphere, known as sinks (see glossary (Annex I) for definition). Because mitigation lowers the anticipated effects of climate change as well as the risks of extreme impacts, it is part of a broader policy strategy that includes adaptation to climate impacts—a topic addressed in more detail in WGII. There is a special role for international cooperation on mitigation policies because most GHGs have long atmospheric lifetimes and mix throughout the global atmosphere. The effects of mitigation policies on economic growth, innovation, and spread of technologies and other important social goals also implicate international concern because nations are increasingly inter-linked through global trade and economic competition. The economic effects of action by one nation depend, in part, on the action of others as well. Yet, while climate change is fundamentally a global issue, the institutions needed for mitigation exist at many different domains of government, including the local and national level.

This chapter introduces the major issues that arise in mitigation policy and also frames the rest of the WGIII Contribution to the AR5. First we focus on the main messages since the publication of AR4 in 2007 (Section 1.2). Then we look at the historical and future trends in emissions and driving forces, noting that the scale of the mitigation challenge has grown enormously since 2007 due to rapid growth of the world economy and the continued lack of much overt effort to control emissions. This trend raises questions about the viability of widely discussed goals such as limiting climate warming to 2 degrees Celsius since the pre-industrial period (Section 1.3). Then we look at the conceptual issues—such as sustainable development, green growth, and risk management—that frame the mitigation challenge and how those concepts are used in practice (Section 1.4). Finally, we offer a roadmap for the rest of the volume (Section 1.5).

1.2 Main messages and changes from previous assessment

Since AR4, there have been many developments in the world economy, emissions, and policies related to climate change. Here we review six of the most consequential trends and then examine their implications for this Fifth Assessment Report by the IPCC (AR5).

1.2.1 Sustainable development

Since AR4 there has been a substantial increase in awareness of how climate change interacts with the goal of sustainable development (see Chapter 4 in this volume and WGII Chapter 20). While there is no single widely accepted definition of sustainable development, the concept implies integrating economic growth with other goals such as eradication of poverty, environmental protection, job creation, security, and justice (World Commission on Environment and Development, 1987; UNDP, 2009; ADB et al., 2012; OECD, 2012; ILO, 2012; United Nations, 2012). Countries differ enormously in which of these elements they emphasize, and for decades even when policymakers and scientific analysts have all embraced the concept of sustainable development they have implied many different particular goals. Since AR4, new concepts have emerged that are consistent with this broader paradigm, such as 'green growth' and 'green economy'—concepts that also reflect the reality that policy is designed to maximize multiple objectives. The practical implications of sustainable development are defined by societies themselves. In many respects, this multi-faceted understanding of sustainable development is not new as it reflects the effort in the social sciences over the last century to develop techniques for measuring and responding to the many positive and negative externalities that arise as economies evolve—concepts discussed in more detail in Chapter 3 of this volume.

New developments since AR4 have been the emergence of quantitative modelling frameworks that explore the synergies and tradeoffs between the different components of sustainable development including climate change (e.g., McCollum et al., 2011; Riahi et al., 2012; Howells et al., 2013).

Scientific research has examined at least three major implications of sustainable development for the mitigation of emissions. First, since AR4 there have been an exceptionally large number of studies that have focused on how policies contribute to particular elements of sustainable development. Examples include:

- The ways that biofuel programs have an impact on poverty alleviation, employment, air quality, rural development, and energy/ food security (see 11.13), such as in Brazil (La Rovere et al., 2011) and the United States (Leiby and Rubin, 2013).
- The socioeconomic implications of climate and energy policies in the EU (Böhringer and Keller, 2013; Boussena and Locatelli, 2013).
- The impacts of Chinese energy efficiency targets on the country's emissions of warming gases (Hu and Rodriguez Monroy, 2012; Paltsev et al., 2012) and the evolution of energy technologies (Xie, 2009; Zhang, 2010; Guo, 2011; Ye, 2011; IEA, 2013).
- The government of India's Jawaharlal Nehru National Solar Mission (JNNSM) that utilizes a wide array of policies with the goal of making solar power competitive with conventional grid power by 2022 (Government of India, 2009).
- The Kyoto Protocol's Clean Development Mechanism (CDM), which was explicitly designed to encourage investment in projects that mitigate GHG emissions while also advancing sustainable development (UNFCCC, 2012d; Wang et al., 2013). Since AR4, researchers have examined the extent to which the CDM has actually yielded such dividends for job creation, rural development, and other elements of sustainable development (Rogger et al., 2011; Subbarao and Lloyd, 2011).

Chapters in this report that cover the major economic sectors (Chapters 7–11) as well as spatial development (Chapter 12) examine such policies. The sheer number of policies relevant to mitigation has made it impractical to develop a complete inventory of such policies let alone a complete systematic evaluation of their impacts. Since AR4, real world experimentation with policies has evolved more rapidly than careful scholarship can evaluate the design and impact of such policies.

A second consequence of new research on sustainable development has been closer examination of the interaction between different policy instruments. Since the concept of sustainable development implies a multiplicity of goals and governments aim to advance those goals with a multiplicity of policies, the interactions between policy interventions can have a large impact on the extent to which goals are actually achieved. Those interactions can also affect how policy is designed, implemented, and evaluated—a matter that is examined in several places in this report (Chapters 3–4, 14–15).

For example, the European Union (EU) has implemented an Emission Trading Scheme (ETS) that covers about half of the EU's emissions, along with an array of other policy instruments. Since AR4 the EU has expanded the ETS to cover aviation within the EU territory. Some other EU policies cover the same sectors that are included in the ETS (e.g., the deployment of renewable energy supplies) as well as sectors that are outside the ETS (e.g., energy efficiency regulations that affect buildings or agricultural policies aimed at promoting carbon sinks). Many of these policies adopted in tandem with the ETS are motivated by policy goals, such as energy security or rural economic development, beyond just concern about climate change. Even as the price of emission credits under the ETS declined since AR4—implying that the ETS itself was having a less binding impact on emissions—the many other mitigation-related policies have remained in place (Chapters 14 and 15).

Such interactions make it impossible to evaluate individual policies in isolation from other policies that have overlapping effects. It has also given rise to a literature that has grown substantially since AR4 that explores how policies and measures adopted for one purpose might have the 'co-benefit' of advancing other goals as well. Most of that literature has looked at non-monetary co-benefits (see Sections 5.7, 7.9, 8.7, 9.7, 10.8, 11.7, 11.A.6)—for example, an energy efficiency policy adopted principally with the goal of advancing energy security might also lead to lower emissions of GHGs or other pollutants. The concept of co-benefits, however, has also raised many challenges for economic evaluation of policies, and since AR4 there have been substantial efforts to clarify how the interactions between policies influence economic welfare. Such research has underscored that while the concept of 'co-benefits' is widely used to create the impression that policies adopted for one goal yield costless improvements in other goals, the interactions can also yield adverse side-effects (see Sections 3.6.3, 4.2 and 6.6).

Third, the continued interest in how climate change mitigation interacts with goals of sustainable development has also led to challenging new perspectives on how most countries mobilize the political, financial, and administrative resources needed to mitigate emissions. More than two decades ago when the topic of climate change was first extensively debated by policymakers around the world, most scholarship treated GHG emissions as an externality that would require new policies designed explicitly with the goal of controlling emissions. Concerns about climate change would lead to policy outcomes tailored for the purpose of mitigation, and those outcomes would interact with the many other goals of sustainable development. Since AR4 policy experience and scholarship have focused on a different perspective—that for most countries a substantial portion of 'climate policy' would emerge as a derivative of other policies aimed at the many facets of sustainable development. A range of policy interventions were identified in theory to enable integration and optimization of climate change policies with other priorities such as land use planning and protection of water resources (Muller, 2012; Pittock et al., 2013; Dulal and Akbar, 2013). Similarly, many of the policies that would reduce emissions of GHGs could also have large beneficial effects on public health (Ganten et al., 2010; Li and Crawford-Brown, 2011; Groosman et al., 2011; Haines, 2012) (see Sections 6.6, 7.9.2 and WGII 11.9).

These new perspectives on the interactions between climate change and sustainable development policies have led to a more realistic view of how most governments are addressing the challenges of mitigation. However, since AR4 it has also become clear that the totality of the global effort remains inconsistent with widely discussed goals for protecting the climate, such as limiting warming to 1.5 or 2 degrees Celsius. Despite the slowing down of emissions growth rate in the wake of the global financial crisis, annual volume of total emissions from emerging countries has been surging from the new century (see Section 1.3 for more details). And the mitigation progress in the developed world is slower than expectation, especially when carbon emissions embodied in trade is considered (Steinberger et al., 2012; Aichele and Felbermayr, 2012). Moreover, per capita energy consumption and emissions of some developing countries remain far lower than that of developed countries, suggesting that per capita emissions will rise as economies converge (Olivier et al., 2012).

1.2.2 The world macroeconomic situation

Shortly after the publication of AR4 in 2007, the world encountered a severe and deep financial crisis (Sornette and Woodard, 2010). The crisis, which spread rapidly in the second half of 2008, destabilized many of the largest financial institutions in the United States, Europe, and Japan, and shocked public confidence in the global financial system. The crisis also wiped out an estimated USD 25 trillion in value from the world's publicly traded companies, with particularly severe effects on banks (Naudé, 2009; IMF, 2009). The effects of the crisis are evident in economic growth—shown in Figure 1.1. The year 2009 witnessed the first contraction in global GDP since the Second World War (Garrett, 2010). International trade of goods and services had grown rapidly since the turn of the millennium—from 18 % of world GDP in 2000 to 28 % in 2008 (WTO, 2011). The crises caused global trade to drop to 22 % in 2009 before rebounding to 25 % in 2010. The effects of the recent economic crisis have been concentrated in the advanced industrialized countries (te Velde, 2008; Lin, 2008; ADB, 2009, 2010). While this particular crisis has been large, studies have shown that these events often recur, suggesting that there is pervasive over-confidence that policy and investment strategies can eliminate such cyclic behaviour (Reinhart and Rogoff, 2011).

Figure 1.1 reveals that countries were affected by the global economic crisis in different ways. The recessions were generally most severe in the advanced industrialized countries, but the contagion of recessions centred on the high income countries has spread, especially to countries with small, open, and export-oriented economies—in large part due to the decline in exports, commodity prices, and associated revenues. The crisis has also affected foreign direct investment (FDI) and official development assistance (ODA) (IMF, 2009, 2011) with few exceptions such as in the area of climate change where ODA for climate mitigation and adaptation increased substantially until 2010 before a decline in 2011 (OECD, 2013). The crisis also had substantial effects on unemployment across most of the major economies and on public budgets. The slow recovery and deceleration of import demand from key advanced economies continued to contribute to the noticeable slowdown in the emerging market and developing economies during 2012 (IMF, 2013). As well, some of the major emerging market economies suffered from the end of their national investment booms (IMF, 2013).

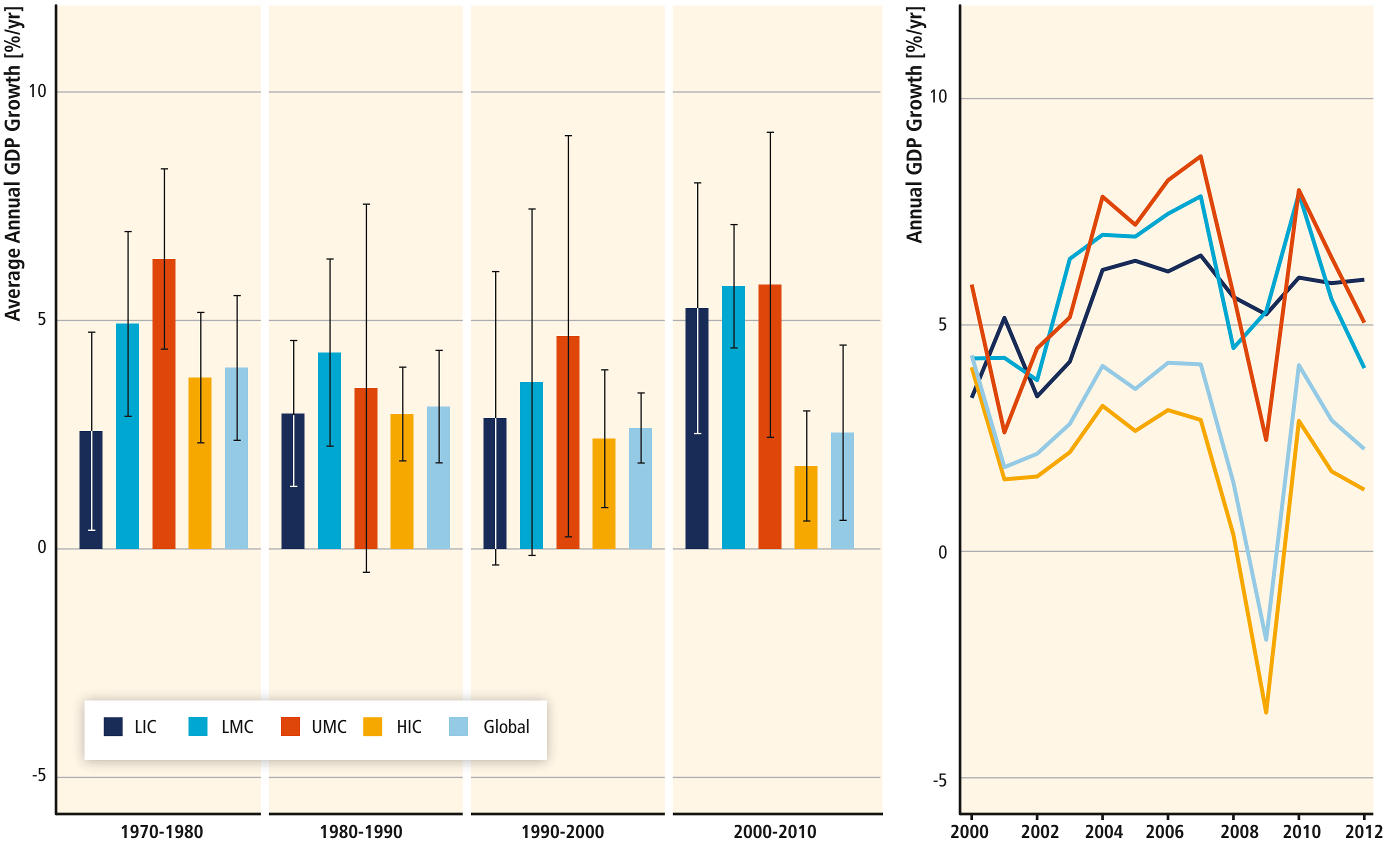


Figure 1.1 | Annual real growth rates of GDP by decade (left panel) and since 2000 (right panel) for four groups of countries as defined by the World Bank (World Bank, 2013): high-income, mature industrialized countries (HIC), upper-middle-income countries (UMC), lower-middle-income (LMC), and low-income countries (LIC) and globally. The category of 49 least developed countries (LDCs) as defined according to the United Nations (United Nations, 2013b) overlaps heavily with the 36 countries that the World Bank classifies as 'low-income'. Estimates weighted by economic size and variations to one standard deviation are shown. Growth rates weighted by size of the economy; whiskers on the decadal averages (left panel) show variation to one standard deviation within each category and decade. Sources: MER converted real growth rates from World Bank (2013) and IMF (2013b).

The continued growth of developing economies, albeit at a slower pace than before the crisis, helps to explain why global commodity prices, such as for oil and metals, have quickly rebounded (see Figure 1.2). Another factor that helps explain continued high prices for some commodities are reductions in supply in response to weakening demand. Among the many implications of high and volatile commodity prices are continued concerns about the availability and security of energy and food supply, especially in the least-developed countries. Those concerns have also reshaped, to some degree, how problems such as global climate change are viewed in many countries and societies. Where climate change mitigation has linked to these broader economic and energy security concerns it has proven politically easier to mobilize action; where they are seen in conflict the other economic and security priorities have often dominated (Chandler et al. 2002; IEA 2007; ADB 2009).

The implications of these macroeconomic patterns are many, but at least five are germane to the challenges of climate change mitigation:

- First, the momentum in global economic growth has shifted to the emerging economies—a pattern that was already evident in the 2000s before the crisis hit. Although accelerated by the recent financial crisis, this shift in production, investment, and technology to emerging economies is a phenomenon that is consistent with the expectation that in a globalized world economy capital resources will shift to emerging economies if they can be used with greater marginal productivity commensurate with associated risks (Zhu, 2011). With that shift has been a shift in the growth of greenhouse gas emissions to these emerging economies as well.

- Second, much of this shift has arisen in the context of globalization in investment and trade, leading to higher emissions that are 'embodied' in traded goods and services, suggesting the need for additional or complementary accounting systems that reflect the ultimate consumption of manufacturing goods that cause emissions rather than just the territorial place where emissions occurred during manufacturing (Houser et al., 2008; Davis and Caldeira, 2010; Peters et al., 2011, 2012a) (see also Chapter 5).

- Third, economic troubles affect political priorities. As a general rule, hard economic times tend to focus public opinion on policies that yield immediate economic benefits that are realized close to home

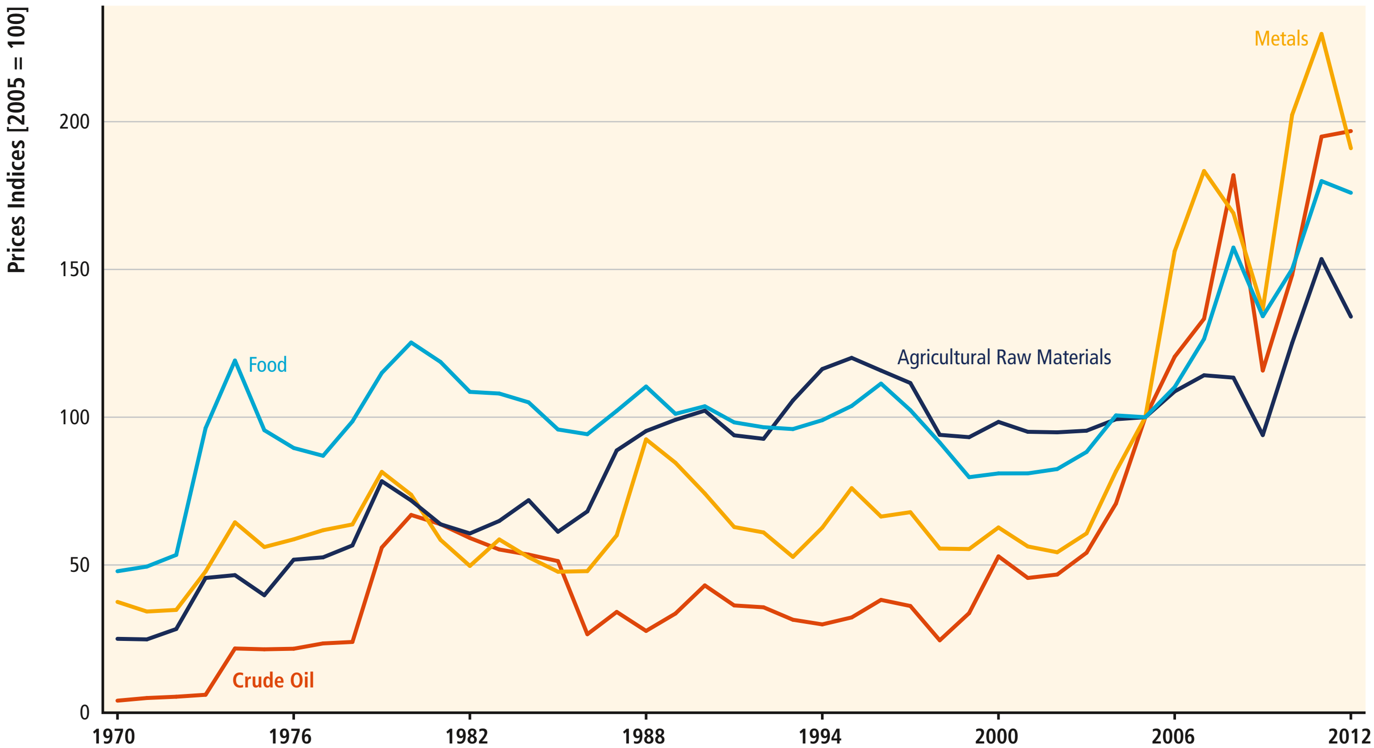


Figure 1.2 | Price indices for four major baskets of commodities: agricultural raw materials, food, crude oil, and metals. Source: IMF (2013a).

(Kahler and Lake, 2013). Long-term goals, such as global climate protection, suffer unless they are framed to resonate with these other, immediate goals. Chapter 2 of this volume looks in more detail at the wider array of factors that affect how humans perceive and manage risks that are spread out over long time horizons.

- Fourth, economic slowdown may also reduce the rate of technological progress that contributes to addressing climate change, such as in energy efficiency (Bowen et al., 2009), but for alternative views, see (Peters et al., 2012b). The crisis also has accelerated shifts in the global landscape for innovation (Gnamus, 2009). The largest emerging economies have all built effective systems for innovation and deployment of new technologies—including low emission technologies. Thus 'technology transfer' now includes 'South-South' although a central role remains for 'North-South' diffusion of technologies as part of a global effort to mitigate emissions (see also Chapters 5 and 16).

- Fifth, commodity prices remain high and volatile despite sluggish economic growth in major parts of the world economy. High costs for food have amplified concerns about competition between food production and efforts to mitigate emissions, notably through the growing of bioenergy crops (see 11.13). High prices for fossil fuels along with steel and other commodities affect the cost of building and operating different energy systems, which could in turn affect mitigation since many of the options for cutting emissions (e.g., power plants with carbon capture and storage technology) are relatively intensive users of steel and concrete. Relatively expensive energy will, as well, encourage conservation and efficiency. Since AR4 there have been substantial changes in the availability, cost, and performance of energy systems—a topic to which we now turn.

1.2.3 The availability, cost and performance of energy systems

The purpose of energy systems—from resource extraction to refining and other forms of conversion, to distribution of energy services for final consumption—is to provide affordable energy services that can catalyze economic and social development. The choice of energy systems depends on a wide array of investment and operating costs, the relative performance of different systems, infrastructures, and lifestyles. These choices are affected by many factors, such as access to information, status, access to technology, culture, price, and performance (Garnaut, 2011). The assessment of different energy options depends critically on how externalities, such as pollution, are included in the calculations.

Following a decade of price stability at low levels, since 2004 energy prices have been high and volatile (see Figure 1.2). Those prices have gone hand-in-hand with substantial geopolitical consequences that have included a growing number of oil importing countries focusing on policies surrounding energy security (e.g., Yergin, 2011). Some analysts interpret these high prices as a sign of imminent 'peak production' of exhaustible resources with subsequent steady decline, while others have argued that the global fossil and fissile resource endowment is plentiful (Rogner, 2012). Concerns about the scarcity of resources have traditionally focused on oil (Aleklett et al., 2010), but more recently the notions of peak coal (Heinberg and Fridley, 2010), peak gas, and peak uranium (EWG, 2006) have also entered the debate (see 7.4).

Sustained high prices have encouraged a series of technological innovations that have created the possibility of large new supplies from unconventional resources (e.g., oil sands, shale oil, extra-heavy oil, deep gas, coal bed methane (CBM), shale gas, gas hydrates). By some estimates, these unconventional oil and gas sources have pushed the 'peak' out to the second half of the 21st century (GEA, 2012), and they are a reminder that 'peak' is not a static concept. These unconventional sources have raised a number of important questions and challenges, such as their high capital intensity, high energy intensity (and cost), large demands on other resources such as water for production and other potential environmental consequences. Consequently, there are many contrasting viewpoints about the future of these unconventional resources (e.g., Hirsch et al., 2006; Smil, 2011; IEA, 2012a; Jordaan, 2012; Rogner et al., 2012).

The importance of these new resources is underscored by the rapid rise of unconventional shale gas supplies in North America—a technology that had barely any impact on gas supplies at the time that the AR4 was being finalized in 2006, but that by 2010 accounted for one-fifth of North American gas supply with exploratory drilling elsewhere in the world now under way. This potential for large new gas supplies—not only from shale gas but also coal-bed methane, deep gas, and other sources—could lower emissions where gas competes with coal if gas losses and additional energy requirements for the fracturing process can be kept relatively small. (A modern gas-fired power plant emits about half the CO_2 per unit of electricity than a comparable coal-fired unit.) In the United States, 49 % of net electricity generation came from coal in 2006; by 2011 that share had declined to 43 % and by 2012 that share had declined to 37 % and could decline further as traditional coal plants face new environmental regulations as well as the competition from inexpensive natural gas (EIA, 2013a; b; d). Worldwide, however, most baseline projections still envision robust growth in the utilization of coal, which already is one of the fastest growing fuels with total consumption rising 50 % between 2000 and 2010 (IEA, 2011a). The future of coal hinges, in particular, on large emerging economies such as China and India as well as the diffusion of technologies that allow coal combustion with lower emissions (GEA, 2012).

An option of particular interest for mitigating emissions is carbon dioxide capture and storage (CCS), which would allow for the utilization of coal while cutting emissions. Without CCS or some other advanced coal combustion system, coal is the most emission intensive of all the major fossil fuels yet, as we discuss below, consumption of coal is expanding rapidly. Thus, since AR4, CCS has figured prominently in many studies that look at the potential for large cuts in global emissions (IEA, 2010a, 2011b; GEA, 2012). However, CCS still has not attracted much tangible investment. By mid-2012 there were eight large-scale projects in operation globally and a further eight under construction. The total CO_2 emissions avoided by all 16 projects in operation or under construction will be about 36 million tonnes a year by 2015, which is less than 0.1 % of total expected world emissions that year (Global CCS Institute, 2012). CCS is much discussed as an option for mitigation but not much deployed. The fuller implementation of large-scale CCS systems generally requires extensive funding and an array of complementary institutional arrangements such as legal frameworks for assigning liability for long-term storage of CO_2. Since AR4, studies have underscored a growing number of practical challenges to commercial investment in CCS (IEA 2010b) (see also Chapter 7).

Since AR4, innovation and deployment of renewable energy supplies has been particularly notable (IEA, 2012a; GEA, 2012). The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (IPCC, 2011) provides a comprehensive assessment of the potential role of renewables in reducing GHG emissions. Globally wind electricity generating capacity has, for example, experienced double-digit annual growth rates since 2005 with an increasing share in developing countries. While still being only a small part of the world energy system, renewable technology capacities, especially wind but also solar, are growing so rapidly that their potential for large scale growth is hard to assess but could be very large (IEA, 2011b; GEA, 2012). Renewable energy potentials exist not only for stationary users via electricity but also for transportation through biofuels and electric-powered vehicles (see 11.13). Renewable energy technologies appear to hold great promise, but like all major sources of energy they also come with an array of concerns. Many renewable sources of electricity are variable and intermittent, which can make them difficult to integrate into electric grids at scale (see Chapter 7; Chapter 8 in IPCC, 2011). Some biofuels are contested due to fears for food security and high lifecycle greenhouse gas emissions of some fuel types (see Chapter 2 in IPCC, 2011; Delucchi, 2010). Other concerns are financial, since nearly every major market for renewable energy has relied heavily on a variety of policy support such as subsidies, leading investors and analysts alike to wonder whether and how these energy sources will continue to be viable for investors if subsidies are curtailed. Indeed, some governments concerned about the size of public budgets have pared back subsidies and claimed that additional cutbacks will be forthcoming.

Since AR4, there have also been substantial advances in the technological possibilities for making energy systems more efficient and responsive. The use of energy efficient devices, plants, and equipment has been legislated in many jurisdictions (RISØ, 2011). Integrating information and communication technology (ICT) into energy networks offers the potential to deliver and use energy more efficiently and flexibly, which could make it much easier to integrate variable and intermittent renewable power sources into existing electric grids. (Improved energy storage technologies could also play a central role.) This interconnection offers the promise of energy systems—especially in electricity, where the potential for pervasive use of ICT is often called a 'smart grid'—that integrate demand response with supplies, allowing for smooth and reliable operation of grids even with fluctuating renewable supplies (EPRI, 2011). Innovations of this type may also interact with behavioural changes that can have large effects on emissions as well. For example, greater flexibility and efficiency could encourage consumers to use more energy, partially offsetting the benefits of these investments in smarter energy supply networks. Or, close attention to energy supplies could encourage shifts in behaviour that are much more frugal with energy (see Chapter 7).

A central challenge in shifting to clean energy supplies and to creating much more efficient end-use of energy is that many energy technologies require large capital costs with long time horizons. Thus, even when such technologies are cost-effective they may face barriers to entry if investors and users are not confident that needed policy and market support will be reliable. Innovations in financing—for example, mechanisms that allow households to lease solar panels rather than pay the full cost up front—can play a role in addressing such issues, as can public schemes to fund initial deployment of new technologies. Such arrangements are part of a broader effort often called 'market transformation' that, if implemented well, can lead to new trajectories for deployment of technologies that otherwise would face many barriers to entry (IEA, 2010c).

Since AR4, a large number of governments have begun to explore the expansion or introduction of nuclear power. They have also faced many challenges in the deployment and management of this technology. Countries with active nuclear power programmes have been contemplating replacing aging plants with new builds or expanding the share of nuclear power in their electricity mix for reasons of economics, supply security, and mitigation of climate change. In addition, more than 20 countries, currently, that have never had commercial reactors have launched national programmes in preparation for the introduction of the technology, and several newcomer countries have entered contractual arrangements with vendors (IAEA, 2011).

After the Fukushima accident in March 2011, an event that forced Japan to review its energy policy substantially, the future patterns in nuclear power investment have become more difficult to parse. Some countries have scaled back nuclear investment plans or ruled out new build (e.g., Switzerland, Belgium); some, notably Germany, have decided to close existing reactors. In the United States, since AR4, several reactors have been slated for closure and owners have announced that still more closures are possible—mainly for reasons of economic competitiveness since aging reactors can be costly to maintain in the face of less expensive gas-fired electricity. At the same time, in 2013 construction began on four new reactors in the United States—the first new construction in that country in three decades. Several countries preparing the introduction of nuclear power have extended the time frame for the final go-ahead decisions; only few in a very early stage of preparation for the introduction stopped their activities altogether. In other countries, including all the countries that have been most active in building new reactors (e.g., China, India, Russia, and South Korea), there aren't many noticeable effects from Fukushima and the investment in this energy source is accelerating, despite some scale-back in the wake of Fukushima (IEA, 2012a). These countries' massive investments in nuclear were much less evident, especially in China, India and South Korea, at the time of AR4.

The Fukushima accident has also increased investment in deployment of new, safer reactor designs such as so-called 'Generation III' reactors and small modular reactors (see Chapter 7.5.4). Despite all of these new investment activities, standard baseline projections for the world energy system see nuclear power declining slightly in share as total demand rises and other electric power sources are more competitive (IEA, 2012a; EIA, 2013c). In many countries, the future competitiveness of nuclear power hinges on the adoption of policies that account for the climate change and energy security advantages of the technology.

1.2.4 International institutions and agreements

For more than two decades formal intergovernmental institutions have existed with the task of promoting coordination of national policies on the mitigation of emissions. In 1992, diplomats finalized the United Nations Framework Convention on Climate Change (UNFCCC), which entered into force in 1994. The first session of the Conference of the Parties (COP) to that Convention met in Berlin in 1995 and outlined a plan for new talks leading to the Kyoto Protocol in 1997, which entered into force in 2005. The main regulatory provisions of the Kyoto Protocol concerned numerical emission targets for industrialized countries (listed in Annex B of the Protocol[1]) during the years 2008 to 2012. When AR4 concluded in 2007, diplomats were in the early stages of negotiations for possible amendment of the Kyoto treaty while also exploring other mechanisms to encourage additional long-term cooperation on mitigation. The regulatory targets of the original Kyoto treaty would expire at the end of 2012. Those negotiations had been expected to finish at the COP 15 meeting in Copenhagen in 2009, but a wide number of disagreements made that impossible. Instead, talks continued while, in tandem, governments made an array of pledges that they solidified at the 2010 COP meeting in Cancun. These 'Cancun pledges' concern the policies they would adopt to mitigate emissions and other related actions on the management of climate risks; some of those pledges are contingent upon actions by other countries. The

[1] In this chapter, Annex B countries are categorized as: countries that are members of Annex B; countries originally listed in Annex B but which are not members of the Kyoto Protocol (non-members are USA and Canada). Countries not listed in Annex B are referred to as non-Annex B.

91 countries that adopted these pledges account for the vast majority (about 80 %) of world emissions (UNFCCC, 2011, 2012a; b; UNEP, 2012). If fully implemented, the pledges might reduce emissions in 2020 about one-tenth below the emissions level that would have existed otherwise—not quite enough to return emissions to 2005 levels—and it would be very hard to attain widely discussed goals of stabilizing warming at 1.5 or 2 degrees without almost immediate and full participation in international agreements that coordinate substantial emission reductions (Figure 1.9). International agreements are discussed in detail in Chapter 13 of this report.

At this writing, diplomatic talks are focused on the goal of adopting a new agreement that would raise the level of ambition in mitigation and be in effect by 2020 (UNFCCC, 2012c). In tandem, governments have also made a number of important decisions, in particular the adoption at Doha in 2012 of the second commitment period of the Kyoto Protocol, from 2013 to 2020. However, five developed countries originally listed in Annex B of the Kyoto Protocol are not participating in the second commitment period: Canada, Japan, New Zealand, Russia, and the United States (UNFCCC, 2013b).

The growing complexity of international diplomacy on climate change mitigation, which has been evident especially since AR4 and the Copenhagen meeting, has led policymakers and scholars alike to look at many other institutional forms that could complement the UN-based process. Some of these initiatives imply diplomatic efforts on separate parallel tracks (see Chapter 13). Proposals exist within the Montreal Protocol on Substances that Deplete the Ozone Layer to regulate some of the gases that have replaced ozone-destroying chemicals yet have proved to have strong impacts on the climate. A wide array of other institutions has become engaged with the climate change issue. The G8—the group of Canada, France, Germany, Italy, Japan, Russia, the UK, and the USA that convenes regularly to address a wide array of global economic challenges—has repeatedly underscored the importance of limiting warming to 2 degrees and implored its members to take further actions. The G20, a much broader group of economies has put climate change matters on its large agenda; the G20 has also helped to organize active efforts to reform fossil fuel subsidies and to implement green growth strategies. The UN, itself, has a large number of complementary diplomatic efforts on related topics, such as the 'Rio+20' process.

Many other institutions are now actively addressing particular aspects of climate change mitigation, such as the International Renewable Energy Agency (IRENA), which focuses on renewable energy; the Climate and Clean Air Coalition (CCAC), which focuses on how limits on short-lived pollutants such as black carbon can help slow climate change, the International Atomic Energy Agency (IAEA), which focuses on nuclear power, the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO) that have focused on emissions from bunker fuels, and many others with expertise in particular domains. The International Energy Agency (IEA) is now extensively engaged in analyzing how developments in the energy sector could affect patterns of emissions (e.g., IEA, 2012). Looking across these many different activities, international institutions that have engaged the climate change topic are highly decentralized rather than hierarchically organized around a single regulatory framework (Keohane and Victor, 2011). Since AR4, research on decentralized international institutions has risen sharply (Alter and Meunier, 2009; Zelli et al., 2010; Johnson and Urpelainen, 2012), building in part on similar concepts that have emerged in other areas of research on collective action (e.g., McGinnis, 1999; Ostrom, 2010).

Since AR4, there has been a sharp increase in scholarly and practical attention to how climate change mitigation could interact with other important international institutions such as the World Trade Organization (WTO) (see also Chapter 13 of this volume) (Brewer, 2010). Relationships between international trade agreements and climate change have been a matter of long standing interest in climate diplomacy and are closely related to a larger debate about how differences in environmental regulation might affect economic competitiveness as well as the spread of mitigation and adaptation technology (Gunther et al., 2012). A potential role for the WTO and other trade agreements also arises because the fraction of emissions embodied in internationally traded goods and services is rising with the globalization of manufacturing (see 1.2.1.2 above and 1.3.1 below). Trade agreements might also play a role in managing (or allowing the use of) trade sanctions that could help enforce compliance with mitigation commitments—a function that raises many legal questions as well as numerous risks that could lead to trade wars and an erosion of political support that is essential to the sustainability of an open trading system (Bacchus et al., 2010). For example, Article 3 of the UNFCCC requires that "[m]easures taken to combat climate change, including unilateral ones, should not constitute a means of arbitrary or unjustifiable discrimination or a disguised restriction on international trade." (UNFCCC, 1992). The impacts of mitigation on trade issues are also related to concerns that have been raised about how emission controls could reduce national employment and income (ILO, 2012, 2013).

Since the AR4 in 2007, the scholarly community has analyzed the potentials, design, and practices of international cooperation extensively. A body of research has emerged to explain why negotiations on complex topics such as climate change are prone to gridlock (Murase, 2011; Victor, 2011; Yamaguchi, 2012). There is also a large and vibrant research program by political scientists and international lawyers on institutional design, looking at issues such as how choices about the number of countries, type of commitments, the presence of enforcement mechanisms, schemes to reduce cost and increase flexibility, and other attributes of international agreements can influence their appeal to governments and their practical effect on behaviour (see e.g., the comprehensive reviews and assessment on these topics by Hafner-Burton, Victor, and Lupu, 2012 as well as earlier research of Abbott et al., 2000; and Koremenos, Lipson, and Snidal, 2001). Much of that research program has sought to explain when and how international institutions, such as treaties, actually help solve common problems. Such research is part of a rich tradition of scholarship aimed at explaining whether and how countries comply with their international commitments (Downs et al., 1996; Simmons, 2010). Some of that research focuses on policy strategies that do not involve formal legalization but, instead, rely more heavily on setting norms through industry organizations, NGOs, and other groups (Vogel, 2008; Buthe and Mattli, 2011). The experience with voluntary industry standards has been mixed; in some settings these standards have led to large changes in behaviour and proved highly flexible while in others they have little or no impact or even divert attention (Rezessy and Bertoldi, 2011).

One of the many challenges in developing and analyzing climate change policy is that there are long chains of action between international institutions such as the UNFCCC and the ultimate actors whose behaviour might be affected, such as individuals and firms. We note that there have been very important efforts to engage the business community on mitigation as well as adaptation to facilitate the market transformations needed for new emission technologies and business practices to become widespread (WEF, 2009; UN Global Compact and UNEP, 2012) (see Chapter 15). While there are diverse efforts to engage these many different actors, measuring the practical impact on emissions has been extremely difficult and much of the scholarship in this area is therefore highly descriptive.

1.2.5 Understanding the roles of emissions other than fossil fuel CO_2

Much policy analysis has focused on CO_2 from burning fossil fuels, which comprise about 60 % of total global greenhouse gas emissions in 2010 (see Section 1.3.1 below). However, the UNFCCC and the Kyoto Protocol cover a wider array of CO_2 sources and of warming substances—including methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6). Nitrogen trifluoride (NF_3) was added as a GHG under the Kyoto Protocol for its second commitment period. This large list was included, in part, to create opportunities for firms and governments to optimize their mitigation efforts flexibly across different substances. The effects of different activities on the climate varies because the total level of emissions and the composition of those emissions varies. For example, at current levels the industrial and power sectors have much larger impacts on climate than agriculture (Figure 1.3).

A variety of studies have shown that allowing for trading across these different gases will reduce the overall costs of action; however, many studies also point to the complexity in agreeing on the correct time horizons and strategies for policy efforts that cover gases with such different properties (Reilly et al., 2003; Ramanathan and Xu, 2010; Shindell et al., 2012). In addition to the gases regulated under the Kyoto Protocol, many of the gases that deplete the ozone layer—and are regulated under the Montreal Protocol on Substances that Deplete the Ozone Layer—are also strong greenhouse gases (Velders et al., 2007). Since AR4 a variety of short-lived climate pollutants (SLCPs) have come under scrutiny (UNEP, 2011a; Shindell et al., 2012; Victor et al., 2012; Smith and Mizrahi, 2013). Those include tropospheric ozone (originating from air pollutant emissions of nitrogen oxides and various forms of incompletely oxidized carbon) and aerosols (such as black carbon and organic carbon and secondary such as sulphates) that affect climate forcing (see Chapter 8, Section 8.2.2 and Section 5.2). This remains an area of active research, not least because some studies suggest that the climate impacts of short-lived pollutants like black carbon could be much larger or smaller (Ramanathan and Carmichael, 2008; Bond et al., 2013) (WGI, Chapters 7 and 8). Such pollutants could have a large role in mitigation strategies since they have a relatively swift impact on the climate—combined with mitigation of long-lived gases like CO_2 such strategies could make it more easily feasible to reach near-term temperature goals, but there are still many debates over the right balance of mitigation effort on short-lived and long-lived pollutants (Ramanathan and Xu, 2010; Penner et al., 2010; Victor et al., 2012; Smith and Mizrahi, 2013). By contrast, other aerosols—notably the sulphate aerosol formed from SO_2 emissions from the industrial and power sectors, shipping, and large-scale biomass burning—have a net cooling effect because they interact with clouds to reflect sunlight back to space (see Section 5.2 and WGI, Chapter 7.4; (Fuglestvedt et al., 2009).

Starting with the FAR, the IPCC has calculated global warming potentials (GWPs) to convert climate pollutants into common units over 20, 100, and 500 year time horizons (Chapter 2, IPCC, 1990b). Indeed, when GWPs were first presented by IPCC the analysis included the statement that "[t]hese three different time horizons are presented as candidates for discussion and should not be considered as having any special significance" (see Chapter 2, page 59 in IPCC, 1990b). In the Kyoto Protocol, diplomats chose the middle value—100 years—despite the lack of any published conclusive basis for that choice (Shine, 2009). That approach emphasizes long-lived pollutants such as CO_2, which are essential to stopping climate warming over many decades to centuries. As shown in Table 1.1, when GWPs are computed with a short time horizon the share of short-lived gases, notably methane, in total warming is much larger and that of CO_2 becomes proportionally smaller. The uncertainty in the GWPs of non-CO_2 substances increases with time horizon and for GWP_{100} the uncertainty is about 30 % to 40 % (90 % confidence interval) (IPCC, 2013a). If policy decisions are taken to emphasize SLCPs as a means of altering short-term rates of climate change rises then alternative GWPs or other metrics and mitigation strategies may be needed (IPCC, 2009; Fuglestvedt et al., 2010; Victor et al., 2012; Daniel et al., 2012; Smith et al., 2012). Additional accounting systems may also be needed.

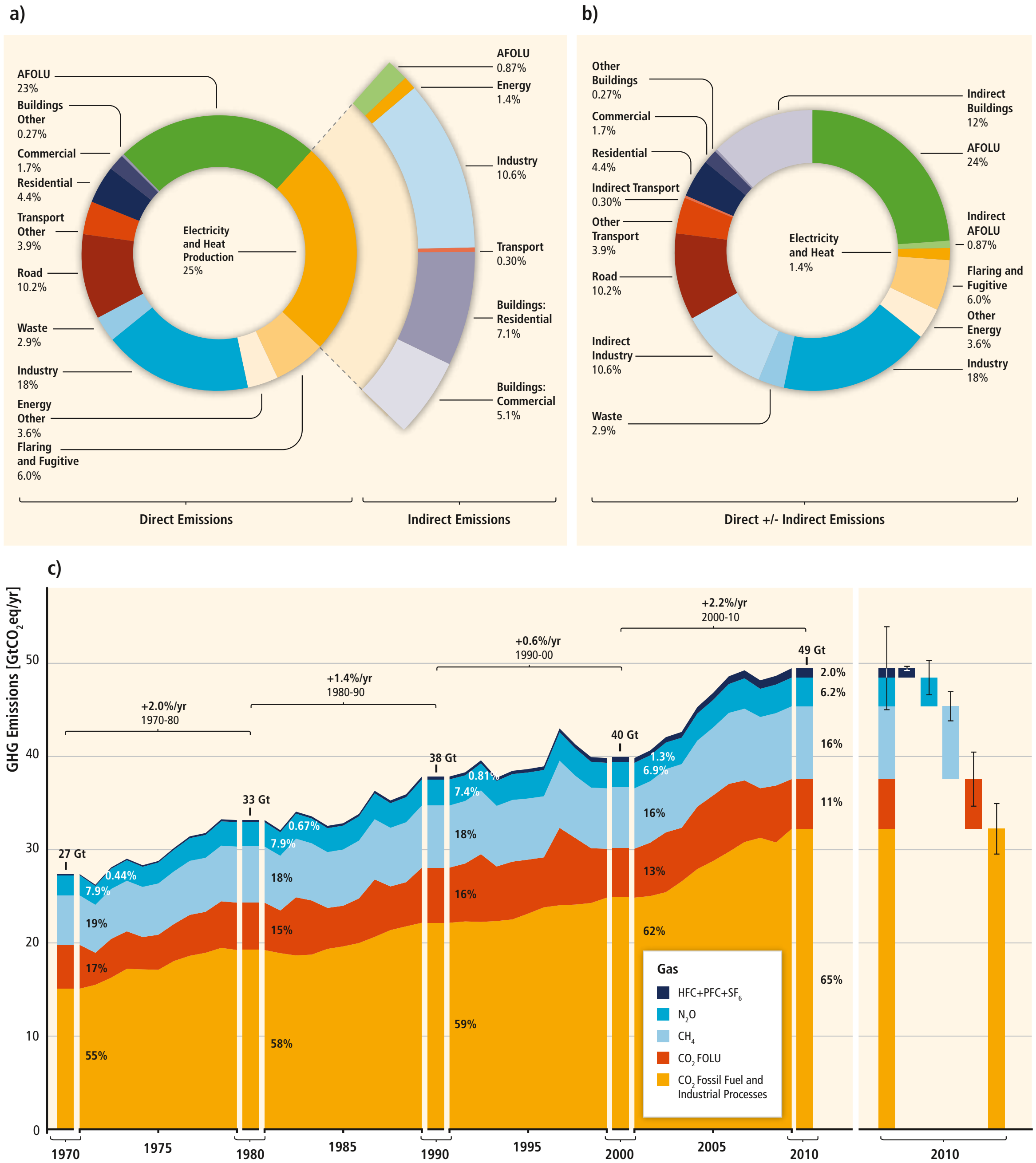


Figure 1.3 | Panel A (top left): Allocation of total GHG emissions in 2010 (49.5 $GtCO_2eq/yr$) across the five sectors examined in detail in this report (see Chapters 7–11). Pullout from panel A allocates indirect CO_2 emission shares from electricity and heat production to the sectors of final energy use. Panel B (top right): Allocates that same total emissions (49.5 $GtCO_2eq/yr$) to reveal how each sector's total increases or decreases when adjusted for indirect emissions. Panel C (lower panel): Total annual GHG emissions by groups of gases 1970–2010, along with estimated uncertainties illustrated for 2010 (whiskers). The uncertainty ranges provided by the whiskers for 2010 are illustrative given the limited literature on GHG emission uncertainties. Sources: Historic Emission Database IEA/EDGAR dataset (JRC/PBL, 2013, IEA, 2012a), see Annex II.9. Data shown for direct emissions on Panels A and B represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthropogenic emissions sources in the FOLU (Forestry and Other Land Use) sub-sector—additional detail on Agriculture and FOLU ('AFOLU', together) fluxes is in Chapter 11, Section 11.2 and Figure 11.2 and 11.6. Emissions weighted with 100-year GWPs as used in the original Kyoto Protocol (i.e., values from the SAR as those values are now widely used in policy discussions) and, in general, sectoral and national/regional allocations as recommended by the 1996 IPCC guidelines (IPCC, 1996). Using the most recent GWP-100 values from the AR5 (see WGI Section 8.6) global GHG emission totals would be slightly higher (52 $GtCO_2eq$) and non-CO_2 emission shares are 20 % for CH4, 5 % for N_2O and 2 % for F-gases. Error bars in panel 1.3c show the 90 % confidence interval of the emission estimates based on these sources: CO_2 from fossil fuel and industrial processes ±8.4 % (Andres et al., 2012; Kirschke et al., 2013) CO_2 from FOLU ±2.9 $GtCO_2/yr$ (estimates from WGI table 6.1 with central value shown on figure 1.3c is per EDGAR/IEA); Methane ±20 % (Kirschke et al. 2013); Nitrous oxide ±60 % (WGI, table 6.9); F-gases ±20 % (UNEP, 2012). Readers are cautioned, however, that the literature basis for all of these uncertainty figures is very weak. There have been very few formal, documented analysis of emissions uncertainty for any gas. Indicative uncertainty for total emissions is from summing the squares of the weighted uncertainty of individual gases (see 5.2.3.4 for more detail), which yields a total uncertainty of +/–9 % for a 90 % confidence interval in 2010. We note, however, that there is insufficient published information to make a rigorous assessment of global uncertainty and other estimates suggest different uncertainties. The calculation leading to 9 % assumes complete independence of the individual gas-based estimates; if, instead, it is assumed that extreme values for the individual gases are correlated then the uncertainty range may be 19 %. Moreover, the 9 % reported here does not include uncertainties related to the choice of index (see table 1.1) and Section 1.2.5.

Table 1.1 | Implications of the choice of Global Warming Potential (GWP) for mitigation strategy. Table shows the main geophysical properties of the major Kyoto gases and the implications of the choice of values for GWPs with different time horizons (20, 100, or 500 years) on the share of weighted total emissions for 2010; other IPCC chapters report detail on alternative indexes such as Global Temperature change Potential (GTP) (Chapter 3; WGI Chapter 8). At present, the 100-year GWPs are used most widely, and we show those values as reported in the IPCC Second Assessment Report (SAR) in 1995 and subsequently used in the Kyoto Protocol. Note that CO_2 is removed by multiple processes and thus has no single lifetime (see WGI Box 6.1). We show CF_4 as one example of the class of perfluorocarbons (PFCs) and HFC-134a and HFC-23 as examples of hydrofluorocarbons (HFCs). All other industrial fluorinated gases listed in the Kyoto Protocol ('F-gases') are summed. We do not show warming agents that are not included in the Kyoto Protocol, such as black carbon. Emissions reported in JRC/PBL (2013) using GWPs reported in IPCC's Second, Fourth and Fifth Assessment Reports (IPCC, 1995, 2007c, 2013a). The AR4 was used for GWP-500 data; interpretation of long time horizon GWPs is particularly difficult due to uncertainties in carbon uptake and climate response—differences that are apparent in how different models respond to different pulses and scenarios for CO_2 and the many nonlinearities in the climate system (see WGI, Supplemental Material 8.SM.11.4 and Joos et al., 2013) and thus IPCC no longer reports 500 year GWPs. Due to changes in the GWP values from AR4 to AR5 the 500-year shares are not precisely comparable with the other GWPs reported here. Geophysical properties of the gases drawn from WGI, Appendix 8.A, Table 8.A.1—final draft data).

Kyoto gases	Geophysical properties		GWP-weighted share of global GHG emissions in 2010			
	Atmospheric lifetime (year)	Instantaneous forcing ($W/m^2/ppb$)	SAR (Kyoto)	WGI (20 and 100 year from AR5 & 500 year from AR4)		
			100 years	20 years	100 years	500 years
CO_2	various	1.37×10^{-5}	76 %	52 %	73 %	88 %
CH_4	12.4	3.63×10^{-4}	16 %	42 %	20 %	7 %
N_2O	121	3.00×10^{-3}	6.2 %	3.6 %	5.0 %	3.5 %
F-gases:			2.0 %	2.3 %	2.2 %	1.8 %
HFC-134a	13.4	0.16	0.5 %	0.9 %	0.4 %	0.2 %
HFC-23	222	0.18	0.4 %	0.3 %	0.4 %	0.5 %
CF_4	50,000	0.09	0.1 %	0.1 %	0.1 %	0.2 %
SF_6	3,200	0.57	0.3 %	0.2 %	0.3 %	0.5 %
NF_3 *	500	0.20	not applicable	0.0 %	0.0 %	0.0 %
Other F-gases **	various	various	0.7 %	0.9 %	0.8 %	0.4 %

* NF_3 was added for the second commitment period of the Kyoto period, NF_3 is included here but contributes much less than 0.1 %.

** Other HFCs, PFCs and SF_6 included in the Kyoto Protocol's first commitment period. For more details see the Glossary (Annex I).

1.2.6 Emissions trajectories and implications for Article 2

Chapter 1 of the WGIII AR4 found that, without major policy changes, the totality of policy efforts do not put the planet on track for meeting the objectives of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) (IPCC, 2007a). Since then, emissions have continued to grow—a topic we examine in more detail below. Article 2 of the UNFCCC describes the ultimate objective of the Convention. It states:

> *The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner. (UNFCCC, 1992).*

Interpreting the UNFCCC goal is difficult. The first part of Article 2, which calls for stabilization of GHG concentration at levels that are not 'dangerous,' requires examining scientific climate impact assessments as well as normative judgments—points that are explored in detail in the WGII contribution. The second part of Article 2 is laden with conditions whose interpretation is even less amenable to scientific analysis. In light of the enormous variations in vulnerability to climate change across regions and ecosystems, it is unlikely that scientific evidence will conclude on a single such goal as 'dangerous'. Variations in what different societies mean by 'dangerous' and the risks they are willing to endure further amplify that observation. Article 2 requires that societies balance a variety of risks and benefits—some rooted in the dangers of climate change itself and others in the potential costs and benefits of mitigation and adaptation.

Since the publication of AR4 a series of high-level political events have sought to create clarity about what Article 2 means in practice. For example, the Bali Action Plan, adopted at COP 13 held in Bali, Indonesia, in December 2007, cited AR4 as a guide for negotiations over long-term cooperation to manage climate change. At the L'Aquila G8 Summit in 2009, five months before the COP15 meeting in Copenhagen, leaders "recognized the broad scientific view that the increase in global average temperature above pre-industrial levels ought not to exceed 2 °C," and they also supported a goal of cutting emissions at least 80 % by 2050 (G8 Leaders, 2009). Later that year, an COP 15, delegates 'took note' of the Copenhagen Accord which recognized "the scientific view that the increase in global temperature should be below 2 degree Celsius," and later meetings arrived at similar conclusions (Decision1/CP.16). Ever since the 2009 Copenhagen Conference the goal of 1.5 degrees has also appeared in official UN documents, and some delegations have suggested that a 1 degree target be adopted. Some scholars suggest that these goals can create focal points that facilitate policy coordination, although there is a variety of perspectives about whether these particular goals are playing that role, in part because of growing evidence that they will be extremely difficult or impossible to attain (Schneider and Lane, 2006; National Research Council of the National Academies, 2011; Victor, 2011; Helm, 2012). Readers should note that each major IPCC assessment has examined the impacts of multiplicity of temperature changes but has left political processes to make decisions on which thresholds may be appropriate (WGIII AR4 Chapter 1).

At present, emissions are not on track for stabilization let alone deep cuts (see Section 1.3 below). This reality has led to growing research on possible extreme effects of climate change and appropriate policy responses. For example, Weitzman (2009) raised the concern that standard policy decision tools such as cost-benefit analysis and expected utility theory have difficulty dealing with climate change decisions, owing to the difficulty in assessing the probability of catastrophic impacts. Partly driven by these concerns, the literature on geoengineering options to manage solar radiation and possibly offset climate change along with technologies that allow removal of CO_2 and other climate-altering gases from the atmosphere has been increasing exponentially (see 6.9). Because they have theoretically high leverage on climate, geoengineering schemes to alter the planet's radiation balance have attracted particular attention; however, because they also create many risks that are difficult if not impossible to forecast, only a small but growing number of scientists have considered them seriously (Rickels et al. 2011; Gardiner 2010; IPCC 2012; Keith, Parson, and Morgan 2010).

1.3 Historical, current and future trends

Since AR4 there have been new insights into the scale of the mitigation challenge and the patterns in emissions. Notably, there has been a large shift in industrial economic activity toward the emerging countries—especially China—that has affected those nations' emission patterns. At the same time, emissions across the industrialized world are largely unchanged from previous levels. Many countries have adopted policies to encourage shifts to lower GHG emissions from the energy system, such as through improved energy efficiency and greater use of renewable energy technologies.

1.3.1 Review of four decades of greenhouse gas emissions

While there are several sources of data, the analysis here relies on the EDGAR data set (JRC/PBL, 2013) [see Annex II.9 Methods and Metrics for a complete delineation of emission categories]. We focus here on all major direct greenhouse gases (GHGs) related to human activities—including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulphur hexafluoride (SF_6). We also examine various ozone-depleting substances (ODS), which are regulated under the Montreal Protocol due to their effects on the ozone layer but also act as long-lived GHG: chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and halons. Due to lack of comparable data we do not here examine black carbon, tropospheric ozone precursors, cooling aerosols, and nitrogen trifluoride (NF_3.) For the analyses that follow we use 100-year GWPs from the SAR because they are widely used by governments, but we are mindful that other time horizons and other global warming metrics also merit attention (see 1.2.5 above).

By sector, the largest sources of greenhouse gases were the sectors of energy production (34 %, mainly CO_2 from fossil fuel combustion), and agriculture, forestry and land-use (AFOLU) (24 %, mainly CH_4 and N_2O) (Figure 1.3a). Within the energy sector, most emissions originate from generation of electricity that is, in turn, used in other sectors. Thus, accounting systems in other sectors often refer to direct emissions from the sector (e.g., CO_2 emissions caused in industry during the production of cement) as well as 'indirect' emissions that arise outside the boundaries of that particular economic sector (e.g., the consumption of electric power in buildings causes indirect emissions in the energy supply sector (Figure 1.3a and 1.3b). Looking at the total source of greenhouse gases at present CO_2 contributes 76 %; CH_4 about 16 %, N_2O about 6 % and the combined F-gases about 2 % (Figure 1.3c).

Following the breakdown in sectors discussed in this report (Chapters 7 to 11), Figure 1.3c looks at emissions over time by gas and sector. Figure 1.4 looks at those patterns over time according to different groups of countries, which reveals the effects of periodic economic slowdowns and contractions on emissions. Globally, emissions of all greenhouse gases increased by about 75 % since 1970. Over the last two decades, a particularly striking pattern has been the globalization of production and trade of manufactured goods (see Section 1.2.1.2 above). In effect, high-income countries are importing large embodied emissions from the rest of the world, mainly the upper middle-income countries (Figure 1.5).

Overall, per-capita emissions in the highly industrialized countries are roughly flat over time and remain, on average, about 5 times higher than those of the lowest income countries whose per-capita emissions are also roughly flat. Per-capita emissions from upper-middle income countries have been rising steadily over the last decade (see inset to Figure 1.4). There are substantial differences between mean and median per-capita emissions, reflecting the huge variation within

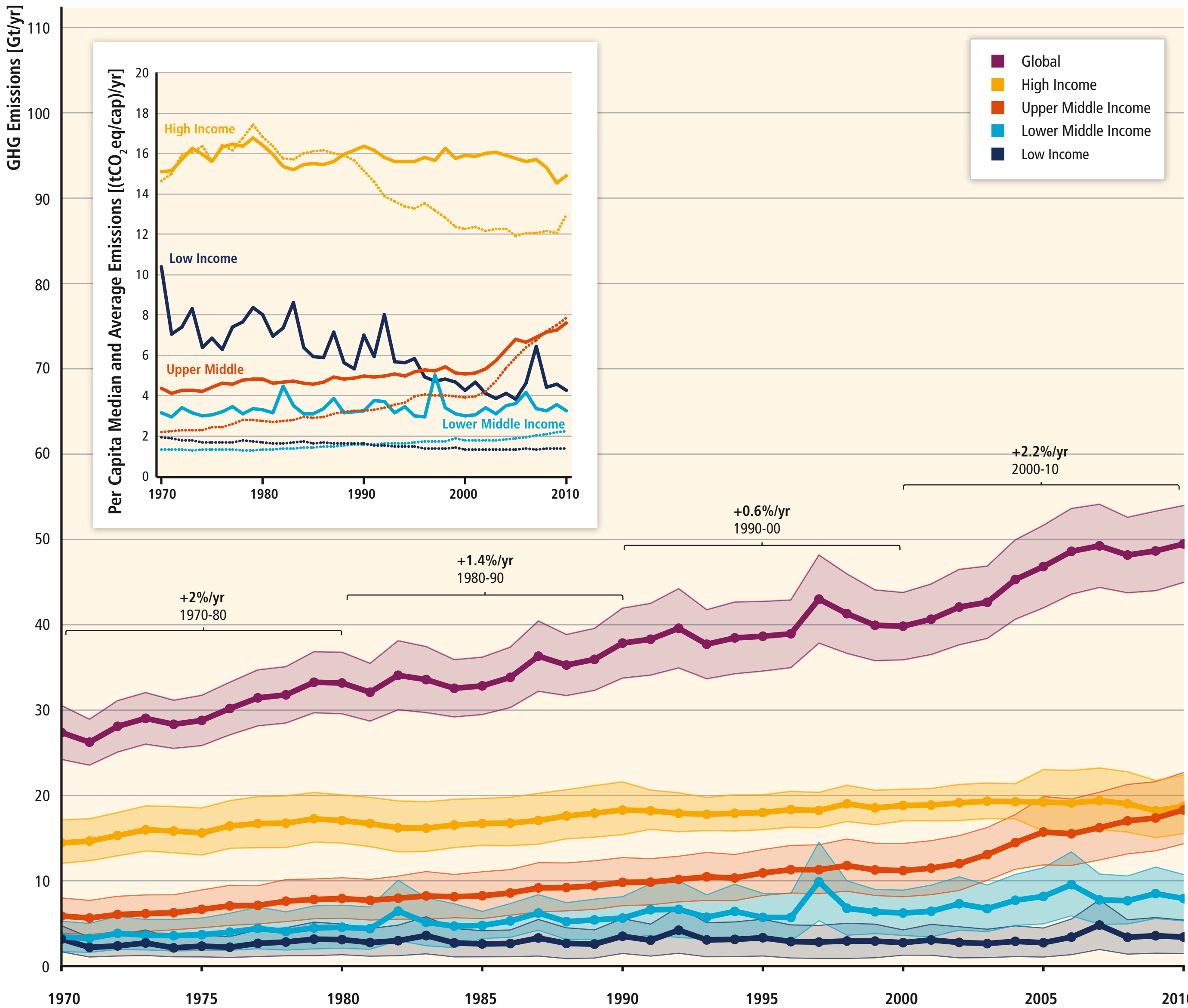


Figure 1.4 | Global growth in emissions of GHGs by economic region. Main figure shows world total (top line) and growth rates per decade, as well as the World Bank's four economic regions (see Figure 1.1 caption for more detail). Inset shows trends in annual per capita mean (solid lines) and median (dotted lines) GHG emissions by region 1970–2010 in tonnes of CO_2eq (t/cap/yr) (United Nations, 2013a). Global totals include bunker fuels; regional totals do not. The data used is from the same sources reported in Figure 1.3c. Error bars are approximated confidence interval of 1 standard deviation, derived by aggregating individual country estimates by gas and sector of the 16th and 84th emission percentiles provided by the MATCH analysis (Höhne et al., 2011); data also available at http://www.match-info.net/. However, we note that this probably over-states actual uncertainty in the totals, since individual country uncertainty estimates under this method are implicitly taken to be completely correlated. Thus, for the global totals we estimate a 90 % uncertainty range using the same method as discussed for Figure 1.3c. While in 2010 the uncertainty using that method is 9 %, over the full time period of Figure 1.4 the value varies from 9 % to 12 % with an average value of 10 %. We caution that multi-country and global uncertainty estimates remain an evolving area of research (see caption 1.3c and Section 5.2.3). Uncertainties shown on this chart are at best indicative of the unknowns but are not a definitive assessment.

these categories. Some very low income countries have extremely low per-capita emissions while some upper middle income developing countries have per-capita emissions comparable with those of some industrialized nations.

Emissions from the energy sector (mainly electricity production) and from transportation dominate the global trends. Worldwide power sector emissions have tripled since 1970 (see Figure 7.3), and transport has doubled (see Figure 8.1). Since 1990 emissions from electricity and heat production increased by 27 % for the group of OECD countries; in the rest of the world the rise has been 64 % (see Figure 7.5). Over the same period, emissions from road transport increased by 29 % in OECD countries and 61 % in the other countries (see Figure 8.3). Emissions from these systems depend on infrastructures such as power grids and roads, and thus there is also large inertia as those infrastructures are slow to change (Davis et al., 2010).

Forest related GHG emissions are due to biomass burning and decay of biomass remaining after forest burning and after logging. In addition, the data shown includes CO_2 emissions from decomposition of drained peatland and from peat fires (Olivier and Janssens-Maenhout, 2012). The forest related figures presented here are in line with the synthesis paper by Houghton et al. (2012) on recent estimates of carbon fluxes from land use and land cover change.

There has been a large effort to quantify the uncertainties in the historical emissions since AR4 was published. Such efforts have been difficult due to the small number of truly independent data sources, especially at the finest level of resolution such as emissions from particular sectors and countries. Uncertainties are particularly large for greenhouse gas emissions associated with agriculture and changes in land use. By contrast, recent estimates of emissions from fossil fuel combustion varied by only 2.7 % across the most widely used data sources (Macknick, 2011). In addition to variations in the total quantity of fossil fuel combusted, the coefficients used by IPCC to calculate emissions also vary from 7.2 % for coal use in industry to 1.5 % for diesel used in road transport (Olivier et al., 2010). Emissions from agriculture and land-use change are estimated to vary by 50 % (Tubiello et al., 2013), and a recent study that compared 13 different estimates of total emissions from changes in land use found broadly comparable results (Houghton et al., 2012). Since land use is a small fraction of total CO_2 emissions the total estimate of anthropogenic CO_2 emissions has uncertainty of only ±10 % (UNEP, 2012). Looking beyond CO_2, estimates for all other warming gases are generally more uncertain. Estimated uncertainties for global emissions of methane, nitrous oxide, and fluorine based gases are ±25 %, ±30 %, and ±20 % respectively (UNEP, 2012).

Statistically significant uncertainty quantifications require large independent and consistent data sets or estimates, which generally do not exist for historical GHG emission data. In such cases, uncertainty is referred to as 'indicative uncertainty' based on the limited information available that does not meet the standard of a rigorous statistical analysis (see 5.2.3).

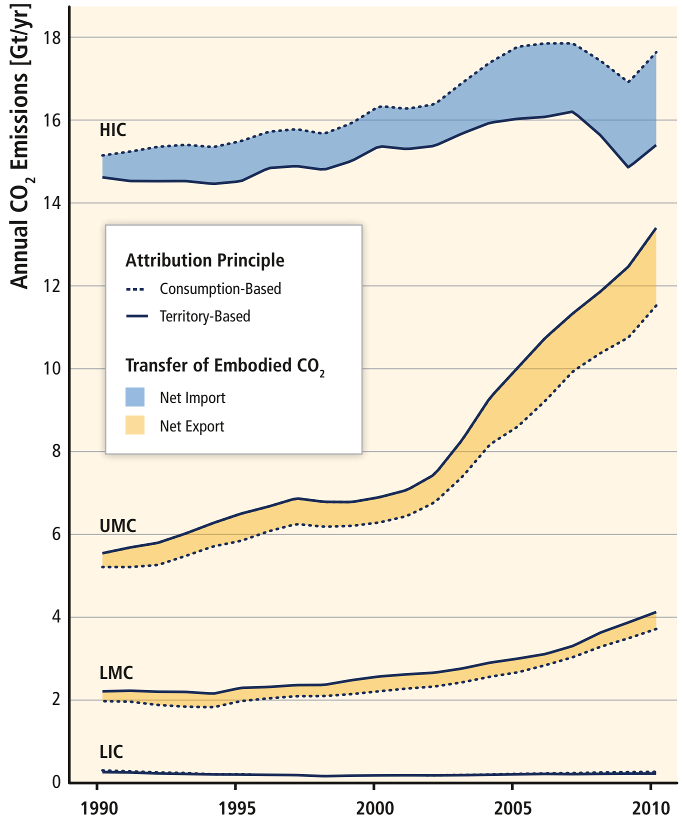


Figure 1.5 | CO_2 emissions from fossil fuel combustion for the four economic regions attributed on the basis of territory (solid line) and final consumption (dotted line) in gigatonnes of CO_2 per year (Gt/yr). The shaded areas are the net CO_2 trade balance (difference) between each of the four country groupings (see Figure 1.1) and the rest of the world. Blue shading indicates that the region is a net importer of emissions, leading to consumption-based CO_2 emission estimates that are higher than traditional territory-based emission estimates. Yellow indicates the reverse situation—net exporters of embodied emissions. Low-income countries, because they are not major players in the global trade of manufactured products, have essentially no difference between territory and consumption based estimates. For high-income countries and upper-middle-income countries, embodied emissions have grown over time. Figures based on Caldeira and Davis (2011) and Peters et al. (2012b), but with data from Eora, a global multi-regional input-output model (Lenzen et al., 2012, 2013).

When adjusting emission statistics to assign indirect GHG emissions from electricity and heat consumption to end-use sectors, as is done in panel 1.3b, the main sectors affected are the industrial and buildings sectors. Those sectors' shares in global GHG emissions then increase by 11 % and 12 % to reach levels of 31 % (industry) and 19 % (buildings). The addition of these so-called 'Scope 2' emissions is sometimes done to show or analyze the more comprehensive impact of total energy consumption of these end-use sectors to total energy-related emissions.

Figure 1.4 looks at these patterns from the global perspective over time. The AR4 worked with the most recent data available at the time (2004). Since then, the world has seen sustained accelerated annual growth of emissions—driven by CO_2 emissions from fossil fuel combustion. There was a temporary levelling off in 2008 linked to high fuel prices and the gathering global economic crisis, but the sustained economic growth in the emerging economies has since fuelled continued growth in world emissions. This is particularly evident in the economic data (Figure 1.1) showing that the large group of countries other than the highly industrialized nations continue to grow despite the world economic crisis. However, growth rates globally, including in these rapidly rising countries, have been slower than the levels seen in the 1990s, which portends less rapid growth in world emissions.

Figure 1.6 shows global GHG emissions since 1970 in 20-year intervals for the five economic sectors covered in Chapters 7–11, i.e., Energy Systems, Transport, Buildings, Industry and Agriculture, Forestry and Other Land Use (AFOLU). International transport ('bunkers') are shown separately as these can neither be attributed to any of these economic sectors or country grouping. In every country grouping except low-income countries, total emissions have risen since 1970 with the largest increases evident in energy systems. The only major sector that does not display these globally rising trends is AFOLU as a growing number of countries adopt policies that lead to better protection of forests, improved yields in agriculture reduce pressure to convert natural forests to cropland, and other trends allow for a 'great restoration' of previously degraded lands (Ausubel et al., 2013). In low-income countries total emissions are dominated by trends in AFOLU; in all other country groupings the energy system plays the central role in emissions.

It is possible to decompose the trends in CO_2 emissions into the various factors that 'drive' these outcomes—an exercise discussed in more detail in Chapter 5. One way to decompose the factors contributing to total emissions is by the product of population, GDP per capita, energy intensity (total primary energy supply per GDP) and the carbon intensity of the energy system (carbon emitted per unit energy). This approach is also known as the 'Kaya Identity' (Kaya, 1990) and resonates with similar earlier work (Holdren and Ehrlich, 1974). A variety of studies have done these decompositions (Raupach et al., 2007; Steckel et al., 2011; Cline, 2011; Akimoto et al., 2013). Figure 1.7 shows such an analysis for the global level, and Chapter 5 in this report offers more detailed decompositions.

The analysis reveals enhanced growth in the 2000s of global income, which drove higher primary energy consumption and CO_2 emissions.

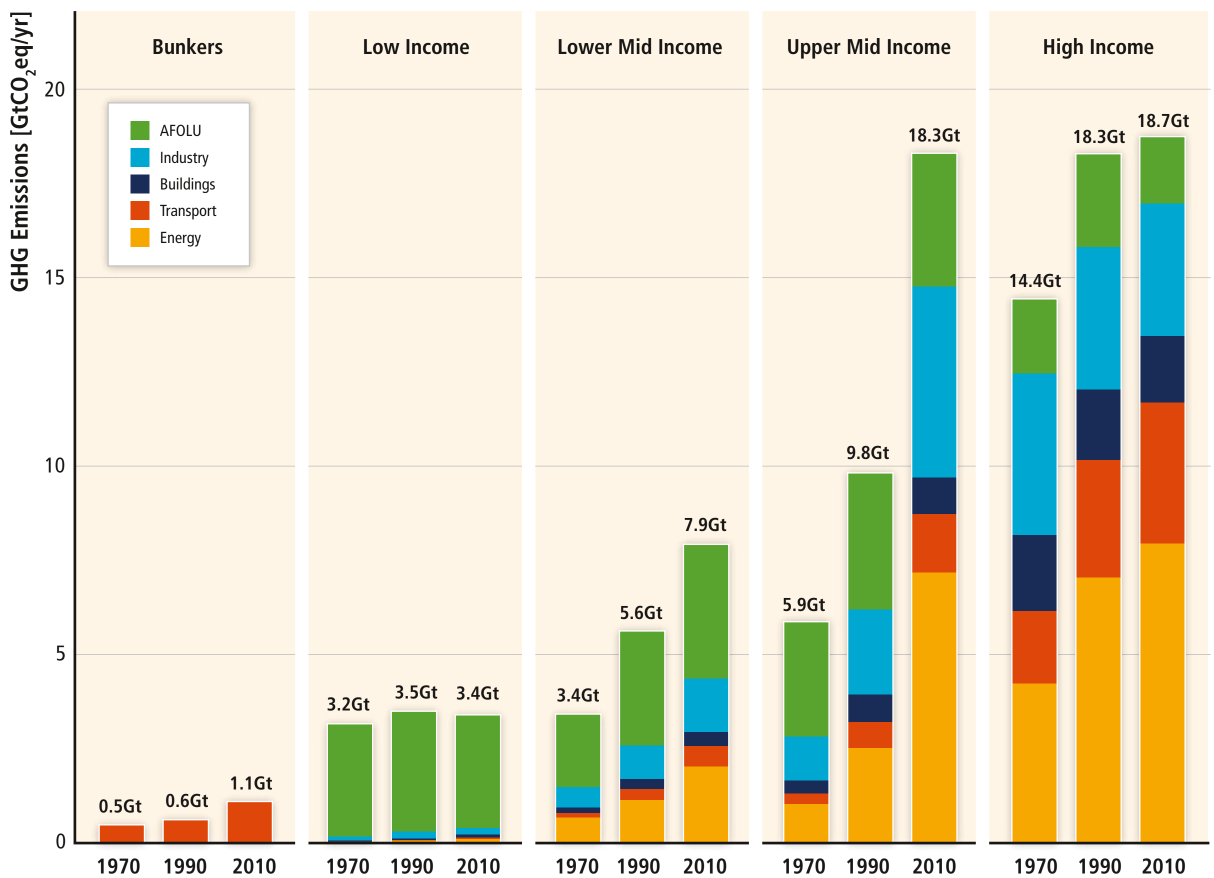


Figure 1.6 | Greenhouse gas emissions measured in gigatonnes of CO_2eq per year (Gt/yr) in 1970, 1990 and 2010 by five economic sectors (Energy supply, Transport, Buildings, Industry, as well as Agriculture, Forestry and Other Land Use (AFOLU) and four economic regions (see caption to Figure 1.1). 'Bunkers' refer to emissions from international transportation and thus are not, under current accounting systems, allocated to any particular nation's territory. Note: The direct emission data from JRC/PBL (2013) (see Annex II.9) represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthropogenic emissions sources in the FOLU (Forestry and Other Land Use) sub-sector. For a more detailed representation of AFOLU GHG flux (Agriculture and FOLU) see Chapter 11, Section 11.2 and Figure 11.2 and 11.6. Source: same sources as reported for Figure 1.3c. We do not report uncertainties because there isn't a reliable way to estimate uncertainties resolved by regional group and sector simultaneously.

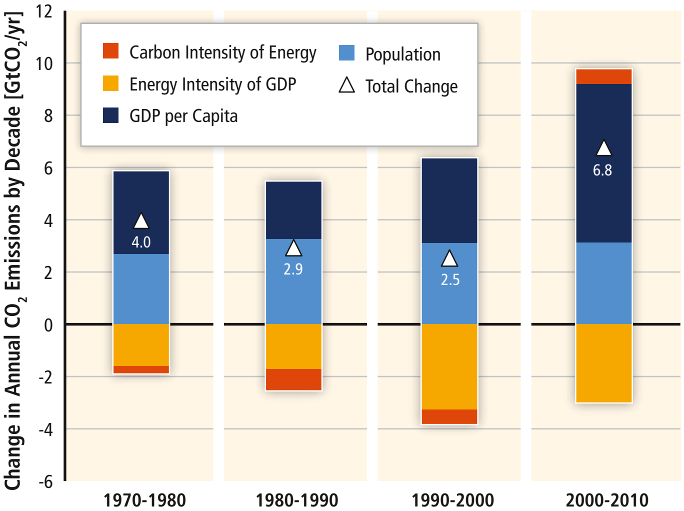


Figure 1.7 | Decomposition of the change in total annual CO_2 emissions from fossil fuel combustion by decade and four driving factors; population (light blue), GDP per capita (dark blue), energy intensity of GDP (yellow) and carbon intensity of energy (red orange). The bar segments show the changes associated with each factor alone, holding the respective other factors constant. Total emission changes are indicated by a white triangle. The change in emissions over each decade is measured in gigatonnes of CO_2 per year [$GtCO_2$/yr]; economic output is converted into common units using purchasing power parities; the use of market exchange rates would lower the share associated with economic output although that would still be the largest single factor. Source: updated from Steckel et al. (2011) using data from IEA (2012c; d).

(That pattern levelled around 2009 when the global recession began to have its largest effects on the world economy.) Also notable is carbon intensity: the ratio of CO_2 emissions to primary energy. On average, since 1970 the world's energy system has decarbonized. However, in the most recent decade there has been a slight re-carbonization. In the portions of the global economy that have grown most rapidly, low-carbon and zero-carbon fuels such as gas, nuclear power and renewables have not expanded as rapidly as relatively high-carbon coal.

Interpreting the Kaya Identity using global data masks important regional and local differences in these drivers. For example, the demographic transition in China is essentially completed while in Africa population growth remains a sizable driver. Technology—a critical factor in improving energy and carbon intensities as well as access to energy resources—varies greatly between regions (see Chapters 5 and 7). The recent re-carbonization is largely the result of expanded coal combustion in developing countries driven by high rates of economic growth, while across the highly industrialized world carbon intensity has been declining due to the shift away from high carbon fuels (notably coal) to natural gas, renewables, and also to nuclear in some countries. The simple Kaya identity relies on broad, composite indicators that neither explain causalities nor explicitly account for economic structures, behavioural patterns, or policy factors, which again vary greatly across regions. Technological change might allow for radically lower emissions in the future, but the pattern over this four-decade history suggests that the most important global driver of emissions is economic growth.

Although the average per capita income levels in the large emerging economies in 2010 were approximately 30 % or less of the per capita income levels of OECD countries in 1980, their levels of carbon intensity and energy intensity are comparable with those of North America in the early 1980s (IEA, 2012b).

1.3.2 Perspectives on mitigation

Looking to the future, it is important to be mindful that the energy system, which accounts for the majority of GHG emissions, is slow to change even in the face of concerted policy efforts (Davis et al., 2010; WEF, 2012; GEA, 2012). For example, many countries have tried to alter trends in CO_2 emissions with policies that would make the energy supply system more efficient and shift to low emission fuels, including renewables and nuclear power (Chapter 7).

There are many different perspectives on which countries and peoples are accountable for the climate change problem, which should make the largest efforts, and which policy instruments are most practical and effective. Many of these decisions are political, but scientific analysis can help frame some of the options. Here we look at six different perspectives on the sources and possible mitigation obligations for world emissions—illustrated in Figure 1.8 and elsewhere in the chapter. This discussion engages questions of burden sharing in international cooperation to mitigate climate change, a topic addressed in more detail in Chapter 4.

One perspective, shown in panel A of Figure 1.8, concerns total emissions and the countries that account for that total. Twenty countries account for 75 % of world emissions; just five countries account for about half. This perspective suggests that while all countries have important roles to play, the overall impact of mitigation efforts are highly concentrated in a few.

A second perspective, shown in panel B of Figure 1.8, concerns the accumulation of emissions over time. The climate change problem is fundamentally due to the 'stock' of emissions that builds up in the atmosphere. Because of the long atmospheric lifetime of CO_2, a fraction of the CO_2 emitted to the atmosphere from James Watt's steam engine that in the late 18th century helped trigger the Industrial Revolution still remains in the atmosphere. Several studies have accounted in detail for the sources of emissions from different countries over time, taking into account the geophysical processes that remove these gases (Botzen et al., 2008; Höhne et al., 2011; Wei et al., 2012). Attributing past cumulative emissions to countries is fraught with uncertainty and depends on method applied and emissions sources included. Because the uncertainties differ by source of emissions, panel B first shows just cumulative emissions from industrial sources (left bar) and then adds the lowest and highest estimates for emissions related to changes in land use (middle two bars). Many studies on the concept of 'historical responsibility' look at cumulative emissions since 1751, but that approach ignores the fact that widespread knowledge of the potential harms of climate change is only a more recent phenomenon—dating, perhaps, to around 1990 when global diplomatic talks that led to the UNFCCC were fully under way. Thus the right bar in panel B shows cumulative emissions for all sources of CO_2 (including a central estimate for sources related to changes in land use) from 1990 to 2010. Each of these different methods leads to a different assignment of responsible shares and somewhat different rankings. Other studies have examined other time horizons (e.g., Le Quéré et al., 2012). Many scholars who use this approach to analysing historical responsibility and similar approaches to assessing possible future contributions often refer to a fixed 'carbon budget' and identify the 'gap' between that fixed budget and allowable future emissions (e.g., IPCC, 2013b; UNEP, 2011b; Chapter 6).

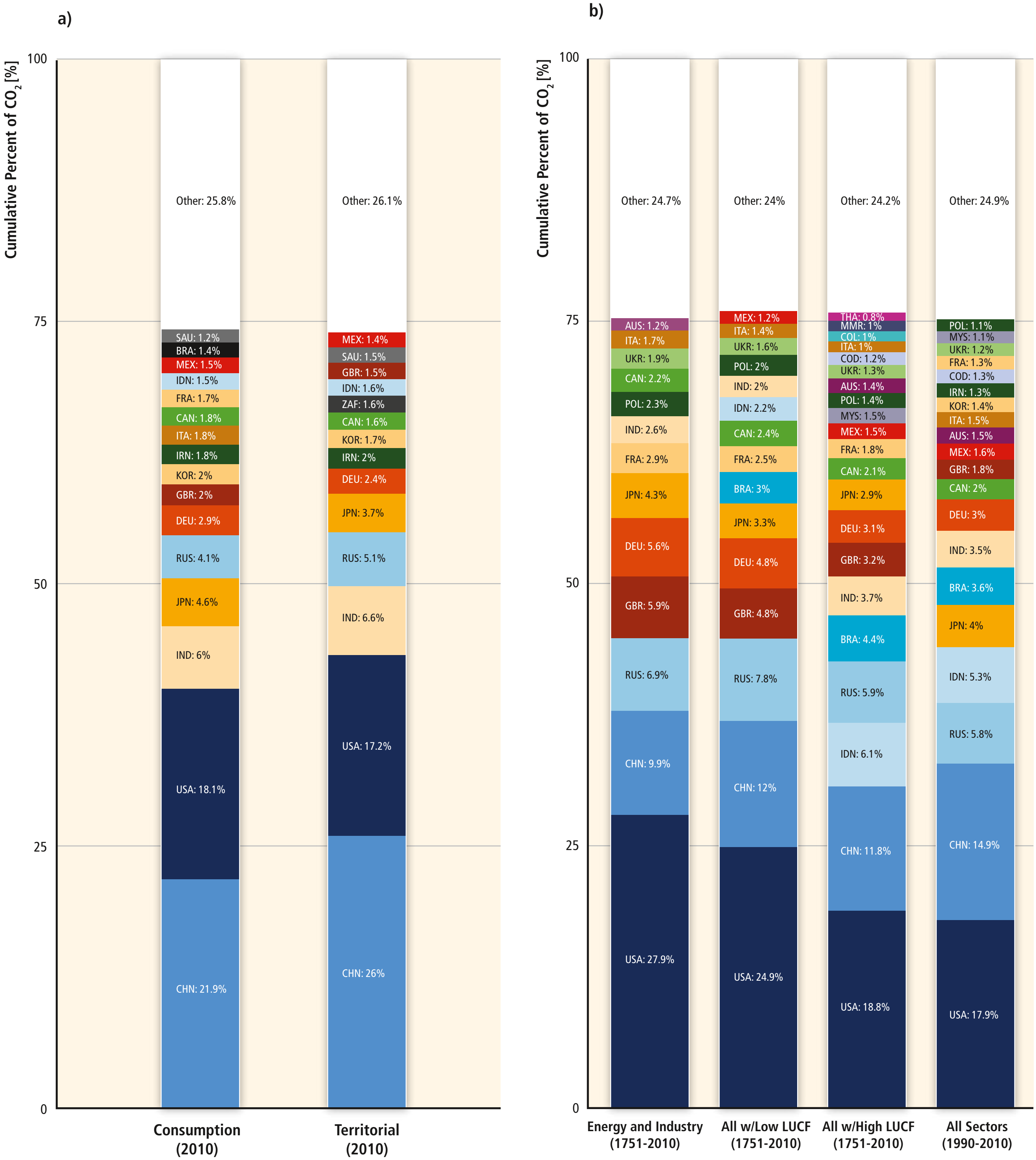
A few studies have extended the concepts of historical responsibility to include other gases as well (den Elzen et al., 2013; Smith et al., 2013). For simplicity, however, in panel B we report total cumulative emissions of just CO_2, the long-lived gas that accounts for the vast majority of long-term climate warming. Adding other gases requires a model that can account for the different atmospheric lifetimes of those gases, which introduces yet more uncertainty and complexity in the analysis of historical responsibility. The results of such analysis are highly sensitive to choices made in the calculation. For example, the share of developed countries can be almost 80 % when excluding non-CO_2 GHGs, Land Use, Land-Use Change, and Forestry, and recent emissions (until 2010) or about 47 % when including these emissions (den Elzen et al., 2013). As a general rule, because emissions of long-lived gases are rising, while emissions of the distant past are highly uncertain, their influence is overshadowed by the dominance of the much higher emissions of recent decades (Höhne et al., 2011).

A third perspective concerns the effects of international trade. So far, nearly all of the statistics presented in this chapter have been organized according to the national territory where the emissions are released into the atmosphere. In reality, of course, some emissions are 'embodied' in products that are exported and discussed in more detail in Section 1.2.2. A tonne of steel produced in China but exported to the United States results in emissions in China when the fundamental demand for the steel originated in the United States. Comparing the emissions estimated from consumption and production (left and right bars of panel A) shows that the total current accounting for world emissions varies considerably—with the largest effects on China and the United States—although the overall ranking does not change much when these trade effects are included. Figure 1.5 earlier in this chapter as well as Section 1.2.1.2 present much more detailed information on this perspective.

A fourth perspective looks at per-capita emissions, shown in panel C of Figure 1.8. This perspective draws attention to fundamental differences in the patterns of development of countries. This panel shows the variation in per-capita emissions for each of the four country groupings. The large variation in emissions in low-income country reflects the large role for changes in land use, such as deforestation and degradation. There are some low-income countries with per-capita emissions that are higher than high-income nations. Some studies have suggested that debates over concepts such as 'common but differentiated responsibility'—the guiding principle for allocating mitigation efforts in talks under the UNFCCC—should focus on individuals rather than nations and assign equal per-capita emission rights to individuals (Chakravarty et al., 2009). Still other studies have looked at the historical cumulative per-capita emissions, thus combining two of the different perspectives discussed here (Teng et al., 2012). Looking within the categories of countries shown in panel C, some developing countries already have higher per-capita emissions than some industrialized nations.

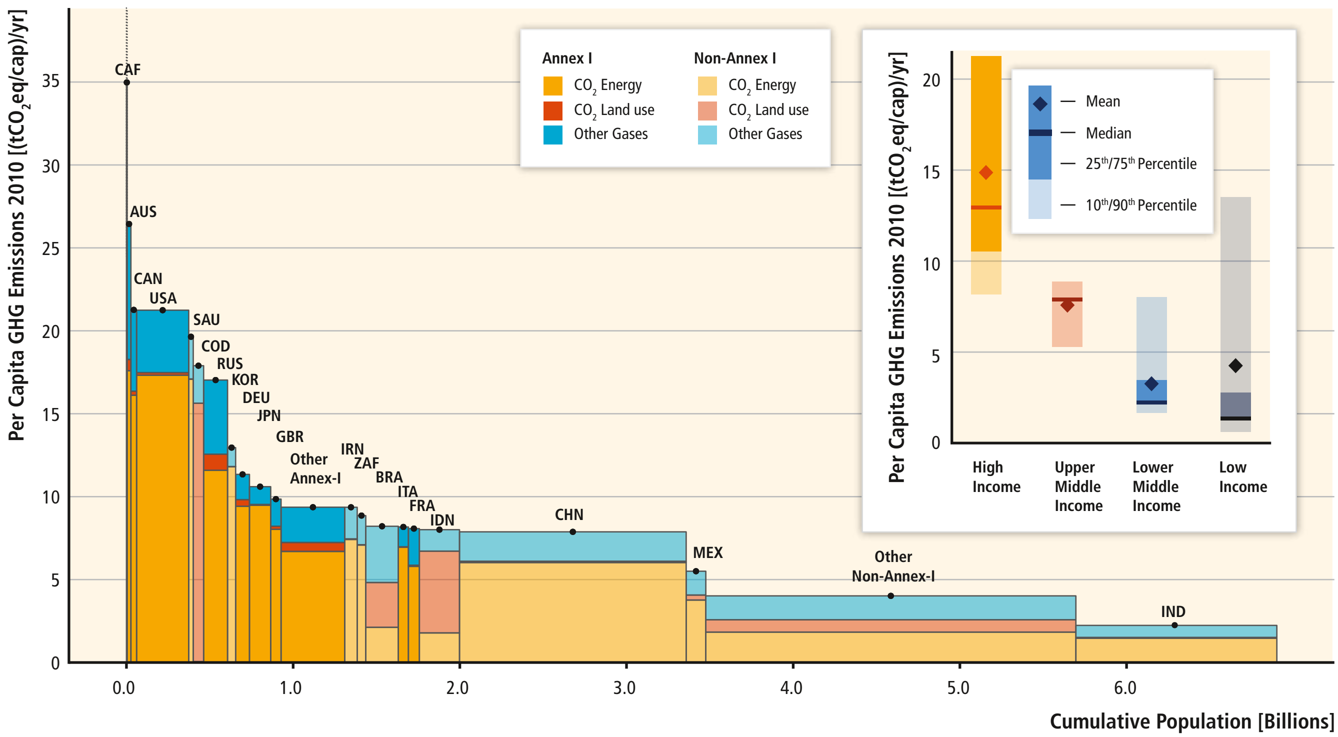
A fifth perspective is the carbon efficiency of different economies. Economies vary in how they convert inputs such as energy (and thus emissions associated with energy consumption) into economic value. This efficiency is commonly measured as the ratio of emission to unit economic output (CO_2/GDP) and illustrated in panel D of Figure 1.8. Typically, economies at an earlier stage of development rely heavily on extractive industries and primary processing using energy intensive methods often reinforced with subsidies that encourage excessive consumption of energy. As the economy matures it becomes more efficient and shifts to higher value-added industries, such as services, that yield low emissions but high economic output. This shift also often includes a change from higher carbon primary fuels to less carbon-intensive fuels. From this perspective, emission obligations might be adjusted to reflect each country's state of economic development while creating incentives for countries to transition to higher economic output without concomitant increases in emissions.

A sixth perspective (panel E of Figure 1.8) looks at the change of emissions between 1990 and 2010. 1990 is a base year for most of the Annex B countries in the Kyoto Protocol. That panel divides the world into three groups—the countries (listed in Annex B) that agreed to targets under the Kyoto Protocol and which formally ratified the Protocol; countries listed in Annex B but which never ratified the treaty (United States) or withdrew (Canada); and countries that joined the Kyoto Protocol but had no formal quantitative emission control targets under the treaty. If all countries listed in Annex B had joined and remained members of the Protocol those countries, on average, would have reduced emissions more than 5 % between 1990 and the compliance period of 2008–2012. From 1990 to 2008–2011, the Annex B nations have reduced their collective emissions by 20 % excluding the United States and Canada and by 9 % if including them, even without obtaining emission credits through the Kyoto Protocol's Clean Development Mechanism (CDM) (UNFCCC, 2013a). (As already noted, the United States never ratified the Kyoto Protocol; Canada ratified but later withdrew.) However, some individual countries will not meet their national target without the CDM or other forms of flexibility that allow them to assure compliance. The trends on this panel reflect many distinct underlying forces. The big decline in Ukraine, Russia, the 12 new members of the EU (EU+12) and one of the original EU members (Germany, which now includes East Germany) reflect restructur-


a)
Cumulative Percent of CO2 [%]
100
75
50
25
0
Other: 25.8%
SAU: 1.2%
BRA: 1.4%
MEX: 1.5%
IDN: 1.5%
FRA: 1.7%
CAN: 1.8%
ITA: 1.8%
IRN: 1.8%
KOR: 2%
GBR: 2%
DEU: 2.9%
RUS: 4.1%
JPN: 4.6%
IND: 6%
USA: 18.1%
CHN: 21.9%
Other: 26.1%
MEX: 1.4%
SAU: 1.5%
GBR: 1.5%
IDN: 1.6%
ZAF: 1.6%
CAN: 1.6%
KOR: 1.7%
IRN: 2%
DEU: 2.4%
JPN: 3.7%
RUS: 5.1%
IND: 6.6%
USA: 17.2%
CHN: 26%
Consumption (2010)
Territorial (2010)
b)
Cumulative Percent of CO2 [%]
100
75
50
25
0
Other: 24.7%
AUS: 1.2%
ITA: 1.7%
UKR: 1.9%
CAN: 2.2%
POL: 2.3%
IND: 2.6%
FRA: 2.9%
JPN: 4.3%
DEU: 5.6%
GBR: 5.9%
RUS: 6.9%
CHN: 9.9%
USA: 27.9%
Other: 24%
MEX: 1.2%
ITA: 1.4%
UKR: 1.6%
POL: 2%
IND: 2%
IDN: 2.2%
CAN: 2.4%
FRA: 2.5%
BRA: 3%
JPN: 3.3%
DEU: 4.8%
GBR: 4.8%
RUS: 7.8%
CHN: 12%
USA: 24.9%
Other: 24.2%
THA: 0.8%
MMR: 1%
COL: 1%
ITA: 1%
COD: 1.2%
UKR: 1.3%
AUS: 1.4%
POL: 1.4%
MYS: 1.5%
MEX: 1.5%
FRA: 1.8%
CAN: 2.1%
JPN: 2.9%
DEU: 3.1%
GBR: 3.2%
IND: 3.7%
BRA: 4.4%
RUS: 5.9%
IDN: 6.1%
CHN: 11.8%
USA: 18.8%
Other: 24.9%
POL: 1.1%
MYS: 1.1%
UKR: 1.2%
FRA: 1.3%
COD: 1.3%
IRN: 1.3%
KOR: 1.4%
ITA: 1.5%
AUS: 1.5%
MEX: 1.6%
GBR: 1.8%
CAN: 2%
DEU: 3%
IND: 3.5%
BRA: 3.6%
JPN: 4%
IDN: 5.3%
RUS: 5.8%
CHN: 14.9%
USA: 17.9%
Energy and Industry (1751-2010)
All w/Low LUCF (1751-2010)
All w/High LUCF (1751-2010)
All Sectors (1990-2010)

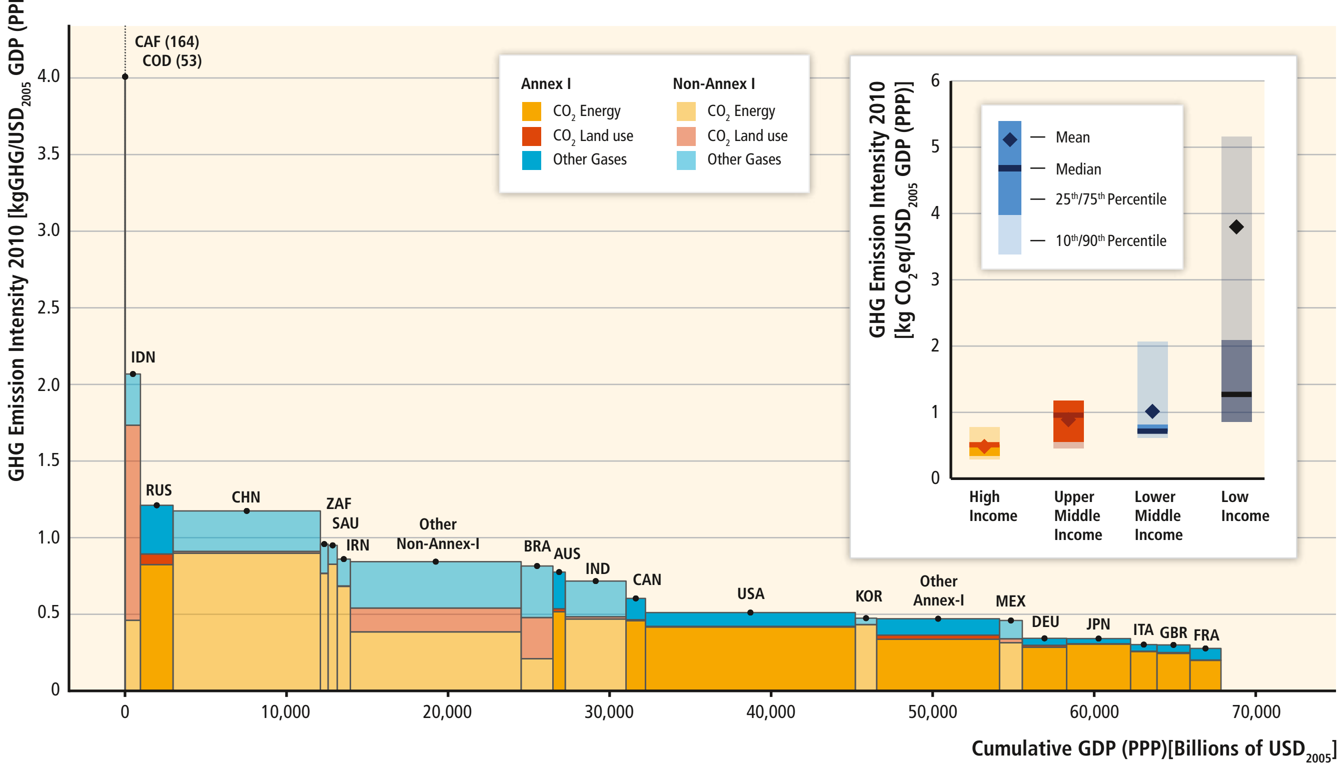
1

c)



Per Capita GHG Emissions 2010 [(tCO2eq/cap)/yr]
Cumulative Population [Billions]
Annex I
CO2 Energy
CO2 Land use
Other Gases
Non-Annex I
CO2 Energy
CO2 Land use
Other Gases
CAF
AUS
CAN
USA
SAU
COD
RUS
KOR
DEU
JPN
GBR
Other Annex-I
IRN
ZAF
BRA
ITA
FRA
IDN
CHN
MEX
Other Non-Annex-I
IND
Mean
Median
25th/75th Percentile
10th/90th Percentile
High Income
Upper Middle Income
Lower Middle Income
Low Income

d)



GHG Emission Intensity 2010 [kgGHG/USD2005 GDP (PPP)]
Cumulative GDP (PPP)[Billions of USD2005]
CAF (164)
COD (53)
IDN
RUS
CHN
ZAF
SAU
IRN
Other Non-Annex-I
BRA
AUS
IND
CAN
USA
KOR
Other Annex-I
MEX
DEU
JPN
ITA
GBR
FRA
Annex I
CO2 Energy
CO2 Land use
Other Gases
Non-Annex I
CO2 Energy
CO2 Land use
Other Gases
GHG Emission Intensity 2010 [kg CO2eq/USD2005 GDP (PPP)]
Mean
Median
25th/75th Percentile
10th/90th Percentile
High Income
Upper Middle Income
Lower Middle Income
Low Income

⇒

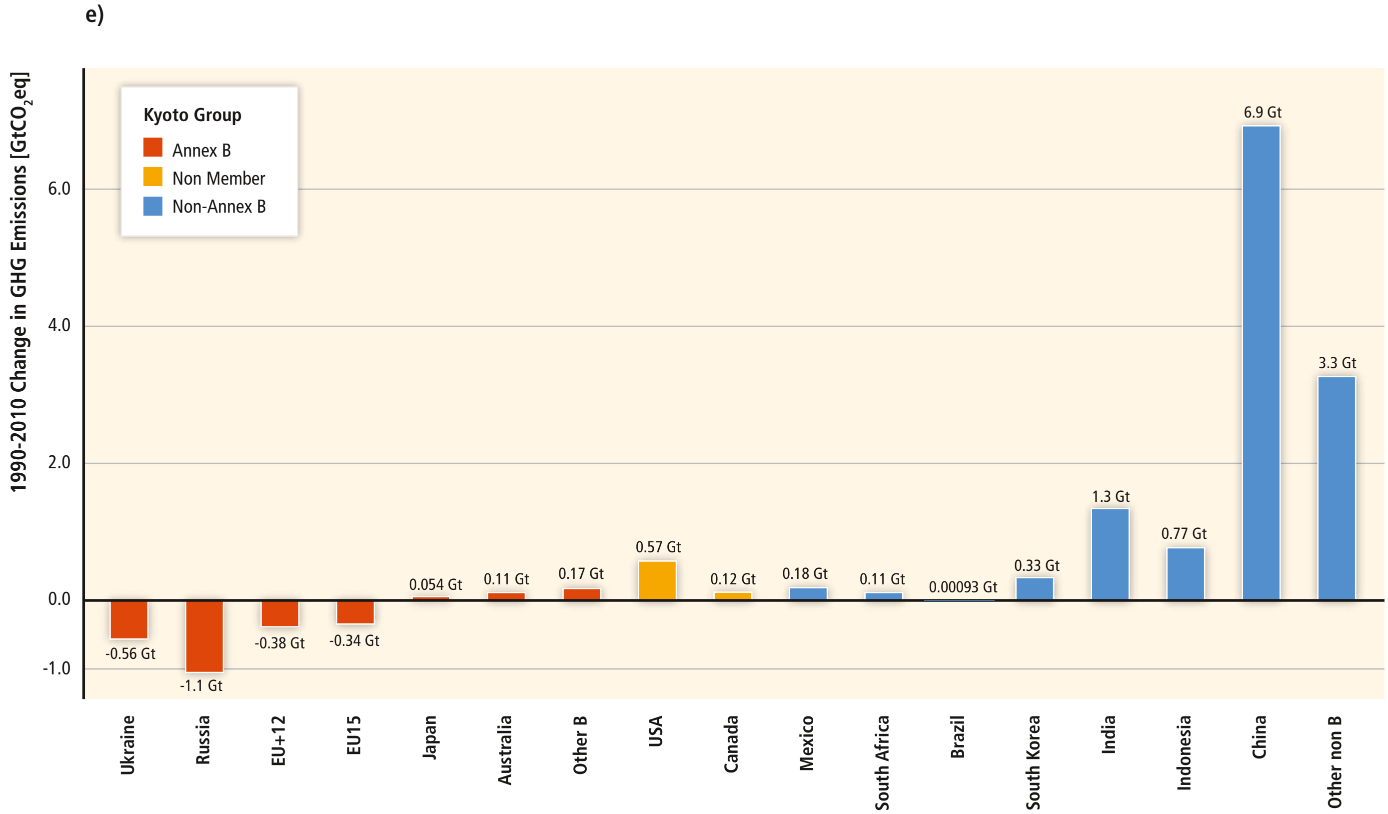


Figure 1.8 | Multiple perspectives on climate change mitigation. Panel A: 2010 emission, ranked in order for the top 75 % of global total. Left bar shows ranking with consumption-based statistics, and right bar shows territorial-based (see Figure 1.5 for more detail). Panel B: Cumulative emissions since 1750 (left three bars) and since 1990 (right bar) for four different methods of emission accounting. The first method looks just at industrial sources of CO_2 (left bar); the second method adds to those industrial sources the lowest plausible estimate for emissions related to changes in land use (second bar), the third uses the highest plausible estimate for land use (third bar) and the final method uses median estimates for land use emissions along with median industrial emissions. (We focus here on uncertainty in land use emissions because those have higher variation than industrial sources.) Panel C: ranking of per-capita emissions by country as well as (inset) for the four groupings of countries Shadings show the 10th to 90th percentile range (light) as well as the 25th to 75th percentile range (dark); horizontal bars identify the median and diamonds the mean. Panel D: Ranking of carbon intensity of economies (emissions per unit GDP, weighted with purchasing power parity) as a function of total size of the economy as well as (inset) for the four groupings of countries Shadings show the 10th to 90th percentile range (light) as well as the 25th to 75th percentile range (dark); horizontal bars identify the median and diamonds the mean. Country names are abbreviated using the three letter standardization maintained by the International Organization for Standardization (ISO, standard 3166). Panel E: Emissions changes from 1990 to 2012 divided into Annex B of the Kyoto Protocol (countries with quantified emission targets, red orange), countries that were eligible for Annex B but are not members (Canada and the United States, yellow) and non-Annex B countries (blue). Sources: Panel A: based on Peters et al., 2011 data; Panel B: based on MATCH data (Höhne et al., 2011). High and low plausible values for land use emissions are two different datasets provided in the MATCH analysis (see Figure 1.4 for more detail and caveat); since the MATCH analysis is based on actual emission data up to 2005, the last four years are were taken from the Historic Emission Database EDGAR/IEA emission data (JRC/PBL, 2013, IEA, 2012a, See Annex II.9). Panel C: JRC/PBL, 2013 and United Nations, 2013a; Panel D: emissions from JRC/PBL, 2013 and national income PPP-adjusted from World Bank *World Development Indicators*; Panel E: JRC/PBL, 2013.

ing of those economies in the midst of a large shift away from central planning. Some of those restructuring economies used base years other than 1990, a process allowed under the Kyoto Protocol, because they had higher emissions in earlier years and a high base year arithmetically leads to larger percentage reductions. The relatively flat emissions patterns across most of the industrialized world reflect the normal growth patterns of mature economies. The sharp rise in emerging markets, notably China and India, reflect their rapid industrialization—a combination of their stage of development and pro-growth economic reforms.

There are many ways to interpret the message from this sixth perspective, which is that all countries collectively are likely to comply with the Kyoto Protocol. One interpretation is that treaties such as the Kyoto Protocol have had some impacts on emissions by setting clear standards as well as institutional reforms that have led countries to adjust their national laws. From that perspective, the presence of the Kyoto obligations is why nearly all the countries that ratified the Kyoto obligations are likely to comply. Another interpretation is that the Kyoto Protocol is a fitting illustration of the concept of 'common but differentiated responsibility', which holds that countries should undertake different efforts and that those most responsible for the underlying problem should do the most. Still another interpretation is that choice of Kyoto obligations largely reveals 'selection effects' through which countries, in effect, select which international commitments to honour. Countries that could readily comply adopted and ratified binding limits; the others avoided such obligations—a phenomenon that, according to this perspective, is evident not just in climate change agreements but other areas of international cooperation as well (e.g., Downs, Rocke, and Barsoom, 1996; Victor 2011).

Still other interpretations are possible as well, with varied implications for policy strategies and the allocation of burdens and benefits among peoples and nations.

1.3.3 Scale of the future mitigation challenge

Future emission volumes and their trajectories are hard to estimate, and there have been several intensive efforts to make these projections. Most such studies start with one or more 'business-as-usual (BAU)' projections that show futures without further policy interventions, along with scenarios that explore the effects of policies and sensitivities to key variables. Chapter 5 looks in more detail at the long-term historical trends in such emissions, and Chapter 6 examines the varied models that are widely used to make emission projections. Using the WGIII AR5 Scenario Database, comprised of those models described in Chapter 6 (See Annex II.10), Figure 1.9 also shows the emission trajectories over the long sweep of history from 1750 through the present and then projections out to 2100.

The long-term scenarios shown on Figure 1.9 illustrate the emissions trajectories that would be needed to stabilize atmospheric concentrations of greenhouse gases at the equivalent of around 450 ppm (430–480) and 550 ppm (530–580) CO_2eq by 2100. The scenarios centered on 450 ppm CO_2eq are likely (> 66 % chance) to avoid a rise in temperature that exceeds 2 degrees above pre-industrial levels. Scenarios reaching 550 ppm CO_2eq have less than a 50 % chance of avoiding warming more than 2 degrees, and the probability of limiting warming to 2 degrees further declines if there is significant overshoot of the 550 ppm CO_2eq concentration. It is important to note that there is no precise relationship between such temperature goals and the accumulation of emissions in the atmosphere largely because the sensitivity of the climate system to changes in atmospheric concentrations is not known with precision. There is also uncertainty in the speed at which future emissions will be net removed from the atmosphere by natural processes since those processes are not perfectly understood. If removal processes are relatively rapid and climate sensitivity is low, then a relatively large quantity of emissions might lead to small changes in global climate. If those parameters prove to have less favourable values then even modest increases in emissions could have big impacts on climate. These uncertainties are addressed in much more detail in WGI Chapter 12 and discussed in Chapter 6 of this report as well. While these uncertainties in how the natural system will respond are important, recent research suggests that a wide range of uncertainties in social systems—such as the design of policies and other institutional factors—are likely to be a much larger factor in determining ultimate impacts on warming from human emissions (Rogelj et al., 2013a; b).

Figure 1.9 underscores the scale of effort that would be needed to move from BAU emissions to goals such as limiting warming to 2 degrees. The rapid rise in emissions since 1970 (left inset) is in stark contrast with the rapid decline that would be needed over the coming century. Because it is practically difficult to orient policy around very long term goals, the middle inset examines the coming few decades—the period during which emissions would need to peak and then decline if stabilization concentrations such as 450 or 550 ppm CO_2eq are to be achieved.

A variety of studies have probed whether national emission reduction pledges, such as those made in the aftermath of the Copenhagen conference, would be sufficient to put the planet on track to meet the 2 degree target (Den Elzen et al., 2011; Rogelj et al., 2011). For example, Den Elzen et al. (2011) found the gap between allowable emissions to maintain a 'medium' chance (50–66 %) of meeting the 2 degree target and the total reduction estimated based on the pledges made at and after COP 15, are as big as 2.6–7.7 $GtCO_2$e in 2020; that analysis assumed that countries would adopt least-cost strategies for mitigation emissions, but if less idealized scenarios are followed, then the gap would be even larger. A large number of other studies also look at the size of the gap between emission trajectories and the levels needed to reach goals such as 2 degrees (Clarke et al., 2009; Cline, 2011; Yamaguchi, 2012). By logical extension, limiting warming to 1.5 degrees (or even 1 degree, as some governments and analysts suggest should be the goal) is even more challenging. In a major inter-comparison of energy models, eight of 14 scenarios found that stabilizing concentrations at 450 ppm CO_2eq (which would be broadly consistent with stabilizing warming at 2 degrees) would be achievable under optimal conditions in which all countries participated immediately in global regulation of emissions and if a temporary overshooting of the 450 ppm goal were allowed (Clarke et al., 2009). As a general rule, it is still difficult to assess scientifically whether the Cancun pledges (which mainly concern the year 2020) are consistent with most long-term stabilization scenarios because a wide range of long-term scenarios is compatible with a wide range of 2020 emissions; as time progresses to 2030 and beyond, there is a tighter constraining relationship between allowable emissions and long-term stabilization (Riahi et al., 2013). The middle inset in figure 1.9 shows those pledges and suggests that they may be consistent with some scenarios that stabilize concentrations at around 550 ppm CO_2eq but are inconsistent with the least cost scenarios that would stabilize concentrations at 450 ppm CO_2eq.

There is no simple relationship between the next few decades and long-term stabilization because lack of much mitigation in the next decades can, in theory, be compensated by much more aggressive mitigation later in the century—if new zero- and negative-emission technologies become available for widespread use. That point is illustrated in the upper right inset which shows how assumptions about the timing of mitigation and the availability of technologies affects a subset of scenarios that stabilize concentrations between 450 ppm CO_2eq and 550 ppm CO_2eq. Least cost, optimal scenarios depart immediately from BAU trajectories. However, such goals can be reached even if there are delays in mitigation over the next two decades provided that new technologies become available that allow for extremely rapid reductions globally in the decades immediately after the delay.

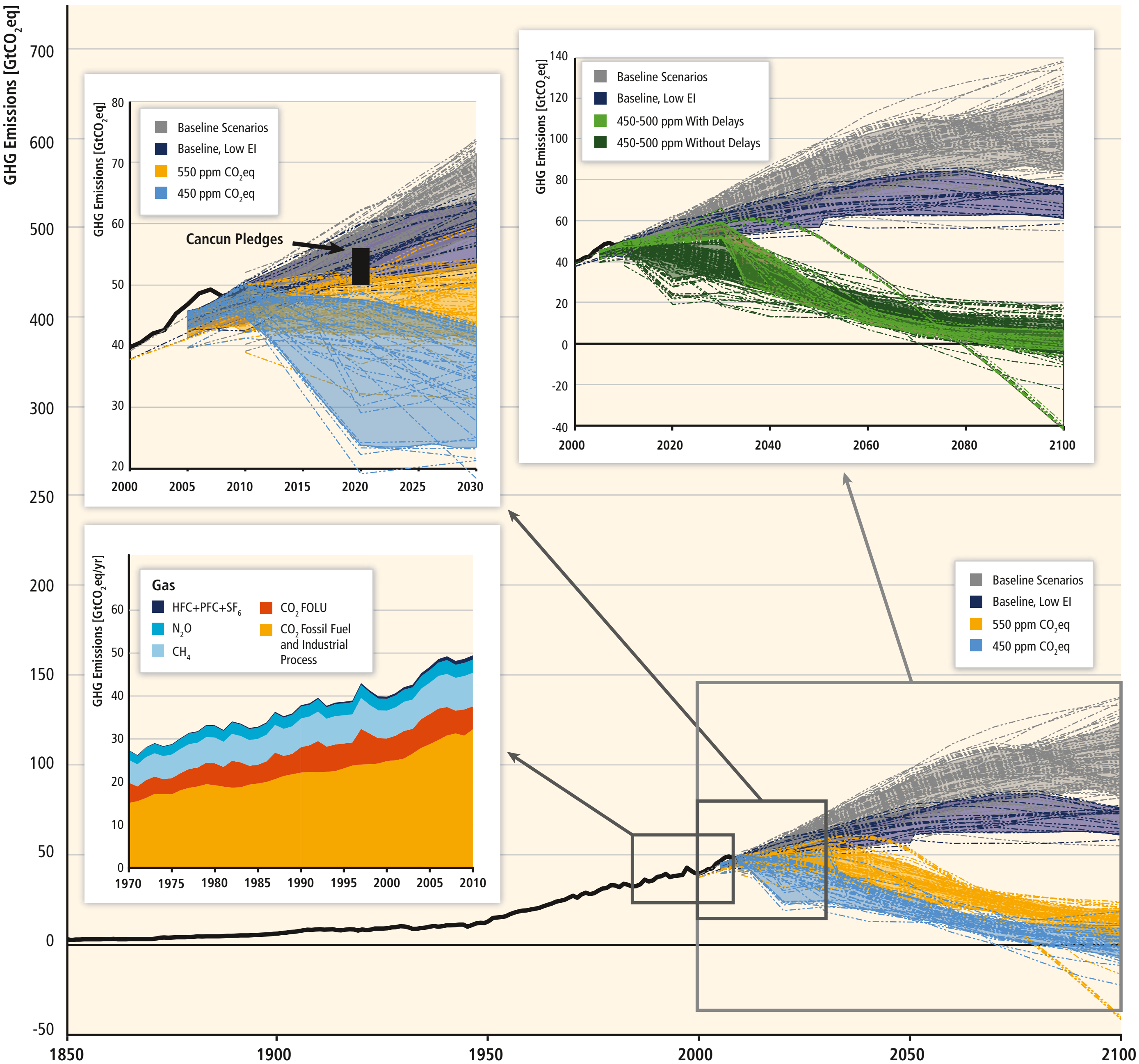


Figure 1.9 | The scale of the mitigation effort needed. Main figure shows the sweep of history from 1750 to 2010 (actual emission estimates) and published projections out to the future. Projections include baseline scenarios that do not assume new mitigation policies (grey shading), baseline scenarios that assume aggressive spread of energy efficiency technologies and changes in behaviour (purple shading), mitigation scenarios that reach concentration levels of about 550 ppm CO_2eq (yellow) and 450 ppm CO_2eq (blue). (The mitigation scenarios include those that assume optimal regulation over time and those with delays to 2030). The bottom left inset shows recent historical emissions and is the same as Figure 1.3c. The top left inset shows the same scenarios from the main figure, but with more detail over the next few decades, including the relationship between the Cancun pledges and the various stabilization scenarios. The top right panel looks instead at long-term patterns in emissions and explores the effects of delays to 2030. It focuses on a subset of the mitigation scenarios from the main panel that are consistent with limiting atmospheric concentrations of CO_2 to about 450 ppm CO_2eq to 500 ppm CO_2eq—a goal broadly consistent with limiting warming to about 2 degrees above pre-industrial levels by 2100 and thus a topic that many models have examined in some detail. The dark green fans show model estimates for optimal least cost strategies for stabilization; light green fans show least cost mitigation with emissions that track baseline scenarios until 2030 and then make deep cuts with the assumption that new technologies come into place. Chart also shows in light black a subset of scenarios based on the premise that very large quantities of net negative emissions (about 40 $GtCO_2eq/yr$ by 2100) can be achieved and thus illustrate how assumptions of negative emissions technology may influence the expected time path of emissions. The black scenarios, the output of just one model, entail substantial overshoot of concentrations before stabilization is achieved and unlikely to limit warming to 2 degrees (see Chapter 6). Sources: Historical data drawn from EDGAR/IEA databases reported in IEA, 2012a See Annex II.9; projections drawn from the WGIII AR5 Scenarios Database described in greater detail in Annex II.10; estimates of the impact of the Copenhagen pledges reported in Chapter 13.

Determining the exact cost required to achieve any particular goal is difficult because the models that are used to analyze emissions must contend with many uncertainties about how the real world will evolve. While the list of those uncertainties is long, the model outcomes are particularly sensitive to five that are discussed in much more detail in Chapter 6:

- **Participation**. Studies typically analyze scenarios in which all nations participate with the same timing and level of effort, which also probably leads to the least costly total level of effort. However, a variety of 'delayed participation' scenarios are also analyzed, and with delays it becomes more difficult (and costly) to meet mitigation goals (Bertram et al., 2013; Riahi et al., 2013; Rogelj et al., 2013b; Luderer et al., 2013).

- **International institutions**. Outcomes such as global participation will require effective institutions, such as international agreements on emission reductions and schemes like international trading of emission offsets and financial transfers. If those institutions prove difficult to create or less than optimally effective then global mitigation goals are harder to reach.

- **Technology**. The least cost outcomes (and greatest ease in meeting mitigation goals) require that all emission control technologies be available as quickly as possible. In many models, meeting aggressive goals also requires the availability of negative emission technologies—for example, power plants fired with biomass and including carbon dioxide capture and storage. No such plant actually exists in the world today and with pessimistic assumptions about the availability of such technologies it becomes much harder or impossible to reach aggressive mitigation goals (Edenhofer et al., 2010; Tavoni et al., 2012; Eom et al., 2013; Kriegler et al., 2013).

- **Economic growth**. Typically, these models assume that if economic growth is high then so are emissions (and, in some models, so is the rate of technological innovation). Of course, in the real world, countries can delink economic output and emissions, such as through mitigation policy. More pessimistic assumptions about growth can make emission goals easier to reach (because there is a smaller gap between likely and desired emissions) or harder to reach (because technologies will not be invented as quickly).

- **Peak timing**. Because long-term climate change is driven by the accumulation of long-lived gases in the atmosphere (notably CO_2), these models are sensitive to the exact year at which emissions peak before emission reductions slow and then stop accumulation of carbon in the atmosphere. Models that allow for early peaks create more flexibility for future years, but that early peak also requires the early appearance of mitigation technologies. Later peak years allow for delayed appearance of new technologies but also require more aggressive efforts after the peak. Some models also allow for an 'overshoot' of peak concentrations, which makes it easier for the model to reach long-term stabilization but lowers the odds that stabilization will limit actual warming to a particular target.

In general, only when the most flexible assumptions are made—such as permission for some temporary overshooting of goals and allowing models the maximum flexibility in the technologies that are utilized—is the result a least cost outcome. Since AR4, the modeling community has devoted much more attention to varying those assumptions to allow for less flexible assumptions that are typically better tuned to real world difficulties. These more realistic assumptions are often called 'second best' or 'less idealized'. At present, with the most flexible idealized assumptions several models suggest that the goal of reaching 2 degrees is feasible. With a variety of less ideal—but more realistic—assumptions that goal is much more difficult to reach, and many models find the goal infeasible or exceptionally expensive. These practical difficulties suggest that while optimal analyses are interesting, the real world may follow pathways that are probably more costly and less environmentally effective than optimal outcomes. They are also a reminder that such models are a portrayal of the world that

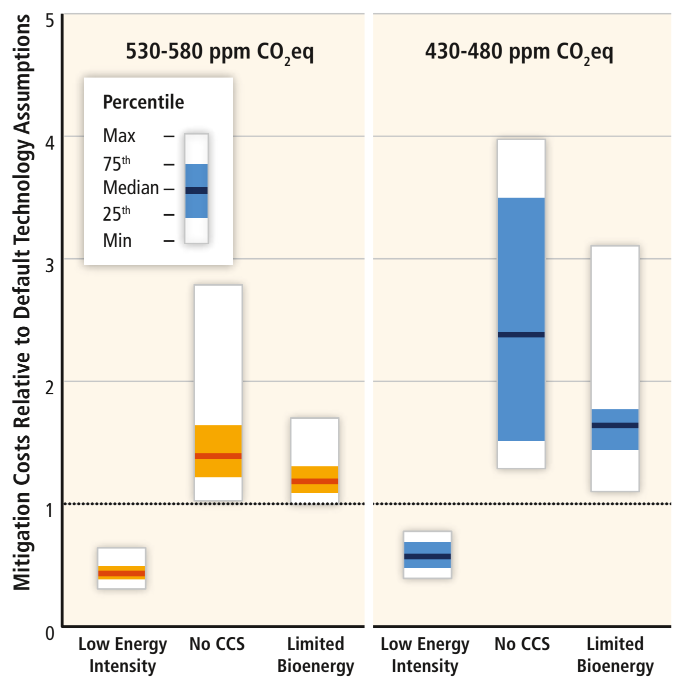


Figure 1.10 | The effects of real world assumptions on mitigation costs. Relative mitigation cost increase in case of technology portfolio variations compared to a scenario with default technology assumptions for stabilizing atmospheric GHG concentrations centered on 450 ppm (430–480 ppm, right) and 550 ppm (530–580 ppm, left) CO_2eq in the year 2100. Boxplots show the 25th to 75th percentile range with median value (heavy line) and unshaded area the total range across all reported scenarios, with the caveat that the numbers of scenarios used in such analyses is relatively small. Scenario names on x-axis indicate the technology variation relative to the default assumptions: Low Energy Intensity= energy intensity rising at less than standard values, such as due to extensive use of energy efficiency programs and technologies (N = 7, 12); No CCS = CCS technologies excluded (N = 3, 11); Limited Bioenergy = maximum of 100 EJ/yr bioenergy supply (N = 7, 12). Source: redrawn from Figure 5 in Kriegler et al. (2013) and Figure 6.24.

is necessarily simplified and highly dependent on assumptions. There can be many unforeseen changes that make such goals easier or more difficult to reach. For example, unexpectedly high economic growth and expansion of coal-fired electricity has raised emissions and made goals harder to reach; unexpected innovations in renewables, energy efficiency and natural gas are possibly making climate goals easier to reach.

The importance of these real world approaches to analysis is illustrated in Figure 1.10, which shows how different assumptions about energy intensity (which is related to human behaviour) and the availability of technologies affect the estimated total cost. Compared with costs under default technology assumption, if energy intensity is assumed to improve rapidly (Low EI) the total cost for mitigating to 430–480 ppm CO_2eq (right boxplot) or 530–580 ppm CO_2eq (left boxplot) then costs are cut in half. (These low EI scenarios are shown, as well, in purple on Figure 1.9—they lead, systematically, to emissions that are significantly lower than standard BAU scenarios.) Most studies that look at technological and behavioural assumptions conclude that real-world costs could be higher than typical, optimal estimates. For example, if CCS technologies are not available then the cost of meeting 450 ppm stabilization could be 1.5 times to 4 times greater than compared to full CCS availability. Similarly, if there is limited bioenergy supply then costs could be dramatically higher than standard least cost estimates.

1.4 Mitigation challenges and strategies

While this report addresses a wide array of subjects related to climate change, our central purpose is to discuss mitigation of emissions. The chapters that follow will examine the challenges for mitigation in more detail, but five are particularly notable. These challenges, in many respects, are themes that will weave through this report and appear in various chapters.

1.4.1 Reconciling priorities and achieving sustainable development

Climate change is definitely one of the most serious challenges human beings face. However, it is not the only challenge. For example, a survey of the Millennium Development Goals (MDGs) offers examples of the wider array of urgent priorities that governments face. These goals, worked out in the context of the United Nations Millennium Declaration in September 2000, cover eight broad areas of development that span eradicating extreme poverty and hunger, reducing child mortality, combating HIV/AIDS, malaria and other diseases. Within those broad areas the MDGs include 18 specific targets. For example, halving, between 1990 and 2015, the proportion of people whose income is less than $1 a day, and halving, between 1990 and 2015, the proportion of people who suffer from hunger, are among targets under the goal of eradicate extreme poverty and hunger. (Since then, the official poverty level has been revise upwards to $1.25/day by the World Bank.) MDGs are unquestionably the urgent issues human beings should cope with immediately and globally. Achieving such goals along with an even broader array of human aspirations is what many governments mean by 'sustainable development' as echoed in many multilateral statements such as the declaration from the Rio +20 conference in 2012 (United Nations, 2012).

All countries, in different ways, seek sustainable development. Each puts its priorities in different places. The need to make tradeoffs and find synergies among priorities may be especially acute in the least developed countries where resources are particularly scarce and vulnerabilities to climate change are systematically higher than in the rest of the world (see Box 1.1). Those priorities also vary over time—something evident as immediate goals such as job creation and economic growth have risen in salience in the wake of the global financial crisis of the late 2000s. Moreover, sustainable development requires tradeoffs and choices because resources are finite. There have been many efforts to frame priorities and determine which of the many topics on global agendas are most worthy. Making such choices, which is a highly political process, requires looking not only at the present but also posterity (Summers, 2007). Applying standard techniques for making tradeoffs—for example, cost-benefit analysis (CBA)—is extremely difficult in such settings, though the importance of CBA itself is well recognized (Sachs, 2004) (See Section 3.6). Important goals, such as equity, are difficult to evaluate alongside other goals that can more readily be monetized. Moreover, with climate change there are additional difficulties such as accounting for low probability but high impact catastrophic damages and estimating the monetary value of non-market damages (Nussbaum, 2000; Weitzman, 2009).

1.4.2 Uncertainty and risk management

The policy challenge in global climate change is one of risk management under uncertainty. The control of emissions will impose costs on national economies, but the exact amount is uncertain. Those costs could prove much higher if, for example, policy instruments are not designed to allow for flexibility. Or they could be much lower if technological innovation leads to much improved energy systems. Mindful of these uncertainties, there is a substantial literature on how policy design can help contain compliance costs, allowing policymakers to adopt emission controls with greater confidence in their cost (Metcalf, 2009).

Perhaps even more uncertain than the costs of mitigation are the potential consequences of climate change. As reviewed elsewhere in the IPCC assessment, there is growing recognition of the importance of considering outcomes at high magnitudes of climate change, which could lead to strong feedbacks and very large impacts—for example, higher sea levels and substantial impacts on natural ecosystems (IPCC, 2014 (forthcoming); see also WGI, Chapters 11–14 and Annex I). Investments in adaptation, which vary in their feasibility, can help reduce exposure to climate impacts and may also lessen uncertainty in the assessment of possible and probable impacts (World Bank, 2010).

Since risks arise on both fronts—on the damages of climate change and on the costs of mitigation responses—scholars often call this a 'risk-risk' problem. In the case of climate change, management in this context of risk and uncertainty must contend with another large challenge. Mitigation actions and effects of climate change involve a multitude of actors working at many different levels, from individual firms and NGOs to national policy to international coordination. The interest of those different actors in undertaking climate change mitigation also varies. Moreover, this multitude faces a large array of decisions and can deploy many different instruments that interact in complex ways. Chapter 2 explores the issues involved with this multitude of actors and instruments. And Chapter 3 introduces a framework for analysing the varied policy instruments that are deployed and assessing their economic, ecological, ethical and other outcomes.

Box 1.1 | Least Developed Countries: mitigation challenges and opportunities

The Least Developed Countries (LDCs) consist of 49 countries and over 850 million people, located primarily in Africa and Asia—with 34 LDCs in Africa alone (UNFPA, 2011). These countries are characterised by low income (three-year average gross national income per capita of less than USD 992), weak human assets index (nutrition, health, school enrolment, and literacy), and high economic vulnerability criterion (UNCTAD, 2012a). Despite their continued marginalization in the global economy, these countries' economies grew at about 6 % per year from 2000 to 2008, largely stimulated by the strong pull-effect of the Asian emerging economies (Cornia, 2011). However, the global economic downturn and the worsening Eurozone crisis have had an effect on most LDC economies. In 2011, LDCs grew by 4.2 %, 1.4 percentage lower than the preceding year, hence mirroring the slowdown of growth worldwide (UNCTAD, 2012a). Many of the traditional domestic handicaps remain as LDC economies continue to be locked into highly volatile external transactions of commodities and low-productivity informal activities, having neither the reserves nor the resources needed to cushion their economies and adjust easily to negative shocks.

Regarding the social trends, LDCs as a group have registered encouraging progress towards achieving some of the Millennium Development Goals (MDGs), especially in primary school enrolment, gender parity in primary school enrolment, HIV/AIDS prevalence rates and the share of women in non-agricultural wage employment (Sachs, 2012). However, poverty reduction has been less successful; only four (of 33) LDCs are on track to cut the incidence of extreme poverty to half 1990 levels by 2015 (UNCTAD, 2011). In line with this, the Istanbul Programme of Action, adopted at the 4th UN Conference on the Least Developed Countries (LDC-IV) highlighted the importance of building the productive base of LDCs' economies and promoting the process of structural transformation involving an increase in the share of high productivity manufacturing and an increase in agricultural productivity (UNCTAD, 2012b).

The LDCs' continued reliance on climate-sensitive activities such as agriculture means that adapting to climate change remains a central focus of economic development. If climate changes become acute the additional burden of adaptation could draw resources away from other activities, such as mitigation. Alternatively, more acute attention to adaptation could help mobilize additional efforts for mitigation within these countries and other countries that are the world's largest emitters. The scientific literature has not been able to determine exactly when and how adaptation and mitigation are complementary or competing activities in LDCs; what is clear, however, is that meeting the climate and development challenge entails integrating mitigation and adaptation actions in the context of sustainable development (Ayers and Huq, 2009; Martens et al., 2009; Moomaw and Papa, 2012). In LDCs, like all other countries, investment in new infrastructures offers the opportunity to avoid future GHG emissions and lower mitigation costs (Bowen and Fankhauser, 2011). Other emissions avoidance options are also available for LDCs in areas of innovative urban development, improvements in material productivity (Dittrich et al., 2012) and the application of enhanced land use efficiency through intensified agricultural practices and sustainable livestock management (Burney et al., 2010).

There could be significant additional costs associated with the expansion of infrastructure in LDCs aimed at decoupling GHG emissions and development. Paying these costs in countries with extremely scarce resources could be a challenge (Krausmann et al., 2009). Moreover, the additional costs could deter private investors in low carbon interventions, leaving the public sector with additional burdens, at least in the short-term (UN DESA, 2009; Collier and Venables, 2012). For most LDC governments, creating the conditions for accelerated economic growth and broad-based improvements in human well-being will remain the main driver of national development policies and could lead to the perception—if not the reality—that development and mitigation are conflicting goals.

Scientific research on risk management has several implications for managing the climate change problem. One is the need to invest in research and assessment that can help reduce uncertainties. In relation to climate change these uncertainties are pervasive and they involve investments across many intellectual disciplines and activities, such as engineering (related to controlling emissions) and the many fields of climate science (related to understanding the risks of climate change). In turn, these knowledge generating and assessment processes must be linked to policy action in an iterative way so that policymakers can act, learn, and adjust while implementing policy measures that are 'robust' across a variety of scenarios (McJeon et al., 2011). Another major implication is the need to examine the possibilities of extreme climate impacts. These so called 'tail' risks in climate impacts could include relatively rapid changes in sea level, feedbacks from melting permafrost that amplify the concentrations of greenhouse gases in the atmosphere, or possibly a range of so far barely analyzed outcomes (see generally Weitzman 2011). There are many options that could play a role in these risk management strategies such as adaptation, rapid deployment of low or negative emission technologies (e.g., nuclear, advanced renewables, or bioenergy plants that store their emissions underground) and geoengineering. Many of these options raise governance and risk management challenges of their own.

1.4.3 Encouraging international collective action

Unlike many matters of national policy, a defining characteristic of the climate change issue is that most of its sources are truly global. Nearly all climate-altering gases have atmospheric lifetimes sufficiently long that it does not matter where on the planet they are emitted. They spread worldwide and affect the climate everywhere. Thus, national governments develop their own individual policies with an eye to what other nations are likely to do and how they might react (Victor, 2011). Even the biggest emitters are mostly affected by emissions from other countries rather than principally their own pollution. International collective action is unavoidable.

As the level of ambition to manage the risks of climate change rises, collective action can help governments achieve efficient and effective outcomes in many ways. Those include not just coordination on policies to control emissions but also collective efforts to promote adaptation to climate change. International coordination is also needed to share information about best practices in many areas. For example, many of the promising options for reducing emissions involve changes in behaviour; governments are learning which policies are most effective in promoting those changes and sharing that information more widely can yield practical leverage on emissions (Aldy and Stavins, 2007; Dubash and Florini, 2011) (see also Chapter 13). Coordination is also essential on matters of finance since many international goals seek action by countries that are unwilling or unable to pay the cost fully themselves (see Chapter 16) (WEF, 2011). Extremely short-lived pollutants, such as soot, do not mix globally yet these, too, entrain many issues of international cooperation. Often this pollution moves across regional borders. And coordination across borders can also help promote diffusion of best practices to limit these pollution sources.

International cooperation, including financial transfers, can also help diffuse knowledge and capabilities to countries as they adapt to the effects of climate change (UNFCCC, 2008, 2012c; World Bank, 2010). Indeed, in response to these many logics for international cooperation on mitigation and adaptation extensive intergovernmental and other coordinating efforts are under way (see Section 1.2.1.4 and also Chapter 13).

One of the central challenges in international cooperation is that while national governments play central roles—for example, negotiating, and implementing treaties—effective cooperation must also engage a large number of other actors, notably in the private sector. Moreover, governments and other actors cooperate not only at the global level through universal forums such as the United Nations but also in a wide array of regional forums. One result of these multiple processes that entrain public institutions as well as private actors is decentralized and overlapping systems for government (see Chapter 13).

1.4.4 Promoting investment and technological change

Radical delinking of GDP growth with emissions will probably require massive changes in technology. Achieving those changes will require closer attention to policies that affect technology innovation and deployment. Technologies vary in many ways—they have different maturity stages and potential for improvement through 'learning'; they have different mitigation potentials and require different policy responses in developing and developed countries. Many studies have looked in detail at how this diversity of technology policy approaches might influence emissions and climate policy in the future (UN DESA, 2009, 2011; WBCSD, 2009; IEA, 2012d).

Nearly all low GHG technology options share one commonality—a shift in the cost structure of supplying energy services from operating/fuel costs to upfront capital costs. Thus policy options are particularly focused on how to create credible assurances for investors who pay these capital costs. Policies that reduce demand for energy—notably those that mobilize investments in energy efficiency in both end use and supply—can play pivotal roles by limiting the total cost needed to transform energy supplies. The rate at which these changes in energy systems can occur is an important area of research. The high fixed cost of infrastructures also create 'lock-in' effects that help explain why it is difficult to change real world emission patterns quickly (Davis et al., 2010; IEA, 2012a).

International cooperation, finance, and technology transfer all have important roles to play as a catalyst to accelerate technology progress at each stage in the lifecycle of a technology (see Chapter 13 on international cooperation). Business plays a central role in this process of innovation and diffusion of technologies. For example, massive improvements in wind turbine technology have arisen through cooperation between innovators and manufacturers in many different markets. Similarly, business has played central roles in innovating and applying energy efficiency technologies and practices that can help cut costs and allow higher profits and additional employment opportunities. (ILO, 2012, 2013). Numerous studies indicate that it will be difficult to achieve widely discussed goals such as limiting warming to 2 degrees at least without drastic efficiency improvements (but also life style changes) (UNECE, 2010; Huntington and Smith, 2011; OECD, 2011; IEA, 2012d; Riahi et al., 2012). Innovations are needed not just in technology but also lifestyles and business practices that often evolve in tandem with technology. For example, after the Fukushima Daiichi accident in March 2011, changes in Japanese life style and behaviour curbed nationwide domestic household electricity demand by 5 % during the winter 2011/12 compared with the previous year after accounting for degree day differences (Ministry of Environment, Japan, 2012). Similarly, electricity demand in the Tokyo area was around 10 % lower in the summer 2011 than in 2010 and about 40 % of the reduction of demand resulted from behavioural changes that allowed for greater conservation of electricity used for air-conditioning (Nishio and Ofuji, 2012).

As a practical matter, strategies for innovating and deploying new technologies imply shifts in policy on many different fronts. In addition to the role for businesses, the public sector has a large role to play in affecting the underlying conditions that affect where and how firms actually make long-lived and at times financially risky investments. Those conditions include respect for contracts, a predictable and credible scheme for public policy, protection of intellectual property, and relatively efficient mechanisms for creating contracts and resolving disputes. These issues, explored in more detail in Chapter 16, are hardly unique to climate change. In addition, there may be large roles for the public sector in making public investments in basic technology that the private sector, on its own, would not adequately provide—a topic covered in more detail in Chapters 3.11 and 15.6.

1.4.5 Rising attention to adaptation

For a long time, nearly all climate policy has focused on mitigation. Now, with some change in climate inevitable (and a lot more likely) there has been a shift in emphasis to adaptation. While adaptation is primarily the scope of WGII, there are important interactions between mitigation and adaptation in the development of a mitigation strategy. If it is expected that global mitigation efforts will be limited, then adaptation will play a larger role in overall policy strategy. If it is expected that countries (and natural ecosystems) will find adaptation particularly difficult, then societies should become more heavily invested in the efforts to mitigate emissions.

Mitigation and adaptation also have quite different implications for collective action by nations. A strategy that relies heavily on mitigation requires collective action because no nation, acting alone, can have much impact on the global concentration of GHGs. Even the biggest nations account for only about one-quarter of global emissions. By contrast, most activities relevant for adaptation are local—while they may rely, at times, on international funding and know-how they imply local expenditures and local benefits. The need for (and difficulty of) achieving international collective action is perhaps less daunting than for mitigation (Victor, 2011).

Developing the right balance between mitigation and adaptation requires many tradeoffs and difficult choices (See WG II Chapter 17 for a more detailed discussion). In general, societies most at risk from climate change—and thus most in need of active adaptation—are those that are least responsible for emissions. That insight arises, in part, from the fact that as economies mature they yield much higher emissions but they also shift to activities that are less sensitive to vagaries of the climate. Other tradeoffs in striking the mitigation/adaptation balance concern the allocation of resources among quite different policy strategies. The world has spent more than 20 years of diplomatic debate on questions of mitigation and has only more recently begun extensive discussions and policy planning on the strategies needed for adaptation. As a practical matter, the relevant policymakers also differ. For mitigation many of the key actions hinge on international coordination and diplomacy. For adaptation the policymakers on the front lines are, to a much greater degree, regional and local officials such as managers of infrastructures that are vulnerable to extreme weather and changes in sea level.

1.5 Roadmap for WG III report

The rest of this report is organized into five major sections.

First, Chapters 2–4 introduce fundamental concepts and framing issues. Chapter 2 focuses on risk and uncertainty. Almost every aspect of climate change—from the projection of emissions to impacts on climate and human responses—is marked by a degree of uncertainty and requires a strategy for managing risks; since AR4, a large number of studies has focused on how risk management might be managed where policies have effects at many different levels and on a diverse array of actors. Scholars have also been able to tap into a rich literature on how humans perceive (and respond to) different types of risks and opportunities. Chapter 3 introduces major social, economic, and ethical concepts. Responding to the dangers of unchecked climate change requires tradeoffs and thus demands clear metrics for identifying and weighing different priorities of individuals and societies. Chapter 3 examines the many different cost and benefit metrics that are used for this purpose along with varied ethical frameworks that are essential to any full assessment. Chapter 4 continues that analysis by focusing on the concept of 'sustainable development'. The varied definitions and practices surrounding this concept reflect the many distinct efforts by societies and the international community to manage tradeoffs and synergies involved with economic growth, protection of the environment, social equity, justice and other goals.

Second, Chapters 5–6 put the sources of emissions and the scale of the mitigation challenge into perspective. Chapter 5 evaluates the factors that determine patterns of anthropogenic emissions of GHGs and particulate pollutants that affect climate. Chapter 6 looks at the suite of computer models that simulate how these underlying driving forces may change over time. Those models make it possible to project future emission levels and assess the certainty of those projections; they also allow evaluation of whether and how changes in technology, economy, behaviour and other factors could lower emissions as needed to meet policy goals.

Third, Chapters 7–11 look in detail at the five sectors of economic activity that are responsible for nearly all emissions. These sectors include energy supply systems (Chapter 7), such as the systems that extract primary energy and convert it into useful forms such as electricity and refined petroleum products. While energy systems are ultimately responsible for the largest share of anthropogenic emissions of climate gases, most of those emissions ultimately come from other sectors, such as transportation, that make final use of energy carriers. Chapter 8 looks at transportation, including passenger and freight systems. Chapter 9 examines buildings and Chapter 10 is devoted to industry. Together, Chapters 7–10 cover the energy system as a whole. Chapter 11 focuses on agriculture, forestry, and other land use (AFOLU), the only sector examined in this study for which the majority of emissions are not rooted in the energy system. Chapter 11 includes an appendix that delves in more detail into the special issues related to bioenergy systems (Section 11.13).

Looking across Chapters 7–11 one major common theme is the consideration and quantification of 'co-benefits' and 'adverse side-effects' of mitigating climate change, i.e., effects that a policy or measure aimed at one objective might have on other objectives. Measures limiting emissions of GHGs or enhancing sinks often also yield other benefits such as lowering the harmful health effects of local air pollution or regional acidification when firms and individuals switch to less polluting combustion technologies and fuels. But fuel switching from coal to gas can have adverse side-effects on the jobs in the coal mining industry. Although difficult to quantify, these co-benefits and adverse side-effects often play a large role in evaluating the costs and benefits of mitigation policies (see also Sections 3.6.3, 4.2, 4.8 and 6.6).

Often, this approach of looking sector-by-sector (and within each sector at individual technologies, processes, and practices) is called 'bottom up'. That perspective, which is evident in Chapters 7–11 complements the 'top down' perspective of Chapters 5–6 in which emissions are analyzed by looking at the whole economy of a nation or the planet.

Fourth, Chapter 12 looks at spatial planning since many emissions are rooted in how humans live, such as the density of population and the infrastructure of cities. Matters of spatial planning are treated distinctly in this report because they are so fundamental to patterns of emissions and the design and implementation of policy options.

Fifth, Chapters 13–16 look at the design and implementation of policy options from a variety of perspectives. Chapter 13 concentrates on the special issues that arise with international cooperation. Since no nation accounts for more than about one-quarter of world emissions, and economies are increasingly linked through trade and competition, a large body of research has examined how national policies could be coordinated through international agreements like the UN Framework Convention on Climate Change and other mechanisms for cooperation. Chapter 14 continues that analysis by focusing on regional cooperation and development patterns.

Chapter 15 looks at what has been learned within countries about the design and implementation of policies. Nearly every chapter in this study looks at an array of mitigation policies, including policies that work through market forces as well as those that rely on other mechanisms such as direct regulation. Chapter 15 looks across that experience at what has been learned.

Chapter 16, finally, looks at issues related to investment and finance. The questions of who pays for mitigation and the mechanisms that can mobilize needed investment capital are rising in prominence in international and national discussions about mitigation. Chapter 16 examines one of the most rapidly growing areas of scholarship and explores the interaction between public institutions such as governments and private firms and individuals that will ultimately make most decisions that affect climate change mitigation. Among its themes is the central role that financial risk management plays in determining the level and allocation of investment financing.

1.6 Frequently Asked Questions

FAQ 1.1 What is climate change mitigation?

The Framework Convention on Climate Change (UNFCCC), in its Article 1, defines *climate change* as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". The UNFCCC thereby makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. The IPCC, in contrast, defines climate change as "a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer", making no such distinction.

Climate Change Mitigation is a "human intervention to reduce the sources or enhance the sinks of greenhouse gases" (GHG) (See Glossary (Annex I)). The ultimate goal of mitigation (per Article 2 of the UNFCCC) is preventing dangerous anthropogenic interference with the climate system within a time frame to allow ecosystems to adapt, to ensure food production is not threatened and to enable economic development to proceed in a sustainable manner.

FAQ 1.2 What causes GHG emissions?

Anthropogenic GHGs come from many sources of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (HFCs, PFCs and SF_6). CO_2 makes the largest contribution to global GHG emissions; fluorinated gases (F-gases) contribute only a few per cent. The largest source of CO_2 is combustion of fossil fuels in energy conversion systems like boilers in electric power plants, engines in aircraft and automobiles, and in cooking and heating within homes and businesses. While most GHGs come from fossil fuel combustion, about one third comes from other activities like agriculture (mainly CH_4 and N_2O), deforestation (mainly CO_2), fossil fuel production (mainly CH_4) industrial processes (mainly CO_2, N_2O and F-gases) and municipal waste and wastewater (mainly CH_4). (See 1.3.1)

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2

Integrated Risk and Uncertainty Assessment of Climate Change Response Policies

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Executive Summary

The scientific understanding of climate change and the impact it has on different levels of decision-making and policy options has increased since the publication of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). In addition, there is a growing recognition that decision makers often rely on intuitive thinking processes rather than undertaking a systematic analysis of options in a deliberative fashion. It is appropriate that climate change risk management strategies take into account both forms of thinking when considering policy choices where there is risk and uncertainty.

Consideration of risk perception and decision processes can improve risk communication, leading to more effective policies for dealing with climate change. By understanding the systematic biases that individuals utilize in dealing with climate change problems, one can more effectively communicate the nature of the climate change risk. An understanding of the simplified decision rules employed by decision makers in making choices may be helpful in designing policies that encourage the adoption of mitigation and adaptation measures. [Section 2.4]

Decision processes often include both deliberative and intuitive thinking. When making mitigation and adaptation choices, decision makers sometimes calculate the costs and benefits of their alternatives (deliberative thinking). They are also likely to utilize emotion- and rule-based responses that are conditioned by personal past experience, social context, and cultural factors (intuitive thinking). [2.4.2]

Laypersons tend to judge risks differently than experts. Laypersons' perceptions of climate change risks and uncertainties are often influenced by past experience, as well as by emotional processes that characterize intuitive thinking. This may lead them to overestimate or underestimate the risk. Experts engage in more deliberative thinking than laypersons by utilizing scientific data to estimate the likelihood and consequences of climate change. [2.4.6]

Cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA) can enable decision makers to examine costs and benefits, but these methodologies also have their limitations. Both approaches highlight the importance of considering the likelihood of events over time and the importance of focusing on long-term horizons when evaluating climate change mitigation and adaptation policies. CBA enables governments and other collective decision-making units to compare the social costs and benefits of different alternatives. However, CBA cannot deal well with infinite (negative) expected utilities arising from low probability catastrophic events often referred to as 'fat tails'. CEA can generate cost estimates for stabilizing greenhouse gas (GHG) concentrations without having to take into account the uncertainties associated with cost estimates for climate change impacts. A limitation of CEA is that it takes the long-term stabilization as a given without considering the economic efficiency of the target level. [2.5.3, 2.5.4]

Formalized expert judgment and elicitation processes improve the characterization of uncertainty for designing climate change strategies (*high confidence*). Experts can quantify uncertainty through formal elicitation processes. Their judgments can characterize the uncertainties associated with a risk but not reduce them. The expert judgment process highlights the importance of undertaking more detailed analyses to design prudent climate policies. [2.5.6]

Individuals and organizations that link science with policy grapple with several different forms of uncertainty. These uncertainties include absence of prior agreement on framing of problems and ways to scientifically investigate them (paradigmatic uncertainty), lack of information or knowledge for characterizing phenomena (epistemic uncertainty), and incomplete or conflicting scientific findings (translational uncertainty). [2.6.2]

The social benefit from investments in mitigation tends to increase when uncertainty in the factors relating GHG emissions to climate change impacts are considered (*medium confidence*). If one sets a global mean temperature (GMT) target, then normative analyses that include uncertainty on the climate response to elevated GHG concentration, suggest that investments in mitigation measures should be accelerated. Under the assumption of nonlinear impacts of a GMT rise, inclusion of uncertainty along the causal chain from emissions to impacts suggests enhancing mitigation. [2.6.3]

The desirability of climate policies and instruments are affected by decision makers' responses to key uncertainties. At the national level, uncertainties in market behaviour and future regulatory actions have been shown to impact the performance of policy instruments designed to influence investment patterns. Both modelling and empirical studies have shown that uncertainty as to future regulatory and market conditions adversely affects the performance of emission allowance trading markets [2.6.5.1]. Other studies have shown that subsidy programmes (e.g., feed-in tariffs, tax credits) are relatively immune to market uncertainties, but that uncertainties with respect to the duration and level of the subsidy program can have adverse effects [2.6.5.2]. In both cases, the adverse effects of uncertainty include less investment in low-carbon infrastructure, increasing consumer prices, and reducing the pressure for technological development.

Decision makers in developing countries often face a particular set of challenges associated with implementing mitigation policies under risk and uncertainty (*medium confidence*). Managing risk and uncertainty in the context of climate policy is of particular importance to developing countries that are resource constrained and face other pressing development goals. In addition, institutional capacity in these countries may be less developed compared to advanced economies. Therefore, decision makers in these countries (governments and economic agents such as firms, farmers, households, to name a few) have less room for 'error' (uncertain outcomes and/or wrong or poorly implemented policies). The same applies to national, regional and local governments in developed countries who can ill afford to waste scarce resources through policy errors. [Box 2.1]

2.1 Introduction

This framing chapter considers ways in which risk and uncertainty can affect the process and outcome of strategic choices in responding to the threat of climate change.

'Uncertainty' denotes a cognitive state of incomplete knowledge that results from a lack of information and/or from disagreement about what is known or even knowable. It has many sources ranging from quantifiable errors in the data to ambiguously defined concepts or terminology to uncertain projections of human behaviour. The *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties* (Mastrandrea et al., 2010) summarizes alternative ways of representing uncertainty. Probability density functions and parameter intervals are among the most common tools for characterizing uncertainty.

'Risk' refers to the potential for adverse effects on lives, livelihoods, health status, economic, social and cultural assets, services (including environmental), and infrastructure due to uncertain states of the world. To the extent that there is a detailed understanding of the characteristics of a specific event, experts will normally be in agreement regarding estimates of the likelihood of its occurrence and its resulting consequences. Risk can also be subjective in the sense that the likelihood and outcomes are based on the knowledge or perception that a person has about a given situation. There may also be risks associated with the outcomes of different climate policies, such as the harm arising from a change in regulations.

There is a growing recognition that today's policy choices are highly sensitive to uncertainties and risk associated with the climate system and the actions of other decision makers. The choice of climate policies can thus be viewed as an exercise in risk management (Kunreuther et al., 2013a). Figure 2.1 suggests a risk management framework that serves as the structure of the chapter.

After defining risk and uncertainty and their relevant metrics (Section 2.2), we consider how choices with respect to climate change policy options are sensitive to risk and uncertainty (Section 2.3). A taxonomy depicts the levels of decision making ranging from international agreements to actions undertaken by individuals in relation to climate change policy options under conditions of risk and uncertainty that range from long-term global temperature targets to lifestyle choices. The goals and values of the different stakeholders given their immediate and long-term agendas will also influence the relative attractiveness of different climate change policies in the face of risk and uncertainty.

Sections 2.4, 2.5 and 2.6 characterize descriptive and normative theories of decision-making and models of choice for dealing with risk and uncertainty and their implications for prescriptive analysis. *Descriptive* refers to theories of actual behaviour, based on experimental evidence and field studies that characterize the perception of risk and decision processes. *Normative* in the context of this chapter refers to theories of choice under risk and uncertainty based on abstract models and axioms that serve as benchmarks as to how decision makers should ideally make their choices. *Prescriptive* refers to ways of improving the decision process and making final choices (Kleindorfer et al., 1993).

A large empirical literature has revealed that individuals, small groups and organizations often do not make decisions in the analytic or rational way envisioned by normative models of choice in the economics and management science literature. People frequently perceive risk in ways that differ from expert judgments, posing challenges for risk communication and response. There is a tendency to focus on short time horizons, utilize simple heuristics in choosing between alternatives, and selectively attend to subsets of goals and objectives.

To illustrate, the voting public in some countries may have a wait-and-see attitude toward climate change, leading their governments to postpone mitigation measures designed to meet specified climate targets (Sterman, 2008; Dutt and Gonzalez, 2011). A coastal village may decide not to undertake measures for reducing future flood risks due to sea level rise (SLR), because their perceived likelihood that SLR will cause problems to their village is below the community council's level of concern.

Section 2.4 provides empirical evidence on behavioural responses to risk and uncertainty by examining the types of biases that influence individuals' perception of the likelihood of an event (e.g., availability, learning from personal experience), the role that emotional, social, and cultural factors play in influencing the perception of climate change risks and strategies for encouraging decision makers to undertake cost-effective measures to mitigate and adapt to the impacts of climate change.

A wide range of decision tools have been developed for evaluating alternative options and making choices in a systematic manner even when probabilities are difficult to characterize and/or outcomes are uncertain. The relevance of these tools for making more informed decisions depends on how the problem is formulated and framed, the nature of the institutional arrangements, and the interactions between stakeholders (Hammond et al., 1999; Schoemaker and Russo, 2001).

Governments debating the merits of a carbon tax may turn to cost-benefit analysis or cost-effectiveness analysis to justify their positions. They may need to take into account that firms who utilize formal approaches, such as decision analysis, may not reduce their emissions if they feel that they are unlikely to be penalized because the carbon tax will not be well enforced. Households and individuals may find the expected utility model or decision analysis to be useful tools for evaluating the costs and benefits of adopting energy efficient measures given the trajectory of future energy prices.

Section 2.5 delineates formal methodologies and decision aids for analysing risk and uncertainty when individuals, households, firms, communities and nations are making choices that impact their own well-being and those of others. These tools encompass variants of expected utility theory, decision analysis, cost-benefit analyses or cost-effectiveness analyses that are implemented in integrated assessment models (IAMs). Decision aids include adaptive management, robust decision making and uncertainty analysis techniques such as structured expert judgment and scenario analysis. The chapter highlights the importance of selecting different methodologies for addressing different problems.

Developing robust policy response strategies and instruments should take into account how the relevant stakeholders perceive risk and their behavioural responses to uncertain information and data (descriptive analysis). The policy design process also needs to consider the methodologies and decision aids for systematically addressing issues of risk and uncertainty (normative analysis) that suggest strategies for improving outcomes at the individual and societal level (prescriptive analysis).

Section 2.6 examines how the outcomes of particular options, in terms of their efficiency or equity, are sensitive to risks and uncertainties and affect policy choices. After examining the role of uncertainty in the science/policy interface, it examines the role of integrated assessment models (IAMs) from the perspective of the social planner operating at a global level and the structuring of international negotiations and paths to reach agreement. Integrated assessment models combined with an understanding of the negotiation process for reaching international agreements may prove useful to delegates for justifying the positions of their country at a global climate conference. The section also examines the role that uncertainty plays in the performance of different technologies now and in the future as well as how lifestyle decisions such as investing in energy efficient measures can be improved.

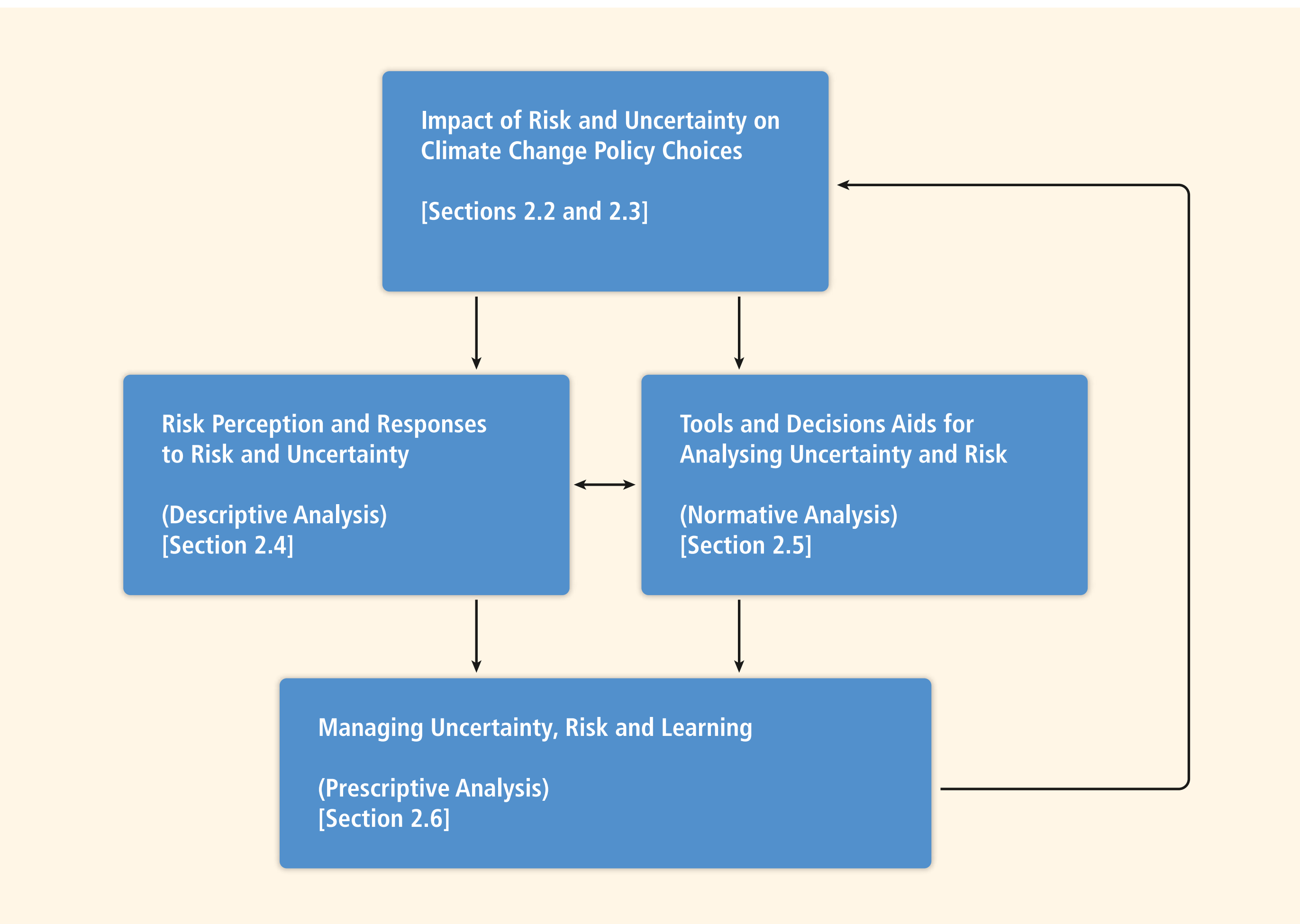

Figure 2.1 | A risk management framework. Numbers in brackets refer to sections where more information on these topics can be found.

The section concludes by examining the roles that risk and uncertainty play in support of or opposition to climate policies.

The way climate change is managed will have an impact on policy choices as shown by the feedback loop in Figure 2.1, suggesting that the risk management process for addressing climate change is iterative. The nature of this feedback can be illustrated by the following examples. Individuals may be willing to invest in solar panels if they are able to spread the upfront cost over time through a long-term loan. Firms may be willing to promote new energy technologies that provide social benefits with respect to climate change if they are given a grant to assist them in their efforts. National governments are more likely to implement carbon markets or international treaties if they perceive the short-term benefits of these measures to be greater than the perceived costs. Education and learning can play key roles in how climate change is managed through a reconsideration of policies for managing the risks and uncertainties associated with climate change.

2.2 Metrics of uncertainty and risk

The IPCC strives for a treatment of risk and uncertainty that is consistent across all three Working Groups based the *Guidance Note (GN) for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties* (Mastrandrea et al., 2010). This section summarizes key aspects of the GN that frames the discussion in this chapter.

The GN indicates that author teams should evaluate the associated evidence and agreement with respect to specific findings that involve risk and uncertainty. The amount of *evidence* available can range from small to large, and can vary in quality and consistency. The GN recommends reporting the degree of certainty and/or uncertainty of a given topic as a measure of the consensus or *agreement* across the scientific community. *Confidence* expresses the extent to which the IPCC authors do in fact support a key finding. If confidence is sufficiently high, the GN suggests specifying the key finding in terms of *probability*. The evaluation of evidence and degree of agreement of any key finding is labelled a *traceable account* in the GN.

The GN also recommends taking a risk-management perspective by stating that "sound decision making that anticipates, prepares for, and responds to climate change depends on information about the full range of possible consequences and associated probabilities." The GN also notes that, "low-probability outcomes can have significant impacts, particularly when characterized by large magnitude, long persistence, broad prevalence, and/or irreversibility." For this reason, the GN encourages the presentation of information on the extremes of the probability distributions of key variables, reporting quantitative estimates when possible and supplying qualitative assessments and evaluations when appropriate.

2.3 Risk and uncertainty in climate change

Since the publication of AR4, political scientists have documented the many choices of climate policy and the range of interested parties concerned with them (Moser, 2007; Andonova et al., 2009; Bulkeley, 2010; Betsill and Hoffmann, 2011; Cabré, 2011; Hoffmann, 2011; Meckling, 2011; Victor, 2011).

There continues to be a concern about global targets for mean surface temperature and GHG concentrations that are discussed in Chapter 6 of this report. This choice is normally made at the global level with some regions, countries, and sub-national political regions setting their own targets consistent with what they believe the global ones should be. Policymakers at all levels of decision making face a second-order set of choices as to how to achieve the desired targets. Choices in this vein that are assessed in Chapters 7–12 of this report, include transition pathways for various drivers of emissions, such as fossil fuels within the energy system, energy efficiency and energy-intensive behavioural patterns, issues associated with land-use and spatial planning, and/or the emissions of non- CO_2 greenhouse gases.

The drivers influencing climate change policy options are discussed in more detail in Chapters 13–16 of this report. These options include information provision, economic instruments (taxes, subsidies, fines), direct regulations and standards, and public investments. At the same time, individuals, groups and firms decide what actions to take on their own. These choices, some of which may be in response to governmental policy, include investments, lifestyle and behaviour.

Decisions for mitigating climate change are complemented by climate adaptation options and reflect existing environmental trends and drivers. The policy options are likely to be evaluated with a set of criteria that include economic impacts and costs, equity and distributional considerations, sustainable development, risks to individuals and society and co-benefits. Many of these issues are discussed in Chapters 3 and 4.

2.3.1 Uncertainties that matter for climate policy choices

The range and number of interested parties who are involved in climate policy choices have increased significantly in recent years. There has been a widening of the governance forums within which climate policies and international agreements are negotiated at the global level (Victor, 2011), across multiple networks within national governments (Andonova et al., 2009; Hoffmann, 2011), and at the local, regional and/or interest group level (Moser, 2007; Bulkeley, 2010). At the same time, the number of different policy instruments under active discussion has increased, from an initial focus on cap-and-trade and carbon tax instruments (Betsill and Hoffmann, 2011; Hoffmann, 2011), to feed-in tariffs or quotas for renewable energy (Wiser et al., 2005; Mendonça, 2007), investments in research and development (Sagar and van der Zwaan, 2006; De Coninck et al., 2008; Grubler and Riahi, 2010), and reform of intellectual property laws (Dechezleprêtre et al., 2011; Percival and Miller, 2011).

Choices are sensitive to the degree of uncertainty with respect to a set of parameters that are often of specific importance to particular climate policy decisions. Here, and as shown in Figure 2.2, we group these uncertainties into five broad classes, consistent with the approach taken in Patt and Weber (2014):

- *Climate responses to greenhouse gas (GHG) emissions, and their associated impacts.* The large number of key uncertainties with respect to the climate system are discussed in Working Group I (WGI). There are even greater uncertainties with respect to the impacts of changes in the climate system on humans and the ecological system as well as their costs to society. These impacts are assessed in WGII.

- *Stocks and flows of carbon and other GHGs.* The large uncertainties with respect to both historical and current GHG sources and sinks from energy use, industry, and land-use changes are assessed in Chapter 5. Knowledge gaps make it especially difficult to estimate how the flows of greenhouse gases will evolve in the future under conditions of elevated atmospheric CO_2 concentrations and their impact on climatic and ecological processes.

- *Technological systems.* The deployment of technologies is likely to be the main driver of GHG emissions and a major driver of climate vulnerability. Future deployment of new technologies will depend on how their price, availability, and reliability evolve over time as a result of technological learning. There are uncertainties as to how fast the learning will take place, what policies can accelerate learning and the effects of accelerated learning on deployment rates of new technologies. Technological deployment also depends on the degree of public acceptance, which in turn is typically sensitive to perceptions of health and safety risks.

- *Market behaviour and regulatory actions.* Public policies can create incentives for private sector actors to alter their investment behaviour, often in the presence of other overlapping regulations. The extent to which firms change their behaviour in response to the policy, however, often depends on their expectations about other highly uncertain market factors, such as fossil fuel prices. There are also uncertainties concerning the macro-economic effects of the aggregated behavioural changes. An additional factor influencing the importance of any proposed or existing policy-driven incentive is the likelihood with which regulations will be enacted and enforced over the lifetime of firms' investment cycles.

- *Individual and firm perceptions*. The choices undertaken by key decision makers with respect to mitigation and adaptation measures are impacted by their perceptions of risk and uncertainties, as well as their perceptions of the relevant costs and expected benefits over time. Their decisions may also be influenced by the actions undertaken by others.

Section 2.6 assesses the effects of uncertainties of these different parameters on a wide range of policy choices, drawing from both empirical studies and the modelling literature. The following three examples illustrate how uncertainties in one or more of the above factors can influence choices between alternative options.

Example 1: Designing a regional emissions trading system (ETS). Over the past decade, a number of political jurisdictions have designed and implemented ETSs, with the European ETS being the one most studied. In designing the European system, policymakers took as their starting point pre-defined emissions reduction targets. It was unclear whether these targets would be met, due to uncertainties with respect to national baseline emissions. The stocks and flows of greenhouse gas emissions were partly determined by the uncertainty of the performance of the technological systems that were deployed. Uncertainties in market behaviour could also influence target prices and the number of emissions permits allocated to different countries (Betsill and Hoffmann, 2011).

Example 2: Supporting scientific research into solar radiation management (SRM). SRM may help avert potentially catastrophic temperature increases, but may have other negative impacts with respect to global and regional climatic conditions (Rasch et al., 2008). Research could reduce the uncertainties as to these other consequences (Robock et al., 2010). The decision to invest in specific research activities requires an assessment as to what impact SRM will have on avoiding catastrophic temperature increases. Temperature change will be sensitive to the stocks and flows of greenhouse gases (GHG) and therefore to the responses by key decision makers to the impacts of GHG emissions. The decision to invest in specific research activities is likely to be influenced by the perceived uncertainty in the actions undertaken by individuals and firms (Blackstock and Long, 2010).

Example 3: Renting an apartment in the city versus buying a house in the suburbs. When families and households face this choice, it is likely to be driven by factors other than climate change concerns. The decision, however, can have major consequences on CO_2 emissions as well as on the impacts of climate change on future disasters such as damage from flooding due to sea level rise. Hence, governments may seek to influence these decisions as part of their portfolio of climate change policies through measures such as land-use regulations or the pricing of local transportation options. The final choice is thus likely to be sensitive to uncertainties in *market behaviour* as well *as actions undertaken by individuals and firms*.

To add structure and clarity to the many uncertainties that different actors face for different types of problems, we introduce a taxonomy shown in Figure 2.2 that focuses on levels of decision making (the rows) that range from international organizations to individuals and households, and climate policy options (the columns) that include long-term targets, transition pathways, policy instruments, resource allocation and lifestyle options. The circles that overlay the cells in Figure 2.2 highlight the principal uncertainties relevant to decision-making levels and climate policy choices that appear prominently in the literature associated with particular policies. These are reviewed in Section 2.6 of this chapter and in many of the following chapters of WGIII. The literature appraises the effects of a wide range of uncertainties, which we group according to the five types described above.

2.3.2 What is new on risk and uncertainty in AR5

Chapter 2 in WGIII AR4 on risk and uncertainty, which also served as a framing chapter, illuminated the relationship of risk and uncertainty to decision making and reviewed the literature on catastrophic or abrupt climate change and its irreversible nature. It examined three pillars for dealing with uncertainties: precaution, risk hedging, and crisis prevention and management. The report also summarized the debate in the economic literature about the limits of cost-benefit analysis in situations of uncertainty.

Since the publication of AR4, a growing number of studies have considered additional sources of risk and uncertainties, such as regulatory and technological risks, and examined the role they play in influencing climate policy. There is also growing awareness that risks in the extremes or tail of the distribution make it problematic to rely on historical averages. As the number of political jurisdictions implementing climate policies has increased, there are now empirical findings to supplement earlier model-based studies on the effects of such risks. At the local level, adaptation studies using scenario-based methods have been developed (ECLACS, 2011).

This chapter extends previous reports in four ways. First, rather than focusing solely at the global level, this chapter expands climate-related decisions to other levels of decision making as shown in Figure 2.2. Second, compared to AR4, where judgment and choice were primarily framed in rational-economic terms, this chapter reviews the psychological and behavioural literature on perceptions and responses to risk and uncertainty. Third, the chapter considers the pros and cons of alternative methodologies and decision aids from the point of view of practitioners. Finally, the chapter expands the scope of the challenges associated with developing risk management strategies in relation to

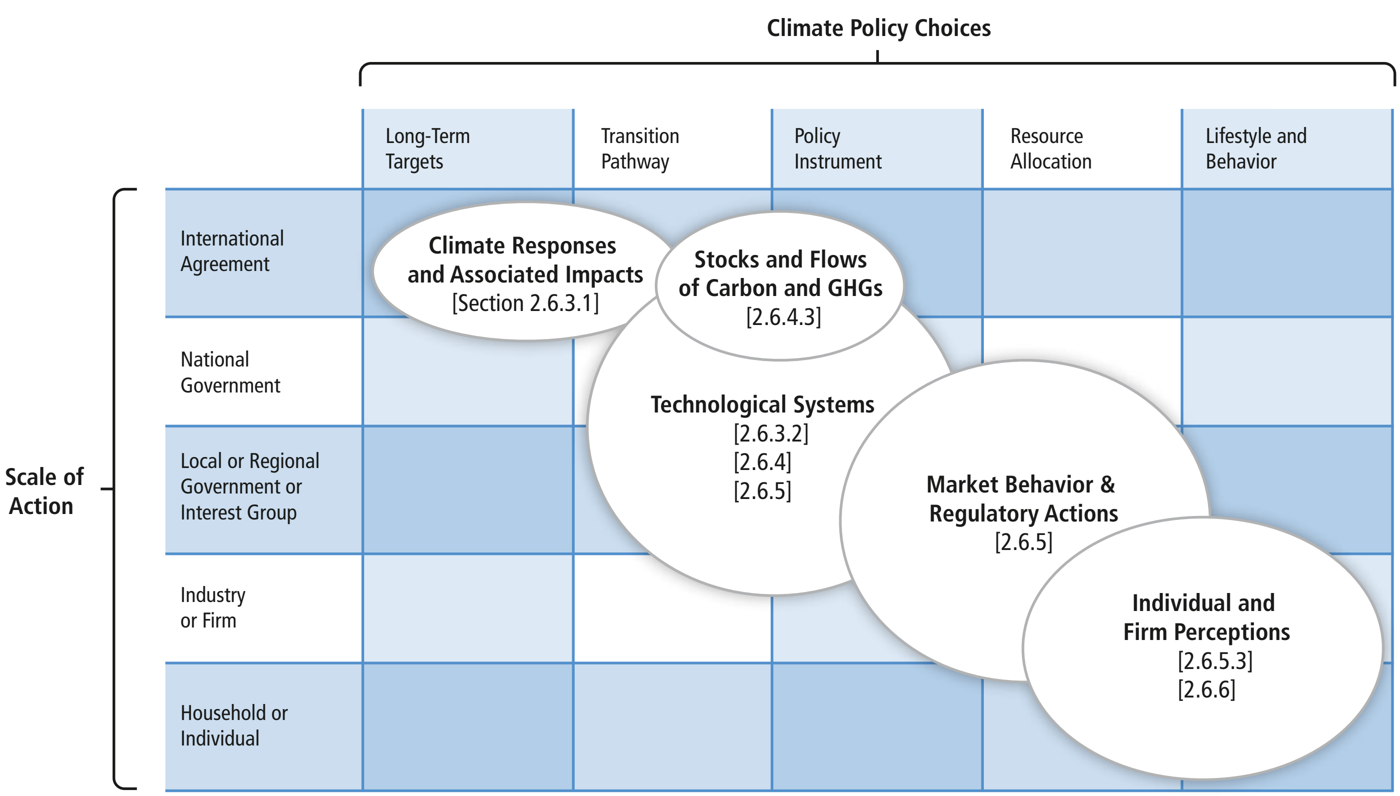

Figure 2.2 | Taxonomy of levels of decision making and climate policy choices. Circles show type and extent of uncertainty sources as they are covered by the literature. Numbers in brackets refer to sections where more information on these uncertainty sources can be found.

AR4 that requires reviewing a much larger body of published research. To illustrate this point, the chapter references more than 50 publications on decision making under uncertainty with respect to integrated assessment models (IAMs), the first time such a detailed examination of this literature has been undertaken.

2.4 Risk perception and responses to risk and uncertainty

2.4.1 Considerations for design of climate change risk reduction policies

When stakeholders are given information about mitigation and adaptation measures to reduce climate change risks, they make the following judgments and choices: How serious is the risk? Is any action required? Which options are ruled out because the costs seem prohibitive? Which option offers the greatest net expected benefits?

In designing such measures and in deciding how to present them to stakeholders, one needs to recognize both the strengths and limitations of decision makers at the different levels delineated in Figure 2.2. Decision makers often have insufficient or imperfect knowledge about climate risks, a deficit that can and needs to be addressed by better data and public education. However, cognitive and motivational barriers are equally or more important in this regard (Weber and Stern, 2011).

Normative models of choice described in Section 2.5 indicate how decisions under risk and uncertainty should be made to achieve efficiency and consistency, but these approaches do not characterize how choices are actually made. Since decision makers have limitations in their ability to process information and are boundedly rational (Simon, 1955), they often use simple heuristics and rules of thumb (Payne et al., 1988). Their choices are guided not only by external reality (objective outcomes and their likelihood) but also by the decision makers' internal states (e.g., needs and goals) and their mental representation of outcomes and likelihood, often shaped by previous experience. In other words, a descriptive model of choice needs to consider cognitive and motivational biases and decision rules as well as factors that are considered when engaging in deliberative thinking. Another complicating factor is that when groups or organizations make decisions, there is the potential for disagreement and conflict among individuals that may require interpersonal and organizational facilitation by a third party.

Mitigation and adaptation decisions are shaped also by existing economic and political institutional arrangements. Policy and market tools for addressing climate change, such as insurance, may not be feasible in developing countries that have no history of this type of protection; however, this option may be viewed as desirable in a country with an active insurance sector (see Box 2.1). Another important determinant of decisions is the status quo, because there is a tendency to give more weight to the negative impacts of undertaking change than the equivalent positive impacts (Johnson et al., 2007). For example, proposing a carbon tax to reduce GHG emissions may elicit much more concern from affected stakeholders as to how this measure will impact on their current activities than the expected climate change benefits from reducing carbon emissions. Choices are also affected by cultural differences in values and needs (Maslow, 1954), in beliefs about the existence and causes of climate change (Leiserowitz et al., 2008), and in the role of informal social networks for cushioning catastrophic losses (Weber and Hsee, 1998). By considering actual judgment and choice processes, policymakers can more accurately characterize the effectiveness and acceptability of alternative mitigation policies and new technologies. Descriptive models also provide insights into ways of framing mitigation or adaptation options so as to increase the likelihood that desirable climate policy choices are adopted. Descriptive models, with their broader assumptions about goals and processes, also allow for the design of behavioural interventions that capitalize on motivations such as equity and fairness.

2.4.2 Intuitive and deliberative judgment and choice

The characterization of judgment and choice that distinguishes intuitive processes from deliberative processes builds on a large body of cognitive psychology and behavioural decision research that can be traced to William James (1878) in psychology and to Friedrich Nietzsche (2008) and Martin Heidegger (1962) in philosophy. A recent summary has been provided by Kahneman (2003; 2011) as detailed in Table 2.1:

Table 2.1 | Intuitive and deliberative process characteristics.

Intuitive Thinking (System 1)
Operates automatically and quickly, with little or no effort and no voluntary control.
Uses simple and concrete associations, including emotional reactions or simple rules of conduct that have been acquired by personal experience with events and their consequences.
Deliberative Thinking (System 2)
Initiates and executes effortful and intentional abstract cognitive operations when these are seen as needed.
These cognitive operations include simple or complex computations or formal logic.

Even though the operations of these two types of processes do not map cleanly onto distinct brain regions, and the two systems often operate cooperatively and in parallel (Weber and Johnson, 2009), the distinction between Systems 1 and 2 helps to clarify the tension in the human mind between the automatic and largely involuntary processes of intuitive decisions, versus the effortful and more deliberate processes of analytic decisions (Kahneman, 2011).

Many of the simplified decision rules that characterize human judgment and choice under uncertainty utilize intuitive (System 1) processes. Simplification is achieved by utilizing the experiences, expectations, beliefs, and goals of the interested parties involved in the decision. Such shortcuts require much less time and effort than a more detailed analysis of the tradeoffs between options and often leads to reasonable outcomes. If one takes into account the constraints on time and attention and processing capacity of decision makers, these decisions may be the best we can do for many choices under uncertainty (Simon, 1955). Intuitive processes are utilized not only by the general public, but also by technical experts such as insurers and regulators (Kunreuther et al., 2013c) and by groups and organizations (Cyert and March, 1963; Cohen et al., 1972; Barreto and Patient, 2013).

Intuitive processes work well when decision makers have copious data on the outcomes of different decisions and recent experience is a meaningful guide for the future, as would be the case in stationary environments (Feltovich et al., 2006). These processes do not work well, however, for low-probability high-consequence events for which the decision maker has limited or no past experience (Weber, 2011). In such situations, reliance on intuitive processes for making decisions will most likely lead to maintaining the status quo and focusing on the recent past. This suggests that intuitive decisions may be problematic in dealing with climate change risks such as increased flooding and storm surge due to sea level rise, or a surge in fossil fuel prices as a result of an unexpected political conflict. These are risks for which there is limited or no personal experience or historical data and considerable disagreement and uncertainty among experts with respect to their risk assessments (Taleb, 2007).

The formal models and tools that characterize deliberative (System 2) thinking require stakeholders to make choices in a more abstract and systematic manner. A deliberative process focuses on potential short- and long-term consequences and their likelihoods, and evenly evaluates the options under consideration, not favouring the status quo. For the low-probability high-consequence situations for which decision makers have limited experience with outcomes, alternative decision frameworks that do not depend on precise specification of probabilities should be considered in designing risk management strategies for climate change (Charlesworth and Okereke, 2010; Kunreuther et al., 2013a).

The remainder of this section is organized as follows. Section 2.4.3 describes some important consequences of the intuitive processes utilized by individuals, groups, and organizations in making decisions. The predicted effectiveness of economic or technological climate change mitigation solutions typically presuppose rational deliberative thinking and evaluation without considering how perceptions and reactions to climate risks impose on these policy options. Section 2.4.4 discusses biases and heuristics that suggest that individuals learn in ways that differ significantly from deliberative Bayesian updating. Section 2.4.5 addresses how behaviour is affected by social amplification of risk and considers the different levels of decision making in Figure 2.2 by discussing the role of social norms, social comparisons, and social networks in the choice process. Section 2.4.6 characterizes the general public's perceptions of climate change risks and uncertainty and their implications for communicating relevant information.

Empirical evidence for the biases associated with climate change response decisions triggered by intuitive processes exists mostly at the level of the individual. As discussed in Sections 2.5 and 2.6, intuitive judgment and choice processes at other levels of decision making, such as those specified in Figure 2.2, need to be acknowledged and understood.

2.4.3 Consequences of intuitive decision making

The behaviour of individuals are captured by descriptive models of choice such as prospect theory (Kahneman and Tversky, 1979) for decisions under risk and uncertainty and the beta-delta model (Laibson, 1997) for characterizing how future costs and benefits are evaluated. While individual variation exists, the patterns of responding to potential outcomes over time and the probabilities of their occurrence have an empirical foundation based on controlled experiments and well-designed field studies examining the behaviour of technical experts and the general public (Loewenstein and Elster, 1992; Camerer, 2000).

2.4.3.1 Importance of the status quo

The tendency to maintain the current situation is a broadly observed phenomenon in climate change response contexts (e.g., inertia in switching to a non-carbon economy or in switching to cost-effective energy efficient products) (Swim et al., 2011). Sticking with the current state of affairs is the easy option, favoured by emotional responses in situations of uncertainty ("better the devil you know than the devil you don't"), by many proverbs or rules ("when in doubt, do nothing"), and observed biases in the accumulation of arguments for different choice options (Weber et al., 2007). Overriding the status quo requires commitment to change and effort (Fleming et al., 2010).

Loss aversion and reference points

Loss aversion is an important property that distinguishes prospect theory (Tversky and Kahneman, 1992) from expected utility theory (von Neumann and Morgenstern, 1944) by introducing a reference-dependent valuation of outcomes, with a steeper slope for perceived losses than for perceived gains. In other words, people experience more pain from a loss than they get pleasure from an equivalent gain. The status quo is often the relevant reference point that distinguishes outcomes perceived as losses from those perceived as gains. Given loss aversion, the potential negative consequences of moving away from the current state of affairs are weighted much more heavily than the potential gains, often leading the decision maker not to take action. This behaviour is referred to as the *status quo bias* (Samuelson and Zeckhauser, 1988).

Loss aversion explains a broad range of decisions in controlled laboratory experiments and real world choices that deviate from the predictions of rational models like expected utility theory (Camerer, 2000). Letson et al. (2009) show that adapting to seasonal and inter-annual climate variability in the Argentine Pampas by allocating land to different crops depends not only on existing institutional arrangements (e.g., whether the farmer is renting the land or owns it), but also on individual differences in farmers' degree of loss aversion and risk aversion. Greene et al. (2009) show that loss aversion combined with uncertainty about future cost savings can explain why consumers frequently appear to be unwilling to invest in energy-efficient technology such as a more expensive but more fuel-efficient car that has positive expected utility. Weber and Johnson (2009) distinguish between perceptions of risk, attitudes towards risk, and loss aversion that have different determinants, but are characterized by a single 'risk attitude' parameter in expected utility models. Distinguishing and measuring these psychologically distinct components of individual differences in risk taking (e.g., by using prospect theory and adaptive ways of eliciting its model parameters; Toubia et al., 2013) provides better targeted entry points for policy interventions.

Loss aversion influences the choices of experienced decision makers in high-stakes risky choice contexts, including professional financial markets traders (Haigh and List, 2005) and professional golfers (Pope and Schweitzer, 2011). Yet, other contexts fail to elicit loss aversion, as evidenced by the failure of much of the global general public to be alarmed by the prospect of climate change (Weber, 2006). In this and other contexts, loss aversion does not arise because decision makers are not emotionally involved (Loewenstein et al., 2001).

Use of framing and default options for the design of decision aids and interventions

Descriptive models not only help explain behaviours that deviate from the predictions of normative models of choice but also provide entry points for the design of decision aids and interventions collectively referred to as choice architecture, indicating that people's choices depend in part on the ways that possible outcomes of different options are framed and presented (Thaler and Sunstein, 2008). Prospect theory suggests that changing decision makers' reference points can impact on how they evaluate outcomes of different options and hence their final choice. Patt and Zeckhauser (2000) show, for example, how information about the status quo and other choice options can be presented differently to create an action bias with respect to addressing the climate change problem. More generally, choice architecture often involves changing the description of choice options and the context of a decision to overcome the pitfalls of intuitive (System 1) processes without requiring decision makers to switch to effortful (System 2) thinking (Thaler and Sunstein, 2008).

One important choice architecture tool comes in the form of behavioural defaults, that is, recommended options that will be implemented if no active decision is made (Johnson and Goldstein, 2013). Default options serve as a reference point so that decision makers normally stick with this option due to loss aversion (Johnson et al., 2007; Weber et al., 2007). 'Green' energy defaults have been found to be very effective in lab studies involving choices between different lighting technologies (Dinner et al., 2011), suggesting that environmentally friendly and cost-effective energy efficient technology will find greater deployment if it were to show up as the default option in building codes and other regulatory contexts. Green defaults are desirable policy options because they guide decision makers towards individual and social welfare maximizing options without reducing choice autonomy. In a field study, German utility customers adopted green energy defaults, a passive choice that persisted over time and was not changed by price feedback (Pichert and Katsikopoulos, 2008). Moser (2010) provides other ways to frame climate change information and response options in ways consistent with the communication goal and characteristics of the audience.

2.4.3.2 Focus on the short term and the here-and-now

Finite attention and processing capacity imply that unaided intuitive choices are restricted in their scope. This makes individuals susceptible to different types of myopia or short-sightedness with respect to their decisions on whether to invest in measures they would consider cost-effective if they engaged in deliberative thinking (Weber and Johnson, 2009; Kunreuther et al., 2013b).

Present bias and quasi-hyperbolic time discounting

Normative models suggest that future costs and benefits should be evaluated using an exponential discount function, that is, a constant discount rate per time period (i.e., exponentially), where the discount rate should reflect the decision maker's opportunity cost of money (for more details see Section 3.6.2). In reality, people discount future costs or benefits much more sharply and at a non-constant rate (i.e., hyperbolically), so that delaying an immediate receipt of a benefit is viewed much more negatively than if a similar delay occurs at a future point in time (Loewenstein and Elster, 1992). Laibson (1997) characterized this pattern by a quasi-hyperbolic discount function, with two parameters: (1) present bias, i.e., a discount applied to all non-immediate outcomes regardless how far into the future they occur, and (2) a rational discounting parameter. The model retains much of the analytical tractability of exponential discounting, while capturing the key qualitative feature of hyperbolic discounting.

Failure to invest in protective measures

In the management of climate-related natural hazards such as flooding, an extensive empirical literature reveals that adoption rates of protective measures by the general public are much lower than if individuals had engaged in deliberative thinking by making relevant tradeoffs between expected costs and benefits. Thus, few people living in flood prone areas in the United States voluntarily purchase flood insurance, even when it is offered at highly subsidized premiums under the National Flood Insurance Program (NFIP) (Kunreuther et al., 1978). In the context of climate change mitigation, many efficient responses like investments in household energy efficiency are not adopted because decision makers focus unduly on the upfront costs of these measures (due to hyperbolic discounting amplified by loss aversion) and weight the future benefits of these investments less than predicted by normative models (see Sections 2.6.4.3 and 3.10). The failure of consumers to buy fuel-efficient cars because of their higher upfront costs (Section 8.3.5) is another example of this behaviour.

At a country or community level, the upfront costs of mitigating CO_2 emissions or of building seawalls to reduce the effects of sea level rise loom large due to loss aversion, while the uncertain and future benefits of such actions are more heavily discounted than predicted by normative models. Such accounting of present and future costs and benefits on the part of consumers and policymakers might make it difficult for them to justify these investments today and arrive at long-term sustainable decisions (Weber, 2013).

Focus on short-term goals

Krantz and Kunreuther (2007) emphasize the importance of goals and plans as a basis for making decisions. In the context of climate change, protective or mitigating actions often require sacrificing short-term goals that are highly weighted in people's choices in order to meet more abstract, distant goals that are typically given very low weight. A strong focus on short-term goals (e.g., immediate survival) may have been helpful as humans evolved, but may have negative consequences in the current environment where risks and challenges are more complex and solutions to problems such as climate change require a focus on long time horizons. Weber et al. (2007) succeeded in drastically reducing people's discounting of future rewards by prompting them to first generate arguments for deferring consumption, contrary to their natural inclination to focus initially on rationales for immediate consumption. To deal with uncertainty about future objective circumstances as well as subjective evaluations, one can adopt multiple points of view (Jones and Preston, 2011) or multiple frames of reference (De Boer et al., 2010); a generalization of the IPCC's scenario approach to an uncertain climate future is discussed in Chapter 6.

Mental accounting as a protection against short-term focus

People often mentally set up separate 'accounts' for different classes of expenditures and do not treat money as fungible between these accounts (Thaler, 1999). Mental accounts for different expenditures serve as effective budgeting and self-control devices for decision makers with limited processing capacity and self-control. A focus on short-term needs and goals can easily deplete financial resources, leaving not enough for long(er)-term goals. Placing a limit on short-term spending prevents this from happening. But such a heuristic also has a downside by unduly limiting people's willingness to invest in climate change mitigation or adaptation measures (e.g., flood proofing or solar panels) that exceed their allocated budget for this account, regardless of future benefits. Such constraints (real or mental) often lead to the use of lexicographic (rather than compensatory) choice processes, where option sets are created or eliminated sequentially, based on a series of criteria of decreasing importance (Payne et al., 1988).

Mental accounting at a nonfinancial level may also be responsible for rebound effects of a more psychological nature, in addition to the economically based rebound effects discussed in Section 8.3.5. Rebound effects describe the increase in energy usage that sometimes follows improvements in household, vehicle, or appliance efficiency. For example, households who weatherize their homes tend to increase their thermostat settings during the winter afterwards, resulting in a decrease in energy savings relative to what is technologically achievable (Hirst et al., 1985). While rebound effects on average equal only 10–30% of the achievable savings, and therefore do not cancel out the benefits of efficiency upgrades (Ehrhardt-Martinez and Laitner, 2010), they are significant and may result from fixed mental accounts that people have for environmentally responsible behaviour. Having fulfilled their self-imposed quota by a particular action allows decision makers to move on to other goals, a behaviour also sometimes referred to as the single-action bias (Weber, 2006).

2.4.3.3 Aversion to risk, uncertainty, and ambiguity

Most people are averse to risk and to uncertainty and ambiguity when making choices. More familiar options tend to be seen as less risky, all other things being equal, and thus more likely to be selected (Figner and Weber, 2011).

Certainty effect or uncertainty aversion

Prospect theory formalizes a regularity related to people's perceptions of certain versus probabilistic prospects. People overweight outcomes they consider certain, relative to outcomes that are merely probable—a phenomenon labelled the *certainty effect* (Kahneman and Tversky, 1979). This frequently observed behaviour can explain why the certain upfront costs of adaptation or mitigation actions are viewed as unattractive when compared to the uncertain future benefits of undertaking such actions (Kunreuther et al., 2013b).

Ambiguity aversion

Given the high degree of uncertainty or ambiguity in most forecasts of future climate change impacts and the effects of different mitigation or adaptation strategies, it is important to consider not only decision makers' risk attitudes, but also attitudes towards ambiguous outcomes. The Ellsberg paradox (Ellsberg, 1961) revealed that, in addition to being risk averse, most decision makers are also ambiguity averse, that is, they prefer choice options with well-specified probabilities over options where the probabilities are uncertain. Heath and Tversky (1991) demonstrated, however, that ambiguity aversion is not present when decision makers believe they have expertise in the domain of choice. For example, in contrast to the many members of the general public who consider themselves to be experts in sports or the stock market, relatively few people believe themselves to be highly competent in environmentally relevant technical domains such as the tradeoffs between hybrid electric versus conventional gasoline engines in cars, so they are likely to be ambiguity averse. Farmers who feel less competent with respect to their understanding of new technology are more ambiguity averse and less likely to adopt farming innovations (in Peru; Engle-Warnick and Laszlo, 2006; and in the USA; Barham et al., 2014). With respect to the likelihood of extreme events, such as natural disasters, insurers feel they do not have special expertise in estimating the likelihood of these events so they also tend to be ambiguity averse and set premiums that are considerably higher than if they had more certainty with respect to the likelihood of their occurrence (Kunreuther et al., 1993; Cabantous et al., 2011).

2.4.4 Learning

The ability to change expectations and behaviour in response to new information is an important survival skill, especially in uncertain and non-stationary environments. Bayesian updating characterizes learning when one engages in deliberative thinking. Individuals who engage in intuitive thinking are also highly responsive to new and especially recent feedback and information, but treat the data differently than that implied by Bayesian updating (Weber et al., 2004).

Availability bias and the role of salience

People's intuitive assessment of the likelihood of an uncertain event is often based on the ease with which instances of its occurrence can be brought to mind, a mechanism called *availability* by Tversky and Kahneman (1973). Sunstein (2006) discusses the use of the availability heuristics in response to climate change risks and how it differs among groups, cultures, and nations. Availability is strongly influenced by recent personal experience and can lead to an underestimation of low-probability events (e.g., typhoons, floods, or droughts) before they occur, and their overestimation after an extreme event has occurred. The resulting availability bias can explain why individuals first purchase insurance after a disaster has occurred and cancel their policies several years later, as observed for earthquake (Kunreuther et al., 1978) and flood insurance (Michel-Kerjan et al., 2012). It is likely that most of these individuals had not suffered any losses during this period and considered the insurance to be a poor investment. It is difficult to convince insured individuals that the best return on their policy is no return at all. They should celebrate not having suffered a loss (Kunreuther et al., 2013c).

Linear thinking

A majority of people perceive climate in a linear fashion that reflects two common biases (Sterman and Sweeney, 2007; Cronin et al., 2009; Dutt and Gonzalez, 2011). First, people often rely on the *correlation heuristic*, which means that people wrongly infer that an accumulation (CO_2 concentration) follows the same path as the inflow (CO_2 emissions). This implies that cutting emissions will quickly reduce the concentration and damages from climate change (Sterman and Sweeney, 2007). According to Dutt (2011) people who rely on this heuristic likely demonstrate wait-and-see behaviour on policies that mitigate climate change because they significantly underestimate the delay between reductions in CO_2 emissions and in the CO_2 concentration. Sterman and Sweeny (2007) show that people's wait-and-see behaviour on mitigation policies is also related to a second bias whereby people incorrectly infer that atmospheric CO_2 concentration can be stabilized even when emissions exceeds absorption.

Linear thinking also leads people to draw incorrect conclusions from nonlinear metrics, like the miles-per-gallon (mpg) ratings of vehicles' gasoline consumption in North America (Larrick and Soll, 2008). When given a choice between upgrading to a 15-mpg car from a 12-mpg car, or to a 50-mpg car from a 29-mpg car, most people choose the latter option. However, for 100 miles driven under both options, it is easily shown that the first upgrade option saves more fuel (1.6 gallons for every 100 miles driven) than the second upgrade option (1.4 gallons for every 100 miles driven).

Effects of personal experience

Learning from personal experience is well predicted by reinforcement learning models (Weber et al., 2004). Such models describe and predict why the general public is less concerned about low-probability high-impact climate risks than climate scientists would suggest is warranted by the evidence (Gonzalez and Dutt, 2011). These learning models also capture the volatility of the public's concern about climate change over time, for example in reaction to the personal experience of local weather abnormalities (an abnormal cold spell or heat wave) that have been shown to influence belief in climate change (Li et al., 2011).

Most people do not differentiate very carefully between weather, climate (average weather over time), and climate variability (variations in weather over time). People confound climate and weather in part because they have personal experience with weather and weather abnormalities but little experience with climate change, an abstract statistical concept. They thus utilize weather events in making judgments about climate change (Whitmarsh, 2008). This confusion has been observed in countries as diverse as the United States (Bostrom et al., 1994; Cullen, 2010) and Ethiopia (BBC World Service Trust, 2009).

Personal experience can differ between individuals as a function of their location, history, and/or socio-economic circumstances (Figner and Weber, 2011). Greater familiarity with climate risks, unless accompanied by alarming negative consequences, could actually lead to a reduction rather than an increase in the perceptions of its riskiness (Kloeckner, 2011). On the other hand, people's experience can make climate a more salient issue. For example, changes in the timing and extent of freezing and melting (and associated effects on sea ice, flora, and fauna) have been experienced since the 1990s in the American and Canadian Arctic and especially indigenous communities (Laidler, 2006), leading to increased concern with climate change because traditional prediction mechanisms no longer can explain these phenomena (Turner and Clifton, 2009).

People's expectations of change (or stability) in climate variables also affect their ability to detect trends in probabilistic environments. For instance, farmers in Illinois were asked to recall growing season temperature or precipitation statistics for seven preceding years. Farmers who believed that their region was affected by climate change recalled precipitation and temperature trends consistent with this expectation, whereas farmers who believed in a constant climate, recalled precipitations and temperatures consistent with that belief (Weber, 1997). Recognizing that beliefs shape perception and memory provides insight into why climate change expectations and concerns vary between segments of the US population with different political ideologies (Leiserowitz et al., 2008).

The evidence is mixed when we examine whether individuals learn from past experience with respect to investing in adaptation or mitigation measures that are likely to be cost-effective. Even after the devastating 2004 and 2005 hurricane seasons in the United States, a large number of residents in high-risk areas had still not invested in relatively inexpensive loss-reduction measures, nor had they undertaken emergency preparedness measures (Goodnough, 2006). Surveys conducted in Alaska and Florida, regions where residents have been exposed more regularly to physical evidence of climate change, show greater concern and willingness to take action (ACI, 2004; Leiserowitz and Broad, 2008; Mozumder et al., 2011).

A recent study assessed perceptions and beliefs about climate change of a representative sample of the Britain public (some of whom had experienced recent flooding in their local area). It also asked whether they would reduce personal energy use to reduce greenhouse gas emission (Spence et al., 2011). Concern about climate change and willingness to take action was greater in the group of residents who had experienced recent flooding. Even though the flooding was only a single and local data point, this group also reported less uncertainty about whether climate change was really happening than those who did not experience flooding recently, illustrating the strong influence of personal experience. Other studies fail to find a direct effect of personal experience with flooding generating concern about climate risks (Whitmarsh, 2008).

Some researchers find that personal experience with ill health from air pollution affects perceptions of and behavioural responses to climate risks (Bord et al., 2000; Whitmarsh, 2008), with the negative effects from air pollution creating stronger pro-environmental values. Myers et al. (2012) looked at the role of experiential learning versus motivated reasoning among highly engaged individuals and those less engaged in the issue of climate change. Low-engaged individuals were more likely to be influenced by their perceived personal experience of climate change than by their prior beliefs, while those highly engaged in the issue (on both sides of the climate issue) were more likely to interpret their perceived personal experience in a manner that strengthens their pre-existing beliefs.

Indigenous climate change knowledge contributions from Africa (Orlove et al., 2010), the Arctic (Gearheard et al., 2009), Australia (Green et al., 2010), or the Pacific Islands (Lefale, 2010), derive from accumulated and transmitted experience and focus mostly on predicting seasonal or interannual climate variability. Indigenous knowledge can supplement scientific knowledge in geographic areas with a paucity of data (Green and Raygorodetsky, 2010) and can guide knowledge generation that reduces uncertainty in areas that matter for human responses (ACI, 2004). Traditional ecological knowledge is embedded in value-institutions and belief systems related to historical modes of experimentation and is transferred from generation to generation (Pierotti, 2011).

Underweighting of probabilities and threshold models of choice

The probability weighting function of prospect theory indicates that low probabilities tend to be overweighted relative to their objective probability unless they are perceived as being so low that they are ignored because they are below the decision maker's threshold level of concern. Prior to a disaster, people often perceive the likelihood of catastrophic events occurring as below their threshold level of concern, a form of intuitive thinking in the sense that one doesn't have to reflect on the consequences of a catastrophic event (Camerer and Kunreuther, 1989). The need to take steps today to deal with future climate change presents a challenge to individuals who are myopic. They are likely to deal with this challenge by using a threshold model that does not require any action for risks below this level. The problem is compounded by the inability of individuals to distinguish between low likelihoods that differ by one or even two orders of magnitude (e.g., between 1 in 100 and 1 in 10,000) (Kunreuther et al., 2001).

2.4.5 Linkages between different levels of decision making

Social amplification of risk

Hazards interact with psychological, social, institutional, and cultural processes in ways that may amplify or attenuate public responses to the risk or risk event by generating emotional responses and other biases associated with intuitive thinking. Amplification may occur when scientists, news media, cultural groups, interpersonal networks, and other forms of communication provide risk information. The amplified risk leads to behavioural responses, which, in turn, may result in secondary impacts such as the stigmatization of a place that has experienced an adverse event (Kasperson et al., 1988; Flynn et al., 2001). The general public's overall concern about climate change is influenced, in part, by the amount of media coverage the issue receives as well as the personal and collective experience of extreme weather in a given place (Leiserowitz et al., 2012; Brulle et al., 2012).

Social norms and social comparisons

Individuals' choices are often influenced by other people's behaviour, especially under conditions of uncertainty. Adherence to formal rules (e.g., standard operating procedures or best practices in organizations) or informal rules of conduct is an important way in which we intuitively decide between different courses of action (Weber and Lindemann, 2007). "When in doubt, copy what the majority is doing" is not a bad rule to follow in many situations, as choices adopted by others are assumed to be beneficial and safe (Weber, 2013). In fact, such social imitation can lead to social norms. Section 3.10.2 describes the effects of social norms in greater detail. Goldstein et al. (2008) demonstrate the effectiveness of providing descriptive norms ("this is what most people do") versus injunctive norms ("this is what you should be doing") to reduce energy use in US hotels. The application of social norms to encourage investment in energy efficient products and technology is discussed in Section 2.6.5.3.

Social comparisons are another effective way to evaluate and learn about the quality of obtained outcomes (Weber, 2004). It helps, for example, to compare one's own energy consumption to that of neighbours in similar-sized apartments or houses to see how effective efforts at energy conservation have been. Such non-price interventions can substantially change consumer behaviour, with effects equivalent to that of a short-run electricity price increase of 11 % to 20 % (Alcott, 2011). Social comparisons, imitation, and norms may be necessary to bring about lifestyle changes that are identified in Chapter 9 as reducing GHG emissions from the current levels (Sanquist et al., 2012).

Social learning and cultural transmission

Section 9.3.10 suggests that indigenous building practices in many parts of the world provide important lessons for affordable low-energy housing design and that developed countries can learn from traditional building practices, transmitted over generations, the social-scale equivalent of 'intuitive' processing and learning at the individual level.

Risk protection by formal (e.g., insurance) and informal institutions (e.g., social networks)

Depending on their cultural and institutional context, people can protect themselves against worst-case and/or potentially catastrophic economic outcomes either by purchasing insurance (Kunreuther et al., 2013c) or by developing social networks that will help bail them out or assist them in the recovery process (Weber and Hsee, 1998). Individualist cultures favour formal insurance contracts, whereas collectivist societies make more use of informal mutual insurance via social networks. This distinction between risk protection by either formal or informal means exists at the individual level and also at the firm level, e.g., the chaebols in Korea or the keiretsus in Japan (Gilson and Roe, 1993).

Impact of uncertainty on coordination and competition

Adaptation and especially mitigation responses require coordination and cooperation between individuals, groups, or countries for many of the choices associated with climate change. The possible outcomes often can be viewed as a game between players who are concerned with their own payoffs but who may still be mindful of social goals and objectives. In this sense they can be viewed in the context of a prisoners' dilemma (PD) or social dilemma. Recent experimental research on two-person PD games reveals that individuals are more likely to be cooperative when payoffs are deterministic than when the outcomes are probabilistic. A key factor explaining this difference is that in a deterministic PD game, the losses of both persons will always be greater when they both do not cooperate than when they do. When outcomes are probabilistic there is some chance that the losses will be smaller when both parties do not cooperate than when they do, even though the expected losses to both players will be greater if they both decide not to cooperate than if they both cooperate (Kunreuther et al., 2009).

In a related set of experiments, Gong et al. (2009) found that groups are less cooperative than individuals in a two-person deterministic PD game; however, in a stochastic PD game, where defection increased uncertainty for both players, groups became more cooperative than they were in a deterministic PD game and more cooperative than individuals in the stochastic PD game. These findings have relevance to behaviour with respect to climate change where future outcomes of specific policies are uncertain. Consider decisions made by groups of individuals, such as when delegations from countries are negotiating at the Conference of Parties (COP) to make commitments for reducing GHG emissions where the impacts on climate change are uncertain. These findings suggest that there is likely to be more cooperation between governmental delegations than if each country was represented by a single decision maker.

Cooperation also plays a crucial role in international climate agreements. There is a growing body of experimental literature that looks at individuals' cooperation when there is uncertainty associated with others adopting climate change mitigation measures. Tavoni et al. (2011) found that communication across individuals improves the likelihood of cooperation. Milinski et al. (2008) observed that the higher the risky losses associated with the failure to cooperate in the provision of a public good, the higher the likelihood of cooperation. If the target for reducing CO_2 is uncertain, Barrett and Dannenberg (2012) show in an experimental setting that cooperation is less likely than if the target is well specified.

2.4.6 Perceptions of climate change risk and uncertainty

Empirical social science research shows that the perceptions of climate change risks and uncertainties depend not only on external reality but also on the observers' internal states, needs, and the cognitive and emotional processes that characterize intuitive thinking. Psychological research has documented the prevalence of affective processes in the intuitive assessment of risk, depicting them as essentially effort-free inputs that orient and motivate adaptive behaviour, especially under conditions of uncertainty that are informed and shaped by personal experience over time (Finucane et al., 2000; Loewenstein et al., 2001; Peters et al., 2006).

Box 2.1 | Challenges facing developing countries

One of the key findings on developing countries is that non-state actors such as tribes, clans, castes, or guilds may be of substantial influence on how climate policy choices are made and diffused rather than having the locus of decision making at the level of the individual or governmental unit. For instance, a farming tribe/caste may address the climate risks and uncertainties faced by their community and opt for a system of crop rotation to retain soil fertility or shift cultivation to preserve the nutritious state of farmlands. Research in developing countries in Africa has shown that people may understand probabilistic information better when it is presented in a group where members have a chance to discuss it (Patt et al., 2005; Roncoli, 2006). This underscores why the risks and uncertainty associated with climate change has shifted governmental responsibility to non-state actors (Rayner, 2007).

In this context, methodologies and decision aids used in individual-centred western societies for making choices that rely on uncertain probabilities and uncertain outcomes may not apply to developing countries. Furthermore, methodologies, such as expected utility theory, assume an individual decision maker whereas in developing countries, decisions are often made by clans or tribes. In addition, tools such as cost-benefit analysis, cost-effectiveness analysis and robust decision making may not always be relevant for developing countries since decisions are often based on social norms, traditions, and customs

The adverse effects of climate change on food, water, security, and incidences of temperature-influenced diseases (Shah and Lele, 2011), are further fuelled by a general lack of awareness about climate change in developing countries (UNDP, 2007); consequently, policymakers in these countries support a wait-and-see attitude toward climate change (Dutt, 2011). Resource allocation and investment constraints may also lead policy-makers to postpone policy decisions to deal with climate change, as is the case with respect to integration of future energy systems in small island states (UNFCCC, 2007). The delay may prevent opportunities for learning and increase future vulnerabilities. It may also lock in countries into infrastructure and technologies that may be difficult to alter.

The tension between short- and long-term priorities in low income countries is often accentuated by uncertainties in political culture and regulatory policies (Rayner, 1993). This may lead to policies that are flawed in design and/or implementation or those that have unintended negative consequences. For example, subsidies for clean fuels such as liquefied petroleum gas (LPG) in a country like India often do not reach their intended beneficiaries (the poor), and at the same time add a large burden to the exchequer (Government of India, Ministry of Finance, 2012; IISD, 2012).

Other institutional and governance factors impede effective climate change risk management in developing countries. These include lack of experience with insurance (Patt et al., 2010), dearth of data, and analytical capacity. A more transparent and effective civil service would also be helpful, for instance in stimulating investments in renewable energy generation capacities (Komendantova et al., 2012). Financial constraints suggest the importance of international assistance and private sector contribution to implement adaptation and mitigation strategies for dealing with climate change in developing countries.

Two important psychological risk dimensions have been shown to influence people's intuitive perceptions of health and safety risks across numerous studies in multiple countries (Slovic, 1987). The first factor, 'dread risk', captures emotional reactions to hazards like nuclear reactor accidents, or nerve gas accidents, that is, things that make people anxious because of a perceived lack of control over exposure to the risks and because consequences may be catastrophic. The second factor, 'unknown risk', refers to the degree to which a risk (e.g., DNA technology) is perceived as new, with unforeseeable consequences and with exposures not easily detectable.

Perceptions of the risks associated with a given event or hazard are also strongly influenced by personal experience and can therefore differ between individuals as a function of their location, history, and/or socio-economic circumstances (see Box 2.1) (Figner and Weber, 2011). Whereas personal exposure to adverse consequences increases fear and perceptions of risk, familiarity with a risk can lower perceptions of its riskiness unless it is accompanied by alarming negative consequences (Kloeckner, 2011). Seeing climate change only as a simple and gradual change from current to future average temperatures and precipitation may make it seem controllable—the non-immediacy of the danger seems to provide time to plan and execute protective responses (Weber, 2006). These factors suggest that laypersons differ in their perception of climate risks more than experts who engage in deliberative thinking and estimate the likelihood and consequences of climate change utilizing scientific data.

Impact of uncertainties in communicating risk

If the uncertainties associated with climate change and its future impact on the physical and social system are not communicated accurately, the general public may misperceive them (Corner and Hahn, 2009). Krosnick et al. (2006) found that perceptions of the seriousness of global warming as a national issue in the United States depended on the degree of certainty of respondents as to whether global warming is occurring and will have negative consequences coupled with their belief that humans are causing the problem and have the ability to solve it. Accurately communicating the degree of uncertainty in both climate risks and policy responses is therefore a critically important challenge for climate scientists and policymakers (Pidgeon and Fischhoff, 2011).

Roser-Renouf et al. (2011), building upon the work of Krosnick et al. (2006), apply social cognitive theory to develop a model of climate advocacy to increase the attention given to climate change in the spirit of social amplification of risk. They found that campaigns looking to increase the number of citizens contacting elected officials to advocate climate policy action should focus on increasing the belief that global warming is real, human-caused, a serious risk, and solvable. These four key elements, coupled with the understanding that there is strong scientific agreement on global warming (Ding et al., 2011), are likely to build issue involvement and support for action to reduce the impacts of climate change.

The significant time lags within the climate system and a focus on short-term outcomes lead many people to believe global warming will have only moderately negative impacts. This view is reinforced because adverse consequences are currently experienced only in some regions of the world or are not easily attributed to climate change. For example, despite the fact that "climate change currently contributes to the global burden of disease and premature deaths" (IPCC, 2007) relatively few people make the connection between climate change and human health risks.

One challenge is how to facilitate correct inferences about the role of climate change as a function of extreme event frequency and severity. Many parts of the world have seen increases in the frequency and magnitude of heat waves and heavy precipitation events (IPCC, 2012). In the United States, a large majority of Americans believe that climate change exacerbated extreme weather events (Leiserowitz et al., 2012). That said, the perception that the impact of climate change is neither immediate nor local persists (Leiserowitz et al., 2008), leading many to think it rational to advocate a wait-and-see approach to emissions reductions (Sterman, 2008; Dutt and Gonzalez, 2013).

Differences in education and numeracy

Individual and group differences in education and training and the resulting different cognitive and affective processes have additional implications for risk communication. It may help to supplement the use of words to characterize the likelihood of an outcome recommended by the current IPCC Guidance Note (GN) with numeric probability ranges (Budescu et al., 2009). Patt and Dessai (2005) show that in the IPCC Third Assessment Report (TAR), words that characterized numerical probabilities were interpreted by decision makers in inconsistent and often context-specific ways, a phenomenon with a long history in cognitive psychology (Wallsten et al., 1986; Weber and Hilton, 1990). These context-specific interpretations of probability words are deeply rooted, as evidenced by the fact that the likelihood of using the intended interpretation of TAR probability words did not differ with level of expertise (attendees of a UN COP conference versus students) or as a function of whether respondents had read the TAR instructions that specify how the probability words characterized numerical probabilities (Patt and Dessai, 2005).

Numeracy, the ability to reason with numbers and other mathematical concepts, is a particularly important individual and group difference in this context as it has implications for the presentation of likelihood information using either numbers (for example, 90 %) or words (for example, "very likely" or "likely") or different graphs or diagrams (Peters et al., 2006; Mastrandrea et al., 2011). Using personal experience with climate variables has been shown to be effective in communicating the impact of probabilities (e.g., of below-, about-, and above-normal rainfall in an El Niño year) to decision makers with low levels of numeracy, for example subsistence farmers in Zimbabwe (Patt et al., 2005).

2.5 Tools and decision aids for analysing uncertainty and risk

This section examines how more formal approaches can assist decision makers in engaging in more deliberative thinking with respect to climate change policies when faced with the risks and uncertainties characterized in Section 2.3.

2.5.1 Expected utility theory

Expected utility [E(U)] theory (Ramsey, 1926; von Neumann and Morgenstern, 1944; Savage, 1954); remains the standard approach for providing normative guidelines against which other theories of individual decision making under risk and uncertainty are benchmarked. According to the E(U) model, the solution to a decision problem under uncertainty is reached by the following four steps:

1. Define a set of possible decision alternatives.
2. Quantify uncertainties on possible states of the world.
3. Value possible outcomes of the decision alternatives as utilities.
4. Choose the alternative with the highest expected utility.

This section clarifies the applicability of expected utility theory to the climate change problem, highlighting its potentials and limitations.

2.5.1.1 Elements of the theory

E(U) theory is based on a set of axioms that are claimed to have normative rather than descriptive validity. Based on these axioms, a person's subjective probability and utility function can be determined by observing preferences in structured choice situations. These axioms have been debated, strengthened, and relaxed by economists, psychologists, and other social scientists over the years. The axioms have been challenged by controlled laboratory experiments and field studies discussed in Section 2.4 but they remain the basis for parsing decision problems and recommending options that maximize expected utility.

2.5.1.2 How can expected utility improve decision making?

E(U) theory provides guidelines for individual choice, such as a farmer deciding what crops to plant or an entrepreneur deciding whether to invest in wind technology. These decision makers would apply E(U) theory by following the four steps above. The perceptions and responses to risk and uncertainty discussed in Section 2.5 provide a rationale for undertaking deliberative thinking before making final choices. More specifically, a structured approach, such as the E(U) model, can reduce the impact of probabilistic biases and simplified decision rules that characterize intuitive thinking. At the same time, the limitations of E(U) must be clearly understood, as the procedures for determining an optimal choice do not capture the full range of information about outcomes and their risks and uncertainties.

Subjective versus objective probability

In the standard E(U) model, each individual has his/her own subjective probability estimates. When there is uncertainty on the scientific evidence, experts' probability estimates may diverge from each other, sometimes significantly. With respect to climate change, observed relative frequencies are always preferred when suitable sets of observations are accessible. When these data are not available, one may want to utilize structured expert judgment for quantifying uncertainty (see Section 2.5.7).

Individual versus social choice

In applying E(U) theory to problems of social choice, a number of issues arise. Condorcet's voting paradox shows that groups of rational individuals deciding by majority rule do not exhibit rational preferences. Using a social utility or social welfare function to determine an optimal course of action for society requires some method of measuring society's preferences. In the absence of these data the social choice problem is not a simple exercise of maximizing expected utility. In this case, a plurality of approaches involving different aggregations of individual utilities and probabilities may best aid decision makers. The basis and use of the social welfare function are discussed in Section 3.4.6.

Normative versus descriptive

As noted above, the rationality axioms of E(U) are claimed to have normative as opposed to descriptive validity. The paradoxes of Allais (1953) and Ellsberg (1961) reveal choice behaviour incompatible with E(U); whether this requires modifications of the normative theory is a subject of debate. McCrimmon (1968) found that business executives willingly corrected violations of the axioms when they were made aware of them. Other authors (Kahneman and Tversky, 1979; Schmeidler, 1989; Quiggin, 1993; Wakker, 2010) account for such paradoxical choice behaviour by transforming the probabilities of outcomes into decision weight probabilities that play the role of likelihood in computing optimal choices but do not obey the laws of probability. However, Wakker (2010, p. 350) notes that decision weighting fails to describe some empirically observed behavioural patterns.

2.5.2 Decision analysis

2.5.2.1 Elements of the theory

Decision analysis is a formal approach for choosing between alternatives under conditions of risk and uncertainty. The foundations of decision analysis are provided by the axioms of expected utility theory. The methodology for choosing between alternatives consists of the following elements that are described in more detail in Keeney (1993):

1. Structure the decision problem by generating alternatives and specifying values and objectives or criteria that are important to the decision maker.
2. Assess the possible impacts of different alternatives by determining the set of possible consequences and the probability of each occurring.
3. Determine preferences of the relevant decision maker by developing an objective function that considers attitudes toward risk and aggregates the weighted objectives.
4. Evaluate and compare alternatives by computing the expected utility associated with each alternative. The alternative with the highest expected utility is the most preferred one.

To illustrate the application of decision analysis, consider a homeowner that is considering whether to invest in energy efficient technology as part of their lifestyle options as depicted in Figure 2.2:

1. The person focuses on two alternatives: (A1) Maintain the status quo, and (A2) Invest in solar panels, and has two objectives: (O1) Minimize cost, and (O2) Assist in reducing global warming.
2. The homeowner would then determine the impacts of A1 and A2 on the objectives O1 and O2 given the risks and uncertainties associated with the impact of climate change on energy usage as well as the price of energy.
3. The homeowner would then consider his or her attitude toward risks and then combine O1 and O2 into a multiattribute utility function.
4. The homeowner would then compare the expected utility of A1 and A2, choosing the one that had the highest expected utility.

2.5.2.2 How can decision analysis improve decision making?

Decision analysis enables one to undertake sensitivity analyses with respect to the uncertainties associated with the various consequences and to different value structures. Suppose alternative A1 had the highest expected utility. The homeowner could determine when the decision to invest in solar panels would be preferred to maintaining the status quo by asking questions such as:

- What would the minimum annual savings in energy expenses have to be over the next 10 years to justify investing in solar panels?
- What is the fewest number of years one would have to reside in the house to justify investing in solar panels?
- What impact will different levels of global warming have on the expected costs of energy over the next 10 years for the homeowner to want to invest in solar panels?
- How will changing the relative weights placed on minimizing cost (O1) and assisting in reducing global warming (O2) affect the expected utility of A1 and A2?

2.5.3 Cost-benefit analysis

2.5.3.1 Elements of the theory

Cost-benefit analysis (CBA) compares the costs and benefits of different alternatives with the broad purpose of facilitating more efficient allocation of society's resources. When applied to government decisions, CBA can indicate the alternative that has the highest social net present value based on a discount rate, normally constant over time, that converts future benefits and costs to their present values (Boardman et al., 2005; see also the extensive discussion in Section 3.6). Social, rather than private, costs and benefits are compared, including those affecting future generations (Brent, 2006). In this regard, benefits across individuals are assumed to be additive. Distributional issues may be addressed by putting different weights on specific groups to reflect their relative importance. Under conditions of risk and uncertainty, one determines expected costs and benefits by weighting outcomes by their likelihoods of occurrence. In this sense, the analysis is similar to expected utility theory and decision analysis discussed in Sections 2.5.1 and 2.5.2.

CBA can be extremely useful when dealing with well-defined problems that involve a limited number of actors who make choices among different mitigation or adaptation options. For example, a region could examine the benefits and costs over the next fifty years of building levees to reduce the likelihood and consequences of flooding given projected sea level rise due to climate change.

CBA can also provide a framework for defining a range of global long-term targets on which to base negotiations across countries (see for example Stern, 2007). However, CBA faces major challenges when defining the optimal level of global mitigation actions for the following three reasons: (1) the need to determine and aggregate individual welfare, (2) the presence of distributional and intertemporal issues, and (3) the difficulty in assigning probabilities to uncertain climate change impacts. The limits of CBA in the context of climate change are discussed at length in Sections 3.6 and 3.9. The discussion that follows focuses on challenges posed by risk and uncertainty.

2.5.3.2 How can CBA improve decision making?

Cost-benefit analysis assumes that the decision maker(s) will eventually choose between well-specified alternatives. To illustrate this point, consider a region that is considering measures that coastal villages in hazard-prone areas can undertake to reduce future flood risks that are expected to increase in part due to sea level rise. The different options range from building a levee (at the community level) to providing low interest loans to encourage residents and businesses in the community to invest in adaptation measures to reduce future damage to their property (at the level of an individual or household).

Some heuristics and resulting biases discussed in the context of expected utility theory also apply to cost-benefit analysis under uncertainty. For example, the key decision maker, the mayor, may utilize a threshold model of choice by assuming that the region will not be subject to flooding because there have been no floods or hurricanes during the past 25 years. By relying solely on intuitive processes there would be no way to correct this behaviour until the next disaster occurred, at which time the mayor would belatedly want to protect the community. The mayor and his advisors may also focus on short-time horizons, and hence do not wish to incur the high upfront costs associated with building flood protection measures such as dams or levees. They are unconvinced that that such an investment will bring significant enough benefits over the first few years when these city officials are likely to be held accountable for the expenditures associated with a decision to go forward on the project.

Cost-benefit analysis can highlight the importance of considering the likelihood of events over time and the need to discount impacts exponentially rather than hyperbolically, so that future time periods are given more weight in the decision process. In addition, CBA can highlight the tradeoffs between efficient resource allocation and distributional issues as a function of the relative weights assigned to different stakeholders (e.g., low income and well-to-do households in flood prone areas).

2.5.3.3 Advantages and limitations of CBA

The main advantage of CBA in the context of climate change is that it is internally coherent and based on the axioms of expected utility theory.

As the prices used to aggregate costs and benefits are the outcomes of market activity, CBA is, at least in principle, a tool reflecting people's preferences. Although this is one of the main arguments in favour of CBA (Tol, 2003), this line of reasoning can also be the basis for recommending that this approach not be employed for making choices if market prices are unavailable. Indeed, many impacts associated with climate change are not valued in any market and are therefore hard to measure in monetary terms. Omitting these impacts distorts the cost-benefit relationship.

Several ethical and methodological critiques have been put forward with respect to the application of CBA to climate policy (Charlesworth and Okereke, 2010; Caney, 2011). For example, the uncertainty surrounding the potential impacts of climate change, including possible irreversible and catastrophic effects on ecosystems, and their asymmetric distribution around the planet, suggests CBA may be inappropriate for assessing optimal responses to climate change in these circumstances.

A strong and recurrent argument against CBA (Azar and Lindgren, 2003; Tol, 2003; Weitzman, 2009, 2011) relates to its failure in dealing with infinite (negative) expected utilities arising from low-probability catastrophic events often referred to as 'fat tails'. In these situations, CBA is unable to produce meaningful results, and thus more robust techniques are required. The debate concerning whether fat tails are indeed relevant to the problem at hand is still unsettled (see for example Pindyck, 2011). Box 3.9 in Chapter 3 addresses the fat tail problem and suggests the importance of understanding the impacts associated with low probability, high impact climate change scenarios in evaluating alternative mitigation strategies.

One way to address the fat tail problem would be to focus on the potential catastrophic consequences of low-probability, high-impact events in developing GHG emissions targets and to specify a threshold probability and a threshold loss. One can then remove events from consideration that are below these critical values in determining what mitigation and/or adaptation to adopt as part of a risk management strategy for dealing with climate change (Kunreuther et al., 2013c). Insurers and reinsurers specify these thresholds and use them to determine the amount of coverage that they are willing to offer against a particular risk. They then diversify their portfolio of policies so the annual probability of a major loss is below a pre-specified threshold level of concern (e.g., 1 in 1000) (Kunreuther et al., 2013c). This approach is in the spirit of a classic paper by Roy (1952) on safety-first behaviour and can be interpreted as an application of probabilistic cost-effectiveness analysis (i.e., chance constrained programming) discussed in the next section. It was applied in a somewhat different manner to environmental policy by Ciriacy-Wantrup (1971) who contended that "*a safe minimum standard* is frequently a valid and relevant criterion for conservation policy."

One could also view uncertainty or risk associated with different options as one of the many criteria on which alternatives should be evaluated. Multi-criteria analysis (MCA) is sometimes proposed to overcome some of the limitations of CBA (see more on its basic features in Chapter 3 and for applications in Chapter 6). MCA implies that the different criteria or attributes should not be aggregated by converting all of them into monetary units. MCA techniques commonly apply numerical analysis in two stages:

- *Scoring:* for each option and criterion, the expected consequences of each option are assigned a numerical score on a strength of preference scale. More (less) preferred options score higher (lower) on the scale. In practice, scales often extend from 0 to 100, where 0 is assigned to a real or hypothetical least preferred option, and 100 is assigned to a real or hypothetical most preferred option. All options considered in the MCA would then fall between 0 and 100.

- *Weighting:* numerical weights are assigned to define their relative performance on a chosen scale that will often range from 0 (no importance) to 1 (highest importance) (Dodgson et al., 2009).

2.5.4 Cost-effectiveness analysis

2.5.4.1 Elements of the theory

Cost-effectiveness analysis (CEA) is a tool based on constrained optimization for comparing policies designed to meet a pre-specified target. The target can be defined through CBA, by applying a specific guideline such as the precautionary principle (see Section 2.5.5), or by specifying a threshold level of concern or environmental standard in the spirit of the safety-first models discussed above. The target could be chosen without the need to formally specify impacts and their respective probabilities. It could also be based on an ethical principle such as minimizing the worst outcome, in the spirit of a Rawlsian fair agreement, or as a result of political and societal negotiation processes.

Cost-effectiveness analysis does not evaluate benefits in monetary terms. Rather, it attempts to find the least-cost option that achieves a desired quantifiable outcome. In one sense CEA can be seen as a special case of CBA in that the technique replaces the criterion of choosing a climate policy based on expected costs and benefits with the objective of selecting the option that minimizes the cost of meeting an exogenous target (e.g., equilibrium temperature, concentration, or emission trajectory).

Like CBA, CEA can be generalized to include uncertainty. One solution concept requires the externally set target to be specified with certainty. The option chosen is the one that minimizes expected costs. Since temperature targets cannot be met with certainty (den Elzen and van Vuuren, 2007; Held et al., 2009), a variation of this solution concept requires that the likelihood that an exogenous target (e.g., equilibrium temperature) will be exceeded is below a pre-defined threshold probability. This solution procedure, equivalent to chance constrained programming (CCP) (Charnes and Cooper, 1959), enables one to use stochastic programming to examine the impacts of uncertainty with respect to the cost of meeting a pre-specified target. Chance constrained programming is a conceptually valid decision-analytic framework for examining the likelihood of attaining climate targets when the probability distributions characterizing the decision maker's state of knowledge is held constant over time (Held et al., 2009).

2.5.4.2 How can CEA improve decision making?

To illustrate how CEA can be useful, consider a national government that wants to set a target for reducing greenhouse gas (GHG) emissions in preparation for a meeting of delegates from different countries at the Conference of Parties (COP). It knows there is uncertainty as to whether specific policy measures will achieve the desired objectives. The uncertainties may be related to the outcomes of the forthcoming negotiation process at the COP and/or to the uncertain impacts of proposed technological innovations in reducing GHG emissions. Cost-effectiveness analysis could enable the government to assess alternative mitigation strategies (or energy investment policies) for reducing GHG emissions in the face of these uncertainties by specifying a threshold probability that aggregate GHG emissions will not be greater than a pre-specified target level.

2.5.4.3 Advantages and limitations of CEA over CBA

Cost-effectiveness analysis has an advantage over CBA in tackling the climate problem in that it does not require formalized knowledge about global warming impact functions (Pindyck, 2013). The focus of CEA is on more tangible elements, such as energy alternatives, where scientific understanding is more established (Stern, 2007). Still, CEA does require scientific input on potential risks associated with climate change. National and international political processes specify temperature targets and threshold probabilities that incorporate the preferences of different actors guided by data from the scientific community. The corresponding drawback of CEA is that the choice of the target is specified without considering its impact on economic efficiency. Once costs to society are assessed and a range of temperature targets is considered, one can assess people's preferences by considering the potential benefits and costs associated with different targets. However, if costs of a desirable action turn out to be regarded as too high, then CEA may not provide sufficient information to support taking action now. In this case additional knowledge on the mitigation benefit side would be required.

An important application of CEA in the context of climate change is evaluating alternative transition pathways that do not violate a predefined temperature target. Since a specific temperature target cannot be attained with certainty, formulating probabilistic targets as a CCP problem is an appropriate solution technique to use. However, introducing anticipated future learning so that probability distributions change over time can lead to infeasible solutions (Eisner et al., 1971). Since this is a problem with respect to specifying temperature targets, Schmidt et al. (2011) proposed an approach that that combines CEA and CBA. The properties of this hybrid model (labelled 'cost risk analysis') require further investigation. At this time, CEA through the use of CCP represents an informative concept for deriving mitigation costs for the case where there is no learning over time. With learning, society would be no worse off than the proposed CEA solution.

2.5.5 The precautionary principle and robust decision making

2.5.5.1 Elements of the theory

In the 1970s and 1980s, the precautionary principle was proposed for dealing with serious uncertain risks to the natural environment and to public health (Vlek, 2010). In its strongest form the precautionary principle implies that if an action or policy is suspected of having a risk that causes harm to the public or to the environment, precautionary measures should be taken even if some cause and effect relationships are not established. The burden of proof that the activity is not harmful falls on the proponent of the activity rather than on the public. A consensus statement to this effect was issued at the Wingspread Conference on the Precautionary Principle on 26 January 1998.

The precautionary principle allows policymakers to ban products or substances in situations where there is the possibility of their causing harm and/or where extensive scientific knowledge on their risks is lacking. These actions can be relaxed only if further scientific findings emerge that provide sound evidence that no harm will result. An influential statement of the precautionary principle with respect to climate change is principle 15 of the 1992 Rio Declaration on Environment and Development: "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

Robust decision making (RDM) is a particular set of methods developed over the last decade to address the precautionary principle in a systematic manner. RDM uses ranges or, more formally, sets of plausible probability distributions to describe uncertainty and to evaluate how well different policies perform with respect to different outcomes arising from these probability distributions. RDM provides decision makers with tradeoff curves that allow them to debate how much expected performance they are willing to sacrifice in order to improve outcomes in worst case scenarios. RDM thus captures the spirit of the precautionary principle in a way that illuminates the risks and benefits of different policies. Lempert et al. (2006) and Hall et al. (2012) review the application of robust approaches to decision making with respect to mitigating or adapting to climate change.

The tolerable windows approach can also be regarded as a 'robust method'. Temperature targets are specified and the bundle of decision paths compatible with the targets is characterized. Mathematically, the tolerable windows approach incorporates the features of CEA or CCP without optimization. The selection of the relevant targets and the paths to achieving it are left to those making the decision. (See Bruckner and Zickfeld (2008) for an introduction and an overview to peer-reviewed literature on the tolerable windows approach.)

2.5.6 Adaptive management

Adaptive management is an approach to governance that that grew out of the field of conservation ecology in the 1970s and incorporates mechanisms for reducing uncertainty over time (Holling, 1978; Walters and Hilborn, 1978). Paraphrasing the IPCC Special Report on Extreme Events (SREX) (IPCC, 2012), adaptive management represents structured processes for improving decision making and policy over time, by incorporating lessons learned. From the theoretical literature, two strands of adaptive management have been developed for improving decision making under uncertainty: passive and active.

Passive adaptive management (PAM) involves carefully designing monitoring systems, at the relevant spatial scales, so as to be able to track the performance of policy interventions and improve them over time in response to what has been learned. Active adaptive management (AAM) extends PAM by designing the interventions themselves as controlled experiments, so as to generate new knowledge. For example, if a number of political jurisdictions were seeking to implement support mechanisms for technology deployment, in an AAM approach they would deliberately design separate mechanisms that are likely to differ across jurisdictions. By introducing such variance into the management regime, however, one would collectively learn more about how industry and investors respond to a range of interventions. All jurisdictions could then use this knowledge in a later round of policymaking, reflecting the public goods character of institutional knowledge.

With respect to the application of PAM, Nilsson (2005) reports on a case study of Sweden, in which policymakers engaged in repetitive ex post analyses of national climate policy, and then responded to the lessons learned by modifying their goals and strategies. There are many documented cases of PAM applications in the area of climate change adaptation (Lawler et al., 2008; Berkes et al., 2000; Berkes and Jolly, 2001; Joyce et al., 2009; Armitage, 2011). The information gathering and reporting requirements of the UNFCCC are also in the spirit of PAM with respect to policy design, as are the diversity of approaches implemented for renewable energy support across the states and provinces of North America and the countries in Europe. The combination of the variance in action with data gathered about the consequences of these actions by government agencies has allowed for robust analysis on the relative effectiveness of different instruments (Blok, 2006; Mendonça, 2007; Butler and Neuhoff, 2008).

Individuals relying on intuitive thinking are unlikely to undertake experimentation that leads to new knowledge, as discussed in Section 2.4.3.1. In theory, adaptive management ought to correct this problem by making the goal of learning through experimentation an explicit policy goal. Lee (1993) illustrates this point by presenting a paradigmatic case of AAM designed to increase salmon stocks in the Columbia River watershed in the western United States and Canada. In this case, there was the opportunity to introduce a number of different management regimes on the individual river tributaries, and to reduce uncertainty about salmon population dynamics. As Lee (1993) documented, policymakers on the Columbia River were ultimately not able to carry through with AAM: local constituencies, valuing their own immediate interests over long-term learning in the entire region, played a crucial role in blocking it. One could imagine such political and institutional issues hindering the application of AAM at a global scale with respect to climate change policies.

To date, there are no cases in the literature specifically documenting climate change policies explicitly incorporating AAM. However, there are a number of examples where policy interventions implicitly follow AAM principles. One of these is promotion of energy research and development (R&D). In this case the government invests in a large number of potential new technologies, with the expectation that some technologies will not prove practical, while others will be successful and be supported by funding in the form of incentives such as subsidies (Fischer and Newell, 2008).

2.5.7 Uncertainty analysis techniques

Uncertainty analysis consists of both qualitative and quantitative methodologies (see Box 2.2 for more details). A Qualitative Uncertainty Analysis (QLUA) helps improve the choice process of decision makers by providing data in a form that individuals can easily understand. QLUA normally does not require complex calculations so that it can be useful in helping to overcome judgmental biases that characterize intuitive thinking. QLUA assembles arguments and evidence and provides a verbal assessment of plausibility, frequently incorporated in a Weight of Evidence (WoE) narrative.

A Quantitative Uncertainty Analysis (QNUA) assigns a joint distribution to uncertain parameters of a specific model used to characterize different phenomena. Quantitative Uncertainty Analysis was pioneered in the nuclear sector in 1975 to determine the risks associated with nuclear power plants (Rasmussen, 1975). The development of QNUA and its prospects for applications to climate change are reviewed by Cooke (2012).

2.5.7.1 Structured expert judgment

Structured expert judgment designates methods in which experts quantify their uncertainties to build probabilistic input for complex

Box 2.2 | Quantifying uncertainty

Natural language is not adequate for propagating and communicating uncertainty. To illustrate, consider the U.S. National Research Council 2010 report Advancing the Science of Climate Change (America's Climate Choices: Panel on Advancing the Science of Climate Change; National Research Council, 2010). Using the AR4 calibrated uncertainty language, the NRC is highly confident that (1) the Earth is warming and that (2) most of the recent warming is due to human activities.

What does the second statement mean? Does it mean the NRC is highly confident that the Earth is warming *and* the recent warming is anthropogenic or that, given the Earth is warming, are they highly confident humans cause this warming? The latter seems most natural, as the warming is asserted in the first statement. In that case the 'high confidence' applies to a conditional statement. The probability of both statements being true is the probability of the condition (Earth is warming) multiplied by the probability of this warming being caused by humans, given that warming is taking place. If both statements enjoy high confidence, then in the calibrated language of AR4 where high confidence implies a probability of 0.8, the statement that both are true would only be "more likely than not" (0.8 x 0.8 = 0.64).

Qualitative uncertainty analysis easily leads the unwary to erroneous conclusions. Interval analysis is a semi-qualitative method in which ranges are assigned to uncertain variables without distributions and can mask the complexities of propagation, as attested by the following statement in an early handbook on risk analysis: "The simplest quantitative measure of variability in a parameter or a measurable quantity is given by an assessed range of the values the parameter or quantity can take. This measure may be adequate for certain purposes (e.g., as input to a sensitivity analysis), but in general it is not a complete representation of the analyst's knowledge or state of confidence and generally will lead to an unrealistic range of results if such measures are propagated through an analysis", (U.S. NRC, 1983, Chapter 12, p.12).

The sum of 10 independent variables each ranging between zero and ten, can assume any value between zero and 100. The upper (lower) bound can be attained only if ALL variables take their maximal (minimal) values, whereas values near 50 can arise through many combinations. Simply stating the interval [0, 100] conceals the fact that very high (low) values are much more exceptional than central values. These same concepts are widely represented throughout the uncertainty analysis literature. According to Morgan and Henrion (1990): "Uncertainty analysis is the computation of the total uncertainty induced in the output by quantified uncertainty in the inputs and models […] Failure to engage in systematic sensitivity and uncertainty analysis leaves both analysts and users unable to judge the adequacy of the analysis and the conclusions reached", (Morgan and Henrion, 1990, p. 39).

decision problems (Morgan and Henrion, 1990; Cooke, 1991; O'Hagan et al., 2006). A wide variety of activities fall under the heading of expert judgment that includes blue ribbon panels, Delphi surveys, and decision conferencing.

Elements

Structured expert judgment such as science-based uncertainty quantification was pioneered in the Rasmussen Report on risks of nuclear power plants (Rasmussen, 1975). The methodology was further elaborated in successive studies and involves protocols for expert selection and training, elicitation procedures and performance-based combinations that are described in more detail in Goossens et al. (2000). In large studies, multiple expert panels provide inputs to computer models with no practical alternative for combining expert judgments except to use equal weighting. Hora (2004) has shown that equal weight combinations of statistically accurate ('well calibrated') experts loses statistical accuracy. Combinations based on experts' statistical accuracy have consistently given more accurate and informative results (see for example Cooke and Goossens, 2008; Aspinall, 2010).

How can this tool improve decision making under uncertainty?

Structured expert judgment can provide insights into the nature of the uncertainties associated with a specific risk and the importance of undertaking more detailed analyses to design meaningful strategies and policies for dealing with climate change in the spirit of deliberative thinking. In addition to climate change (Morgan and Keith, 1995; Zickfeld et al., 2010), structured expert judgment has migrated into many fields such as volcanology (Aspinall, 1996, 2010), dam/dyke safety (Aspinall, 2010), seismicity (Klügel, 2008), civil aviation (Ale et al., 2009), ecology (Martin et al., 2012; Rothlisberger et al., 2012), toxicology (Tyshenko et al., 2011), security (Ryan et al., 2012), and epidemiology (Tuomisto et al., 2008).

The general conclusions emerging from experience with structured expert judgments to date are: (1) formalizing the expert judgment process and adhering to a strict protocol adds substantial value to understanding the importance of characterizing uncertainty; (2) experts differ greatly in their ability to provide statistically accurate and informative quantifications of uncertainty; and (3) if expert judgments must be combined to support complex decision problems, the combination method should be subjected to the following quality controls: statistical accuracy and informativeness (Aspinall, 2010).

As attested by a number of governmental guidelines, structured expert judgment is increasingly accepted as quality science that is applicable when other methods are unavailable (U.S. Environmental Protection Agency, 2005). Some expert surveys of economists concerned with climate change examine damages (Nordhaus, 1994) and appropriate discount rates (Weitzman, 2001). Structured expert judgments of climate scientists were recently used to quantify uncertainty in the ice sheet contribution to sea level rise, revealing that experts' uncertainty regarding the 2100 contribution to sea level rise from ice sheets increased between 2010 and 2012 (Bamber and Aspinall, 2013).

Damages or benefits to ecosystems from invasions of non-indigenous species are difficult to quantify and monetize on the basis of historical data. However ecologists, biologists and conservation economists have substantial knowledge regarding the possible impacts of invasive species. Recent studies applied structured expert judgment with a performance-based combination and validation to quantify the costs and benefits of the invasive species introduced since 1959 into the U.S. Great Lakes by opening the St. Lawrence Seaway (Rothlisberger et al., 2009, 2012). Lessons from studies such as these reveal that experts may have applicable knowledge that can be captured in a structured elicitation when historical data have large uncertainties associated with them.

Advantages and limitations of structured expert judgment

Expert judgment studies do not reduce uncertainty; they merely quantify it. If the uncertainties are large, as indeed they often are, then decision makers cannot expect science to relieve them of the burden of deciding under conditions of ambiguity. Since its inception, structured expert judgment has been met with scepticism in some quarters; it is, after all, just opinions and not hard facts. Its steady growth and widening acceptance over 35 years correlates with the growth of complex decision support models. The use of structured expert judgment must never justify a diminution of effort in collecting hard data.

2.5.7.2 Scenario analysis and ensembles

Scenario analysis develops a set of possible futures based on extrapolating current trends and varying key parameters, without sampling in a systematic manner from an uncertainty distribution. Utilizing sufficiently long time horizons ensures that structural changes in the system are considered. The futurist Herman Kahn and colleagues at the RAND Corporation are usually credited with inventing scenario analysis (Kahn and Wiener, 1967). In the climate change arena, scenarios are currently presented as different emission pathways or Representative Concentration Pathways (RCPs). Predicting the effects of such pathways involves modelling the Earth's response to changes in GHG concentrations from natural and anthropogenic sources. Different climate models will yield different projections for the same emissions scenario. Model Intercomparison studies generate sets of projections termed 'ensembles' (van Vuuren et al., 2011).

Elements of the theory

Currently, RCPs are carefully constructed on the bases of plausible storylines while insuring (1) they are based on a representative set of peer-reviewed scientific publications by independent groups, (2) they provide climate and atmospheric models as inputs, (3) they are harmonized to agree on a common base year, and (4) they extend to the year 2100. The four RCP scenarios, shown in Figure 2.3 relative to the range of baseline scenarios in the literature, roughly span the entire scenario literature, which includes control scenarios reaching 430 ppm CO_2eq or lower by 2100. The scenarios underlying the RCPs were originally developed by four independent integrated assessment models, each with their own carbon cycle. To provide the climate community with four harmonized scenarios, they were run through the same carbon cycle/climate model (Meinshausen et al., 2011). Note that a representative set is not a random sample from the scenarios as they do not represent independent samples from some underlying uncertainty distribution over unknown parameters.

Ensembles of model runs generated by different models, called multimodel ensembles or super-ensembles, convey the scatter of the climate response and natural internal climate variability around reference scenarios as sampled by a set of models, but cannot be interpreted probabilistically without an assessment of model biases, model interdependence, and how the ensemble was constructed (see WGI AR5 Section 12.2; Knutti et al., 2010). In many cases the assessed uncertainty is larger than the raw model spread, as illustrated in Figure 2.4. The shaded areas (+/-1 standard deviation) around the time series do not imply that 68 % are certain to fall in the shaded areas, but the modelers' assessed uncertainty (likely ranges, vertical bars on the right) are larger. These larger ranges reflect uncertainty in the carbon cycle and the full range of climate sensitivity (WGI AR4 Section 10.5.4.6 and Box 10.3; Knutti et al., 2008) but do not reflect other possible sources of uncertainty (e.g., ice sheet dynamics, permafrost, or changes in future solar and volcanic forcings). Moreover, many of these models have common ancestors and share parameterizations or code (Knutti et al., 2013) creating dependences between different model runs. Probability statements on global surface warming require estimating the models' bias and interdependence (see WGI AR5 Sections 12.2 and 12.4.1.2). WGI AR5 assigns likelihood statements (calibrated language) to global temperature ranges for the RCP scenarios (WGI AR5 Table SPM.2) but does not provide probability density functions (PDFs), as there is no established formal method to generate PDFs based on results from different published studies.

Advantages and limitation of scenario and ensemble analyses

Scenario and ensemble analyses are an essential step in scoping the range of effects of human actions and climate change. If the scenarios span the range of possible outcomes, they may be seen as providing support for uncertainty distributions in a formal uncertainty analysis. If specific assumptions are imposed when generating the scenarios, then

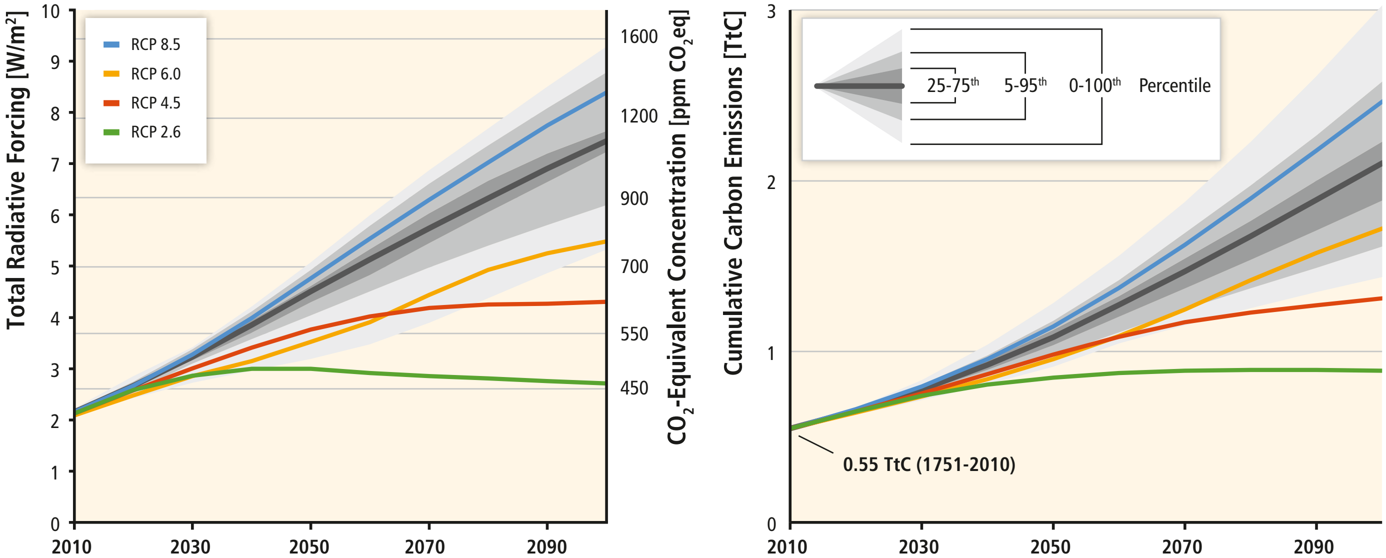

Figure 2.3 | Total radiative forcing (left panel) and cumulative carbon emissions since 1751 (right panel) in baseline scenario literature compared to RCP scenarios. Forcing was estimated ex-post from models with full coverage using the median output from the MAGICC results. Secondary axis in the left panel expresses forcing in CO_2eq concentrations. Scenarios are depicted as ranges with median emboldened; shading reflects interquartile range (darkest), 5th–95th percentile range (lighter), and full extremes (lightest). Source: Figure 6.6 from WGIII AR5.

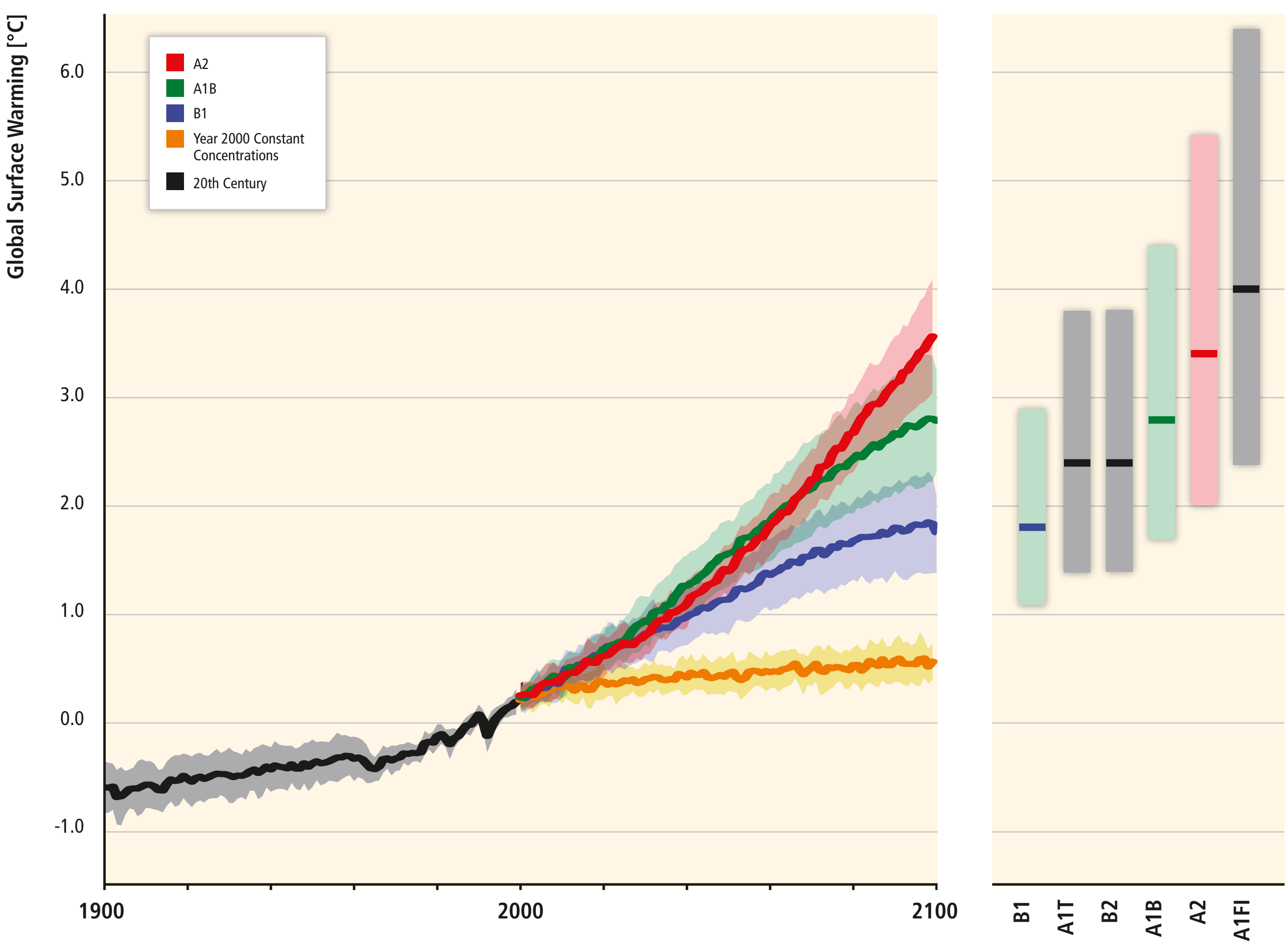

Figure 2.4 | Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six families of emissions scenarios discussed in the IPCC's Fourth Assessment Report (AR4). The assessment of the best estimate and likely ranges in the grey bars includes the Atmosphere-Ocean General Circulation Models (AOGCMs) in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. Based on: Figure SPM.5 from WGI AR5.

the support is conditional on these assumptions (see Section 6.2.3). The advantage of scenario/ensemble analyses is that they can be performed without quantifying the uncertainty of the underlying unknown parameters. On the downside, it is easy to read more into these analyses than is justified. Analysts often forget that scenarios are illustrative possible futures along a continuum. They tend to use one of those scenarios in a deterministic fashion without recognizing that they have a low probability of occurrence and are only one of many possible outcomes. The use of probabilistic language in describing the swaths of scenarios (such as standard deviations in Figure 2.4) may also encourage the misunderstandings that these represent science-based ranges of confidence.

The study of representative scenarios based on probabilistic forecasts have been shown to facilitate strategic planning by professional groups such as military commanders, oil company managers, and policymakers (Schoemaker, 1995; Bradfield et al., 2005). Recent work on ice sheet modelling (Little et al., 2013) points in this direction. Using modelling assumptions and prior distributions on model coefficients, Monte Carlo simulations are used to produce probabilistic predictions. Expert informed modelling is methodologically intermediate between structured expert judgment (Bamber and Aspinall, 2013) and non-probabilistic scenario sweeps. Structured expert judgment leaves the modelling assumptions to the experts who quantify their uncertainty on future observables.

2.6 Managing uncertainty, risk and learning

2.6.1 Guidelines for developing policies

This section assesses how the risks and uncertainties associated with climate change can affect choices with respect to policy responses, strategies, and instruments. At the time of the AR4, there was some modelling-based literature on how uncertainties affected policy design, but very few empirical studies. In the intervening years, international negotiations failed to establish clear national emissions reductions targets, but established a set of normative principles, such as limiting global warming to 2 °C. These are now reflected in international, national, and subnational planning processes and have affected the risks and uncertainties that matter for new climate policy development. Greater attention and effort has been given to finding synergies between climate policy and other policy objectives, so that it is now important to consider multiple benefits of a single policy instrument. For example, efforts to protect tropical rainforests (McDermott et al., 2011), rural livelihoods (Lawlor et al., 2010), biodiversity (Jinnah, 2011), public health (Stevenson, 2010), fisheries (Axelrod, 2011), arable land (Conliffe, 2011), energy security (Battaglini et al., 2009), and job creation (Barry et al., 2008) have been framed as issues that should be considered when evaluating climate policies.

The treatment here complements the examination of policies and instruments in later chapters of this report, such as Chapter 6 (which assesses the results of IAMs) and Chapters 13–15 (which assess policy instruments at a range of scales). Those later chapters provide greater details on the overall tradeoffs to be made in designing policies. The focus here is on the special effects of various uncertainties and risks on those tradeoffs.

- Section 2.6.2 discusses how institutions that link science with policy grapple with several different forms of uncertainty so that they meet both scientific and political standards of accountability.
- Section 2.6.3 presents the results of integrated assessment models (IAMs) that address the choice of a climate change temperature target or the optimal transition pathway to achieve a particular target. IAMs normally focus on a social planner operating at the global level.
- Section 2.6.4 summarizes the findings from modelling and empirical studies that examine the processes and architecture of international treaties.
- Section 2.6.5 presents the results of modelling studies and the few empirical analyses that examine the choice of particular policy instruments at the sovereign state level for reducing GHG emissions. It also examines how the adoption of energy efficiency products and technologies can be promoted at the firm and household levels. Special attention is given to how uncertainties affect the performance and effectiveness of these policy instruments.
- Section 2.6.6 discusses empirical studies of people's support or opposition with respect to changes in investment patterns and livelihood or lifestyles that climate policies will bring about. These studies show people's sensitivity to the impact that climate change will have on their personal health or safety and their perceptions of the health and safety risks associated with the new technologies addressing the climate change problem.

Linking intuitive thinking and deliberative thinking processes for dealing with uncertainties associated with climate change and climate policy should increase the likelihood that instruments and robust policies will be implemented. In this sense, the concepts presented in this section should be viewed as a starting point for integrating descriptive models with normative models of choice for developing risk management strategies.

2.6.2 Uncertainty and the science/policy interface

Science/policy interfaces are defined as social processes which encompass relationships between scientists and other actors in the policy process, and which allow for exchanges, co-evolution, and joint construction of knowledge with the aim of enriching decision making (Van den Hove, 2007). Analysts have called attention to several different forms of uncertainty affecting the science/policy relationship that can be summarized as follows:

- *Paradigmatic uncertainty* results from the absence of prior agreement on the framing of problems, on methods for scientifically investigating them, and on how to combine knowledge from disparate research traditions. Such uncertainties are especially common in cross-disciplinary, application-oriented research and assessment for meeting policy objectives (Gibbons, 1994; Nowotny et al., 2001).

- *Epistemic uncertainty* results from lack of information or knowledge for characterizing phenomena. Stirling (2007) further distinguishes between uncertainty (insufficient knowledge to assess probabilities), ambiguity (insufficient knowledge about possible outcomes), and ignorance (insufficient knowledge of likely outcomes and their probabilities). Others have noted that producing more knowledge may exacerbate uncertainty, especially when actors disagree about how to frame a problem for scientific investigation (Beck, 1992; Gross, 2010).

- *Translational uncertainty* results from scientific findings that are incomplete or conflicting, so that they can be invoked to support divergent policy positions (Sarewitz, 2010). In such circumstances, protracted controversy often occurs, as each side challenges the methodological foundations of the other's claims in a process called 'experimenters' regress' (Collins, 1985).

Institutions that link science to policy must grapple with all of the above forms of uncertainty, often simultaneously. Because their work cuts across conventional lines between science and politics, these institutions have been called 'boundary organizations' (Guston, 2001) and their function has been termed 'hybrid management' (Miller, 2001). Straddling multiple worlds, science-policy institutions are required to meet both scientific and political standards of accountability. Whereas achieving scientific consensus frequently calls for bounding and closing down disagreements, achieving political legitimacy requires opening up areas of conflict in order to give voice to divergent perspectives.

The task of resolving conflicts in policy-relevant science is generally entrusted to multidisciplinary expert bodies. These organizations are best suited to addressing the paradigmatic uncertainties that arise when problems are novel or when synthesis is required across fields with different standards of good scientific practice. Bridging epistemic and translational uncertainties, however, imposes added demands. For expert advisory bodies to be viewed as legitimate they must represent all relevant viewpoints in a politically acceptable manner (Jasanoff, 1990; 2005a). What counts as acceptable varies to some degree across national decision-making cultures. Each culture may place different weights on experts' personal integrity, the reliability of their disciplinary judgments, and their ability to forge agreement across competing values (Jasanoff, 2005b, pp. 209–224).

To achieve legitimacy, institutions charged with linking science to policy must also open themselves up to public input at one or more stages in their deliberations. This process of "extended peer review" (Funtowicz and Ravetz, 1992) is regarded as necessary, though insufficient, for the production of "socially robust knowledge", that is, knowledge that can withstand public scrutiny and scepticism (Gibbons, 1994). Procedures that are sufficient to produce public trust in one political context may not work in others because national political cultures are characterized by different "civic epistemologies", i.e., culturally specific modes of generating and publicly testing policy-relevant knowledge (Jasanoff, 2005a).

International and global scientific assessment bodies confront additional problems of legitimacy because they operate outside long-established national decision-making cultures and are accountable to publics subscribing to different civic epistemologies (Jasanoff, 2010). The temptation for such bodies has been to seek refuge in the linear model in the hope that the strength of their internal scientific consensus will be sufficient to win wide political buy-in. The recent research on linking science to policy suggests otherwise.

2.6.3 Optimal or efficient stabilization pathways (social planner perspective)

Integrated assessment models (IAMs) vary widely in their underlying structure and decision-making processes. IAMs designed for cost-benefit analysis typically simulate the choices of an idealized 'social planner', who by definition is someone who makes decisions on behalf of society, in order to achieve the highest social welfare by weighting the benefits and cost of mitigation measures. In contrast, many IAMs designed for cost-effectiveness analysis (CEA) specify the social planner's objective as identifying the transformation pathway that achieves a pre-defined climate goal at the lowest discounted aggregated costs to society. In both cases, the analyses do not consider distributional effects of policies on different income groups, but instead focus on the effect on total macroeconomic costs. Hence, with these types of IAMs, negotiators that are part of the political process are able to rank the relative desirability of alternative policies to the extent that they share the definition of social welfare embedded in the model (e.g., discounted aggregate cost minimization), and believe that those implementing the policy will do so cooperatively.

Chapter 6 describes in more detail important structural characteristics of a set of IAMs used to generate transformation pathways. The modelling analyses highlighted in Chapter 6 utilize the scenario approach to represent uncertainty. In this section we instead focus on IAM results where uncertainty is an integral part of the decision-analytic framework.

Climate policy assessment should be considered in the light of uncertainties associated with climate or damage response functions, the costs of mitigation technology and the uncertainty in climate change policy instruments. A key question these analyses address is how uncertainty with respect to the above factors alters the optimal social planner's short-term reactions to climate change. A subset also asks whether adjusting behaviour to uncertainty and designing more flexible policies and technology solutions would induce a significant welfare gain.

Table 2.2 provides an overview of the existing literature on IAMs that examine mitigation actions. The rows classify the literature on the basis of the type of uncertainty: *upstream*, associated with emission baseline drivers, such as economic and population growth; *downstream continuous*, associated with climate feedbacks and damages; *downstream strongly nonlinear*, associated with the possibility of thresholds and irreversibilities; *policy responses*, associated with the uncertain adoption of policy tools; and *multiple sources*, when more than one of the sources above are considered simultaneously. The three columns categorize the literature according to the ways introducing uncertainty influence the findings. The theoretical economic literature shows that the effect of including uncertainty in decision making on near-term mitigation is ambiguous (for an overview see e.g., Lange and Treich, 2008; De Zeeuw and Zemel, 2012). However, for most studies that assume *downstream strongly nonlinear* uncertainties under a social welfare maximization or *downstream* uncertainties in combination with a temperature target, including uncertainty in the analysis leads to an optimal or efficient level of mitigation that is greater and/or accelerated than under conditions of certainty.

The literature on IAMs incorporating uncertainty uses either Monte Carlo simulations or fully stochastic programming techniques. Monte Carlo studies provide insights regarding the order-of-magnitude effect of multiple model parameter uncertainties for model output (Nordhaus and Popp, 1997; Tol, 1999; Webster et al., 2002; Hope, 2008, p. 200; Ackerman et al., 2010; Dietz, 2011; Pycroft et al., 2011). In this sense they can be interpreted as a preparatory step towards a full-fledged decision analysis under uncertainty.

Table 2.2 | Overview of literature on integrated assessment models examining mitigation actions. (cea) indicates: analysis based on a probabilistic generalization of CEA. Papers that appear several times report different scenarios or assumptions. The few studies highlighted by "*" use non-probabilistic decision criteria under uncertainty (e.g., minimax regret or maximin).[1]

Type of Uncertainty Considered	Effect on Mitigation Action		
	Accelerates/Increases Mitigation Action	*Delays/Decreases Mitigation Action*	*Ambiguous Effect*
Upstream (emission drivers)	Reilly et al., 1987; Webster et al., 2002; O'Neill and Sanderson, 2008; Rozenberg et al., 2010		O'Neill and Sanderson, 2008
Downstream (climate and damages)—mildly nonlinear damages	Chichilnisky and Heal, 1993; Peck and Teisberg, 1994; Ha-Duong and Treich, 2004; Syri et al., 2008; Athanassoglou and Xepapadeas, 2011; Kaufman, 2012; Ackerman et al., 2013	Kolstad, 1994, 1996a; Baranzini et al., 2003	Clarke and Reed, 1994; Kolstad, 1996b; Tsur and Zemel, 1996; Gollier et al., 2000; Fisher and Narain, 2003; Ha-Duong and Treich, 2004; Baker et al., 2006; Lange and Treich, 2008; Lorenz et al., 2012b; Ulph and Ulph, 1997; Ackerman et al., 2013
Downstream (climate and damages)—strongly nonlinear event or temperature target	Ha-Duong, 1998; Gjerde et al., 1999; O'Neill and Oppenheimer, 2002; Baranzini et al., 2003; Dumas and Ha-Duong, 2005; Syri et al., 2008(cea); Johansson et al., 2008(cea); Hope, 2008; Webster, 2008; Tsur and Zemel, 2009; Schmidt et al., 2011(cea); Funke and Paetz, 2011; Iverson and Perrings, 2012*; Lorenz et al., 2012b; de Zeeuw and Zemel, 2012	Peck and Teisberg, 1995	Gollier and Treich, 2003
Uncertainty on Policy Response	Ha-Duong et al., 1997; Blanford, 2009; Bosetti and Tavoni, 2009; Bosetti et al., 2009; Durand-Lasserve et al., 2010(cea)	Baudry, 2000; Baker and Shittu, 2006(cea)[2]	Farzin and Kort, 2000(cea)
Multiple Sources of Uncertainty	Nordhaus and Popp, 1997; Grubb, 1997; Pizer, 1999; Tol, 1999; Obersteiner et al., 2001; Yohe et al., 2004; Keller et al., 2004; Baker and Shittu, 2008; Baker and Adu-Bonnah, 2008; Bahn et al., 2008; Held et al., 2009; Hope, 2009; Labriet et al., 2012(cea), 2010; Hof et al., 2010* ; Funke and Paetz, 2011*	Scott et al., 1999	Manne and Richels, 1991; Baker and Shittu, 2008(4); Baker and Adu-Bonnah, 2008[3]

Notes:
1 In some studies the 'baseline case' is a decision analysis based on a reduced form of uncertainty.
2 The impact on R&D investments depend on technology; the most common result is, however, that uncertainty decreases the optimal level of R&D investments.
3 In the sense of: increasing damage uncertainty would lead to higher investments in less risky programmes, but the effect depends on the type of technology.

Table 2.2 also characterizes the effect of the inclusion of uncertainty on early-period mitigation efforts. A decision analysis is generally compared to a baseline-case represented by a deterministic study utilizing average values of uncertain parameters. (In some studies, the baseline case is a decision analysis based on a reduced form of uncertainty.)

It should be noted that, although IAMs mimic decision makers who utilize deliberative processes, in reality social planners might resort to intuitive thinking to simplify their decision processes, leading to biases and inferior choices. To date there is no research that considers such behaviour by decision makers and how it affects the projections of IAMs. We discuss the need for such studies in Section 2.7 on gaps in knowledge and data.

2.6.3.1 Analyses predominantly addressing climate or damage response uncertainty

Although studies differ in their approaches, the case against accelerated or increased mitigation action is the possibility that irreversible sunk cost investments in abatement options outweigh the irreversible effects of climate change. This has been an infrequent finding, with the exception of those studies that have not included catastrophic/threshold damage and give no consideration to the non-climate related benefits of these investments, such as enhancing energy security or local pollution benefits. Indeed, the one set of papers that finds a need for increased or accelerated mitigation action is ambiguous when the social welfare optimum is examined under *downstream continuous/mildly nonlinear damages* uncertainty. Lorenz et al. (2012a) show that this is due primarily to the fact that damage nonlinearities are often compensated by other nonlinearities such as a concave (i.e., sublinear) concentration-temperature relation.

Studies that cluster in the first column (accelerated or increased mitigation action) assumed strongly non-linear damage functions or temperature targets (3rd row). Cost-effectiveness analysis has been applied to reflect targets when the models have been generalized to include uncertainty. In this regard, Held et al. (2009), utilizing chance constrained programming (CCP) (see Section 2.5.4.1), examine uncertainty in climate and technology response properties. As their reference case they calculated the mitigation effort needed to achieve a 2 °C temperature target, assuming average values for all uncertain parameters. Given uncertainty, however, it is clear that any given mitigation effort will exceed the target with some probability; for the reference case this is approximately 50 %. As the required probability for meeting the target increases, a greater level of mitigation effort is required. (An analogous argument holds for tipping-point derived targets. See McInerney and Keller, 2008). If the required probability is 66.6 % rather than 50 %, investments in mitigation technologies need to occur in earlier decades.

The effects on investment in mitigation also depend on whether uncertainty is expected to be reduced. Is a reduction of uncertainty on climate sensitivity and related climate response properties realistic? In an early paper, Kelly and Kolstad (1999) evaluated the amount of time needed to significantly reduce uncertainty about the parameters influencing climate sensitivity by observing global warming. They found the required time to be 90 to 160 years. Leach (2007) conducted a similar analysis that allowed two rather than one independent sources of downstream uncertainty. In that case, the time required to resolve the climate sensitivity parameters is likely to be even longer. These kind of studies assumed that our basic understanding of atmospheric chemistry and physics would remain unchanged over time. If one were to relax this constraint, then one could imagine that learning would progress more rapidly.

Another set of papers examines the ‘anticipation effect’, namely what it means if we believe we will learn in the future, rather than that our knowledge will remain constant. Lange and Treich (2008) showed that the sign and magnitude of mitigation depend on the particular numerical model and type of uncertainty when introducing the anticipation effect. Using CBA, for example, Lorenz et al. (2012b), Peck and Teisberg (1993), Webster et al. (2008), and Yohe and Wallace (1996) showed the anticipation effect to be negligible when assuming continuous and only weakly non-linear damages. However, Lorenz (2012b) showed slightly less immediate mitigation (compared to no-learning) if one anticipates learning within a given, narrow, time window with respect to threshold-type impacts. Such a mild reduction of early mitigation in response to anticipation was also reported in Keller et al. (2004) in accordance with Ulph and Ulph (1997).

When CEA is used to represent temperature targets in combination with climate response uncertainty, it is difficult to evaluate learning effects (see the discussion in Section 2.5.4.3). One way to allow for numerical solutions in this case is to assume an upper limit on the distribution of climate sensitivity to examine the effect of learning in the presence of a climate target. Under this assumption, more mitigation is called for (Bahn et al., 2008; Syri et al., 2008; Fouquet and Johansson, 2008; Webster, 2008).

A further set of papers considers the impossibility of specifying a precise probability density function for characterizing climate sensitivity as suggested by many climate scientists. This implies that these probabilities are difficult to estimate and decisions have to be made under conditions of ambiguity. Funke and Paetz (2011) account for model structure uncertainty by employing a robust control approach based on a maximin principle. When considering uncertainty on the ecological side of the balance, they conclude that model uncertainty implies a need for more aggressive near-term emissions reductions. Athanassoglou and Xepapadeas (2011) extend this approach to include adaptation. Iverson and Perrings (2012) apply combinations of maximin and/or minimax decision criteria, examining the effects of widening the range of climate sensitivity. Hof et al. (2010), contrast a CBA with a minimax regret approach and find that the minimax regret approach leads to more stringent and robust climate targets for relatively low discount rates if both high climate sensitivity and high damage estimates are assumed. What remains unresearched is the possibility of using non-probabilistic methods to evaluate the effects of an unbounded, or 'fat-tails', distribution for climate responses and climate impacts.

Finally, a potentially path-breaking development in economics is the effort of Ackerman et al. (2013), Crost and Traeger (2013), and Kaufman (2012) to disentangle risk aversion (a static effect) from consumption smoothing (an intertemporal effect) (for a conceptual discussion see Ha-Duong and Treich, 2004) in an Integrated Assessment Model. Compared to the results of a standard discounted expected utility model that relates risk aversion to consumption smoothing, Ackerman (2013) as well as Crost and Traeger (2013) find optimal mitigation to be twice as great. Since these are the first papers on this topic, it is too early to tell whether their results represent a robust result that captures society's risk preferences.

2.6.3.2 Analyses predominantly addressing policy response uncertainty

There are two strands of research in the area of policy response uncertainty. The first has focused on examining how the extent and timing of mitigation investments are affected by the uncertainty on the effectiveness of Research, Development, and Demonstration (RD&D) and/or the future cost of technologies for reducing the impact of climate change. An example of this would be optimal investment in energy technologies that a social planner should undertake, knowing that there might be a nuclear power ban in the near future. Another strand of research looks at how uncertainty concerning future climate policy instruments in combination with climate and/or damage uncertainty affects a mitigation strategy. An example would be the optimal technological mix in the power sector to hedge future climate regulatory uncertainty.

With respect to the first strand, the main challenge is to quantify uncertainty related to the future costs and/or availability of mitigation technologies. Indeed, there does not appear to be a single stochastic process that underlies all (RD&D) programmes' effectiveness or innovation processes. Thus elicitation of expert judgment on the probabilistic improvements in technology performance and cost becomes a crucial input for numerical analysis. A literature is emerging that uses expert elicitation to investigate the uncertain effects of RD&D investments on the prospect of success of mitigation technologies (see for example Baker et al., 2008; Curtright et al., 2008; Chan et al., 2010; Baker and Keisler, 2011). In future years, this new body of research will allow the emergence of a literature studying the probabilistic relationship between R&D and the future cost of energy technologies in IAMs.

The few existing papers reported in Table 2.2 under the Policy Response uncertainty column (see Blanford, 2009; Bosetti and Tavoni, 2009) point to increased investments in energy RD&D and in early deployment of carbon-free energy technologies in response to uncertainty. An interesting analysis has been performed in Goeschl and Perino (2009), where the potential for technological 'boomerangs' is considered. Indeed, while studies cited above consider an innovation failure an R&D project that does not deliver a clean technology at a competitive cost, Goeschl and Perino (2009) define R&D failure when it brings about a new, environmentally harmful, technology. Under such characterization they find that short-term R&D investments are negatively affected.

Turning to the second strand of literature reported in the Policy Response or in the Multiple Uncertainty columns of Table 2.2 (see Ha-Duong et al., 1997; Baker and Shittu, 2006; Durand-Lasserve et al., 2010), most analyses imply increased mitigation in the short term when there is uncertainty about future climate policy due to the asymmetry of future states of nature. In the event of the realization of the 'no climate policy' state, investment in carbon-free capital has low or zero value. Conversely, if a 'stringent climate policy' state of nature is realized, it will be necessary to rapidly ramp up mitigation to reduce the amount of carbon in the atmosphere. This cost is consistently higher, thus implying higher mitigation prior to the realization of the uncertain policy state.

2.6.4 International negotiations and agreements

Social planner studies, as reviewed in the previous sub-sections, consider the appropriate magnitude and pace of aggregate global emissions reduction. These issues have been the subject of negotiations about long-term strategic issues at the international level along with the structuring of national commitments and the design of mechanisms for compliance, monitoring, and enforcement.

2.6.4.1 Treaty formation

A vast literature looks at international treaties in general and how they might be affected by uncertainties. Cooper (1989) examined two centuries of international agreements that aimed to control the spread of communicable diseases and concludes that it is only when uncertainty is largely resolved that countries will enter into agreements. Young (1994), on the other hand, suggests that it may be easier to enter into agreements when parties are uncertain over their individual net benefits from an agreement than when that uncertainty has been resolved. Coalition theory predicts that for international negotiations related to a global externality such as climate change, stable coalitions will generally be small and/or ineffective (Barrett, 1994). Recently, De Canio and Fremstad (2013) show how the recognition of the seriousness of a climate catastrophe on the part of leading governments—which increases the incentives for reaching an agreement—could transform a prisoner's dilemma game into a coordination game leading to an increased likelihood of reaching an international agreement to limit emissions.

Relatively little research has been undertaken on how uncertainty affects the stability of multilateral environmental agreements (MEAs) and when uncertainty and learning has the potential to unravel agreements. Kolstad (2007), using a game theoretic model, looks specifically at environmental agreements. He finds that systematic uncertainty decreases the size of the largest stable coalition of an MEA. Kolstad and Ulph (2011) show that partial or complete learning has a negative impact on the formation of an MEA because as outcomes become more certain, some countries also learn the MEA will reduce their own welfare benefits, which deters them from joining the coalition. Baker (2005), using a model of the impacts of uncertainty and learning in a non-cooperative game, shows that the level of correlation of damages across countries is a crucial determinant of outcome.

Barrett (2013) has investigated the role of catastrophic, low probability events on the likelihood of cooperation with respect to a global climate agreement. By comparing a cooperative agreement with the Nash equilibrium it is possible to assess a country's incentives for participating in such an agreement. Looking at stratospheric ozone as an analogy for climate, Heal and Kunreuther (2013) observed that the signing of the Montreal Protocol by the United States led many other countries to follow suit. The authors in turn suggest how it could be applied to foster an international treaty on greenhouse gas emissions by tipping a non-cooperative game from an inefficient to an efficient equilibrium.

Several analyses, including Victor (2011) and Hafner-Burton et al. (2012), contend that the likelihood of a successful comprehensive international agreement for climate change is low because of the sensitivity of negotiations to uncertain factors, such as the precise alignment and actions of participants. Keohane and Victor (2011), in turn, suggest that the chances of a positive outcome would be higher in the case of numerous, more limited agreements. Developing countries have been unlikely to agree to binding targets in the context of international agreements due in part to the interests of developed countries dominating the negotiation process. For the situation to change, the developing countries would have to enhance their negotiating power in international climate change discussions by highlighting their concerns (Rayner and Malone, 2001).

The above analyses all assume that the agents are deliberative thinkers, each of whom has the same information on the likelihood and consequences of climate change. Section 2.7 indicates the need for future research that examines the impact of intuitive thinking on behaviour on international negotiations and processes for improving the chances of reaching an agreement on treaties.

2.6.4.2 Strength and form of national commitments

Buys et al. (2009) construct a model to predict national level support for a strong global treaty based on both the climatic and economic risks that parties to the treaty face domestically; however Buys et al. do not test the model empirically. Their model distinguishes between vulnerabilities to climate impacts and climate policy restrictions with respect to carbon emissions and implies that countries would be most supportive of strong national commitments when they are highly vulnerable to climate impacts and their emitting sectors are not greatly affected by stringent policy measures.

Victor (2011) analyzes the structure of the commitments themselves, or what Hafner-Burton et al. (2012) call rational design choices. Victor suggests that while policymakers have considerable control over the carbon intensity of their economies, they have much less control over the underlying economic growth of their country. As a result, there is greater uncertainty on the magnitude of emissions reductions, which depends on both factors, than on the reductions in carbon intensity. Victor suggests that this could account for the reluctance by many countries to make binding commitments with respect to emissions reductions. Consistent with this reasoning, Thompson (2010) examined negotiations within the UNFCCC and found that greater uncertainty with respect to national emissions was associated with a decrease in support for a national commitment to a global treaty.

Webster et al. (2010) examined whether uncertainty with respect to national emissions increases the potential for individual countries to hedge by joining an international trade agreement. They found that hedging had a minor impact compared to the other effects of international trade, namely burden sharing and wealth transfer. These findings may have relevance for structuring a carbon market to reduce emissions by taking advantage of disparities in marginal abatement costs across different countries. In theory, the right to trade emission permits or credits could lessen the uncertainties associated with any given country's compliance costs compared to the case where no trading were possible. Under a trading scheme, if a country discovered its own compliance costs to be exceptionally high, for example, it could purchase credits on the market.

2.6.4.3 Design of measurement, verification regimes, and treaty compliance

A particularly important issue in climate treaty formation and compliance is uncertainty with respect to actual emissions from industry and land use. Measurement, reporting, and verification (MRV) regimes have the potential to set incentives for participation in a treaty and still be stringent, robust, and credible with respect to compliance. The effects of strategies for managing GHG emissions are uncertain because the magnitude of the emissions of carbon dioxide and other GHG gases, such as methane, often cannot be detected given the error bounds associated with the measurement process. This is especially the case in the agriculture, forestry, and other land-use (AFOLU) sectors.

In the near term, an MRV regime that met the highest standards could require stock and flow data for carbon and other GHGs. These data are currently available only in wealthy countries, thus precluding developing countries from participating (Oliveira et al., 2007). By contrast, there are design options for MRV regimes that are less accurate, but which still provide data on the drivers of emissions so that the developing countries could be part of the system. By being more inclusive, these options could be a more effective way to actually reduce aggregate emissions, at least in the near term (Bucki et al., 2012). In the longer term, robust and harmonized estimation of GHG flows—emissions and their removal—in agriculture and forestry requires investment in monitoring and reporting capacity, especially in developing countries (Böttcher et al., 2009; Romijn et al., 2012). Reflecting this need for an evolving MRV regime to match data availability, the 2006 Guidelines for National Greenhouse Gas Inventories, prepared by an IPCC working group, suggested three hierarchical tiers of data for emission and carbon stock change factors with increasing levels of data requirements and analytical complexity. Tier 1 uses IPCC default values of high uncertainty; Tier 2 uses country-specific data; and Tier 3 uses higher spatial resolution, models, and inventories. In 2008, only Brazil, India and Mexico had the capacity to use Tier 2 and no developing country was able to use tier 3 (Hardcastle and Baird, 2008). Romijn et al. (2012) focused on 52 tropical countries and found that four of them had a very small capacity gap regarding the monitoring of their forests through inventories, while the remaining 48 had limited or no ability to undertake this monitoring process.

In order to overcome the gaps and uncertainties associated with lower tier approaches, different principles can be applied to form pools (Böttcher et al., 2008). For example, a higher level of aggregation by including soil, litter and harvested products in addition to a biomass pool as part of the MRV regime decreases relative uncertainty: the losses in one pool (e.g., biomass) are likely to be offset by gains in other pools (e.g., harvested products) (Böttcher et al., 2008). Researchers have suggested that the exclusion of a pool (e.g., soil) in an MRV regime should be allowed only if there is adequate documentation that the exclusion provides a more conservative estimate of emissions (Grassi et al., 2008). They also suggest that an international framework needs to create incentives for investments. In this respect, overcoming initialization costs and unequal access to monitoring technologies would be crucial for implementation of an integrated monitoring system, and fostering international cooperation (Böttcher et al., 2009).

2.6.5 Choice and design of policy instruments

Whether motivated primarily by a binding multilateral climate treaty or by some other set of factors, there is a growing set of policy instruments that countries have implemented or are considering to deal with climate change. Typically, these instruments will influence the decisions of firms and private individuals, so that policymakers try to anticipate how these agents will react to them.

Some policy instruments operate by mandating particular kinds of behaviour, such as the installation of pollution control technology or limits on emissions from particular sources. There is an extensive literature in political science demonstrating that the effects of these instruments are fairly predictable (Shapiro and McGarity, 1991) and are insensitive to market or regulatory uncertainties, simply because they prescribe particular technologies or practices which must be strictly adhered to. There is a literature in economics, however, suggesting that their very inflexibility makes them inefficient (Malueg, 1990; Jaffe and Stavins, 1995).

In the presence of substantial technological uncertainty, no matter what policy instrument is employed, interventions that shift investment behaviour from currently low cost to currently high cost technologies run the risk of increasing short-term costs and energy security concerns for consumers (Del Rio and Gual, 2007; Frondel et al., 2008, 2010). In some cases, long-term costs may be higher or lower, depending on how different technologies evolve over time (Williges et al., 2010; Reichenbach and Requate, 2012). This section is structured by considering two broad classes of interventions for targeting the energy supply: interventions that focus on emissions, by placing a market price or tax on CO_2 or other greenhouse gases; and interventions that promote Research, Development, Deployment, and Diffusion (RDD&D) of particular technologies. In both types of interventions, policy choices can be sensitive to uncertainties in technology costs, markets, and the state of regulation in other jurisdictions and over time. In the case of technology-oriented policy, choices are also sensitive to the risks that particular technologies present. We then describe instruments for reducing energy demand by focusing on lifestyle choice and energy efficient products and technologies. Finally, we briefly contrast the effects of uncertainties in the realm of climate change adaptation with climate change mitigation, recognizing that more detail on adaptation can be found in the WGII AR5.

2.6.5.1 Instruments creating market penalties for GHG emissions

Market-based instruments increase the cost of energy derived from fossil fuels, potentially leading firms involved in the production and conversion of energy to invest in low carbon technologies. Considerable research prior to AR4 identified the differences between two such instruments—carbon taxes and cap-and-trade regimes—with respect to uncertainty. Since AR4, research has examined the effects of regulatory risk and market uncertainty on one instrument or the other by addressing the following question: how is the mitigation investment decision affected by uncertainty with respect to whether and to what extent a market instrument and well-enforced regulations will be in place in the future?

Much of this research has focused on uncertainty with respect to carbon prices under a cap-and-trade system. A number of factors influence the relationship between the size of the cap and the market price that includes fossil fuel prices, consumer demand for energy, and economic growth more generally. Each of these factors can lead to volatility in carbon market prices (Alberola et al., 2008; Carraro et al., 2009; Chevallier, 2009). Vasa and Michaelowa (2011) assessed the impact of policy uncertainty on carbon markets and found that the possibility of easily creating and destroying carbon markets leads to extreme short-term rent-seeking behaviour and high volatility in market prices. Experience so far with the most developed carbon market—the European Emissions Trading System (ETS)—reveals high volatility marked by not-infrequent decreases of the price of carbon to very low values (Feng et al., 2011).

Numerous modelling studies have shown that regulatory uncertainty reduces the effectiveness of market-based instruments. More specifically, a current or expected carbon price induces a decrease in investment into lower carbon infrastructure and hence less technological learning, when there is uncertainty as to future market conditions, compared to the case where future conditions are known (Yang et al., 2008; Fuss et al., 2009; Oda and Akimoto, 2011). In order to compensate and maintain a prescribed level of change in the presence of uncertainty, carbon prices would need to be higher. Estimates of the additional macroeconomic costs range from 16–37 % (Blyth et al., 2007) to as much as 50 % (Reinelt and Keith, 2007), depending on the particular type of investment under consideration. The precise instrument design details can affect investment behaviour. Patiño-Echeverri et al. (2007, 2009), for example, found that less frequent but larger regulatory policy changes had less of a negative interactive effect with uncertainty, while Zhao (2003) found a greater impact of uncertainty on the performance of a carbon tax than on a cap-and-trade system. Fan et al. (2010) added to this analysis by examining the sensitivity of these results to increasing risk aversion, under two alternative carbon market designs: one in which carbon allowances were auctioned by the government to firms, and a second in which existing firms received free allowances due to a grandfathering rule.

Under an auctioned system for carbon allowances, increasing risk aversion leads to greater investments in low carbon technologies. In contrast, under a grandfathered market design, increasing risk aversion combined with uncertainty pushes investment behaviour closer to what it would be in the absence of the carbon market: more investment in coal. The intuition behind this finding is that the grandfathered scheme would create a situation of windfall profits (since the freely allocated permits have a value to the firms receiving them), and risk-averse investors would be more influenced by the other, less desirable state of the world, the absence of carbon markets. Fan et al., (2012) replicated these results using a broader range of technological choices than in their earlier paper. Whereas these latter two papers used a game-theoretic model, Fuss et al., (2012) employed a real options theory model to arrive at qualitatively the same conclusions.

One option for reducing carbon price volatility is to set a cap or floor for that price to stabilize investment expectations (Jacoby and Ellerman, 2004; Philibert, 2009). Wood and Jotzo (2011) found that setting a price floor increased the effectiveness of the carbon price in stimulating investments in low carbon technologies, given a particular expectation of macroeconomic drivers (e.g., economic growth and fossil fuel prices that influence the degree to which a carbon cap is a constraint on emissions). Szolgayova et al., (2008), using a real options model to examined the value of waiting for information, found the cap stabilized expectations. In the process, the cap lessened the effectiveness of an expected carbon price at altering investment behaviour, as many investments in low carbon technologies are undertaken only because of the possibility of very high carbon prices in the future. In another study assuming rational actor behaviour, Burtraw et al. (2010) found that a symmetric safety valve that sets both a floor and a ceiling price outperforms a single-sided safety valve in terms of both emissions reduction and economic efficiency. Murray et al. (2009) suggested that a reserve allowance for permits outperforms a simple safety valve in this regard.

Empirical research on the influence of uncertainty on carbon market performance has been constrained by the small number of functioning markets, thus making it difficult to infer the effects of differences in market design. The few studies to date suggest that the details of market design can influence the perception of uncertainty, and in turn the performance of the market. More specifically, investment behaviour into the Clean Development Mechanism (CDM) has been influenced by uncertainties in terms of what types of projects are eligible (Castro and Michaelowa, 2011), as well as the actual number of Certified Emissions Reductions (CERs) that can be acquired from a given project (Richardson, 2008).

Looking at the European Union's Emission Trading System (ETS), researchers have observed that expected carbon prices do affect investment behaviour, but primarily for investments with very short amortization periods. High uncertainty with respect to the longer-term market price of carbon has limited the ETS from having an impact on longer-term investments such as R&D or new power plant construction (Hoffmann, 2007). Blyth and Bunn (2011) found that uncertainty for post-2012 targets was a major driver of ETS prices, with an effect of suppressing those prices. The literature suggests that prices have not been high enough to drive renewable energy investment in the absence of feed-in tariffs (Blanco and Rodrigues, 2008). Barbose et al. (2008) examined a region—the western United States—where no ETS was functioning but many believed that it would, and found that most utilities did consider the possibility of carbon prices in the range of USD 4 to USD 22 a ton. At the same time, the researchers could not determine whether this projection of carbon prices would have an actual effect on utilities' decisions, were an actual ETS in place, because they were unable to document the analysis underlying the utilities' investment decisions.

2.6.5.2 Instruments promoting technological RDD&D

Several researchers suggest that future pathways for RDD&D will be the determining factor for emissions reductions (Prins and Rayner, 2007; Lilliestam et al., 2012). Policy instruments can provide an incentive for firms not only to alter their investment portfolio towards low carbon technologies, but also to devote resources towards innovation (Baker et al., 2008). Because instruments differ in terms of how they influence behaviour, such as whether or not they create an immediate incentive or one that accrues over the lifetime of the investment, their relative effectiveness can be sensitive to relevant market uncertainties.

The literature reviewed in the previous section reveals that in the presence of substantial regulatory uncertainty, market-based instruments do a poor job of promoting RDD&D. This has given rise to policy proposals to supplement a pure-market system with another instrument—such as a cap, floor, or escape valve—to reduce price volatility and stabilize expectations. By contrast, combining a market-based instrument with specific technology support can lead to greater volatility in the carbon price, even when there is very little uncertainty about which technologies will be assisted in the coming years (Blyth et al., 2009).

Several empirical studies with a focus on risk and uncertainty have compared the effectiveness of market instruments with other instruments such as feed-in tariffs or renewable quota systems, in stimulating low carbon investments and R&D. Butler and Neuhoff (2008) compared the feed-in tariff in Germany with the quota system in the United Kingdom, and found the German system outperformed the UK system on two dimensions: stimulating overall investment quantity, and reducing costs to consumers. The primary driver was the effectiveness of the feed-in tariff in reducing risks associated with future revenues from the project investment, therefore making it possible to lower the cost of project financing. Other researchers replicate this finding using other case studies (Mitchell et al., 2006; Fouquet and Johansson, 2008). Lüthi and Wüstenhagen (2012) surveyed investors with access to a number of markets, and found that they steered their new projects to those markets with feed-in tariff systems, as it was more likely than other policy instruments to reduce their risks. Lüthi (2010) compared policy effectiveness across a number of jurisdictions with feed-in tariffs, and found that above a certain level of return, risk-related factors did more to influence investment than return-related factors.

Looking at the early stages in the technology development process, Bürer and Wüstenhagen (2009) surveyed 'green' tech venture capitalists in the United States and Europe using a stated preference approach to identify which policy instrument or instruments would reduce the perceived risks of investment in a particular technology. They identified a strong preference in both continents, but particularly Europe, for feed-in tariffs over cap-and-trade and renewable quota systems, because of the lower risks to return on investment associated with the former policy instrument. Moreover, venture capital investors typically look for short- to medium-term returns on their investment, for which the presence of feed-in tariffs has the greatest positive effect.

Held et al. (2006) identified patterns of success across a wide variety of policy instruments to stimulate investment in renewable energy technologies in Europe. They found that long-term regulatory consistency was vital for new technology development. Other studies have shown that regulatory inconsistency with respect to subsidy programs—such as feed-in tariffs in Spain or tax credits in the United States—can lead to temporarily overheated markets, pushing up investment costs and consumer prices, and reducing the pressure for technological development (Del Rio and Gual, 2007; Sáenz de Miera et al., 2008; Barradale, 2010).

In contrast to the large literature looking at the overall effects of uncertainty, there have only been a few empirical papers documenting the particular risks that concern investors the most. Leary and Esteban (2009) found regulatory uncertainty—particularly with respect to issues of siting—to concern investors in wave- and tide-based energy projects. Komendantova et al. (2012) examined perceptions among European investors in solar projects in North Africa, and found concerns about regulatory change and corruption were much greater than concerns about terrorism and technology risks. The same researchers modelled the sensitivity of required state subsidies for project development in response to these risks, and found the subsidies required to stimulate a given level of solar investment rose by a factor of three, suggesting large benefits from stemming corruption and stabilizing regulations (Komendantova et al., 2011). Meijer et al. (2007) examined the perceived risks for biogas project developers in the Netherlands, and found technological, resource, and political uncertainty to be their most important concerns. These studies are useful by documenting policymakers' concerns so they can address these issues in the future.

Table 2.3 synthesizes the modelling and empirical results on renewable quota systems and feed-in tariffs, as well as with results for cap-and-trade systems from the previous sub-section. The table highlights the

Table 2.3 | Uncertainties affecting the effectiveness of alternative policy instruments.

Instrument	Uncertainty	Investor fears	Effect on low carbon technology
Allowance trading market	Technological systems	Other low carbon technologies will prove more cost-effective	Dampened investment
	Market behaviour	Growth in energy demand will decline	Dampened investment
	Market behaviour	Fossil fuel prices will fall	Dampened investment
	Regulatory actions	Governments will increase the number of allowances	Dampened investment
Renewable quotas	Technological systems	Other low carbon technologies will prove more cost-effective	Dampened investment
	Market behaviour	Supply for renewable energy will rise faster than the quota	Dampened investment
Subsidies and feed-in tariffs	Regulatory actions	Subsidy for this particulartechnology will decline	Overheated market

effects of three of the classes of uncertainties identified earlier in this chapter, namely with respect to technological systems, market behaviour, and the future regulatory actions of governments.

2.6.5.3 Energy efficiency and behavioural change

As pointed out in Section 2.6.5.2 and earlier sections, one way to mitigate climate risk is to encourage RD&D with respect to providing energy from renewable sources, such as wind and solar, as well as to promote low energy use products. For firms to undertake these investments, there needs to be some guarantee that a market for their products will exist. Currently consumers are reluctant to adopt energy efficient measures, such as compact fluorescent bulbs, energy efficient refrigerators, boilers and cooling systems, as well as new technologies such as solar installations and wind power. This can be attributed to the uncertainties associated with future energy prices and consumption of energy coupled with misperceptions of the products' benefits and an unwillingness to incur the upfront costs of these measures as discussed in Section 2.4.3.2.

Gardner and Stern (2008) identified a list of energy efficient measures that could reduce North American consumers' energy consumption by almost 30 % but found that individuals were not willing to invest in them because they have misconceptions about the measures' effectiveness. Other studies show that the general public has a poor understanding of energy consumption associated with familiar activities (Sterman and Sweeney, 2007). A national online survey of 505 participants by Attari et al. (2010) revealed that most respondents felt that measures such as turning off the lights or driving less were much more effective as energy efficient improvements than experts' viewed them to be.

There are both behavioural and economic factors described in Section 2.4.3.2 that can explain the reluctance of households to incur the upfront costs of these energy efficient measures. Due to a focus on short-term horizons, individuals may underestimate the savings in energy costs from investing in energy efficient measures. In addition they are likely to discount the future hyperbolically so that the upfront cost is perceived to be greater than expected discounted reduction in energy costs (Dietz et al., 2013; Kunreuther et al., 2013b). Coupled with these descriptive models or choices that are triggered by intuitive thinking, households may have severe budget constraints that discourage them from investing in these energy efficient measures. If they intend to move in several years and feel that the investment in the energy efficient measure will not be adequately reflected in an increase in their property value, then it is inappropriate for them *not* to invest in these measures if they undertake deliberative thinking.

To encourage households to invest in energy efficient measures, messages that communicate information on energy use and savings from undertaking these investments need to be conveyed (Abrahamse et al., 2005). Recent research has indicated the importance of highlighting indirect and direct benefits (e.g., being 'green', energy independence, saving money) in people's adoption of energy efficiency measures to address the broad range and heterogeneity in people's goals and values that contribute to the subjective utility of different courses of action (Jakob, 2006). One also needs to recognize the importance of political identity considerations when choosing the nature of these messages, as different constituencies have different associations to options that mitigate climate change and labels that convey potential benefits from adopting energy efficient measures (Hardisty et al., 2010; Gromet et al., 2013).

The advent of the 'smart' grid in Western countries, with its 'smart' metering of household energy consumption and the development of 'smart' appliances will make it feasible to provide appliance-specific feedback about energy use and energy savings to a significant number of consumers within a few years. A field study involving more than 1,500 households in Linz, Austria revealed that feedback on electricity consumption corresponded with electricity savings of 4.5 % for the average household in this pilot group (Schleich et al., 2013).

To deal with budget constraints, the upfront costs of these measures need to be spread over time so the measures are viewed as economically viable and attractive. The Property Assessed Clean Energy (PACE) programme in the United States is designed to address the budget constraint problem. Participants in this programme receive financing for improvements that is repaid through an assessment on their property taxes for up to 20 years. Financing spreads the cost of energy improvements over the expected life of measures such as weather sealing, energy efficient boilers and cooling systems, and solar installations and allows for the repayment obligation to transfer automatically to the next property owner if the property is sold. The program addresses two important barriers to increased adoption of energy efficiency and small-scale renewable energy: high upfront costs and fear that project costs will not be recovered prior to a future sale of the property (Kunreuther and Michel-Kerjan, 2011).

Social norms that encourage greater use of energy efficient technology at the household level can also encourage manufacturers to invest in the R&D for developing new energy efficient technologies and public sector actions such as well-enforced standards of energy efficiency as part of building sale requirements, (Dietz et al., 2013).

2.6.5.4 Adaptation and vulnerability reduction

Compared to mitigation measures, investments in adaptation appear to be more sensitive to uncertainties in the local impacts associated with the damage costs of climate change. This is not surprising for two reasons. First, while both mitigation and adaptation may result in lower local damage costs associated with climate impacts, the benefits of adaptation flow directly and locally from the actions taken (Prato, 2008). Mitigation measures in one region or country, by contrast, deliver benefits that are global; however, they are contingent on the actions of people in other places and in the future, rendering their local benefits more uncertain. One cannot simply equate marginal local damage costs with marginal mitigation costs, and hence the importance of uncertainty with respect to the local damage costs is diminished (Webster et al., 2003).

Second, politically negotiated mitigation targets, such as the 2 °C threshold appear to have been determined by what is feasible and affordable in terms of the pace of technological diffusion, rather than by an optimization of mitigation costs and benefits (Hasselmann et al., 2003; Baker et al., 2008; Hasselmann and Barker, 2008). Hence, mitigation actions taken to achieve a temperature target would not be changed if the damage costs (local or global) were found to be somewhat higher or lower. This implies that mitigation measures will be insensitive to uncertainty of these costs associated with climate change. Adaptation decisions, in contrast, face fewer political and technical constraints, and hence can more closely track what is needed in order to minimize local expected costs and hence will be more sensitive to the uncertainties surrounding future damage costs from climate change (Patt et al., 2007, 2009).

There are two situations where decisions on adaptation policies and actions may be largely insensitive to uncertainties about the potential impacts of climate change on future damage. The first is where adaptation is constrained by the availability of finance, such as international development assistance. Studies by the World Bank, OECD, and other international organizations have estimated the financing needs for adaptation in developing countries to be far larger than funds currently available (Agrawala and Fankhauser, 2008; World Bank, 2010; Patt et al., 2010). In this case, adaptation actions are determined by decisions with respect to the allocation of available funds in competing regions rather than the local impacts of climate change on future damage (Klein et al., 2007; Hulme et al., 2011). Funding decisions and political constraints at the national level can also constrain adaptation so that choices no longer are sensitive to uncertainties with respect to local impacts (Dessai and Hulme, 2004, 2007).

The other situation is where adaptation is severely constrained by cultural norms and/or a lack of local knowledge and analytic skill as to what actions can be taken (Brooks et al., 2005; Füssel and Klein, 2006; O'Brien, 2009; Jones and Boyd, 2011). In this case, adaptive capacity could be improved through investments in education, development of local financial institutions and property rights systems, women's rights, and other broad-based forms of poverty alleviation. There is a growing literature to suggest that such policies bring substantial benefits in the face of climate change that are relatively insensitive to the precise nature and extent of local climate impacts (Folke et al., 2002; World Bank, 2010; Polasky et al., 2011). These policies are designed to reduce these countries' vulnerability to a wide range of potential risks rather than focusing on the impacts of climate change (Thornton et al., 2008; Eakin and Patt, 2011).

2.6.6 Public support and opposition to climate policy

In this section, we review what is known about public support or opposition to climate policy, climate-related infrastructure, and climate science. In all three cases, a critical issue is the role that perceptions of risks and uncertainties play in shaping support or opposition. Hence, the material presented here complements the discussion of perceptions of climate change risks and uncertainties (see Section 2.4.6). Policy discussions on particular technologies often revolve around the health and safety risks associated with technology options, transition pathways, and systems such as nuclear energy (Pidgeon et al., 2008; Whitfield et al., 2009), coal combustion (Carmichael et al., 2009; Hill et al., 2009), and underground carbon storage (Itaoka et al., 2009; Shackley et al., 2009). There are also risks to national energy security that have given rise to political discussions advocating the substitution of domestically produced renewable energy for imported fossil fuels (Eaves and Eaves, 2007; Lilliestam and Ellenbeck, 2011).

2.6.6.1 Popular support for climate policy

There is substantial empirical evidence that people's support or opposition to proposed climate policy measures is determined primarily by emotional factors and their past experience rather than explicit calculations as to whether the personal benefits outweigh the personal costs. A national survey in the United States found that people's support for climate policy also depended on cultural factors, with regionally differentiated worldviews playing an important role (Leiserowitz, 2006), as did a cross-national comparison of Britain and the United States (Lorenzoni and Pidgeon, 2006), and studies comparing developing with developed countries (Vignola et al., 2012).

One of the major determinants of popular support for climate policy is whether people have an underlying belief that climate change is dangerous. This concern can be influenced by both cultural factors and the methods of communication (Smith, 2005; Pidgeon and Fischhoff, 2011). Leiserowitz (2005) found a great deal of heterogeneity linked to cultural effects with respect to the perception of climate change in the United States. The use of language used to describe climate change—such as the distinction between 'climate change' and 'global warming'— play a role in influencing perceptions of risk, as well as considerations of immediate and local impacts (Lorenzoni et al., 2006). The portrayal of uncertainties and disagreements with respect to climate impacts was found to have a weak effect on whether people perceived the impacts as serious, but a strong effect on whether they felt that the impacts deserved policy intervention (Patt, 2007). Studies in China (Wang et al., 2012) and Austria (Damm et al., 2013) found that people's acceptance of climate-related policies was related to their underlying perceptions of risk but also to their beliefs about government responsibility.

An important question related to climate change communication is whether the popular reporting of climate change through disaster scenarios has the effect of energizing people to support aggressive policy intervention, or to become dismissive of the problem. A study examining responses to fictionalized disaster scenarios found them to have differential effects on perceptions and support for policy. They reduced people's expectation of the local impacts, while increasing their support for global intervention (Lowe et al., 2006). Other studies found interactive effects: those with a low awareness of climate change became concerned about being exposed to disaster scenarios, while those with a high awareness of climate change were dismissive of the possible impacts (Schiermeier, 2004).

Finally, the extent to which people believe it is possible to actually influence the future appears to be a major determinant of their support for both individual and collective actions to respond to climate change. In the case of local climate adaptation, psychological variables associated with self-empowerment were found to have played a much larger role in influencing individual behaviour than variables associated with economic and financial ability (Grothmann and Patt, 2005; Grothmann and Reusswig, 2006). With respect to mitigation policy, perceptions concerning the barriers to effective mitigation and beliefs that it was possible to respond to climate change were found to be important determinants of popular support (Lorenzoni et al., 2007).

2.6.6.2 Local support and opposition to infrastructure projects

The issue of local support or opposition to infrastructure projects in implementing climate policy is related to the role that perceived technological risks play in the process. This has been especially important with respect to nuclear energy, but is of increasing concern for carbon storage and renewable energy projects, and has become a major issue when considering expansion of low carbon energy technologies (Ellis et al., 2007; Van Alphen et al., 2007; Zoellner et al., 2008).

In the case of renewable energy technologies, a number of factors appear to influence the level of public support or opposition, factors that align well with a behavioural model in which emotional responses are highly contextual. One such factor is the relationship between project developers and local residents. Musall and Kuik (2011) compared two wind projects, where residents feared negative visual impacts. They found that their fear diminished, and public support for the projects increased when there was co-ownership of the development by the local community. A second factor is the degree of transparency surrounding project development. Dowd et al. (2011) investigated perceived risks associated with geothermal projects in Australia. Using a survey instrument, they found that early, transparent communication of geothermal technology and risks tended to increase levels of public support.

A third such factor is the perception of economic costs and benefits that go hand-in-hand with the perceived environmental risks. Zoellner et al. (2008) examined public acceptance of three renewable technologies (grid-connected PV, biomass, and wind) and found that perceived economic risks associated with higher energy prices were the largest predictor of acceptance. Concerns over local environmental impacts, including visual impacts, were of concern where the perceived economic risks were high. Breukers and Wolsink (2007) also found that that the visual impact of wind turbines was the dominant factor in explaining opposition against wind farms. Their study suggests that public animosity towards a wind farm is partly reinforced by the planning procedure itself, such as when stakeholders perceive that norms of procedural justice are not being followed.

Many studies have assessed the risks and examined local support for carbon dioxide capture and storage (CCS). According to Ha-Duong et al. (1997), the health and safety risks associated with carbon dioxide capture and transportation technologies differ across causal pathways but are similar in magnitude to technologies currently supported by the fossil-fuel industry. Using natural analogues, Roberts et al. (2011) concluded that the health risks of natural CO_2 seepage in Italy was significantly lower than many socially accepted risks. For example, it were three orders of magnitude lower than the probability of being struck by lightning.

Despite these risk assessments, there is mixed evidence of public acceptance of CO_2 storage. For example, a storage research project was authorized in Lacq, France, but another was halted in Barendreich, The Netherlands due to public opposition. On the other hand, Van Alphen et al. (2007) evaluated the concerns with CCS among important stakeholders, including government, industry, and NGO representatives and found support if the facility could be shown to have a low probability of leakage and was viewed as a temporary measure.

Wallquist et al. (2012) used conjoint analysis to interpret a Swiss survey on the acceptability of CCS and found that concerns over local risks and impacts dominated the fears of the long-term climate impacts of leakage. The local concerns were less severe, and the public acceptance higher, for CCS projects combined with biomass combustion, suggesting that positive feelings about removing CO_2 from the atmosphere, rather than simply preventing its emission into the atmosphere, influences perceptions of local risks. Terwel et al. (2011) found that support for CCS varied as a function of the stakeholders promoting and opposing it, in a manner similar to the debate on renewable energy. Hence, there was greater support of CCS when its promoters were perceived to be acting in the public interest rather than purely for profit. Those opposing CCS were less likely to succeed when they were perceived to be acting to protect their own economic interests, such as property values, rather than focusing on environmental quality and the public good.

In the period between the publication of AR4 and the accident at the Fukushima power plant in Japan in March 2011, the riskiness of nuclear power as a climate mitigation option has received increasing attention. Socolow and Glaser (2009) highlight the urgency of taking steps to reduce these risks, primarily by ensuring that nuclear fuels and waste materials are not used for weapons production. A number of papers examine the public's perceived risks of nuclear power. In the United States, Whitfield et al. (2009) found risk perceptions to be fairly stable over time, with those people expressing confidence in 'traditional values' perceiving nuclear power to be less risky than others. In the United Kingdom, Pidgeon et al. (2008) found a willingness to accept the risks of nuclear power when it was framed as a means of reducing the risks of climate change, but that this willingness largely dissipated when nuclear power was suggested as an alternative to renewable energy for accomplishing this same objective.

2.7 Gaps in knowledge and data

The interface between science and policy is affected by epistemic uncertainty or uncertainty due to lack of information or knowledge for characterizing phenomena. Below we characterize suggested areas for future research that may enable us to reduce epistemic uncertainty.

Perceptions and responses to risk and uncertainty:

- Examine cross-cultural differences in human perception and reaction to climate change and response options.
- Understand the rebound effect induced by adopting mitigation measures for reducing the impact of climate change (e.g., increased driving when switching to a more fuel efficient car).
- Consider the design of long-term mitigation and adaptation strategies coupled with short-term economic incentives to overcome myopic behaviour (e.g., loans for investing in energy efficient technologies so yearly payments are lower than the reduction in the annual energy bill).
- Encourage deliberative thinking in the design of policies to overcome biases such as a preference for the current state of affairs or business-as-usual.
- Understand judgment and choice processes of key decision makers in firms and policymakers, especially in a climate change response context.
- Use descriptive models and empirical studies to design strategies for climate change negotiations and implementation of treaties.

Tools and decision aids for improving choices related to climate change:

- Characterize the likelihood of extreme events and examine their impact on the design of climate change policies.
- Study how robust decision making can be used in designing climate policy options when there is uncertainty with respect to the likelihood of climate change and its impacts.
- Examine how integrated assessment models can quantify the value of new climate observing systems.
- Empirically study how decision makers could employ intuitive and deliberative thinking to improve decisions and climate policy choices.
- Study the effectiveness of experiential methods like simulations, games, and movies in improving public understanding and perception of climate change processes.
- Consider the role of structured expert judgment in characterizing the nature of uncertainties associated with climate change and the design of mitigation and adaptation policies for addressing this risk.

Managing uncertainty risk and learning:

- Exploit the effectiveness of social norms in promoting mitigation and adaptation.
- Quantify the environmental and societal risks associated with new technologies.
- Consider the special challenges faced by developing countries in dealing with risk and uncertainty with respect to climate change policies.
- Measure investor rankings of different risks associated with new technologies.
- Examine impact of government policy on mitigation decisions by firms and households.
- Determine what risks and uncertainties matter the most in developing policy instruments for dealing with climate change.
- Examine the risks to energy systems, energy markets, and the security of energy supply stemming from mitigation policies.
- Integrate analysis of the effects of interrelated policy decisions, such as how much to mitigate, what policy instruments to use for promoting climate change mitigation, and adaptation investment under conditions of risk and uncertainty.

2.8 Frequently Asked Questions

FAQ 2.1 When is uncertainty a reason to wait and learn rather than acting now in relation to climate policy and risk management strategies? [Section 2.6.3]

Faced with uncertainty, policymakers may have a reason to wait and learn before taking a particular action rather than taking the action now. Waiting and learning is desirable when external events are likely to generate new information of sufficient importance as to suggest that the planned action would be unwise. Uncertainty may not be a reason to delay when the action itself generates new information and knowledge.

Uncertainty may also be a reason to avoid actions that are irreversible and/or have lock-in effects, such as making long-term investments in fossil-fuel based energy systems when climate outcomes are uncertain. This behaviour would reflect the precautionary principle for not undertaking some measures or activities.

While the above criteria are fairly easy to understand, their application can be complicated because a number of uncertainties relevant to a given decision may reinforce each other or may partially cancel each other out (e.g., optimistic estimates of technological change may offset pessimistic estimates of climate damages). Different interested parties may reach different conclusions as to whether external information is likely or not to be of sufficient importance as to render the original action/inaction regrettable.

A large number of studies examine the act-now-or-wait-and-see question in the context of climate change mitigation. So far, most of these analyses have used integrated assessment models (IAMs). At the national level, these studies examine policy strategies and instruments to achieve mitigation targets; at the firm or individual level the studies examine whether one should invest in a particular technology.

A truly integrated analysis of the effects of multiple types of uncertainty on interrelated policy decisions, such as how much to mitigate, with what policy instruments, promoting what investments, has yet to be conducted. The probabilistic information needed to support such an analysis is currently not available.

FAQ 2.2 How can behavioural responses and tools for improving decision making impact on climate change policy? [Section 2.4]

The choice of climate change policies can benefit from examining the perceptions and responses of relevant stakeholders. Empirical evidence indicates decision makers such as firms and households tend to place undue weight on short-run outcomes. Thus, high upfront costs make them reluctant to invest in mitigation or adaptation measures. Consistent with the theory of loss aversion, investment costs and their associated risks have been shown to be of greater importance in decisions to fund projects that mitigate climate change than focusing on the expected returns associated with the investment.

Policy instruments (e.g., long-term loans) that acknowledge these behavioural biases and spread upfront costs over time so that they yield net benefits in the short-run have been shown to perform quite well. In this context, policies that make investments relatively risk free, such as feed-in tariffs, are more likely to stimulate new technology than those that focus on increasing the expected price such as cap-and-trade systems.

Human responses to climate change risks and uncertainties can also indicate a failure to put adequate weight on worst-case scenarios. Consideration of the full range of behavioural responses to information will enable policymakers to more effectively communicate climate change risks to stakeholders and to design decision aids and climate change policies that are more likely to be accepted and implemented.

FAQ 2.3 How does the presence of uncertainty affect the choice of policy instruments? [Section 2.6.5]

Many climate policy instruments are designed to provide decision makers at different levels (e.g., households, firms, industry associations, guilds) with positive incentives (e.g., subsidies) or penalties (e.g., fines) to incentivize them to take mitigation actions. The impact of these incentives on the behaviour of the relevant decision makers depends on the form and timing of these policy instruments.

Instruments such as carbon taxes that are designed to increase the cost of burning fossil fuels rely on decision makers to develop expectations about future trajectories of fuel prices and other economic conditions. As uncertainty in these conditions increases, the responsiveness of economic agents decreases. On the other hand, investment subsidies and technology standards provide immediate incentives to change behaviour, and are less sensitive to long-term market uncertainty. Feed-in tariffs allow investors to lock in a given return on investment, and so may be effective even when market uncertainty is high.

FAQ 2.4 What are the uncertainties and risks that are of particular importance to climate policy in developing countries? [Box 2.1]

Developing countries are often more sensitive to climate risks, such as drought or coastal flooding, because of their greater economic reliance on climate-sensitive primary activities, and because of inadequate infrastructure, finance, and other enablers of successful adaptation and mitigation. Since AR4, research on relevant risks and uncertainties in developing countries has progressed substantially, offering results in two main areas.

Studies have demonstrated how uncertainties often place low carbon energy sources at an economic disadvantage, especially in developing countries. The performance and reliability of new technologies may be less certain in developing countries than in industrialized countries because they could be unsuited to the local context and needs. Other reasons for uncertain performance and reliability could be due to poor manufacturing, a lack of adequate testing in hot or dusty environments, or limited local capacity to maintain and repair equipment. Moreover, a number of factors associated with economic, political, and regulatory uncertainty result in much higher real interest rates in developing countries than in the developed world. This creates a disincentive to invest in technologies with high upfront but lower operating costs, such as renewable energy, compared to fossil-fuel based energy infrastructure.

Given the economic disadvantage of low carbon energy sources, important risk tradeoffs often need to be considered. On the one hand, low-carbon technologies can reduce risks to health, safety, and the environment, such as when people replace the burning of biomass for cooking with modern and efficient cooking stoves. But on the other hand, low-carbon modern energy is often more expensive than its higher-carbon alternatives. There are however, some opportunities for win-win outcomes on economic and risk grounds, such as in the case of off-grid solar power.

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3

Social, Economic, and Ethical Concepts and Methods

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Executive Summary

This framing chapter describes the strengths and limitations of the most widely used concepts and methods in economics, ethics, and other social sciences that are relevant to climate change. It also provides a reference resource for the other chapters in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), as well as for decision makers.

The significance of the social dimension and the role of ethics and economics is underscored by Article 2 of the United Nations Framework Convention on Climate Change, which indicates that an ultimate objective of the Convention is to avoid dangerous anthropogenic interference with the climate system. Two main issues confronting society (and the IPCC) are: what constitutes 'dangerous interference' with the climate system and how to deal with that interference. Determining what is dangerous is not a matter for natural science alone; it also involves value judgements—a subject matter of the theory of value, which is treated in several disciplines, including ethics, economics, and other social sciences.

Ethics involves questions of justice and value. Justice is concerned with equity and fairness, and, in general, with the rights to which people are entitled. Value is a matter of worth, benefit, or good. Value can sometimes be measured quantitatively, for instance, through a social welfare function or an index of human development.

Economic tools and methods can be used in assessing the positive and negative values that result from particular decisions, policies, and measures. They can also be essential in determining the mitigation and adaptation actions to be undertaken as public policy, as well as the consequences of different mitigation and adaptation strategies. Economic tools and methods have strengths and limitations, both of which are detailed in this chapter.

Economic tools can be useful in designing climate change mitigation policies (*very high confidence*). While the limitations of economics and social welfare analysis, including cost-benefit analysis, are widely documented, economics nevertheless provides useful tools for assessing the pros and cons of taking, or not taking, action on climate change mitigation, as well as of adaptation measures, in achieving competing societal goals. Understanding these pros and cons can help in making policy decisions on climate change mitigation and can influence the actions taken by countries, institutions and individuals. [Section 3.2]

Mitigation is a public good; climate change is a case of 'the tragedy of the commons' (*high confidence*). Effective climate change mitigation will not be achieved if each agent (individual, institution or country) acts independently in its own selfish interest, suggesting the need for collective action. Some adaptation actions, on the other hand, have characteristics of a private good as benefits of actions may accrue more directly to the individuals, regions, or countries that undertake them, at least in the short term. Nevertheless, financing such adaptive activities remains an issue, particularly for poor individuals and countries. [3.1, 3.2]

Analysis contained in the literature of moral and political philosophy can contribute to resolving ethical questions that are raised by climate change (*medium confidence*). These questions include how much overall climate mitigation is needed to avoid 'dangerous interference', how the effort or cost of mitigating climate change should be shared among countries and between the present and future, how to account for such factors as historical responsibility for emissions, and how to choose among alternative policies for mitigation and adaptation. Ethical issues of wellbeing, justice, fairness, and rights are all involved. [3.2, 3.3, 3.4]

Duties to pay for some climate damages can be grounded in compensatory justice and distributive justice (*medium confidence*). If compensatory duties to pay for climate damages and adaptation costs are not due from agents who have acted blamelessly, then principles of compensatory justice will apply to only some of the harmful emissions [3.3.5]. This finding is also reflected in the predominant global legal practice of attributing liability for harmful emissions [3.3.6]. Duties to pay for climate damages can, however, also be grounded in distributive justice [3.3.4, 3.3.5].

Distributional weights may be advisable in cost-benefit analysis (*medium confidence*). Ethical theories of value commonly imply that distributional weights should be applied to monetary measures of benefits and harms when they are aggregated to derive ethical conclusions [3.6.1]. Such weighting contrasts with much of the practice of cost-benefit analysis.

The use of a temporal discount rate has a crucial impact on the evaluation of mitigation policies and measures. The social discount rate is the minimum rate of expected social return that compensates for the increased intergenerational inequalities and the potential increased collective risk that an action generates. Even with disagreement on the level of the discount rate, a consensus favours using declining risk-free discount rates over longer time horizons (*high confidence*). [3.6.2]

An appropriate social risk-free discount rate for consumption is between one and three times the anticipated growth rate in real per capita consumption (*medium confidence*). This judgement is based on an application of the Ramsey rule using typical values in the literature of normative parameters in the rule. Ultimately, however, these are normative choices. [3.6.2]

Co-benefits may complement the direct benefits of mitigation (*medium confidence*). While some direct benefits of mitigation are reductions in adverse climate change impacts, co-benefits can include a broad range of environmental, economic, and social effects, such as reductions in local air pollution, less acid rain, and increased energy security. However, whether co-benefits are net positive or negative in terms of wellbeing (welfare) can be difficult to determine because of interaction between climate policies and pre-existing non-climate policies. The same results apply to adverse side-effects. [3.6.3]

Tax distortions change the cost of all abatement policies (*high confidence*). A carbon tax or a tradable emissions permit system can exacerbate tax distortions, or, in some cases, alleviate them; carbon tax or permit revenue can be used to moderate adverse effects by cutting other taxes. However, regulations that forgo revenue (e.g., by giving permits away) implicitly have higher social costs because of the tax interaction effect. [3.6.3]

Many different analytic methods are available for evaluating policies. Methods may be quantitative (for example, cost-benefit analysis, integrated assessment modelling, and multi-criteria analysis) or qualitative (for example, sociological and participatory approaches). However, no single-best method can provide a comprehensive analysis of policies. A mix of methods is often needed to understand the broad effects, attributes, trade-offs, and complexities of policy choices; moreover, policies often address multiple objectives. [3.7]

Four main criteria are frequently used in evaluating and choosing a mitigation policy (*medium confidence*). They are: cost-effectiveness and economic efficiency (excluding environmental benefits, but including transaction costs); environmental effectiveness (the extent to which the environmental targets are achieved); distributional effects (impact on different subgroups within society); and institutional feasibility, including political feasibility. [3.7.1]

A broad range of policy instruments for climate change mitigation is available to policymakers. These include: economic incentives, direct regulatory approaches, information programmes, government provision, and voluntary actions. Interactions between policy instruments can enhance or reduce the effectiveness and cost of mitigation action. Economic incentives will generally be more cost-effective than direct regulatory interventions. However, the performance and suitability of policies depends on numerous conditions, including institutional capacity, the influence of rent-seeking, and predictability or uncertainty about future policy settings. The enabling environment may differ between countries, including between low-income and high-income countries. These differences can have implications for the suitability and performance of policy instruments. [3.8]

Impacts of extreme events may be more important economically than impacts of average climate change (*high confidence*). Risks associated with the entire probability distribution of outcomes in terms of climate response [WGI] and climate impacts [WGII] are relevant to the assessment of mitigation. Impacts from more extreme climate change may be more important economically (in terms of the expected value of impacts) than impacts of average climate change, particularly if the damage from extreme climate change increases more rapidly than the probability of such change declines. This is important in economic analysis, where the *expected* benefit of mitigation may be traded off against mitigation costs. [3.9.2]

Impacts from climate change are both market and non-market. Market effects (where market prices and quantities are observed) include impacts of storm damage on infrastructure, tourism, and increased energy demand. Non-market effects include many ecological impacts, as well as changed cultural values, none of which are generally captured through market prices. The economic measure of the value of either kind of impact is 'willingness-to-pay' to avoid damage, which can be estimated using methods of revealed preference and stated preference. [3.9]

Substitutability reduces the size of damages from climate change (*high confidence*). The monetary damage from a change in the climate will be lower if individuals can easily substitute for what is damaged, compared to cases where such substitution is more difficult. [3.9]

Damage functions in existing Integrated Assessment Models (IAMs) are of low reliability (*high confidence*). The economic assessments of damages from climate change as embodied in the damage functions used by some existing IAMs (though not in the analysis embodied in WGIII) are highly stylized with a weak empirical foundation. The empirical literature on monetized impacts is growing but remains limited and often geographically narrow. This suggests that such damage functions should be used with caution and that there may be significant value in undertaking research to improve the precision of damage estimates. [3.9, 3.12]

Negative private costs of mitigation arise in some cases, although they are sometimes overstated in the literature (*medium confidence*). Sometimes mitigation can lower the private costs of production and thus raise profits; for individuals, mitigation can raise wellbeing. Ex-post evidence suggests that such 'negative cost opportunities' do indeed exist but are sometimes overstated in engineering analyses. [3.9]

Exchange rates between GHGs with different atmospheric lifetimes are very sensitive to the choice of emission metric. The choice of an emission metric depends on the potential application and involves explicit or implicit value judgements; no consensus surrounds the question of which metric is both conceptually best and practical to implement (*high confidence*). In terms of aggregate mitigation costs alone, the Global Warming Potential (GWP), with a 100-year time horizon, may perform similarly to selected other metrics (such as the time-dependent Global Temperature Change Potential or the Global Cost Potential) of reaching a prescribed climate target; however, various metrics may differ significantly in terms of the implied distribution of costs across sectors, regions, and over time (*limited evidence, medium agreement*). [3.9]

The behaviour of energy users and producers exhibits a variety of anomalies (*high confidence*). Understanding climate change as a physical phenomenon with links to societal causes and impacts is a very complex process. To be fully effective, the conceptual frameworks and methodological tools used in mitigation assessments need to take into account cognitive limitations and other-regarding preferences that frame the processes of economic decision making by people and firms. [3.10]

Perceived fairness can facilitate cooperation among individuals (*high confidence*). Experimental evidence suggests that reciprocal behaviour and perceptions of fair outcomes and procedures facilitate voluntary cooperation among individual people in providing public goods; this finding may have implications for the design of international agreements to coordinate climate change mitigation. [3.10]

Social institutions and culture can facilitate mitigation and adaptation (*medium confidence*). Social institutions and culture can shape individual actions on mitigation and adaptation and be complementary to more conventional methods for inducing mitigation and adaptation. They can promote trust and reciprocity and contribute to the evolution of common rules. They also provide structures for acting collectively to deal with common challenges. [3.10]

Technological change that reduces mitigation costs can be encouraged by institutions and economic incentives (*high confidence*). As pollution is not fully priced by the market, private individuals and firms lack incentives to invest sufficiently in the development and use of emissions-reducing technologies in the absence of appropriate policy interventions. Moreover, imperfect appropriability of the benefits of innovation further reduces incentives to develop new technologies. [3.11]

3.1 Introduction

This framing chapter has two primary purposes: to provide a framework for viewing and understanding the human (social) perspective on climate change, focusing on ethics and economics; and to define and discuss key concepts used in other chapters. It complements the two other framing chapters: Chapter 2 on risk and uncertainty and Chapter 4 on sustainability. The audience for this chapter (indeed for this entire volume) is decision makers at many different levels.

The significance of the social dimension and the role of ethics and economics is underscored by Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), which indicates that the ultimate objective of the Convention is to avoid dangerous anthropogenic interference with the climate system. Two main issues confronting society are: what constitutes 'dangerous interference' with the climate system and how to deal with that interference (see box 3.1). Providing information to answer these inter-related questions is a primary purpose of the IPCC. Although natural science helps us understand how emissions can change the climate, and, in turn, generate physical impacts on ecosystems, people, and the physical environment, determining what is dangerous involves judging the level of adverse consequences, the steps necessary to mitigate these consequences, and the risk that humanity is willing to tolerate. These are questions requiring value judgement. Although economics is essential to evaluating the consequences and trade-offs associating with climate change, how society interprets and values them is an ethical question.

Our discussion of ethics centres on two main considerations: justice and value. Justice requires that people and nations should receive what they are due, or have a right to. For some, an outcome is just if the process that generated it is just. Others view justice in terms of the actual outcomes enjoyed by different people and groups and the values they place on those outcomes. Outcome-based justice can range from maximizing economic measures of aggregate welfare to rights-based views of justice, for example, believing that all countries have a right to clean air. Different views have been expressed about what is valuable. All values may be anthropocentric or there may be non-human values. Economic analysis can help to guide policy action, provided that appropriate, adequate, and transparent ethical assumptions are built into the economic methods.

The significance of economics in tackling climate change is widely recognized. For instance, central to the politics of taking action on climate change are disagreements over how much mitigation the world should undertake, and the economic costs of action (the costs of mitigation) and inaction (the costs of adaptation and residual damage from a changed climate). Uncertainty remains about (1) the costs of reducing emissions of greenhouse gases (GHGs), (2) the damage caused by a change in the climate, and (3) the cost, practicality, and effectiveness of adaptation measures (and, potentially, geoengineering). Prioritizing action on climate change over other significant social goals with more near-term payoffs is particularly difficult in developing countries. Because social concerns and objectives, such as the preservation of traditional values, cannot always be easily quantified or monetized, economic costs and benefits are not the only input into decision making about climate change. But even where costs and benefits can be quantified and monetized, using methods of economic analysis to steer social action implicitly involves significant ethical assumptions. This chapter explains the ethical assumptions that must be made for economic methods, including cost-benefit analysis (CBA), to be valid, as well as the ethical assumptions that are implicitly being made where economic analysis is used to inform a policy choice.

The perspective of economics can improve our understanding of the challenges of acting on mitigation. For an individual or firm, mitigation involves real costs, while the benefits to themselves of their own mitigation efforts are small and intangible. This reduces the incentives for individuals or countries to unilaterally reduce emissions; free-riding on the actions of others is a dominant strategy. Mitigating greenhouse

Box 3.1 | Dangerous interference with the climate system

Article 2 of the United Nations Framework Convention on Climate Change states that "the ultimate objective of the Convention […] is to achieve […] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Judging whether our interference in the climate system is dangerous, i.e., risks causing a very bad outcome, involves two tasks: estimating the physical consequences of our interference and their likelihood; and assessing their significance for people. The first falls to science, but, as the Synthesis Report of the IPCC Fourth Assessment Report (AR4) states, "Determining what constitutes 'dangerous anthropogenic interference with the climate system' in relation to Article 2 of the UNFCCC involves value judgements" (IPCC, 2007, p. 42). Value judgements are governed by the theory of value. In particular, valuing risk is covered by decision theory and is dealt with in Chapter 2. Central questions of value that come within the scope of ethics, as well as economic methods for measuring certain values are examined in this chapter.

gas (GHG) emissions is a public good, which inhibits mitigation. This also partly explains the failure of nations to agree on how to solve the problem.

In contrast, adaptation tends not to suffer from free-riding. Gains to climate change from adaptation, such as planting more heat tolerant crops, are mainly realized by the parties who incur the costs. Associated externalities tend to be more localized and contemporaneous than for GHG mitigation. From a public goods perspective, global coordination may be less important for many forms of adaptation than for mitigation. For autonomous adaptation in particular, the gains from adaptation accrue to the party incurring the cost. However, public adaptation requires local or regional coordination. Financial and other constraints may restrict the pursuit of attractive adaptation opportunities, particularly in developing countries and for poorer individuals.

This chapter addresses two questions: what *should be done* about action to mitigate climate change (a normative issue) and how the world works in the multifaceted context of climate change (a descriptive or positive issue). Typically, ethics deals with normative questions and economics with descriptive or normative questions. Descriptive questions are primarily value-neutral, for example, how firms have reacted to cap-and-trade programmes to limit emissions, or how societies have dealt with responsibility for actions that were not known to be harmful when they were taken. Normative questions use economics and ethics to decide what *should* be done, for example, determining the appropriate level of burden sharing among countries for current and future mitigation. In making decisions about issues with normative dimensions, it is important to understand the implicit assumptions involved. Most normative analyses of solutions to the climate problem implicitly involve contestable ethical assumptions.

This chapter does not attempt to answer ethical questions, but rather provides policymakers with the tools (concepts, principles, arguments, and methods) to make decisions. Summarizing the role of economics and ethics in climate change in a single chapter necessitates several caveats. While recognizing the importance of certain non-economic social dimensions of the climate change problem and solutions to it, space limitations and our mandate necessitated focusing primarily on ethics and economics. Furthermore, many of the issues raised have already been addressed in previous IPCC assessments, particularly AR2 (published in 1995). In the past, ethics has received less attention than economics, although aspects of both subjects are covered in AR2. The literature reviewed here includes pre-AR4 literature in order to provide a more comprehensive understanding of the concepts and methods. We highlight 'new' developments in the field since the last IPCC assessment in 2007.

3.2 Ethical and socio-economic concepts and principles

When a country emits GHGs, its emissions cause harm around the globe. The country itself suffers only a part of the harm it causes. It is therefore rarely in the interests of a single country to reduce its own emissions, even though a reduction in global emissions could benefit every country. That is to say, the problem of climate change is a "tragedy of the commons" (Hardin, 1968). Effective mitigation of climate change will not be achieved if each person or country acts independently in its own interest.

Consequently, efforts are continuing to reach effective international agreement on mitigation. They raise an ethical question that is widely recognized and much debated, namely, 'burden-sharing' or 'effort-sharing'. How should the burden of mitigating climate change be divided among countries? It raises difficult issues of justice, fairness, and rights, all of which lie within the sphere of ethics.

Burden-sharing is only one of the ethical questions that climate change raises.[1] Another is the question of how much overall mitigation should

[1] A survey of the ethics of climate change is Gardiner (2004), pp. 555–600.

take place. UNFCCC sets the aim of "avoiding dangerous anthropogenic interference with the climate system", and judging what is dangerous is partly a task for ethics (see Box 3.1). Besides justice, fairness, and rights, a central concern of ethics is *value*. Judgements of value underlie the question of what interference with the climate system would be dangerous.

Indeed, ethical judgements of value underlie almost every decision that is connected with climate change, including decisions made by individuals, public and private organizations, governments, and groupings of governments. Some of these decisions are deliberately aimed at mitigating climate change or adapting to it. Many others influence the progress of climate change or its impacts, so they need to take climate change into account.

Ethics may be broadly divided into two branches: justice and value. Justice is concerned with ensuring that people get what is *due* to them. If justice requires that a person should not be treated in a particular way—uprooted from her home by climate change, for example—then the person has a *right* not to be treated that way. Justice and rights are correlative concepts. On the other hand, criteria of value are concerned with improving the world: making it a better place. Synonyms for 'value' in this context are 'good', 'goodness' and 'benefit'. Antonyms are 'bad', 'harm' and 'cost'.

To see the difference between justice and value, think of a transfer of wealth made by a rich country to a poor one. This may be an act of restitution. For example, it may be intended to compensate the poor country for harm that has been done to it by the rich country's emissions of GHG. In this case, the transfer is made on grounds of justice. The payment is taken to be due to the poor country, and to satisfy a right that the poor country has to compensation. Alternatively, the rich country may make the transfer to support the poor country's mitigation effort, because this is beneficial to people in the poor country, the rich country, and elsewhere. The rich country may not believe the poor country has a right to the support, but makes the payment simply because it does 'good'. This transfer is made on grounds of value. What would be good to do is not necessarily required as a matter of justice. Justice is concerned with what people are entitled to as a matter of their rights.

The division between justice and value is contested within moral philosophy, and so is the nature of the interaction between the two. Some authors treat justice as inviolable (Nozick, 1974): justice sets limits on what we may do and we may promote value only within those limits. An opposite view—called 'teleological' by Rawls (1971)—is that the right decision to make is always determined by the value of the alternatives, so justice has no role. But despite the complexity of their relationship and the controversies it raises, the division between justice and value provides a useful basis for organizing the discussion of ethical concepts and principles. We have adopted it in this chapter: sections 3.3 and 3.4 cover justice and value, respectively. One topic appears in both sections because it bridges the divide: this topic is distributive justice viewed one way and the value of equality viewed the other. Section 3.3.7 on geoengineering is also in an intermediate position because it raises ethical issues of both sorts. Section 3.6 explains how some ethical values can be measured by economic methods of valuation. Section 3.5 describes the scope and limitations of these methods. Later sections develop the concepts and methods of economics in more detail. Practical ways to take account of different values in policy-making are discussed in Section 3.7.1.

3.3 Justice, equity and responsibility

Justice, fairness, equity, and responsibility are important in international climate negotiations, as well as in climate-related political decision making within countries and for individuals.

In this section we examine distributive justice, which, for the purpose of this review, is about outcomes, and procedural justice or the way in which outcomes are brought about. We also discuss compensation for damage and historic responsibility for harm. In the context of climate change, considerations of justice, equity, and responsibility concern the relations between individuals, as well as groups of individuals (e.g., countries), both at a single point in time and across time. Accordingly, we distinguish intra-generational from intergenerational justice. The literature has no agreement on a correct answer to the question, what is just? We indicate where opinions differ.

3.3.1 Causal and moral responsibility

From the perspective of countries rather than individuals or groups of individuals, historic emissions can help determine causal responsibility for climate change (den Elzen et al., 2005; Lamarque et al., 2010; Höhne et al., 2011). Many developed countries are expected to suffer relatively modest physical damage and some are even expected to realize benefits from future climate change (see Tol, 2002a; b). On the other hand, some developing countries bear less causal responsibility, but could suffer significant physical damage from climate change (IPCC, 2007, WG II AR4 SPM). This asymmetry gives rise to the following questions of justice and moral responsibility: do considerations of justice provide guidance in determining the appropriate level of present and future global emissions; the distribution of emissions among those presently living; and the role of historical emissions in distributing global obligations? The question also arises of who might be considered morally responsible for achieving justice, and, thus, a bearer of duties towards others. The question of moral responsibility is also key to determining whether anyone owes compensation for the damage caused by emissions.

3.3.2 Intergenerational justice and rights of future people

Intergenerational justice encompasses some of the moral duties owed by present to future people and the rights that future people hold against present people.[2] A legitimate acknowledgment that future or past generations have rights relative to present generations is indicative of a broad understanding of justice.[3] While justice considerations so understood are relevant, they cannot cover all our concerns regarding future and past people, including the continued existence of humankind and with a high level of wellbeing.[4]

What duties do present generations owe future generations given that current emissions will affect their quality of life? Some justice theorists have offered the following argument to justify a cap on emissions (Shue, 1993, 1999; Caney, 2006a; Meyer and Roser, 2009; Wolf, 2009). If future people's basic rights include the right to survival, health, and subsistence, these basic rights are likely to be violated when temperatures rise above a certain level. However, currently living people can slow the rise in temperature by limiting their emissions at a reasonable cost to themselves. Therefore, living people should reduce their emissions in order to fulfil their minimal duties of justice to future generations. Normative theorists dispute the standard of living that corresponds to people's basic rights (Page, 2007; Huseby, 2010). Also in dispute is what level of harm imposed on future people is morally objectionable. Some argue that currently living people wrongfully harm future people if they cause them to have a lower level of wellbeing than their own (e.g., Barry, 1999); others that currently living people owe future people a decent level of wellbeing, which might be lower than their own (Wolf, 2009). This argument raises objections on grounds of justice since it presupposes that present people can violate the rights of future people, and that the protection of future people's rights is practically relevant for how present people ought to act.

Some theorists claim that future people cannot hold rights against present people, owing to special features of intergenerational relations: some claim that future people cannot have rights because they cannot exercise them today (Steiner, 1983; Wellman, 1995, ch. 4). Others point out that interaction between non-contemporaries is impossible (Barry, 1977, pp. 243–244, 1989, p. 189). However, some justice theorists argue that neither the ability to, nor the possibility of, mutual interaction are necessary in attributing rights to people (Barry, 1989; Buchanan, 2004). They hold that rights are attributed to beings whose interests are important enough to justify imposing duties on others.

The main source of scepticism about the rights of future people and the duties we owe them is the so-called 'non-identity problem'. Actions we take to reduce our emissions will change people's way of life and so affect new people born. They alter the identities of future people. Consequently, our emissions do not make future people worse off than they would otherwise have been, since those future people would not exist if we took action to prevent our emissions. This makes it hard to claim that our emissions harm future people, or that we owe it to them as a matter of their rights to reduce our emissions.[5]

It is often argued that the non-identity problem can be overcome (McMahan, 1998; Shiffrin, 1999; Kumar, 2003; Meyer, 2003; Harman, 2004; Reiman, 2007; Shue, 2010). In any case, duties of justice do not include all the moral concerns we should have for future people. Other concerns are matters of value rather than justice, and they too can be understood in such a way that they are not affected by the non-identity problem. They are considered in Section 3.4.

If present people have a duty to protect future people's basic rights, this duty is complicated by uncertainty. Present people's actions or omissions do not necessarily violate future people's rights; they create a risk of their rights being violated (Bell, 2011). To determine what currently living people owe future people, one has to weigh such uncertain consequences against other consequences of their actions, including the certain or likely violation of the rights of currently living people (Oberdiek, 2012; Temkin, 2012). This is important in assessing many long-term policies, including on geoengineering (see Section 3.3.7), that risk violating the rights of many generations of people (Crutzen, 2006; Schneider, 2008; Victor et al., 2009; Baer, 2010; Ott, 2012).

3.3.3 Intergenerational justice: distributive justice

Suppose that a global emissions ceiling that is intergenerationally just has been determined (recognizing that a ceiling is not the only way to deal with climate change), the question then arises of how the ceiling ought to be divided among states (and, ultimately, their individual members) (Jamieson, 2001; Singer, 2002; Meyer and Roser, 2006; Caney, 2006a). Distributing emission permits is a way of arriving at a globally just division. Among the widely discussed views on distributive justice are strict egalitarianism (Temkin, 1993), indirect egalitarian views including prioritarianism (Parfit, 1997), and sufficientarianism (Frankfurt, 1999). Strict egalitarianism holds that equality has value in itself. Prioritarianism gives greater weight to a person's wellbeing the less well off she is, as described in Section 3.4. Sufficientarianism recommends that everyone should be able to enjoy a particular level of wellbeing.

[2] In the philosophical literature, "justice between generations" typically refers to the relations between people whose lifetimes do not overlap (Barry, 1977). In contrast, "justice between age groups" refers to the relations of people whose lifetimes do overlap (Laslett and Fishkin, 1992). See also Gardiner (2011), pp. 145–48.

[3] See Rawls (1971, 1999), Barry (1977), Sikora and Barry (1978), Partridge (1981), Parfit (1986), Birnbacher (1988), and Heyd (1992).

[4] See Baier (1981), De-Shalit (1995), Meyer (2005), and for African philosophical perspectives see, Behrens (2012). See Section 3.4 on the wellbeing of future people.

[5] For an overview of the issue see Meyer (2010). See also Schwartz (1978), Parfit (1986), and Heyd (1992). For a different perspective see Perrett (2003).

For example, two options can help apply prioritarianism to the distribution of freely allocated and globally tradeable emission permits. The first is to ignore the distribution of other goods. Then strict egalitarianism or prioritarianism will require emission permits to be distributed equally, since they will have one price and are thus equivalent to income. The second is to take into account the unequal distribution of other assets. Since people in the developing world are less well off than in the developed world, strict egalitarianism or prioritarianism would require most or all permits to go to the developing world. However, it is questionable whether it is appropriate to bring the overall distribution of goods closer to the prioritarian ideal through the distribution of just one good (Wolff and de-Shalit, 2007; Caney, 2009, 2012).

3.3.4 Historical responsibility and distributive justice

Historical responsibility for climate change depends on countries' contributions to the stock of GHGs. The UNFCCC refers to "common but differentiated responsibilities" among countries of the world.[6] This is sometimes taken to imply that current and historical causal responsibility for climate change should play a role in determining the obligations of different countries in reducing emissions and paying for adaptation measures globally (Rajamani, 2000; Rive et al., 2006; Friman, 2007).

A number of objections have been raised against the view that historical emissions should play a role (see, e.g., Gosseries, 2004; Caney, 2005; Meyer and Roser, 2006; Posner and Weisbach, 2010). First, as currently living people had no influence over the actions of their ancestors, they cannot be held responsible for them. Second, previously living people may be excused from responsibility on the grounds that they could not be expected to know that their emissions would have harmful consequences. Thirdly, present individuals with their particular identities are not worse or better off as a result of the emission-generating activities of earlier generations because, owing to the non-identity problem, they would not exist as the individuals they are had earlier generations not acted as they did.

From the perspective of distributive justice, however, these objections need not prevent past emissions and their consequences being taken into account (Meyer and Roser, 2010; Meyer, 2013). If we are only concerned with the distribution of benefits from emission-generating activities during an individual's lifespan, we should include the benefits present people have received from their own emission-generating activities. Furthermore, present people have benefited since birth or conception from past people's emission-producing actions. They are therefore better off as a result of past emissions, and any principle of distributive justice should take that into account. Some suggest that taking account of the consequences of some past emissions in this way should not be subject to the objections mentioned in the previous paragraph (see Shue, 2010). Other concepts associated with historical responsibility are discussed in Chapter 4.

3.3.5 Intra-generational justice: compensatory justice and historical responsibility

Do those who suffer disproportionately from the consequences of climate change have just claims to compensation against the main perpetrators or beneficiaries of climate change (see, e.g., Neumayer, 2000; Gosseries, 2004; Caney, 2006b)?

One way of distinguishing compensatory from distributive claims is to rely on the idea of a just baseline distribution that is determined by a criterion of distributive justice. Under this approach, compensation for climate damage and adaptation costs is owed only by people who have acted wrongfully according to normative theory (Feinberg, 1984; Coleman, 1992; McKinnon, 2011). Other deviations from the baseline may warrant redistributive measures to redress undeserved benefits or harms, but not as compensation. Some deviations, such as those that result from free choice, may not call for any redistribution at all.

The duty to make compensatory payments (Gosseries, 2004; Caney, 2006b) may fall on those who emit or benefit from wrongful emissions or who belong to a community that produced such emissions. Accordingly, three principles of compensatory justice have been suggested: the polluter pays principle (PPP), the beneficiary pays principle (BPP), and the community pays principle (CPP) (Meyer and Roser, 2010; Meyer, 2013). None of the three measures is generally accepted, though the PPP is more widely accepted than the others. The PPP requires the emitter to pay compensation if the agent emitted more than its fair share (determined as outlined in Section 3.3.2) and it either knew, or could reasonably be expected to know, that its emissions were harmful. The victim should be able to show that the emissions either made the victim worse off than before or pushed below a specified threshold of harm, or both.

The right to compensatory payments for wrongful emissions under PPP has at least three basic limitations. Two have already been mentioned in Section 3.3.4. Emissions that took place while it was permissible to be ignorant of climate change (when people neither did know nor could be reasonably be expected to know about the harmful consequences of emissions) may be excused (Gosseries, 2004, pp. 39–41). See also Section 3.3.6. The non-identity problem (see Section 3.3.2) implies that earlier emissions do not harm many of the people who come into existence later. Potential duty bearers may be dead and cannot therefore have a duty to supply compensatory measures. It may therefore be difficult to use PPP in ascribing compensatory duties and identifying wronged persons. The first and third limitations restrict the

[6] Specifically, Article 3 of the UNFCCC includes the sentence: "The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities."

assignment of duties of compensation to currently living people for their most recent emissions, even though many more people are causally responsible for the harmful effects of climate change. For future emissions, the third limitation could be overcome through a climate change compensation fund into which agents pay levies for imposing the risk of harm on future people (McKinnon, 2011).

According to BPP, a person who is wrongfully better off relative to a just baseline is required to compensate those who are worse off. Past emissions benefit some and impose costs on others. If currently living people accept the benefits of wrongful past emissions, it has been argued that they take on some of the past wrongdoer's duty of compensation (Gosseries, 2004). Also, we have a duty to condemn injustice, which may entail a duty not to benefit from an injustice that causes harm to others (Butt, 2007). However, BPP is open to at least two objections. First, duties of compensation arise only from past emissions that have benefited present people; no compensation is owed for other past emissions. Second, if voluntary acceptance of benefits is a condition of their giving rise to compensatory duties, the bearers of the duties must be able to forgo the benefits in question at a reasonable cost.

Under CPP, moral duties can be attributed to people as members of groups whose identity persists over generations (De-Shalit, 1995; Thompson, 2009). The principle claims that members of a community, including a country, can have collective responsibility for the wrongful actions of other past and present members of the community, even though they are not morally or causally responsible for those actions (Thompson, 2001; Miller, 2004; Meyer, 2005). It is a matter of debate under what conditions present people can be said to have inherited compensatory duties. Although CPP purports to overcome the problem that a polluter might be dead, it can justify compensatory measures only for emissions that are made wrongfully. It does not cover emissions caused by agents who were permissibly ignorant of their harmfulness. (The agent in this case may be the community or state).

The practical relevance of principles of compensatory justice is limited. Insofar as the harms and benefits of climate change are undeserved, distributive justice will require them to be evened out, independently of compensatory justice. Duties of distributive justice do not presuppose any wrongdoing (see Section 3.3.4). For example, it has been suggested on grounds of distributive justice that the duty to pay for adaptation should be allocated on the basis of people's ability to pay, which partly reflects the benefit they have received from past emissions (Jamieson, 1997; Shue, 1999; Caney, 2010; Gardiner, 2011). However, present people and governments can be said to know about both the seriously harmful consequences of their emission-generating activities for future people and effective measures to prevent those consequences. If so and if they can implement these measures at a reasonable cost to themselves to protect future people's basic rights (see, e.g., Birnbacher, 2009; Gardiner, 2011), they might be viewed as owing intergenerational duties of justice to future people (see Section 3.3.2).

3.3.6 Legal concepts of historical responsibility

Legal systems have struggled to define the boundaries of responsibility for harmful actions and are only now beginning to do so for climate change. It remains unclear whether national courts will accept lawsuits against GHG emitters, and legal scholars vigorously debate whether liability exists under current law (Mank, 2007; Burns and Osofsky, 2009; Faure and Peeters, 2011; Haritz, 2011; Kosolapova, 2011; Kysar, 2011; Gerrard and Wannier, 2012). This section is concerned with moral responsibility, which is not the same as legal responsibility. But moral thinking can draw useful lessons from legal ideas.

Harmful conduct is generally a basis for liability only if it breaches some legal norm (Tunc, 1983), such as negligence, or if it interferes unreasonably with the rights of either the public or property owners (Mank, 2007; Grossman, 2009; Kysar, 2011; Brunée et al., 2012; Goldberg and Lord, 2012; Koch et al., 2012). Liability for nuisance does not exist if the agent did not know, or have reason to know, the effects of its conduct (Antolini and Rechtschaffen, 2008). The law in connection with liability for environmental damage still has to be settled. The European Union, but not the United States, recognizes exemption from liability for lack of scientific knowledge (United States Congress, 1980; European Union, 2004). Under European law, and in some US states, defendants are not responsible if a product defect had not yet been discovered (European Commission, 1985; Dana, 2009). Some legal scholars suggest that assigning blame for GHG emissions dates back to 1990 when the harmfulness of such emissions was established internationally, but others argue in favour of an earlier date (Faure and Nollkaemper, 2007; Hunter and Salzman, 2007; Haritz, 2011). Legal systems also require a causal link between a defendant's conduct and some identified harm to the plaintiff, in this case from climate change (Tunc, 1983; Faure and Nollkaemper, 2007; Kosolapova, 2011; Kysar, 2011; Brunée et al., 2012; Ewing and Kysar, 2012; Goldberg and Lord, 2012). A causal link might be easier to establish between emissions and adaptation costs (Farber, 2007). Legal systems generally also require causal foreseeability or directness (Mank, 2007; Kosolapova, 2011; van Dijk, 2011; Ewing and Kysar, 2012), although some statutes relax this requirement in specific cases (such as the US Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as Superfund. Emitters might argue that their contribution to GHG levels was too small and the harmful effects too indirect and diffuse to satisfy the legal requirements (Sinnot-Armstrong, 2010; Faure and Peeters, 2011; Hiller, 2011; Kysar, 2011; van Dijk, 2011; Gerrard and Wannier, 2012).

Climate change claims could also be classified as unjust enrichment (Kull, 1995; Birks, 2005), but legal systems do not remedy all forms of enrichment that might be regarded as ethically unjust (Zimmermann, 1995; American Law Institute, 2011; Laycock, 2012). Under some legal systems, liability depends on whether benefits were conferred without legal obligation or through a transaction with no clear change of ownership (Zimmermann, 1995; American Law Institute, 2011; Laycock, 2012). It is not clear that these principles apply to climate change.

As indicated, legal systems do not recognize liability just because a positive or negative externality exists. Their response depends on the behaviour that caused the externality and the nature of the causal link between the agent's behaviour and the resulting gain or loss to another.

3.3.7 Geoengineering, ethics, and justice

Geoengineering (also known as climate engineering [CE]), is large-scale technical intervention in the climate system that aims to cancel some of the effects of GHG emissions (for more details see Working Group I (WGI) 6.5 and WGIII 6.9). Geoengineering represents a third kind of response to climate change, besides mitigation and adaptation. Various options for geoengineering have been proposed, including different types of solar radiation management (SRM) and carbon dioxide removal (CDR). This section reviews the major moral arguments for and against geoengineering technologies (for surveys see Robock, 2008; Corner and Pidgeon, 2010; Gardiner, 2010; Ott, 2010; Betz and Cacean, 2012; Preston, 2013). These moral arguments do not apply equally to all proposed geoengineering methods and have to be assessed on a case-specific basis.[7]

Three lines of argument support the view that geoengineering technologies might be desirable to deploy at some point in the future. First, that humanity could end up in a situation where deploying geoengineering, particularly SRM, appears as a lesser evil than unmitigated climate change (Crutzen, 2006; Gardiner, 2010; Keith et al., 2010; Svoboda, 2012a; Betz, 2012). Second, that geoengineering could be a more cost-effective response to climate change than mitigation or adaptation (Barrett, 2008). Such efficiency arguments have been criticized in the ethical literature for neglecting issues such as side-effects, uncertainties, or fairness (Gardiner, 2010, 2011; Buck, 2012). Third, that some aggressive climate stabilization targets cannot be achieved through mitigation measures alone and thus must be complemented by either CDR or SRM (Greene et al., 2010; Sandler, 2012).

Geoengineering technologies face several distinct sets of objections. Some authors have stressed the substantial uncertainties of large-scale deployment (for overviews of geoengineering risks see also Schneider (2008) and Sardemann and Grunwald (2010)), while others have argued that some intended and unintended effects of both CDR and SRM could be irreversible (Jamieson, 1996) and that some current uncertainties are unresolvable (Bunzl, 2009). Furthermore, it has been pointed out that geoengineering could make the situation worse rather than better (Hegerl and Solomon, 2009; Fleming, 2010; Hamilton, 2013) and that several technologies lack a viable exit option: SRM in particular would have to be maintained as long as GHG concentrations remain elevated (The Royal Society, 2009).

Arguments against geoengineering on the basis of fairness and justice deal with the intra-generational and intergenerational distributional effects. SRM schemes could aggravate some inequalities if, as expected, they modify regional precipitation and temperature patterns with unequal social impacts (Bunzl, 2008; The Royal Society, 2009; Svoboda et al., 2011; Preston, 2012). Furthermore, some CDR methods would require large-scale land transformations, potentially competing with agricultural land-use, with uncertain distributive consequences. Other arguments against geoengineering deal with issues including the geopolitics of SRM, such as international conflicts that may arise from the ability to control the "global thermostat" (e.g., Schelling, 1996; Hulme, 2009), ethics (Hale and Grundy, 2009; Preston, 2011; Hale and Dilling, 2011; Svoboda, 2012b; Hale, 2012b), and a critical assessment of technology and modern civilization in general (Fleming, 2010; Scott, 2012).

One of the most prominent arguments against geoengineering suggests that geoengineering research activities might hamper mitigation efforts (e.g., Jamieson, 1996; Keith, 2000; Gardiner, 2010), which presumes that geoengineering should not be considered an acceptable substitute for mitigation. The central idea is that research increases the prospect of geoengineering being regarded as a serious alternative to emission reduction (for a discussion of different versions of this argument see Hale, 2012a; Hourdequin, 2012). Other authors have argued, based on historical evidence and analogies to other technologies, that geoengineering research might make deployment inevitable (Jamieson, 1996; Bunzl, 2009), or that large-scale field tests could amount to full-fledged deployment (Robock et al., 2010). It has also been argued that geoengineering would constitute an unjust imposition of risks on future generations, because the underlying problem would not be solved but only counteracted with risky technologies (Gardiner, 2010; Ott, 2012; Smith, 2012). The latter argument is particularly relevant to SRM technologies that would not affect greenhouse gas concentrations, but it would also apply to some CDR methods, as there may be issues of long-term safety and capacity of storage.

Arguments in favour of research on geoengineering point out that research does not necessarily prepare for future deployment, but can, on the contrary, uncover major flaws in proposed schemes, avoid premature CE deployment, and eventually foster mitigation efforts (e.g. Keith et al., 2010). Another justification for Research and Development (R&D) is that it is required to help decision-makers take informed decisions (Leisner and Müller-Klieser, 2010).

[7] While the literature typically associates some arguments with particular types of methods (e.g., the termination problem with SRM), it is not clear that there are two groups of moral arguments: those applicable to all SRM methods on the one side and those applicable to all CDR methods on the other side. In other words, the moral assessment hinges on aspects of geoengineering that are not connected to the distinction between SRM and CDR.

3.4 Values and wellbeing

One branch of ethics is the theory of value. Many different sorts of value can arise, and climate change impinges on many of them. Value affects nature and many aspects of human life. This section surveys some of the values at stake in climate change, and examines how far these values can be measured, combined, or weighed against each other. Each value is subject to debate and disagreement. For example, it is debatable whether nature has value in its own right, apart from the benefit it brings to human beings. Decision-making about climate change is therefore likely to be contentious.

Since values constitute only one part of ethics, if an action will increase value overall it by no means follows that it should be done. Many actions benefit some people at the cost of harming others. This raises a question of justice even if the benefits in total exceed the costs. Whereas a cost to a person can be compensated for by a benefit to that same person, a cost to a person cannot be compensated for by a benefit to someone else. To suppose it can is not to "take seriously the distinction between persons", as John Rawls puts it (1971, p. 27). Harming a person may infringe their rights, or it may be unfair to them. For example, when a nation's economic activities emit GHG, they may benefit the nation itself, but may harm people in other nations. Even if the benefits are greater in value than the harms, these activities may infringe other nations' rights. Other nations may therefore be entitled to object to them on grounds of justice.

Any decision about climate change is likely to promote some values and damage others. These may be values of very different sorts. In decision making, different values must therefore be put together or balanced against each other. Some pairs of values differ so radically from each other that they cannot be determinately weighed together. For example, it may be impossible to weigh the value of preserving a traditional culture against the material income of the people whose culture it is, or to weigh the value of biodiversity against human wellbeing. Some economists claim that one person's wellbeing cannot be weighed against another's (Robbins, 1937; Arrow, 1963). When values cannot be determinately weighed, they are said to be 'incommensurable' or 'incomparable' (Chang, 1997). Multi-Criteria Analysis (MCA) (discussed in Section 3.7.2.1) is a technique that is designed to take account of several incommensurable values (De Montis et al., 2005; Zeleny and Cochrane, 1982).

3.4.1 Non-human values

Nature provides great benefits to human beings in ways that range from absorbing our waste, to beautifying the world we inhabit. An increasing number of philosophers have argued in recent years that nature also has value in its own right, independently of its benefits to human beings (Leopold, 1949; Palmer, 2011). They have argued that we should recognize animal values, the value of life itself, and even the value of natural systems and nature itself.

In moral theory, rational adult humans, who are self-conscious subjects of a life, are often taken (following Kant, 1956) to have a kind of unconditional moral worth—sometimes called 'dignity'—that is not found elsewhere on earth. Others believe that moral worth can be found elsewhere (Dryzek, 1997). Many human beings themselves lack rationality or subjectivity, yet still have moral worth—the very young, the very old and people with various kinds of impairment among them. Given that, why deny moral worth to those animals that are to some extent subjects of a life, who show emotional sophistication (Regan, 2004), and who experience pleasure, pain, suffering, and joy (Singer, 1993)?

An argument for recognizing value in plants as well as animals was proposed by Richard Routley (1973). Routley gives the name 'human chauvinism' to the view that humans are the sole possessors of intrinsic value. He asks us to imagine that the last man on earth sets out to destroy every living thing, animal or plant. Most people believe this would be wrong, but human chauvinists are unable to explain why. Human chauvinism appears to be simply a prejudice in favour of the human species (Routley and Routley, 1980). In contrast, some philosophers argue that value exists in the lives of all organisms, to the extent that they have the capacity to flourish (Taylor, 1986; Agar, 2001).

Going further, other philosophers have argued that biological communities and holistic ecological entities also have value in their own right. Some have argued that a species has more value than all of its individuals have together, and that an ecosystem has still more value (Rolston, 1988, 1999; compare discussion in Brennan and Lo, 2010). It has further been proposed that, just as domination of one human group by another is a moral evil, showing disrespect for the value of others, then so is the domination of nature by humans in general. If nature and its systems have moral worth, then the domination of nature is also a kind of disrespect (Jamieson, 2010).

If animals, plants, species, and ecosystems do have value in their own right, then the moral impact of climate change cannot be gauged by its effects on human beings alone. If climate change leads to the loss of environmental diversity, the extinction of plant and animal species, and the suffering of animal populations, then it will cause great harms beyond those it does to human beings. Its effects on species numbers, biodiversity, and ecosystems may persist for a very long time, perhaps even longer than the lifetime of the human species (Nolt, 2011).

It is very difficult to measure non-human values in a way that makes them commensurate with human values. Economists address this issue by dividing value into use value (associated with actual use of nature—instrumental value) and nonuse or existence value (intrinsic value of nature). As an example, biodiversity might have value because of the medical drugs that might be discovered among the diverse biota (use value). Or biodiversity might be valued by individuals simply because they believe that biologic diversity is important, over and above any use to people that might occur. The total amount people are willing to pay has sometimes been used as an economic measure of the total value (instrumental and intrinsic) of these features (Aldred, 1994). As the discussion of the past few paragraphs has suggested, nature may have additional value, over and above the values placed by individual humans (Broome, 2009; Spash et al., 2009).

3.4.2 Cultural and social values

The value of human wellbeing is considered in Section 3.4.3, but the human world may also possess other values that do not form part of the wellbeing of individual humans. Living in a flourishing culture and society contributes to a person's wellbeing (Kymlicka, 1995; Appiah, 2010), but some authors claim that cultures and societies also possess values in their own right, over and above the contribution they make to wellbeing (Taylor, 1995). Climate change threatens damage to cultural artefacts and to cultures themselves (Adger et al., 2012). Evidence suggests that it may already be damaging the culture of Arctic indigenous peoples (Ford et al., 2006, 2008; Crate, 2008; Hassol, 2004; see also WGII Chapter 12). Cultural values and indigenous peoples are discussed in Section 3.10.2.

The degree of equality in a society may also be treated as a value that belongs to a society as a whole, rather than to any of the individuals who make up the society. Various measures of this value are available, including the Gini coefficient and the Atkinson measure (Gini, 1912; Atkinson, 1970); for an assessment see (Sen, 1973). Section 3.5 explains that the value of equality can alternatively be treated as a feature of the aggregation of individual people's wellbeings, rather than as social value separate from wellbeing.

3.4.3 Wellbeing

Most policy concerned with climate change aims ultimately at making the world better for people to live in. That is to say, it aims to promote people's wellbeing. A person's wellbeing, as the term is used here, includes everything that is good or bad for the person—everything that contributes to making their life go well or badly. What things are those—what constitutes a person's wellbeing? This question has been the subject of an extensive literature since ancient times.[8] One view is that a person's wellbeing is the satisfaction of their preferences. Another is that it consists in good feelings such as pleasure. A third is that wellbeing consists in possessing the ordinary good things of life, such as health, wealth, a long life, and participating well in a good community. The 'capabilities approach' in economics (Sen, 1999) embodies this last view. It treats the good things of life as 'functionings' and 'capabilities'—things that a person does and things that they have a real opportunity of doing, such as living to old age, having a good job, and having freedom of choice.

A person's wellbeing will be affected by many of the other values that are mentioned above, and by many of the considerations of justice mentioned in Section 3.3. It is bad for a person to have their rights infringed or to be treated unfairly, and it is good for a person to live within a healthy culture and society, surrounded by flourishing nature.

Various concrete measures of wellbeing are in use (Fleurbaey, 2009; Stiglitz et al., 2009). Each reflects a particular view about what wellbeing consists in. For example, many measures of 'subjective wellbeing' (Oswald and Wu, 2010; Kahneman and Deaton, 2010) assume that wellbeing consists in good feelings. Monetary measures of wellbeing, which are considered in Section 3.6, assume that wellbeing consists in the satisfaction of preferences. Other measures assume wellbeing consists in possessing a number of specific good things. The Human Development Index (HDI) is intended to be an approximate measure of wellbeing understood as capabilities and functionings (UNDP, 2010). It is based on three components: life expectancy, education, and income. The capabilities approach has inspired other measures of wellbeing too (Dervis and Klugman, 2011). In the context of climate change, many different metrics of value are intended to measure particular components of wellbeing: among them are the numbers of people at risk from hunger, infectious diseases, coastal flooding, or water scarcity. These metrics may be combined to create a more general measure. Schneider et al. (2000) advocates the use of a suite of five metrics: (1) monetary loss, (2) loss of life, (3) quality of life (taking account of forced migration, conflict over resources, cultural diversity, and loss of cultural heritage sites), (4) species or biodiversity loss, and (5) distribution and equity.

3.4.4 Aggregation of wellbeing

Whatever wellbeing consists of, policy-making must take into account the wellbeing of everyone in the society. So the wellbeings of different people have somehow to be aggregated together. How do they combine to make up an aggregate value of wellbeing for a society as a whole? Social choice theory takes up this problem (Arrow, 1963; Sen, 1970). Section 3.6 will explain that the aim of economic valuation is to measure aggregate wellbeing.

Assume that each person has a level of wellbeing at each time they are alive, and call this their 'temporal wellbeing' at that time. In a society, temporal wellbeing is distributed across times and across the people. When a choice is to be made, each of the options leads to a particular distribution of wellbeing. Our aim is to assess the value of such distributions. Doing so involves aggregating wellbeings across times and across people, to arrive at an overall, social value for the distribution.

[8] For example: Aristotle, *Nicomachean Ethics*. Recent work includes: Griffin (1986); Sumner (1999); Kraut (2007).

3

3.4.5 Lifetime wellbeing

Next let us assume that each person's temporal wellbeings can be aggregated to determine a 'lifetime wellbeing' for the person, and that the social value of the distribution of wellbeing depends only on these lifetime wellbeings. This is the assumption that each person's wellbeing is "separable", to use a technical term. It allows us to split aggregation into two steps. First, we aggregate each person's temporal wellbeings across the times in their life in order to determine their lifetime wellbeing. The second step in the next section is to aggregate across individuals using a social welfare function.

On one account, a person's lifetime wellbeing is simply the total of their temporal wellbeings at each time they are alive. If a person's wellbeing depended only on the state of their health, this formula would be equivalent to 'QALYs' or 'DALYs' (quality-adjusted life years or disability-adjusted life years), which are commonly used in the analysis of public health (Murray, 1994; Sassi, 2006). These measures take a person's lifetime wellbeing to be the total number of years they live, adjusted for their health in each year. Since wellbeing actually depends on other things as well as health, QALYs or DALYs provide at best an approximate measure of lifetime wellbeing. If they are aggregated across people by simple addition, it assumes implicitly that a year of healthy life is equally as valuable to one person as it is to another. That may be an acceptable approximation for the broad evaluation of climate change impacts and policies, especially for evaluating their effects on health (Nord et al., 1999; Mathers et al., 2009; but also see Currie et al., 2008).

Other accounts give either increasing, (Velleman, 1991) or alternatively decreasing, (Kaplow et al., 2010) weight to wellbeing that comes in later years of life, in determining a person's lifetime wellbeing.

3.4.6 Social welfare functions

Once we have a lifetime wellbeing for each person, the next step is to aggregate these lifetime wellbeings across people, to determine an overall value for society. This involves comparing one person's wellbeing with another's. Many economists have claimed that interpersonal comparisons of wellbeing are impossible.[9] If they are right, the wellbeings of different people are incommensurable and cannot be aggregated. In this section we set this view aside, and assume that temporal wellbeings are measured in a way that is comparable across people.[10] This allows us to aggregate different people's lifetime wellbeings through a social welfare function (SWF) to arrive at an overall value or 'social welfare'.[11]

[9] Examples are: Robbins (1937), Archibald (1959), Arrow (1963). A survey and discussion of this sceptical view appears in Hammond (1993).

[10] Potential bases of interpersonal comparisons are examined in: Fleurbaey and Hammond (2004); Sen (1982); Elster and Roemer (1993); Mirrlees (1982); Broome, (2004); Arrow (1977); Harsanyi (1977); Adler (2011).

[11] A recent major study is Adler (2011).

We shall first consider SWFs under the simplifying but unrealistic assumption that the decisions that are to be made do not affect how many people exist or which people exist: all the options contain the same people. A theorem of Harsanyi's (1955) gives some grounds for thinking that, given this assumption, the SWF is additively separable between people. This means it has the form:

Equation 3.4.1 $V = v_1(w_1) + v_2(w_2) + \ldots + v_J(w_J)$

Here w_i is person i's lifetime wellbeing. This formula says that each person's wellbeing can be assigned a value $v_i(w_i)$, and all these values—one for each person—are added up to determine the social value of the distribution.

The proof of Harsanyi's Theorem depends on assumptions that can be challenged (Diamond, 1967; Broome, 2004; Fleurbaey, 2010). So, although the additively separable form shown in Equation 3.4.1 is commonly assumed in economic valuations, it is not entirely secure. In particular, this form makes it impossible to give any value to equality except indirectly through prioritarianism, which was introduced in Section 3.3.2 and is defined below. The value of inequality cannot be measured by the Gini coefficient, for example, since this measure is not additively separable (Sen, 1973).

It is often assumed that the functions $v_i(\,)$ all have the same form, which means that each person's wellbeing is valued in the same way:

Equation 3.4.2 $V = v(w_1) + v(w_2) + \ldots + v(w_J)$

Alternatively, the wellbeing of people who live later is sometimes discounted relative to the wellbeing of people who live earlier; this implies that the functional form of $v_i(\,)$ varies according to the date when people live. Discounting of later wellbeing is often called 'pure' discounting. It is discussed in Section 3.6.2.

Even if we accept Equation 3.4.2, different ethical theories imply different SWFs. Utilitarianism values only the total of people's wellbeing. The SWF may be written:

Equation 3.4.3 $V = w_1 + w_2 + \ldots + w_J$

Utilitarianism gives no value to equality in the distribution of wellbeing: a given total of wellbeing has the same value however unequally it is distributed among people.

But the idea of distributive justice mentioned in Section 3.3.3 suggests that equality of wellbeing does have value. Equation 3.4.2 will give value to equality if the function $v()$ is strictly concave. This means the graph of $v()$ curves downwards, as Figure 3.1 illustrates. (Section 3.6.1.1 explains that a person's wellbeing w_i is commonly assumed to be a strictly concave function of her consumption, but this is a different point.) The resulting ethical theory is called prioritarianism. As Figure 3.1 shows, according to prioritarianism, improv-

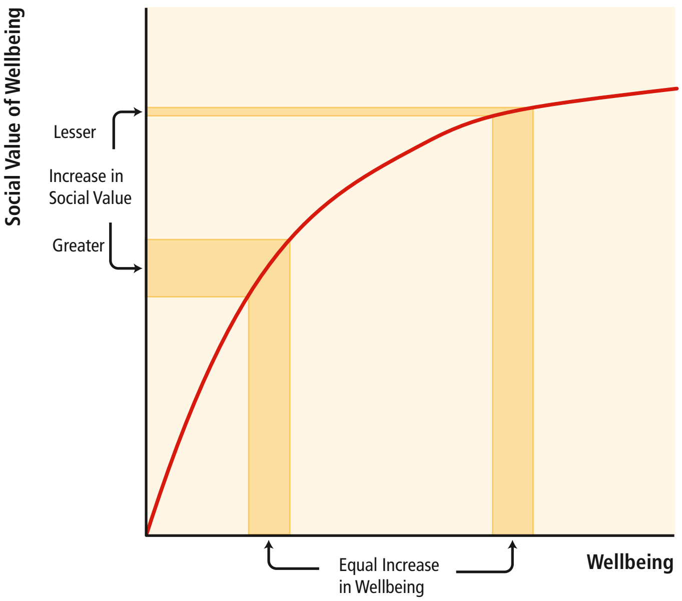

Figure 3.1 | The prioritarian view of social welfare. The figure compares the social values of increases in wellbeing for a better-off and a worse-off person.

ing a *person's* wellbeing contributes more to social welfare if the person is badly off than if they are well off. The prioritarian slogan is "priority to the worse off". Prioritarianism indirectly gives value to equality: it implies that a given total of wellbeing is more valuable the more equally it is distributed (Sen, 1973; Weirich, 1983; Parfit, 1997). In judgements about climate change, a prioritarian function will give relatively more importance to the interests of poorer people and poorer countries.

3.4.7 Valuing population

The next problem in aggregating wellbeing is to take account of changes in population. Climate change can be expected to affect the world's human population. Severe climate change might even lead to a catastrophic collapse of the population (Weitzman, 2009), and even to the extinction of human beings. Any valuation of the impact of climate change and of policies to mitigate climate change should therefore take changes in population into account.

The utilitarian and prioritarian SWFs for a fixed population may be extended in a variety of ways to a variable population. For example, the utilitarian function may be extended to 'average utilitarianism' (Hurka, 1982), whose SWF is the average of people's wellbeing. Average utilitarianism gives no value to increasing numbers of people. The implicit or explicit goal of a great deal of policy-making is to promote per capita wellbeing (Hardin, 1968). This is to adopt average utilitarianism. This goal tends to favour anti-natalist policies, aimed at limiting population. It would strongly favour population control as a means of mitigating climate change, and it would not take a collapse of population to be, in itself, a bad thing.

The utilitarian function may alternatively be extended to 'critical-level utilitarianism', whose SWF is the total of the amount by which each person's wellbeing exceeds some fixed critical level. It is

Equation 3.4.4 $V = (w_1 - c) + (w_2 - c) + \dots + (w_J - c)$

where c is the critical level (Broome, 2004; Blackorby et al., 2005). Other things being equal, critical-level utilitarianism favours adding people to the population if their wellbeing is above the critical level.

'Total utilitarianism' (Sidgwick, 1907) is critical-level utilitarianism with the critical level set to zero. Its SWF is the total of people's wellbeing. Total utilitarianism is implicit in many Integrated Assessment Models (IAMs) of climate change (e.g., Nordhaus, 2008). Its meaning is indeterminate until it is settled which level of lifetime wellbeing to count as zero. Many total utilitarians set the zero at the level of a life that has no good or bad experiences—that is lived in a coma throughout, for instance (Arrhenius, forthcoming). Since people on average lead better lives than this, total utilitarianism with this zero tends to be less anti-natalist than average utilitarianism. However, it does not necessarily favour increasing population. Each new person damages the wellbeing of existing people, through their emissions of GHG, their other demands on Earth's limited resources, and the emissions of their progeny. If the damage an average person does to others in total exceeds their own wellbeing, total utilitarianism, like average utilitarianism, favours population control as a means of mitigating climate change.[12]

Each of the existing ethical theories about the value of population has intuitively unattractive implications (Parfit, 1986). Average utilitarianism is subject to particularly severe objections. Arrhenius (forthcoming) crystallizes the problems of population ethics in the form of impossibility theorems. So far, no consensus has emerged about the value of population. Yet climate change policies are expected to affect the size of the world's population, and different theories of value imply very different conclusions about the value of these policies. This is a serious difficulty for evaluating policies aimed at mitigating climate change, which has largely been ignored in the literature (Broome, 2012).

3.5 Economics, rights, and duties

Sections 3.2, 3.3 and 3.4 have outlined some of the ethical principles that can guide decision making for climate change. The remainder of this chapter is largely concerned with the concepts and methods of

[12] Harford (1998) shows that an additional person causes damage from her own emissions and the emissions of her children (and of their children, etc.). Kelly and Kolstad (2001) examine this issue in the specific context of climate change.

economics. They can be used to aggregate values at different times and places, and weigh aggregate value for different policy actions. They can also be used to draw information about value from the data provided by prices and markets. Economics can measure diverse benefits and harms, taking account of uncertainty, to arrive at overall judgements of value. It also has much to contribute to the choice and design of policy mechanisms, as Section 3.8 and later chapters show.

Valuations provided by economics can be used on a large scale: IAMs can be used to simulate the evolution of the world's economy under different climate regimes and determine an economically efficient reduction in GHG emissions. On a smaller scale, economic methods of CBA can be used in choosing between particular policies and technologies for mitigation.

Economics is much more than a method of valuation. For example, it shows how decision making can be decentralized through market mechanisms. This has important applications in policy instruments for mitigation with potential for cost-effectiveness and efficiency (Chapters 6 and 15). Economic analysis can also give guidance on how policy mechanisms for international cooperation on mitigation can be designed to overcome free-rider problems (Chapters 13 and 14). However, the methods of economics are limited in what they can do. They can be based on ethical principles, as Section 3.6 explains. But they cannot take account of every ethical principle. They are suited to measuring and aggregating the wellbeing of humans, but not to taking account of justice and rights (with the exception of distributive justice—see below), or other values apart from human wellbeing. Moreover, even in measuring and aggregating wellbeing, they depend on certain specific ethical assumptions. This section describes the limits of economic methods.

Because of their limitations, economic valuations are often not on their own a good basis for decision making. They frequently need to be supplemented by other ethical considerations. It may then be appropriate to apply techniques of multi-criteria analysis (MCA), discussed in Section 3.7.2.1 (Zeleny and Cochrane, 1982; Keeney and Raiffa, 1993; De Montis et al., 2005).

3.5.1 Limits of economics in guiding decision making

Economics can measure and aggregate human wellbeing, but Sections 3.2, 3.3 and 3.4 explain that wellbeing may be only one of several criteria for choosing among alternative mitigation policies. Other ethical considerations are not reflected in economic valuations, and those considerations may be extremely important for particular decisions that have to be made. For example, some have contended that countries that have emitted a great deal of GHG in the past owe restitution to countries that have been harmed by their emissions. If so, this is an important consideration in determining how much finance rich countries should provide to poorer countries to help with their mitigation efforts. It suggests that economics alone cannot be used to determine who should bear the burden of mitigation (also see Box 3.2).

What ethical considerations can economics cover satisfactorily? Since the methods of economics are concerned with value, they do not take account of justice and rights in general. However, distributive justice can be accommodated within economics, because it can be understood as a value: specifically the value of equality. The theory of fairness within economics (Fleurbaey, 2008) is an account of distributive justice. It assumes that the level of distributive justice within a society is a function of the wellbeings of individuals, which means it can be reflected in the aggregation of wellbeing. In particular, it may be measured by the degree of inequality in wellbeing, using one of the standard measures of inequality such as the Gini coefficient (Gini, 1912), as discussed in the previous section. The Atkinson measure of inequality (Atkinson, 1970) is based on an additively separable SWF, and is therefore particularly appropriate for representing the prioritarian theory described in Section 3.4.6. Furthermore, distributive justice can be reflected in weights incorporated into economic evaluations as Section 3.6 explains.

Economics is not well suited to taking into account many other aspects of justice, including compensatory justice. For example, a CBA might not show the drowning of a Pacific island as a big loss, since the island has few inhabitants and relatively little economic activity. It might conclude that more good would be done in total by allowing the island to drown: the cost of the radical action that would be required to save the island by mitigating climate change globally would be much greater than the benefit of saving the island. This might be the correct conclusion in terms of overall aggregation of costs and benefits. But the island's inhabitants might have a right not to have their homes and livelihoods destroyed as a result of the GHG emissions of richer nations far away. If that is so, their right may override the conclusions of CBA. It may give those nations who emit GHG a duty to protect the people who suffer from it, or at least to make restitution to them for any harms they suffer.

Even in areas where the methods of economics can be applied in principle, they cannot be accepted without question (Jamieson, 1992; Sagoff, 2008). Particular simplifying assumptions are always required, as shown throughout this chapter. These assumptions are not always accurate or appropriate, and decision-makers need to keep in mind the resulting limitations of the economic analyses. For example, climate change will shorten many people's lives. This harm may in principle be included within a CBA, but it remains highly contentious how that should be done. Another problem is that, because economics can provide concrete, quantitative estimates of some but not all values, less quantifiable considerations may receive less attention than they deserve.

The extraordinary scope and scale of climate change raises particular difficulties for economic methods (Stern, forthcoming). First, many of the common methods of valuation in economics are best designed for marginal changes, whereas some of the impacts of climate change and

Box 3.2 | Who mitigates versus who pays?

To mitigate climate change, emissions of GHG will need to be reduced to varying degrees worldwide. Economic analysis tells us that, for the sake of cost-effectiveness, the greatest reductions should be made where they can be made most cheaply. Ideally, emissions should be reduced in each place to just the extent that makes the marginal cost of further reductions the same everywhere. One way of achieving this result is to have a carbon price that is uniform across the world; or it might be approximated by a mix of policy instruments (see Section 3.8).

Since, for efficiency, mitigation should take place where it is cheapest, emissions of GHG should be reduced in many developing countries, as well as in rich ones. However, it does not follow that mitigation must be paid for by those developing countries; rich countries may pay for mitigation that takes place in poor countries. Financial flows between countries make it possible to separate the question of where mitigation should take place from the question of who should pay for it. Because mitigating climate change demands very large-scale action, if put in place these transfers might become a significant factor in the international distribution of wealth. Provided appropriate financial transfers are made, the question of where mitigation should take place is largely a matter for the economic theory of efficiency, tempered by ethical considerations. But the distribution of wealth is a matter of justice among countries, and a major issue in the politics of climate change (Stanton, 2011). It is partly a matter of distributive justice, which economics can take into account, but compensatory justice may also be involved, which is an issue for ethics (Section 3.3).

efforts at mitigation are not marginal (Howarth and Norgaard, 1992). Second, the very long time scale of climate change makes the discount rate crucial at the same time as it makes it highly controversial (see Section 3.6.2). Third, the scope of the problem means it encompasses the world's extremes of wealth and poverty, so questions of distribution become especially important and especially difficult. Fourth, measuring non-market values—such as the existence of species, natural environments, or traditional ways of life of local societies—is fraught with difficulty. Fifth, the uncertainty that surrounds climate change is very great. It includes the likelihood of irreversible changes to societies and to nature, and even a small chance of catastrophe. This degree of uncertainty sets special problems for economics (Nelson, 2013).

3.6 Aggregation of costs and benefits

3.6.1 Aggregating individual wellbeing

Policies that respond to climate change almost always have some good and some bad effects; we say they have 'benefits' and 'costs'. In choosing a policy, we may treat one of the available options as a standard of comparison—for instance, the status quo. Other options will have costs and benefits relative to this standard. Most mitigation strategies have costs in the present and yield benefits in the future. Policy-making involves assessing the values of these benefits and costs and weighing them against each other. Chapter 6 contains an example in which different mitigation strategies yielding different temporal allocations of climate impacts are compared. The weighing of costs and benefits need not be a precise process. Sections 3.2 and 3.4 explain that costs and benefits may be values of very different sorts, which cannot be precisely weighed against each other. They may also be very uncertain.

Nevertheless, the discipline of economics has developed methods for measuring numerically values of one particular sort: human wellbeing. In this section, we describe these methods; Section 3.5 explains their serious limitations. Economists often use money as their unit of measurement for values, but not always. In health economics, for example, the unit of benefit for health care is often the 'quality-adjusted life year' (QALY) (see Box 3.3). In economics, monetary measures of value are used in cost-effectiveness analysis (see Weimer and Vining, 2010), in estimating the social cost of carbon (see Section 3.9.4), in inter-temporal optimization within IAMs (e.g., Stern, 2007; Nordhaus, 2008), in CBA and elsewhere.

Generally the overall value of aggregate wellbeing needs to be measured, and not merely the wellbeing of each individual. A numerical measure of overall wellbeing may be based on ethical analysis, through a SWF of the sort introduced in Section 3.4. This basis of valuation is described here. The literature contains a putative alternative basis built on the 'potential Pareto criterion' (see Box 3.4), but this is subject to severe objections (De Scitovszky, 1941; Gorman, 1955; Arrow, 1963, Chapter 4; Boadway and Bruce, 1984; Blackorby and Donaldson, 1990).

We take as our point of departure the formulation of the SWF in Equation 3.4.2, which is based on assumptions described in Section 3.4.6. To these we now add a further assumption that times are separable, meaning that the distribution of wellbeing can be evaluated at each time separately and its overall value is an aggregate of these separate 'snap-shot' values. A theorem of Gorman's (1968) ensures that social welfare then takes the fully additively separable form:

Equation 3.6.1 $V = \delta_1 V_1 + \delta_2 V_2 + \ldots + \delta_T V_T$

where each V_t is the value of wellbeing at time t and is the total of the values of individual wellbeings at that time. That is:

Equation 3.6.2 $V_t = v(w_{1t}) + v(w_{2t}) + \ldots + v(w_{It})$

Each w_{it} is the temporal wellbeing of person i at time t. Each δ_t is a 'discount factor', which shows how wellbeing at time t is valued relative to wellbeing at other times.

The assumption that times are separable has some unsatisfactory consequences. First, it cannot give value to equality between people's lives taken as a whole, but only to equality at each particular time. Second, Equation 3.6.1 is inconsistent with average utilitarianism, or with valuing per capita temporal wellbeing at any time, whereas per capita wellbeing is a common object of climate-change policy. Third, Equation 3.6.1 makes no distinction between discounting within a single person's life and intergenerational discounting. Yet a case can be made for treating these two sorts of discounting differently (Kaplow et al., 2010). Nevertheless, this assumption and the resulting equation Equation 3.6.1 underlies the usual practice of economists when making valuations. First they aggregate temporal wellbeing across people at each time to determine a snapshot social value for each time. Then all these values are aggregated across times. This section and the next describe the usual practice based on these equations.[13] The second step—aggregation across time—is considered in Section 3.6.1. The rest of this section considers the first step—aggregation at time.

[13] An alternative approach does not assume separability of times. First it determines a lifetime wellbeing for each person in the way described in Section 3.4.5. For instance, *i*'s lifetime wellbeing might be a discounted total of her temporal wellbeings. Then this approach aggregates across people using Equation 3.4.2. See Fullerton and Rogers (1993), Murphy and Topel (2006) and Kaplow et al. (2010).

Box 3.3 | The value of life

Climate change may shorten many people's lives, and mitigating climate change may extend many people's lives. Lives must therefore be included in any CBA that is concerned with climate change. The literature contains two different approaches to valuing a person's life. One is based on the length of time the person gains if their life is saved, adjusted according to the quality of their life during that time (QALY), an approach widely used to value lives in health economics and public health. For assessing the impact of climate on human health and longevity, the World Health Organization uses the 'disability-adjusted life year' (DALY), which is similar (Mathers et al., 2009; for DALYs see, Murray, 1994).

The other approach values the extension of a person's life on the basis of what they would be willing to pay for it. In practice, this figure is usually derived from what the person would be willing to pay for an increased chance of having an extended life. If, say, a person is willing to pay $100 to reduce her chance of dying in a road accident from 2 in 10,000 to 1 in 10,000, then her willingness to pay (WTP) for extending her life is $100 x 10,000 = $1 million. A WTP measure of the value of life is widely used in environmental economics (e.g., U.S. Environmental Protection Agency, 2010 Appendix B); it is often known as a 'value of statistical life' (Viscusi and Aldy, 2003).

The main differences between these approaches are:

1. Since WTP is measured in money, it is immediately comparable with other values measured in money. QALYs need to be assigned a monetary value to make them comparable (Mason et al., 2009).
2. The use of QALYs implies a theoretical assumption about the value of extending a life—that it is proportional to the length of the extension, adjusted for quality—whereas WTP methods generally leave it entirely to the individual to set a value on extending their own life (Broome, 1994).
3. Each measure implies a different basis for interpersonal comparisons of value. When QALYs are aggregated across people by addition, the implicit assumption is that a year of healthy life has the same value for each person. When WTP is aggregated across people by addition (without distributional weights), the implicit assumption is that a dollar has the same value for each person. Neither assumption is accurate, but for comparisons involving very rich countries and very poor ones, the former assumption seems nearer the truth (Broome, 2012, Chapter 9).

The two approaches can converge. The text explains that distributional weights should be applied to monetary values before they are aggregated, and this is true of WTP for extending life. If appropriate weights are applied, WTP becomes more nearly proportional to QALYs. Indeed, if we adopt the assumption that a QALY has the same value for each person, we may use it to give us a basis for calculating distributional weights to apply to money values (Somanathan, 2006). For example, suppose WTP for a 30-year extension to healthy life in the United States is USD 5 million, and in India it is USD 250,000; then, on this assumption, USD 1 to an Indian has the same social value as USD 20 to an American.

3.6.1.1 Monetary values

Climate policies affect the wellbeing of individuals by changing their environment and their individual consumption. The first step in a practical economic valuation is to assign a monetary value to the costs and benefits that come to each person at each time from the change. This value may be either the amount of money the person is willing to pay for the change, or the amount they are willing to accept as compensation for it. If the change is a marginal increase or decrease in the person's consumption of a marketed commodity, it will be equal to the price of the commodity.

The effect of a change on the person's wellbeing is the monetary value of the change multiplied by the rate at which money contributes to the person's wellbeing. This rate is the marginal benefit of money or marginal utility of money to the person. It is generally assumed to diminish with increasing income (Marshall, 1890; Dalton, 1920; Pigou, 1932, p. 89; Atkinson, 1970).

The effects of the change on each person's wellbeing at each time must next be aggregated across people to determine the effect on social value. Equation 3.6.2 shows how each person's wellbeing contributes to social value through the value function v(). The change in wellbeing must therefore be multiplied by the marginal social value of wellbeing, which is the first derivative of this function. It is an ethical parameter. According to utilitarianism, that marginal social value is constant and the same for everyone; according to prioritarianism, it diminishes with increasing wellbeing.

Box 3.4 | Optimality versus Pareto improvement in climate change

The assessment of a change normally requires benefits to be weighed against costs. An exception is a change – known as a 'Pareto improvement' – that benefits some people without harming anyone. Climate change provides one possible example. GHG is an externality: a person whose activities emit GHG does not bear the full cost of their activities; some of the costs are borne by those who are harmed by the emissions. Consequently, climate change causes Pareto inefficiency, which means that a Pareto improvement would in principle be possible. Indeed it would be possible to remove the inefficiency in a way that requires no sacrifice by anyone in any generation, compared to business-as-usual (BAU). To achieve this result, the present generation must reallocate investment towards projects that reduce emissions of GHG, while maintaining its own consumption. Because it maintains its own consumption, the present generation makes no sacrifice. Because it reduces its conventional investment, this generation bequeaths less conventional capital to future generations. Other things being equal, this reallocation would make future generations less well off, but the reduction in emissions will more than compensate them for that loss (Stern, forthcoming; Foley, 2009; Rezai et al., 2011).

It is commonly assumed that climate change calls for sacrifices by the present generation for the sake of future generations. Figure 3.2 illustrates why. The possibility frontier shows what combinations of consumption are possible for present and future generations. Because of the externality, Business-as-usual lies below this frontier. The frontier can be reached by a Pareto improvement. Contours of two different SWFs are shown: one SWF places more value than the other on future consumption relative to present consumption. The two contours reflect in a purely illustrative way SWFs that are implicit in Stern (2007) and Nordhaus (2008) respectively. The point where a contour touches the possibility frontier is the social optimum according to that function. Neither optimum is a Pareto improvement on business-as-usual. Although the inefficiency could be removed without any sacrifices, the best outcomes described by both Stern and Nordhaus do require a sacrifice by the present generation.

From an international rather than an intergenerational perspective, it is also true on the same grounds that the inefficiency of climate change can be removed without any nation making a sacrifice (Posner and Weisbach, 2010). But it does not follow that this would be the best outcome.

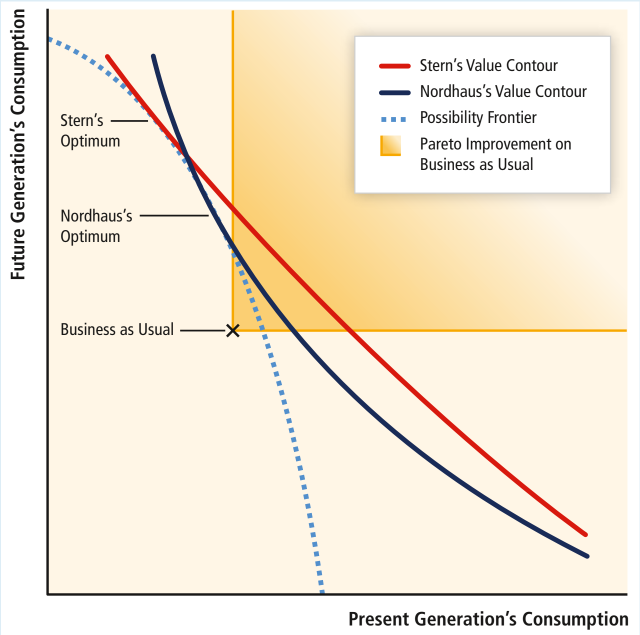

Figure 3.2 | Illustrating optimality versus Pareto improvement in climate change.

In sum, the effect of a change in social value at a particular time is calculated by aggregating the monetary value of the change to each person, weighted by the social marginal value of money to the person, which is the product of the marginal benefit of money to that person and the marginal social value of their wellbeing (Fleurbaey, 2009). Since the marginal benefit of money is generally assumed to diminish with increasing income, the marginal social value of money can be assumed to do the same.

Many practical CBAs value costs and benefits according to aggregated monetary values without any weighting. The implicit assumption is that the marginal social value of money is the same for each person. The consequence of omitting weights is particularly marked when applying CBA to climate change, where extreme differences in wealth between rich and poor countries need to be taken into account. An example appeared in the Second Assessment Report of the IPCC (1995), where it considered the value of human life. The report showed that the effect of ignoring weighting factors would be to assign perhaps twenty times more value to an American life than to an Indian life. (See also Box 3.3). Even within a single country, weighting makes a big difference. Drèze (1998) examined the benefits of reducing pollution in Delhi and contrasts New Delhi, which is relatively rich, with Delhi, which is relatively poorer. If the criterion is reducing pollution for the greatest number of people, then projects in Delhi will be favoured; whereas projects in New Delhi will be favoured if the criterion is unweighted net benefits.

Another example of a monetary measure of value that does not incorporate distributional weights is Gross Domestic Product (GDP). To evaluate changes by their effect on GDP is, once again, to assume that the value of a dollar to a rich person is the same as its value to a poor person (Schneider et al., 2000).

It is sometimes assumed that CBA is conducted against the background of efficient markets and an optimal redistributive taxation system, so that the distribution of income can be taken as ideal from society's point of view. If that were true, it might reduce the need for distributional weights. But this is not an acceptable assumption for most projects aimed at climate change. Credit and risk-sharing markets are imperfect at the world level, global coordination is limited by agency problems, information is asymmetric, and no supra-national tax authority can reduce worldwide inequalities. Furthermore, intergenerational transfers are difficult. In any case, the power of taxation to redistribute income is limited because redistributive taxes create inefficiency (Mirrlees, 1971). Even optimal taxation would therefore not remove the need for distributional weights. Thus, the assumption that incomes are (second-best) optimally redistributed does not neutralize the argument for welfare weights in aggregating costs and benefits.

The need for weights makes valuation more complicated in practice. The data available for costs and benefits is generally aggregated across people, rather than separated for particular individuals. This means that weights cannot be applied directly to individuals' costs and benefits, as they ideally should be. This difficulty can be overcome by applying suitably calculated weights to the prices of commodities, calculated on the basis of income distribution of each commodity's consumers.[14]

3.6.2 Aggregating costs and benefits across time

In climate change decisions, aggregating the pros and cons of alternative actions is particularly difficult because most benefits of mitigation will materialize only in the distant future. On the other hand, the costs of mitigation are borne today. Using a discount rate can therefore make a big difference in evaluating long-term projects or investments for climate change mitigation. For example, a benefit of $1 million occurring in 100 years has a present value of $369,000 if the discount rate is 1 %, $52,000 if it is 3 %, and $ 1,152 if it is 7 %. An important debate in economics since AR4, spawned in part by the Stern (2007) Review, has centred on the discount rate that should be applied in evaluating climate change impacts and mitigation costs (Nordhaus, 2007; Stern, 2008; Dasgupta, 2008; Smith, 2010; see also Quiggin, 2008).

A descriptive approach to discounting examines how human beings trade-off the present against their own futures. It focuses on how individuals and markets make inter-temporal financial decisions, as revealed by the market interest rate. A simple arbitrage argument favours using the interest rate as the discount rate for climate policy decisions: if one reallocates capital from a safe but marginal project (whose return must be equal to the interest rate) to a safe project with the same maturity whose return is smaller than the interest rate, the net impact is null for the current generation, and is negative for future generations. Thus, when projects are financed by a reallocation of capital rather than an increase in aggregate saving (reducing consumption), the discount rate should be equal to the shadow cost of capital.

Table 3.1 documents real returns on different classes of assets in western countries, including government bonds, which are usually considered to be the safest, most risk-free assets. As can be seen, these rates are close to zero.

The same arbitrage argument could be used to discount risky projects. In that case, the discount rate should be equal to the expected rate of return of traded assets with the same risk profile. For example, if the project has the same risk profile as a diversified portfolio of equity, one should use the expected rate of return of equity, as documented in Table 3.1. It contains a relatively large equity premium.

This descriptive approach to the discount rate has many drawbacks. First, we should not expect markets to aggregate preferences efficiently when some agents are not able to trade, as is the case for future generations (Diamond, 1977). Second, current interest rates

[14] The method is presented in Drèze and Stern (1989, pp. 909–989). Applications of distributional weights to climate change appear in Azar and Sterner (1996); and Fankhauser et al. (1997).

Table 3.1 | Real returns of financial assets. Source: Updated data from (Dimson, 2002), in Gollier (2012).

	Government Bills (maturity < 1 year)		Government Bonds (maturity =10 years)		Equity	
	1900–2006	1971–2006	1900–2006	1971–2006	1900–2006	1971–2006
Australia	0.6 %	2.5 %	1.3 %	2.8 %	7.8 %	6.3 %
France	−2.9 %	1.2 %	−0.3 %	6.6 %	3.7 %	7.8 %
Japan	−2.0 %	0.4 %	−1.3 %	3.9 %	4.5 %	5.0 %
United Kingdom	1.0 %	1.9 %	1.3 %	3.9 %	5.6 %	7.1 %
USA	1.0 %	1.3 %	1.9 %	4.0 %	6.6 %	6.6 %

are driven by the potentially impatient attitude of current consumers towards transferring their *own* consumption to the future. But climate change is about transferring consumption across different people and generations, so that determining the appropriate social discount rate is mostly a normative problem. Thirdly, we do not observe safe assets with maturities similar to those of climate impacts, so the arbitrage argument cannot be applied.

We now examine the problem of a social policy-maker who must make climate policy choices using a SWF discussed earlier. In aggregating damages and costs over time, in order to make things comparable across long periods we value consumption changes in the future by equivalent changes in consumption today. These changes in the structure of consumption should be evaluated in monetary terms using values described in Section 3.6.1.1. The incorporation of the intergenerational equity objective has challenged the traditional CBA approach for the evaluation of climate change policies. Practitioners of CBA and evaluators are expected to use discount rates that are consistent with the pre-specified SWF that represents the society's intergenerational values, as in AR2 (1995). We simplify the model used in Section 3.6.1.1 by assuming only one generation per period and only one consumer good. In an uncertain context, an action is socially desirable if it raises the SWF given by 3.6.1:

Equation 3.6.3 $$V = \sum_{t=0}^{\infty} e^{-\delta t} Eu(c_t)$$

where $u(c_t) = v(w(c_t)) = V_t$ is the contribution to the SWF of generation t consuming c_t. Because c_t is uncertain, one should take the expectation $Eu(c_t)$ of this uncertain contribution. The concavity of function u combines prioritarism (inequality aversion) and risk aversion. Parameter δ measures our collective pure preference for the present, so that the discount factor $d(t) = e^{-\delta t}$ decreases exponentially. δ is an ethical parameter that is not related to the level of impatience shown by individuals in weighting their own future wellbeing (Frederick et al., 2002). Many authors have argued for a rate of zero or near-zero (Ramsey, 1928; Pigou, 1932; Harrod, 1949; Parfit, 1986; Cowen, 1992; Schelling, 1995; Broome, 2004; Stern, 2008). Assuming $\delta > 0$ would penalize future generations just because they are born later. Many regard such 'datism' to be as ethically unacceptable as sexism or racism. Cowen (1992) points out that discounting violates the Pareto principle for a person who might live either at one time or at a later time. Some have argued for a positive rate (Dasgupta and Heal, 1980; Arrow, 1999). A traditional argument against a zero rate is that it places an extremely heavy moral burden on the current generation (see, e.g., Dasgupta, 2007). But even when $\delta = 0$, as we see below, we still end up with a discount rate of about 4 %, which is higher than it was during the last century. Stern (2008) used $\delta = 0.1$ % to account for risk of extinction. We conclude that a broad consensus is for a zero or near-zero pure rate of time preference for the present.

In a growing economy ($c_t > c_0$), investing for the future in a safe project has the undesirable effect of transferring consumption from the poor (current generations) to the wealthy (future generations). Thus, investing in safe projects raises intergenerational inequalities. The discount rate can then be interpreted as the minimum rate of return that is necessary to compensate for this adverse effect on the SWF of investing for the future. This is summarized by the Ramsey rule (i.e., the consumption approach to discounting) (Ramsey, 1928). Assuming a standard constant elasticity in the consumption utility function (e.g., $u(c) = c^{1-\eta}/(1-\eta)$), and no uncertainty,[15] the minimum rate of return ρ_t of a project that marginally transfers consumption from 0 to t and that guarantees an increase of intergenerational welfare V is defined as follows:

Equation 3.6.4 $$\rho_t = \delta + \eta g_t$$

where δ represents the pure rate at which society discounts the utility of future generations, and g_t is the annualized growth rate of monetized consumption anticipated at date *t*, and $\eta > 0$ measures inequality aversion. The greater the anticipated economic growth rate g_t, the higher the social discount rate ρ_t. The growth rate g_t is an empirical variable that represents our collective beliefs about prospective economic growth. In Box 3.5, we discuss plausible values for the inequality aversion parameter η.

[15] For alternative assumptions, see Gollier (2002).

Box 3.5 | Plausible values for collective inequality aversion (η)

Consider the following thought experiment. A country has two equally populated social groups. The wealthy group consumes twice as many goods and services as the poor group. Consider also an economic policy whose aim is to increase consumption by 1 unit for every person in the poor group. This implies a reduction of consumption for every wealthy person by x units, which may not be equal to 1 owing to inherent inefficiencies in the tax system. If one is neutral about inequalities, one would not accept this policy if x is larger than 1. Inequality aversion justifies accepting some productive inefficiency, so that an x larger than 1 may be allowed. What is the maximum value of x that one would accept to implement the policy? Answering this question tells us something about inequality aversion, with a large x being associated with a larger η. If one is collectively ready to sacrifice as much as x = 2 units of consumption from the rich to provide one unit of consumption to the poor, this is compatible with an inequality aversion index $\eta = 1$. An x of 4 or 8 would correspond to an index of inequality aversion of 2 and 3, respectively.

Behind the veil of ignorance (Rawls, 1971), our collective preferences towards inequality should be identified as our individual risk aversion. The economic literature in finance and macroeconomics usually assumes a η between 1 and 5 to explain observed behaviours towards risk, as well as asset prices (Kocherlakota, 1996).

By using a near-zero time discount rate, Stern (2007, see also 2008) advanced the debate in the literature. Despite disagreement on the empirical approach to estimating the discount rate, the literature suggests consensus for using declining discount rates over time. Different prominent authors and committees have taken different positions on the values of δ, η and g, making different recommendations for the social discount rate ρ. We summarize them in Table 3.2.

In Table 3.2, the Ramsey formula can be seen to yield a wide range of discount rates, although most or all of the estimates reflect developed country experience. From this table and Box 3.5, a relative consensus emerges in favour of $\delta = 0$ and η between 1 and 3, although they are prescriptive parameters. This means that the normative Ramsey rule leads to a recommendation for a social discount rate of between one and three times the estimated growth rate in consumption between today and the relevant safe benefit or cost to be discounted. The social discount rate is normative because it relies on the intensity of our collective inequality aversion. However, the practical coherence of our ethical principles requires that if one has high inequality aversion, one should also redistribute wealth more assiduously from the currently rich to the currently poor. Furthermore, it is ultimately a judgement by the policymaker on the appropriate value of the parameters of the Ramsey rule, and thus the social discount rate.

The discount rate described here should be used to discount risk-free costs and benefits (Anthoff et al., 2009). The rates that appear in Table 3.2 are higher than real interest rates observed on financial markets, as documented in Table 3.1. This discrepancy defines the risk-free rate puzzle (Weil, 1989). The recent literature on discounting has tried to solve this puzzle by taking into account the uncertainty surrounding economic

Table 3.2 | Calibration of the discount rate based on the Ramsey rule (Equation 3.6.4).

Author	Rate of pure preference for present	Inequality aversion	Anticipated Growth rate	Implied social discount rate
Cline (1992)	0 %	1.5	1 %	1.5 %
IPCC (1996)	0 %	1.5–2	1.6 %–8 %	2.4 %–16 %
Arrow (1999)	0 %	2	2 %	4 %
UK: Green Book (HM Treasury, 2003)	1.5 %	1	2 %	3.5 %*
US UMB (2003)**				3 %–7 %
France: Rapport Lebègue (2005)	0 %	2	2 %	4 %*
Stern (2007)	0.1 %	1	1.3 %	1.4 %
Arrow (2007)		2–3		
Dasgupta (2007)	0.1 %	2–4		
Weitzman (2007a)	2 %	2	2 %	6 %
Nordhaus (2008)	1 %	2	2 %	5 %

Notes:
* Decreasing with the time horizon.
** OMB uses a descriptive approach.

Table 3.3 | Country-specific discount rate computed from the Ramsey rule (Equation 3.6.5) using the historical mean g and standard deviation σ of growth rates of real GDP/cap 1969–2010, together with $\delta = 0$, and $\eta = 2$. Source: Gollier (2012).

	Country	g	σ	Discount rate	
				Ramsey rule Equation 3.6.4	Extended Ramsey rule
OECD countries	United States	1.74 %	2.11 %	3.48 %	3.35 %
	United Kingdom	1.86 %	2.18 %	3.72 %	3.58 %
	Japan	2.34 %	2.61 %	4.68 %	4.48 %
Economies in transition	China	7.60 %	3.53 %	15.20 %	14.83 %
	India	3.34 %	3.03 %	6.68 %	6.40 %
	Russia	1.54 %	5.59 %	3.08 %	2.14 %
Africa	Gabon	1.29 %	9.63 %	2.58 %	−0.20 %
	Zaire (RDC)	−2.76 %	5.31 %	−5.52 %	−6.37 %
	Zambia	−0.69 %	4.01 %	−1.38 %	−1.86 %
	Zimbabwe	−0.26 %	6.50 %	−0.52 %	−1.79 %

growth. Prudent agents should care more about the future if the future is more uncertain, in line with the concept of sustainable development. Assuming a random walk for the growth rate of consumption per capita, this argument applied to Equation 3.6.4 leads to an extended Ramsey rule in which a negative precautionary effect is added:

Equation 3.6.5 $$\rho_t = \delta + \eta g_t - 0.5\, \eta(\eta + 1)\sigma_t^2$$

where σ_t is the annualized volatility of the growth rate of GDP/cap, and g_t is now the expected annualized growth rate until time horizon t. In Table 3.3, we calibrate this formula for different countries by using the estimation of the trend and volatility parameters of observed growth rates of consumption per capita over the period 1969–2010, using $\eta = 2$. We learn from this Table that the Ramsey rule (Equation 3.4.1) often provides a good approximation of the social discount rate to be applied to consumption. It also shows that because of differences in growth expectations, nations may have different attitudes towards reducing present consumption for the benefit of future generations. This is also a further source of international disagreement on the strength of GHG mitigation efforts. The global discount rate for evaluating global actions will therefore depend on how costs and benefits are allocated across countries.[16]

A prudent society should favour actions that generate more benefits for the generations that face greater uncertainty, which justifies a decreasing term structure for risk-free discount rates (Gollier, 2012; Arrow et al., 2013; Weitzman, 2013). These results are related to the literature on Gamma discounting (Weitzman, 1998, 2001, 2010b; Newell and Pizer, 2003; Gollier and Weitzman, 2010). A simple guideline emerging from this literature is that the long-maturity discount rate is equal to the smallest discount rate computed from Equation 3.6.5 with the different plausible levels of its parameters. For example, assuming $\eta = 2$, if the trend of growth g_t is unknown but somewhere between 1 % and 3 %, a discount rate around 2 x mean (1 %, 3 %) = 4 % is socially desirable in the short term, although a discount rate of only 2 x min (1 %, 3 %) = 2 % is desirable for very long maturities.

Assuming a constant rate of pure preference for the present (actually $\delta = 0$), these recommendations yield a perfectly time-consistent valuation strategy, although the resulting discount rates decrease with maturity. A time inconsistency problem arises only if we assume that the rate of pure preference for the present varies according to the time horizon. Economists have tended to focus on hyperbolic discounting and time inconsistency (Laibson, 1997) and the separation between risk aversion and consumption aversion fluctuations over time (Epstein and Zin, 1991). See Section 3.10.1 and Chapter 2.

The literature deals mainly with the rate at which safe projects should be discounted. In most cases, however, actions with long-lasting impacts are highly uncertain, something that must be taken into account in their evaluation. Actions that reduce the aggregated risk borne by individuals should be rewarded and those that increase risk should be penalized. This has traditionally been done by raising the discount rate of a project by a risk premium $\pi = \beta\pi_g$ that is equal to the project-specific risk measure β times a global risk premium π_g. The project-specific beta is defined as the expected increase in the benefit of the project when the consumption per capita increases by 1 %. It measures the additional risk that the action imposes on the community. On average, it should be around 1. As we see from Table 3.3,

[16] Table 3.3 is based on the assumption that the growth process is a random walk, so that the average growth rate converges to its mean in the very long run. It would be more realistic to recognize that economic growth has a much more uncertain nature in the long run: shocks on growth rates are often persistent, economies faces long-term cycles of uncertain length, and some parameters of the growth process are uncertain. Because these phenomena generate a positive correlation in future annual growth rates, they tend to magnify the uncertainty affecting the wellbeing of distant generations, compared to the random walk hypothesis of the extended Ramsey rule (Equation 3.6.5).

the risk premium as measured by the difference between the rate of return on bonds and the rate of return on equity is between 3 % and 6 %. A more normative approach described by the consumption-based capital asset pricing model (Cochrane, 2001) would lead to a much smaller risk premium equalling $\pi_{gt} = \eta\sigma_t^2$ if calibrated on the volatility of growth in western economies.[17] However, Barro (2006, 2009) and Martin (2013) recently showed that the introduction of rare catastrophic events—similar to those observed in some developing countries during the last century—can justify using a low safe discount rate of around 1 % and a large aggregate risk premium of around 4 % at the same time. The true discount rate to be used in the context of climate change will then rely heavily on the climate beta. So far, almost no research has been conducted on the value of the climate beta, that is, the statistical relationship between the level of climate damage and the level of consumption per capita in the future. The exception is Sandsmark and Vennemo (2006), who suggest that it is almost zero. But existing Integrated Assessment Models (IAMs) show that more climate damage is incurred in scenarios with higher economic growth, suggesting that combating climate change does not provide a hedge against the global risk borne by future generations. Nordhaus (2011b) assumes that the actual damages borne by future generations are increasing, so that the climate beta is positive, and the discount rate for climate change should be larger than just applying the extended Ramsey rule.

Several authors (Malinvaud, 1953; Guesnerie, 2004; Weikard and Zhu, 2005; Hoel and Sterner, 2007; Sterner and Persson, 2008; Gollier, 2010; Traeger, 2011; Guéant et al., 2012) emphasize the need to take into account the evolution of relative prices in CBAs involving the distant future. In a growing economy, non-reproducible goods like environmental assets will become relatively scarcer in the future, thereby implying an increasing social value.

3.6.3 Co-benefits and adverse side-effects

This section defines the concept of co-benefits and provides a general framework for analysis in other chapters (a negative co-benefit is labelled an 'adverse side effect'). A good example of a co-benefit in the literature is the reduction of local pollutants resulting from a carbon policy that reduces the use of fossil fuels and fossil-fuel-related local pollutants (see Sections 5.7 and 6.6.2.1). It is also important to distinguish between co-benefits and the societal welfare consequences of generated co-benefits. To use the same example, if local pollutants are already heavily regulated, then the net welfare benefits of further reductions in local pollutants may be small or even negative.

3.6.3.1 A general framework for evaluation of co-benefits and adverse side-effects

As a simple example, suppose social welfare V is a function of different goods or objectives z_i ($i = 1, \ldots, m$), and that each of those objectives might be influenced by some policy instrument, p_1.[18] The policy may have an impact on several objectives at the same time. Now consider a marginal change dp_1 in the policy. The welfare effect is given by:

Equation 3.6.6 $$dV = \sum_{i=1}^{m} \frac{\partial V}{\partial z_i}\frac{\partial z_i}{\partial p_1} dp_1$$

For example, suppose $dp_1 > 0$ is additional GHG abatement (tightening the cap on carbon dioxide (CO_2) emissions). Then the 'direct' benefits of that climate policy might include effects on climate objectives, such as mean global temperature (z_1), sea level rise (z_2), agricultural productivity (z_3), biodiversity (z_4), and health effects of global warming (z_5). The 'co-benefits' of that climate policy might include changes in a set of objectives such as SO_2 emissions (z_6), energy security (z_7), labour supply and employment (z_8), the distribution of income (z_9), the degree of urban sprawl (z_{10}), and the sustainability of the growth of developing countries (z_{11}). See Table 15.1 for an overview of objectives discussed in the sector chapters in the context of co-benefits and adverse side effects. The few studies that attempt a full evaluation of the global welfare effects of mitigation co-benefits focus only on a few objectives because of methodological challenges (as assessed in Section 6.6). For discussion of income distribution objectives, see the 'social welfare functions' in Section 3.4.6.

Because this problem inherently involves multiple objectives, it can be analysed using Multi-Criteria Analysis (MCA) that "requires policymakers to state explicit reasons for choosing policies, with reference to the multiple objectives that each policy seeks to achieve" (Dubash et al., 2013, p. 47). See also Section 3.7.2.1, Section 6.6 and McCollum et al. (2012).

Even external effects on public health could turn out to be either direct benefits of climate policy or co-benefits. The social cost of carbon includes the increased future incidence of heat stroke, heart attacks, malaria, and other warm climate diseases. Any reduction in such health-related costs of climate change is therefore a direct benefit of climate policy. The definition of a co-benefit is limited to the effect of reductions in health effects caused by non-climate impacts of mitigation efforts.

Use of the terminology should be clear and consistent. CBAs need to include *all* gains and losses from the climate policy being analysed—as shown in Equation 3.6.6—the sum of welfare effects from direct benefits net of costs, plus the welfare effects of co-benefits and adverse side effects.

[17] With a volatility in the growth rate of consumption per capita around $\sigma_t = 4\,\%$ (see Table 3.3), and a degree of inequality aversion of, $\eta = 2$, we obtain a risk premium of only $\pi_{gt} = 0.32\,\%$.

[18] This V is a loose interpretation of a social welfare function, such as defined in Equation 3.6.2, insofar as welfare is not usually represented a function of policy objectives or aggregate quantities of goods.

Here, the co-benefit is defined as the effect on a non-climate objective ($\partial z_i/\partial p_1$), leaving aside social welfare (not multiplied by $\partial V/\partial z_i$). In contrast, the 'value' of the co-benefit is the effect on social welfare ($\partial V/\partial z_i$), which could be evaluated by economists using valuation methods discussed elsewhere in this chapter.[19] It may require use of a 'second-best' analysis that accounts for multiple market distortions (Lipsey and Lancaster, 1956). This is not a minor issue. In particular, $\partial V/\partial z_i$ may be positive or negative.

The full evaluation of dV in the equation above involves four steps: first, identify the various multiple objectives z_i ($i = 1, \ldots,$ m) (see, e.g., Table 4.8.1 for a particular climate policy such as a CO_2 emissions cap); second, identify all significant effects on all those objectives (direct effects and co-effects $\partial z_i/\partial p_1$, for $i = 1, \ldots,$ m) (see Chapters 7–12); third, evaluate each effect on social welfare (multiply each $\partial z_i/\partial p_1$ by $\partial V/\partial z_i$); and fourth, aggregate them as in Equation 3.6.6. Of course, computing social welfare also has normative dimensions (see Section 3.4.6).

3.6.3.2 The valuation of co-benefits and adverse side-effects

The list of goods or objectives z_i ($i = 1, \ldots, m$) could include any commodity, but some formulations allow the omission of goods sold in markets with no market failure or distortion, where the social marginal benefit (all to the consumer) is equal to the social marginal cost (all on the producer). With no distortion in a market for good i, a small change in quantity has no net effect on welfare ($\partial V/\partial z_i = 0$). The effect on welfare is *not* zero, however, if climate policy affects the quantity of a good sold in a market with a 'market failure', such as non-competitive market power, an externality, or any pre-existing tax. In general, either monopoly power or a tax would raise the price paid by consumers relative to the marginal cost faced by producers. In such cases, any increase in the commodity would have a social marginal benefit higher than social marginal cost (a net gain in welfare).

We now describe a set of studies that have evaluated some co-benefits and adverse side-effects (many more studies are reviewed in Sections 5.7, 7.9, 8.7, 9.7, 10.8, 11.7, 12.8 and synthesized in Section 6.6). First, oligopolies may exert market power and raise prices above marginal cost in large industries such as natural resource extraction, iron and steel, or cement. And climate policy may affect that market power. Ryan (2012) finds that a prominent environmental policy in the United States actually increased the market power of incumbent cement manufactures, because it decreased competition from potential entrants that faced higher sunk costs. That is, it created barriers to entry. That effect led to a significant loss in consumer surplus that was not incorporated in the policy's initial benefit-cost analysis.

Second, Ren et al. (2011) point out that a climate policy to reduce CO_2 emissions may increase the use of biofuels, but that "corn-based ethanol production discharges nitrogen into the water environment … [which] … can cause respiratory problems in infants and exacerbate algae growth and hypoxia in water bodies" (p. 498). In other words, a change in climate policy (dp_1) affects the use of nitrogen fertilizer and its runoff ($\partial z_i/\partial p_1$). The effect is an 'adverse side effect.' If nitrogen runoff regulation is less than optimal, the effect on social welfare is negative ($\partial V/\partial z_i < 0$).

Third, arguably the most studied co-benefits of climate policy are the effects on local air pollutant emissions, air quality, and health effects of ground-level ozone (see Section 6.6 for a synthesis of findings from scenario literature and sector-specific measures). Burtraw et al. (2003) conclude that a USD 25 per tonne carbon tax in the United States would reduce NO_X emissions and thereby provide health improvements. Further, the researchers valued these health co-benefits at USD_{1997} 8 (USD_{2010} 10,50) per tonne of carbon reduction in the year 2010. More recently, Groosman et al. (2011) model a specific U.S. climate policy proposal (Warner-Lieberman, S.2191). They calculate effects on health from changes in local flow pollutants (a co-benefit). These health co-benefits mainly come from reductions in particulates and ozone, attributable to reductions in use of coal-fired power plants (Burtraw et al., 2003; Groosman et al., 2011).[20] The authors also value that co-benefit at USD_{2006} 103 billion to USD_{2006} 1.2 trillion (USD_{2010} 111 billion to USD_{2010} 1,3 billion) for the years 2010–2030. That total amount corresponds to USD 1 to USD 77 per tonne of CO_2 (depending on model assumptions and year; see Section 5.7 for a review of a broader set of studies with higher values particularly for developing countries).

Researchers have calculated climate policy co-benefits in many other countries; for instance, Sweden (Riekkola et al., 2011), China (Aunan et al., 2004), and Chile (Dessus and O'Connor, 2003).

A complete analysis of climate policy would measure all such direct or side-effects ($\partial z_i/\partial p_1$) while recognizing that other markets may be functioning properly or be partially regulated (for optimal regulation, $\partial V/\partial z_i = 0$). If the externality from SO_2 is already partly corrected by a tax or permit price that is less than the marginal environmental damage (MED) of SO_2, for example, then the welfare gain from a small reduction in SO_2 may be less than its MED. Or, if the price per tonne of SO_2 is equal to its MED, and climate policy causes a small reduction in SO_2, then the social value of that co-benefit is zero.[21] Similarly, if the labour market is functioning properly with no involuntary unemploy-

[19] We distinguish here between the welfare effect of the co-benefit ($\partial V/\partial z_i$) and the welfare effect of the policy operating through a particular co-benefit ($\frac{\partial V}{\partial z_i}\frac{\partial z_i}{\partial p_1} dp_1$).

[20] Both of the cited studies estimate the dollar value of health improvements, but these are 'gross' benefits that may or may not correctly account for the offsetting effects of existing controls on these local pollution emissions, which is necessary to determine the net welfare effects.

[21] This 'marginal' analysis contemplates a small change in either CO_2 or SO_2. If either of those changes is large, however, then the analysis is somewhat different.

ment, then climate policy may have direct costs from use of that labour but no welfare gain from changes in employment. In other words, in measuring the welfare effects of co-benefits, it is not generally appropriate simply to use the gross marginal value associated with a co-benefit.

In the context of externalities and taxes, this point can be formalized by the following extension of Fullerton and Metcalf (2001):

Equation 3.6.7 $$dV = \sum_{i=1}^{m} (t_i - \mu_i) \frac{\partial z_i}{\partial p_1} dp_1$$

On the right side of the equation, μ_i is the MED from the i[th] commodity; and t_i is its tax rate (or permit price, or the effect of a mandate that makes an input such as emissions more costly). The effect of each good on welfare ($\partial V/\partial z_i$ in Equation 3.6.6 above) is reduced in this model to just $(t_i - \mu_i)$. The intuition is simple: t_i is the buyer's social marginal benefit minus the seller's cost; the externality μ_i is the social marginal cost minus the seller's cost. Therefore, $(t_i - \mu_i)$ is the social marginal benefit minus social marginal cost. It is the net effect on welfare from a change in that commodity. If every externality μ_i is corrected by a tax rate or price exactly equal to μ_i, then the outcome is 'first best'. In that case, dV in Equation 3.6.7 is equal to zero, which means welfare cannot be improved by any change in any policy. If any t_i is not equal to μ_i, however, then the outcome is not optimal, and a 'second best' policy might improve welfare if it has any direct or indirect effect on the amount of that good.

Although the model underlying Equation 3.6.7 is static and climate change is inherently dynamic, the concepts represented in the static model can be used to understand the application to climate. Climate policy reduces carbon emissions, but Equation 3.6.7 shows that this 'direct' effect does not add to social welfare unless the damage per tonne of carbon (μ_C) exceeds the tax on carbon (t_C). The social cost of carbon is discussed in Section 3.9.4. To see a co-benefit in this equation, suppose z_S is the quantity of SO_2 emissions, t_S is the tax per tonne, and μ_S is the MED of additional SO_2. If the tax on SO_2 is too small to correct for the externality ($t_S - \mu_S < 0$), then the market provides 'too much' of it, and any policy such as a carbon tax that reduces the amount of SO_2 ($\partial z_S/\partial p_1 < 0$) would increase economic welfare. The equation sums over all such effects in all markets for all other inputs, outputs, and pollutants.

If those local pollution externalities are already completely corrected by a tax or other policy ($t_S = \mu_S$), however, then a reduction in SO_2 adds nothing to welfare. The existing policy raises the firm's cost of SO_2 emissions by exactly the MED. That firm's consumers reap the full social marginal benefit per tonne of SO_2 through consumption of the output, but those consumers also pay the full social marginal cost per tonne of SO_2. In that case, one additional tonne of SO_2 has social costs exactly equal to social benefits, so any small increase or decrease in SO_2 emissions caused by climate policy provides no net social gain. In fact, if $t_S > \mu_S$, then those emissions are already over-corrected, and any decrease in SO_2 would reduce welfare.

3.6.3.3 The double dividend hypothesis

Another good example of a co-benefit arises from the interaction between carbon policies and other policies (Parry, 1997; Parry and Williams, 1999). Though enacted to reduce GHG emissions, a climate policy may also raise product prices and thus interact with other taxes that also raise product prices. Since the excess burden of taxation rises more than proportionately with the size of the overall effective marginal tax rate, the carbon policy's addition to excess burden may be much larger if it is added into a system with high taxes on output or inputs.

This logic has given rise to the 'double dividend hypothesis' that an emissions tax can both improve the environment and provide revenue to reduce other distorting taxes and thus improve efficiency of the tax system (e.g., Oates and Schwab, 1988; Pearce, 1991; Parry, 1995; Stern, 2009).[22] Parry (1997) and Goulder et al. (1997) conclude that the implementation of a carbon tax or emissions trading can increase the deadweight loss of pre-existing labour tax distortions (the 'tax interaction effect'), but revenue can be used to offset distortionary taxes (the 'revenue recycling effect'). Parry and Williams (1999) investigate the impacts of existing tax distortions in the labour market for eight climate policy instruments (including energy taxes and performance standards) for the United States in 1995. They conclude that pre-existing tax distortions raise the costs of all abatement policies, so the co-benefits of carbon taxes or emissions trading depend on whether generated revenues can be directed to reduce other distortionary taxes. A lesson is that forgoing revenue-raising opportunities from a GHG regulation can significantly increase inefficiencies. The European Union is auctioning an increasing share of permits with revenue going to Member States (see 14.4.2). Australia is using a large share of carbon pricing revenue to reduce income tax (Jotzo, 2012).

To put this discussion into the context of co-benefits, note that Fullerton and Metcalf (2001) use their version of Equation 3.6.7 to consider labour (z_L), taxed at a pre-existing rate t_L (with marginal external damages of zero, so $\mu_L = 0$). Suppose the only other distortion is from carbon emissions (z_C), with MED of μ_C. Thus the economy has 'too little' labour supply, and 'too much' pollution. The combination 'policy change' is a small carbon tax with revenue used to cut the tax rate t_L. Other taxes and damages are zero ($t_i = \mu_i = 0$) for all goods other than z_L and z_C. Thus, Equation 3.6.7 above simplifies further, to show that the two key outcomes are just the net effect on pollution (dz_C) and the net effect on labour (dz_L):

Equation 3.6.8 $$dV = t_L dz_L + (t_C - \mu_C) dz_C$$

[22] The literature contains two versions of the double dividend hypothesis. A 'strong' version says that efficiency gains from diminishing distortionary taxes can more than compensate the costs of pollution taxes. Another 'weak' version says that those gains compensate only part of the costs of pollution taxes (Goulder, 1995).

Therefore, an increase in the carbon tax that reduces emissions ($d z_C < 0$) has a direct benefit of increased economic welfare through the second term, but only to the extent that emissions damages exceed the tax rate ($\mu_C > t_C$). If the labour tax cut increases labour supply, then the first term also increases welfare (a double dividend). But the carbon tax also raises the cost of production and the equilibrium output price, which itself *reduces* the *real* net wage (the tax interaction effect). If that effect dominates the reduction in the labour tax rate (from the revenue recycling effect), then labour supply may fall ($dz_L < 0$). In that case, the first term has a negative effect on wellbeing. In other words, the double-dividend is possible under some circumstances and not others. If the revenue is *not* used to cut the labour tax rate, then the real net wage does fall, and the labour supply may fall.

3.7 Assessing methods of policy choice

Specific climate policies are discussed in Section 3.8; in this section, we discuss methods for evaluating the relative merits of different policies. See also Alkin (2004), Pawson and Tilley (1997), Bardach (2005), Majchrzak (1984), Scriven (1991) Rossi et al. (2005), and Chen (1990). The design and choice of a specific climate policy instrument (or mix of instruments) depends on many economic, social, cultural, ethical, institutional, and political contexts. Different methods for ex-ante and ex-post analysis are available and different types of analytical approaches may be used in tandem to provide perspectives to policymakers.

3.7.1 Policy objectives and evaluation criteria

In addition to reducing GHG emissions, climate policy may have other objectives. Following WGIII AR4 (Gupta et al., 2007), these objectives are organized below in four broad categories: economic, distributional/fairness, environmental, and institutional/political feasibility.[23] The relative importance of these policy objectives differs among countries, especially between developed and developing countries.

In this section we discuss elements of these four categories and expand on recent policy evaluation studies (e.g., Opschoor and Turner, 1994; Ostrom, 1999; Faure and Skogh, 2003; Sterner, 2003; Mickwitz, 2003; Blok, 2007), leaving details of applications and evidence to Chapters 8–11 and 13–15.

[23] Political factors have often been more important than economic factors in explaining instrument choice (Hepburn, 2006). Redistribution to low-income households is an important feature in Australia's emissions pricing policy (Jotzo and Hatfield-Dodds, 2011).

The basic economic framework for policy analysis is depicted in Figure 3.3. This diagram illustrates both the impacts of policies and the criteria for evaluating them in the context of the production of a polluting good (i.e., emissions associated with producing a good). The focus is stylized, but we note that many 'non-economic' values can still be incorporated, to the extent that values can be placed on other considerations, such as effects on nature, culture, biodiversity and 'dignity' (see Sections 3.4.1 and 3.4.2).

As shown in Figure 3.3, the quantity of GHG emissions from producing a good, such as electricity, is shown on the horizontal axis, and the price or cost per unit of that good is shown on the vertical axis. The demand for the emissions is derived from the demand for electricity, as shown by the curve called Private Marginal Benefit (PMB). The private market supply curve is the Private Marginal Cost (PMC) of production, and so the unfettered equilibrium quantity would be Q^0 at equilibrium price P^0. This polluting activity generates external costs, however, and so each unit of output has a Social Marginal Cost (SMC) measured by the vertical sum of PMC plus Marginal External Cost (MEC). With no externalities on the demand side, PMB = SMB.

Under the stated simplifying assumptions, the social optimum is where SMC = PMB, at Q'. The first point here, then, is that the optimal quantity can be achieved by several different policies under these simple conditions. A simple regulatory quota could restrict output from Q^0 to Q', or a fixed number of tradeable permits could restrict pollution to the quantity Q'. In that case, P^n is the equilibrium price net of permit cost (the price received by the firm), while P^g is the price gross of permit cost (paid by the consumer). The permit price is the difference,

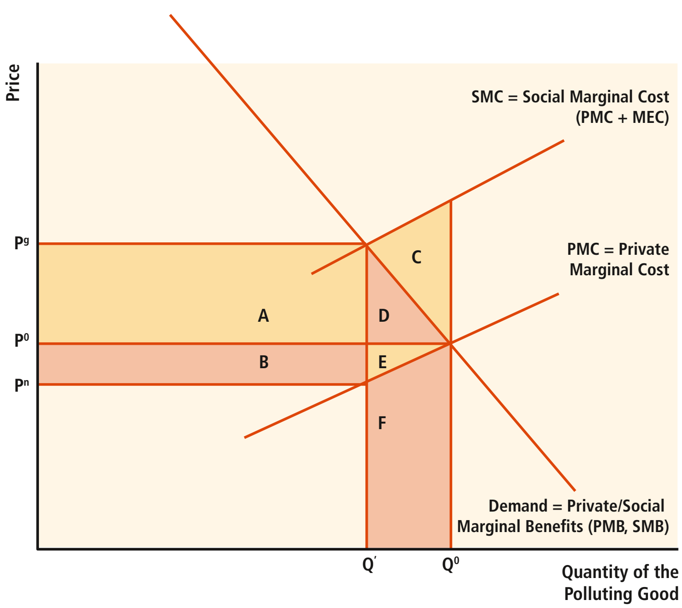

Figure 3.3 | A partial equilibrium model of the costs and benefits of a market output, assuming perfect competition, perfect information, perfect mobility, full employment, and many identical consumers (so all individuals equally benefit from production and they equally bear the external cost of pollution).

$P^g - P^n$. Alternatively, a tax of ($P^g - P^n$) per unit of pollution would raise the firm's cost to SMC and result in equilibrium quantity Q'.

The diagram in Figure 3.3 will be used below to show how the equivalence of these instruments breaks down under more general circumstances, as well as gains and losses to various groups. In other words, we use this diagram to discuss economic as well as distributional, other environmental and cultural objectives, and institutional/political feasibility.

3.7.1.1 Economic objectives

Economic efficiency. Consider an economy's allocation of resources (goods, services, inputs, and productive activities). An allocation is efficient if it is not possible to reallocate resources so as to make at least one person better off without making someone else worse off. This is also known as the Pareto criterion for efficiency (discussed in Section 3.6.1) (see e.g., Sterner, 2003; Harrington et al., 2004; Tietenberg, 2006). In Figure 3.3, any reduction in output from Q^0 improves efficiency because it saves costs (height of SMC) that exceed the benefits of that output (height of PMB).[24] This reduction can be achieved by a tax levied on the externality (a carbon tax), or by tradeable emission permits. Further reductions in output generate further net gains, by the extent to which SMC exceeds SMB, until output is reduced to Q' (where SMC = SMB). Hence, the gain in economic efficiency is area C. Perfect efficiency is difficult to achieve, for practical reasons, but initial steps from Q^0 achieve a larger gain (SMC > SMB) than the last step to Q' (because SMC ≈ SMB near the left point of triangle C).

An aspect of economic efficiency over time is the extent to which a carbon policy encourages the right amount of investment in research, innovation, and technological change, in order to reduce GHG emissions more cheaply (Jung et al., 1996; Mundaca and Neij, 2009). See Section 3.11.

Cost-effectiveness. Pollution per unit of output in Figure 3.3 is fixed, but actual technologies provide different ways of reducing pollution per unit of output. A policy is cost-effective if it reduces pollution (given a climate target) at lowest cost. An important condition of cost-effectiveness is that marginal compliance costs should be equal among parties (ignoring other distortions such as regulations) (Babiker et al., 2004).

Transaction costs. In addition to the price paid or received, market actors face other costs in initiating and completing transactions. These costs alter the performance and relative effectiveness of different policies and need to be considered in their design, implementation, and assessment (Mundaca et al., 2013; see also Matthews, 1986, p. 906).

[24] Other approaches are discussed in Section 3.6.

3.7.1.2 Distributional objectives

Six distributional effects. A policy may generate gains to some and losses to others. The fairness or overall welfare consequences of these distributional effects is important to many people and can be evaluated using a SWF, as discussed in Section 3.4.6. These effects fall into six categories (Fullerton, 2011), and are illustrated in Box 3.6 below. In Figure 3.3, any policy instrument might reduce the quantity of polluting output, such as from Q^0 to Q', which reduces emissions, raises the equilibrium price paid by consumers (from P^0 to P^g), and reduces the price received by firms (from P^0 to P^n). The six effects are illustrated in Box 3.6. The framework can be applied to any environmental problem and any policy to correct it.

With reference to Box 3.6, the first effect of a carbon policy on consumers is generally regressive (though most analyses are for developed countries), because the higher price of electricity imposes a heavier burden on lower income groups who spend more of their income on electricity (Metcalf, 1999; Grainger and Kolstad, 2010). However, fuel taxes tend to be progressive in developing countries (Sterner, 2011). The sign of the second effect, on factors of production, is generally ambiguous. The third effect is regressive if permits are given to firms, because then profits accrue to shareholders who tend to be in high-income brackets (Parry, 2004). But if government captures the scarcity rents by selling permits or through a carbon tax, the funds can be used to offset burdens on low-income consumers and make the overall effect progressive instead of regressive. Other effects are quite difficult to measure.

Much of the literature on 'environmental justice' discusses the potential effects of a pollution policy on neighbourhoods with residents from different income or ethnic groups (Sieg et al., 2004). Climate policies affect both GHG emissions and other local pollutants such as SO_2 or NO_X, whose concentrations vary widely. Furthermore, the cost of mitigation may not be shared equally among all income or ethnic groups. And even 'global' climate change can have different temperature impacts on different areas, or other differential effects (e.g., on coastal areas via rise in sea level).

The distributional impacts of policies include aspects such as fairness/equity (Gupta et al., 2007). A perceived unfair distribution of costs and benefits could prove politically challenging (see below), since efficiency may be gained at the expense of equity objectives.

3.7.1.3 Environmental objectives

Environmental effectiveness. A policy is environmentally effective if it achieves its expected environmental target (e.g., GHG emission reduction). The simple policies mentioned above might be equally effective in reducing pollution (from Q^0 to Q' in Figure 3.3), but actual policies differ in terms of ambition levels, enforcement and compliance.

Box 3.6 | Six distributional effects of climate policy, illustrated for a permit obligation or emissions tax on coal-fired electricity, under the assumption of perfectly competitive electricity markets

First, the policy raises the cost of generating electricity and if cost increases are passed through to consumers, for example through competitive markets or changes in regulated prices, the consumer's price increases (from P^0 to P^g), so it reduces consumer surplus. In Figure 3.3, the loss to consumers is the sum of areas A + D. Losses are greater for those who spend more on electricity.

Second, the policy reduces the net price received by the firm (from P^0 to P^n), so it reduces producer surplus by the sum of areas B + E. The effect is reduced payments to factors of production, such as labour and capital. Losses are greater for those who receive more income from the displaced factor.

Third, pollution and output are restricted, so the policy generates 'scarcity rents' such as the value of a restricted number of permits (areas A + B). If the permits are given to firms, these rents accrue to shareholders. The government could partly or fully capture the rents by selling the permits or by a tax per unit of emissions (Fullerton and Metcalf, 2001).

Fourth, because the policy restricts GHG emissions, it confers benefits on those who would otherwise suffer from climate change. The value of those benefits is areas C + D + E.

Fifth, the electricity sector uses less labour, capital and other resources. It no longer pays them (areas E + F). With perfect mobility, these factors are immediately redeployed elsewhere, with no loss. In practice however, social costs may be substantial, including transaction costs of shifting to other industries or regions, transitional or permanent unemployment, and social and psychological displacement.

Sixth, any gain or loss described above can be capitalized into asset prices, with substantial immediate effects for current owners. For example, the value of a corporation that owns coal-fired generation assets may fall, in line with the expected present value of the policy change, while the value of corporations that own low-emissions generation technologies may rise.

The connection between these distributional effects and 'economic efficiency' is revealed by adding up all the gains and losses just described: the consumer surplus loss is A + D; producer surplus loss is B + E; the gain in scarcity rents is A + B; and the environmental gain is C + D + E, assuming the gainers and losers receive equal weights. The net sum of the gains and losses is area C, described above as the net gain in economic efficiency.

In many cases, a distributional implication of imposing efficient externality pricing (e.g., area A + B) is much larger than the efficiency gains (area C). This illustrates the importance of distributional considerations in discussions on emissions-reducing policies, and it indicates why distributional considerations often loom large in debates about climate policy.

Co-benefits. Climate policy may reduce both GHG emissions and local pollutants, such as SO_2 emissions that cause acid rain, or NO_X emissions that contribute to ground level ozone. As described in Section 3.6.3, reductions in other pollutants may not yield any net gain to society if they are already optimally regulated (where their marginal abatement costs and their marginal damages are equal). If pollutants are inefficiently regulated, however, climate regulations can yield positive or negative net social gains by reducing them.

Climate policy is also likely to affect other national objectives, such as energy security. For countries that want to reduce their dependence on imported fossil fuels, climate policy can bolster energy efficiency and the domestic renewable energy supply, while cutting GHG emissions. See Section 3.6.3 on co-benefits.

Carbon leakage. The effectiveness of a national policy to reduce emissions can be undermined if it results in increased emissions in other countries, for example, because of trading advantages in countries with more relaxed policies (see Section 3.9.5). Another type of leakage occurs within emission trading systems. Unilateral emission reductions by one party will release emission permits and be outweighed by new emissions within the trading regime.

3.7.1.4 Institutional and political feasibility

Administrative burden. This depends on how a policy is implemented, monitored, and enforced (Nordhaus and Danish, 2003). The size of the burden reflects, inter alia, the institutional framework, human and financial costs and policy objectives (Nordhaus and Danish, 2003; Mundaca et al., 2010). Administrative costs in public policy are often overlooked (Tietenberg, 2006)

Political feasibility is the likelihood of a policy gaining acceptance and being adopted and implemented (Gupta et al., 2007, p. 785). It covers the obstacles faced and key design features that can generate or reduce resistance among political parties (Nordhaus and Danish, 2003). Political feasibility may also depend on environmental effectiveness and whether regulatory and other costs are equitably distributed across society (Rist, 1998). The ability of governments to implement political decisions may be hampered by interest groups; policies will be more feasible if the benefits can be used to buy the support of a winning coalition (Compston, 2010). *Ex ante*, these criteria can be used in assessing and improving policies. *Ex post*, they can be used to verify results, withdraw inefficient policies and correct policy performance. For specific applications, see Chapters 7–15.

3.7.2 Analytical methods for decision support

Previous IPCC Assessment Reports have addressed analytical methods to support decision making, including both numerical and case-based methods. Bruce et al. (1996, chap. 2 and 10) focus heavily on quantitative methods and IAMs. Metz et al. (2001) provide a wider review of approaches, including emerging participatory forms of decision making. Metz et al. (2007) briefly elaborate on quantitative methods and list sociological analytical frameworks. In this section, we summarize the core information on methodologies separated into quantitative- and qualitative-oriented approaches.

3.7.2.1 Quantitative-oriented approaches

In decision making, quantitative methods can be used to organize and manage numerical information, provide structured analytical frameworks, and generate alternative scenarios—with different levels of uncertainty (Majchrzak, 1984). An approach that attempts to estimate and aggregate monetized values of all costs and benefits that could result from a policy is CBA. It may require estimating non-market values, and choosing a discount rate to express all costs and benefits in present value. When benefits are difficult to estimate in monetary terms, a Cost-Effectiveness Analysis (CEA) may be preferable. A CEA can be used to compare the costs of different policy options (Tietenberg, 2006) for achieving a well-defined goal. It can also estimate and identify the lowest possible compliance costs, thereby generating a ranking of policy alternatives (Levin and McEwan, 2001). Both CEA and CBA are similarly limited in their ability to generate data, measure and value future intangible costs.

Various types of model can provide information for CBA, including energy-economy-environment models that study energy systems and transitions towards more sustainable technology. A common classification of model methodologies includes 'bottom-up' and 'top-down' approaches. Hybrids of the two can compensate for some known limitations and inherent uncertainties (Rivers and Jaccard, 2006):[25]

- Given exogenously defined macroeconomic and demographic scenarios, bottom-up models can provide detailed representations of supply- and demand-side technology paths that combine both cost and performance data. Conventional bottom-up models may lack a realistic representation of behaviour (e.g., heterogeneity) and may overlook critical market imperfections, such as transaction costs and information asymmetries (e.g., Craig et al., 2002; DeCanio, 2003; Greening and Bernow, 2004).

- By contrast, top-down models, such as computable general equilibrium (CGE), represent technology and behaviour using an aggregate production function for each sector to analyze effects of policies on economic growth, trade, employment, and public revenues (see, e.g., DeCanio, 2003). They are often calibrated on real data from the economy. However, such models may not represent all markets, all separate policies, all technological flexibility, and all market imperfections (Laitner et al., 2003). Parameters are estimated from historical data, so forecasts may not predict a future that is fundamentally different from past experience (i.e., path dependency) (Scheraga, 1994; Hourcade et al., 2006). For potential technology change, many models use sub-models of specific supply or end-use devices based on engineering data (Jacoby et al., 2006; Richels and Blanford, 2008; Lüken et al., 2011; Karplus et al., 2013).

With CBA, it is difficult to reduce all social objectives to a single metric. One approach to dealing with the multiple evaluation criteria is Multi-Criteria Analysis, or MCA (Keeney and Raiffa, 1993; Greening and Bernow, 2004). Some argue that analyzing environmental and energy policies is a multi-criteria problem, involving numerous decision makers with diverse objectives and levels of understanding of the science and complexity of analytical tools (Sterner, 2003; Greening and Bernow, 2004). The advantage of MCA is that the analyst does not have to determine how outcomes are traded-off by the policymaker. For instance, costs can be separated from ecosystem losses. But even with MCA, one must ultimately determine the appropriate trade-off rates among the different objectives. Nevertheless, it can be a useful way of analyzing problems where being restricted to one metric is problematic, either politically or practically. CGE models can specify consumer and producer behaviour and 'simulate' effects of climate policy on various outcomes, including real gains and losses to different groups (e.g., households that differ in income, region or demographic characteristics). With behavioural reactions, direct burdens are shifted from one taxpayer to another through changes in prices paid for various outputs and received for various inputs. A significant challenge is the definition of a 'welfare baseline' (i.e., identifying each welfare level without a specific policy).

Integrated Assessment Models (IAMs) or simply Integrated Models (IAs) combine some or all of the relevant components necessary to evaluate the consequences of mitigation policies on economic activity, the global climate, the impacts of associated climate change, and the relevance of that change to people, societies, and economies. Some

[25] The literature acknowledges that it is difficult to make a clear classification among modelling approaches, as variations among categories and also alternative simulation methodologies do exist (e.g., macroeconometric Keynesian models, agent-based approaches) (Hourcade et al., 2006; Mundaca et al., 2010; Scrieciu et al., 2013).

models may only be able to represent how the economy responds to mitigation policy and no more; some models may include a physical model of the climate and be able to translate changes in emissions into changes in global temperature; some models may also include a representation of the impacts of climate change; and some models may translate those impacts into damage to society and economies. Models can be highly aggregate (top-down) or detailed process analysis models (bottom-up), or a combination of both (see also Chapter 6). Some IAMs relate climate change variables with other physical and biological variables like crop yield, food prices, premature death, flooding or drought events, or land use change (Reilly et al., 2013). Computational limits may preclude the scales required for some climate processes (Donner and Large, 2008),[26] but recent attempts are directed towards integrating human activities with full Earth System models (Jones et al., 2013). All of the models used in WGIII (primarily Chapter 6) focus on how mitigation policies translate into emissions; none of those models have a representation of climate damages. IAMs have been criticized in recent years (e.g., Ackerman et al., 2009; Pindyck, 2013). Much of the most recent criticism is directed at models that include a representation of climate damage; none of the models used in Chapter 6 fall into this category. Refer to Chapter 6 for more detail in this regard.

Other quantitative-oriented approaches to support policy evaluation include tolerable windows (Bruckner et al., 1999), safe-landing/guard rail (Alcamo and Kreileman, 1996), and portfolio theory (Howarth, 1996). Outside economics, those who study decision sciences emphasize the importance of facing difficult value-based trade-offs across objectives, and the relevance of various techniques to help stakeholders address trade-offs (see, e.g., Keeney and Raiffa, 1993).

3.7.2.2 Qualitative approaches

Various qualitative policy evaluation approaches focus on the social, ethical, and cultural dimensions of climate policy. They sometimes complement quantitative approaches by considering contextual differences, multiple decision makers, bounded rationality, information asymmetries, and political and negotiation processes (Toth et al., 2001; Halsnæs et al., 2007). Sociological analytical approaches examine human behaviour and climate change (Blumer, 1956), including beliefs, attitudes, values, norms, and social structures (Rosa and Dietz, 1998). Focus groups can capture the fact that "people often need to listen to others' opinions and understandings to form their own" (Marshall and Rossman, 2006, p. 114). Participatory approaches focus on process, involving the active participation of various actors in a given decision-making process (van den Hove, 2000). Participatory approaches in support of decision making include appreciation-influence-control, goal oriented project planning, participatory rural appraisal, and beneficiary assessment. MCA can also take a purely qualitative form. For the pros and cons of participatory approaches, see Toth et al. (2001, p. 652). Other qualitative-oriented approaches include systematic client consultation, social assessment and team up (Toth et al., 2001; Halsnæs et al., 2007).

[26] Stanton et al. (2009) also place climate change models into categories (welfare maximization, general equilibrium, partial equilibrium, cost minimization, and simulation models).

3.8 Policy instruments and regulations

A broad range of policy instruments for climate change mitigation is available to policymakers. These include economic incentives, such as taxes, tradeable allowances, and subsidies; direct regulatory approaches, such as technology or performance standards; information programs; government provision, of technologies or products; and voluntary actions.

Chapter 13 of WGIII AR4 provided a typology and definition of mitigation policy instruments. Here we present an update on the basis of new research on the design, applicability, interaction, and political economy of policy instruments, as well as on applicability of policy instruments in developed and developing countries (see Box 3.8). For details about applications and empirical assessments of mitigation policy instruments, see Chapters 7–12 (sectoral level), Chapter 13 (international cooperation), Chapter 14 (regional cooperation), and Chapter 15 (national and sub-national policies).

3.8.1 Economic incentives

Economic (or market) instruments include incentives that alter the conditions or behaviour of target participants and lead to a reduction in aggregate emissions. In economic policy instruments, a distinction is made between 'price' and 'quantity'. A tradeable allowance or permit system represents a quantity policy whereby the total quantity of pollution (a cap) is defined, and trading in emission rights under that cap is allowed. A price instrument requires polluters to pay a fixed price per unit of emissions (tax or charge), regardless of the quantity of emissions.

3.8.1.1 Emissions taxes and permit trading

Both the approaches described above create a price signal as an incentive to reducing emissions (see Box 3.7), which can extend throughout the economy. Economic instruments will tend to be more cost-effective than regulatory interventions and may be less susceptible to rent-seeking by interest groups. The empirical evidence is that economic instruments have, on the whole, performed better than regulatory instruments, but that in many cases improvements could have been made through better policy design (Hahn, 1989; Anthoff and Hahn, 2010).

3.8.1.2 Subsidies

Subsidies can be used as an instrument of mitigation policy by correcting market failures in the provision of low-carbon technologies and products. They have a particular role in supporting new technologies. Empirical research has shown that social rates of return on R&D can be higher than private rates of return, since spillovers are not fully internalized by the firms (see 3.11).

Subsidies are also used to stimulate energy efficiency and renewable energy production. Such subsidies do generally not fully correct negative externalities but rather support the alternatives, and are less efficient alternatives to carbon taxes and emission trading for inducing mitigation. Energy subsidies are often provided for fossil fuel production or consumption, and prove to increase emissions and put heavy burdens on public budgets (Lin and Jiang, 2011; Arze del Granado et al., 2012; Gunningham, 2013). Lowering or removing such subsidies would contribute to global mitigation, but this has proved difficult (IEA et al., 2011).

Subsidies to renewable energy and other forms of government expenditure on mitigation also have other drawbacks. First, public funds need to be raised to finance the expenditures, with well-known economic inefficiencies arising from taxation (Ballard and Fullerton, 1992). Second, subsidies, if not correcting market failures, can lead to excessive entry into, or insufficient exit from, an industry (Stigler, 1971). Third, subsidies can become politically entrenched, with the beneficiaries lobbying governments for their retention at the expense of society overall (Tullock, 1975).

Hybrids of fees and subsidies are also in use. A renewable energy certificate system can be viewed as a hybrid with a fee on energy consumption and a subsidy to renewable production (e.g., Amundsen and Mortensen, 2001). Feebates (Greene et al., 2005) involve setting an objective, such as average vehicle fuel economy; then firms or individuals that under-perform pay a fee per unit of under-performance and over-performers receive a subsidy. The incentives may be structured to generate no net revenue—the fees collected finance the subsidy.

3.8.2 Direct regulatory approaches

Prescriptive regulation involves rules that must be fulfilled by polluters who face a penalty in case of non-compliance. Examples are performance standards that specify the maximum allowable GHG emissions from particular processes or activities; technology standards that mandate specific pollution abatement technologies or production methods; and product standards that define the characteristics of potentially polluting products, including labelling of appliances in buildings, industry, and the transport sector (Freeman and Kolstad, 2006).

These regulatory approaches will tend to be more suitable in circumstances where the reach or effectiveness of market-based instruments is constrained because of institutional factors, including lack of markets in emissions intensive sectors such as energy. In 'mixed economies', where parts of the economy are based on command-and-control

Box 3.7 | Equivalence of emissions taxes and permit trading schemes

Price-based and quantity-based instruments are equivalent under certainty, but differ in the extent of mitigation and costs if emissions and abatement costs are uncertain to the regulator (Weitzman, 1974). Hybrid instruments, where a quantity constraint can be overridden if the price is higher or lower than a threshold, have been shown to be more efficient under uncertainty (Roberts and Spence, 1976; McKibbin and Wilcoxen, 2002; Pizer, 2002). Variants of hybrid approaches featuring price ceilings and price floors have been implemented in recent emissions trading schemes (Chapters 14 and 15). The possibility of periodic adjustments to tax rates and caps and their implementation under permit schemes further breaks down the distinction between price-based and quantity-based market-based instruments.

Equivalence also exists for fiscal effects and the costs imposed on emitters. Until recently, most of the literature has assumed that emissions taxes and permit trading differ in the revenue they yield for governments and the costs imposed on emitters, assuming that emissions tax revenue fully accrues to governments while under emissions trading schemes permits are given freely to emitters. This was also the case in early policy practice (Chapters 14 and 15). It has been widely assumed that permit schemes are easier to implement politically because permits are allocated free to emitters. However, recognition has grown that permits can be wholly or partly auctioned, and that an emissions tax need not apply to the total amount of emissions covered (e.g., Aldy J. E. et al., 2010; Goulder, 2013). Tax thresholds could exempt part of the overall amount of an emitter's liabilities, while charging the full tax rate on any extra emissions, analogous to free permits (Pezzey, 2003; Pezzey and Jotzo, 2012). Conversely, governments could auction some or all permits in an emissions trading scheme, and use the revenue to reduce other more distorting taxes and charges (Section 3.6.3.3), assist consumers, or pay for complementary policies.

approaches while others rely on markets, effective climate change mitigation policy will generally require a mix of market and non-market instruments.

3.8.3 Information programmes

Reductions in GHG emissions can also be achieved by providing accurate and comprehensive information to producers and consumers on the costs and benefits of alternative options. Information instruments include governmental financing of research and public statistics, and awareness-raising campaigns on consumption and production choices (Mont and Dalhammar, 2005).

3.8.4 Government provision of public goods and services, and procurement

Government funding of public goods and services may be aimed directly at reducing GHG emissions, for example, by providing infrastructures and public transport services that use energy more efficiently; promoting R&D on innovative approaches to mitigation; and removing legal barriers (Creutzig et al., 2011).

3.8.5 Voluntary actions

Voluntary agreements can be made between governments and private parties in order to achieve environmental objectives or improve environmental performance beyond compliance with regulatory obligations. They include industry agreements, self-certification, environmental management systems, and self-imposed targets. The literature is ambiguous about whether any additional environmental gains are obtained through voluntary agreements (Koehler, 2007; Lyon and Maxwell, 2007; Borck and Coglianese, 2009).

3.8.6 Policy interactions and complementarity

Most of the literature deals with the use and assessment of one instrument, or compares alternative options, whereas, in reality, numerous, often overlapping instruments are in operation (see Chapters 7–16). Multiple objectives in addition to climate change mitigation, such as energy security and affordability and technological and industrial development, may call for multiple policy instruments. Another question is whether and to what extent emissions pricing policies need to be complemented by regulatory and other instruments to achieve cost-effective mitigation, for example, because of additional market failures, as in the case of energy efficiency (Box 3.10) and technological development (3.11.1).

However, the coexistence of different instruments creates synergies, overlaps and interactions that may influence the effectiveness and costs of policies relative to a theoretical optimum (Kolstad et al., 1990; see also Section 3.6 above). Recent studies have analyzed interactions between tradeable quotas or certificates for renewable energy and emission trading (e.g., Möst and Fichtner, 2010; Böhringer and Rosendahl, 2010) and emissions trading and tradeable certificates for energy efficiency improvements (e.g., Mundaca, 2008; Sorrell et al., 2009) (see also Chapters 9 and 15). Similar effects occur in the overlay of other selective policy instruments with comprehensive pricing instruments. Policy interactions can also create implementation and enforcement challenges when policies are concurrently pursued by different legal or administrative jurisdictions (Goulder and Parry, 2008; Goulder and Stavins, 2011).

3.8.7 Government failure and policy failure

To achieve large emissions reductions, policy interventions will be needed. But failure is always a possibility, as shown by recent experiences involving mitigation policies (Chapters 13–16). The literature is beginning to reflect this. The failure of such policies tends to be associated with the translation of individual preferences into government action.

3.8.7.1 Rent-seeking

Policy interventions create rents, including subsidies, price changes arising from taxation or regulation, and emissions permits. Private interests lobby governments for policies that maximize the value of their assets and profits. The sums involved in mitigating climate change provide incentives to the owners of assets in GHG intensive industries or technologies for low-carbon production to engage in rent-seeking.[27]

The political economy of interest group lobbying (Olson, 1971) is apparent in the implementation of climate change mitigation policies. Examples include lobbying for allocations of free permits under the emissions trading schemes in Europe (Hepburn et al., 2006; Sijm et al., 2006; Ellerman, 2010) and Australia (Pezzey et al., 2010) as well as renewable energy support policies in several countries (Helm, 2010).

To minimize the influence of rent-seeking and the risk of regulatory capture, two basic approaches have been identified (Helm, 2010). One is to give independent institutions a strong role, for example, the United Kingdom's Committee on Climate Change (McGregor et al., 2012) and Australia's Climate Change Authority (Keenan R.J et al., 2012) (see also Chapter 15).

Another approach to reducing rent-seeking is to rely less on regulatory approaches and more on market mechanisms, which are less prone to capture by special interests because the value and distribution of rents

[27] CBA takes into account that governments are social-profit maximizers, which may not necessarily be the case.

Box 3.8 | Different conditions in developed and developing countries and implications for suitability of policy instruments

Differences in economic structure, institutions, and policy objectives between low-income and high-income countries can mean differences in the suitability and performance of policy instruments. Overriding policy objectives in most developing countries tend to be strongly oriented towards facilitating development (Kok et al., 2008), increasing access to energy and alleviating poverty (see Chapters 4 and 14). In general, they have fewer human and financial resources, less advanced technology, and poorer institutional and administrative capacity than developed countries. This may constrain their ability to evaluate, implement, and enforce policies. Further, the prerequisites for effectiveness, such as liberalized energy markets to underpin price-based emissions reduction instruments, are often lacking. Thus, the use of some policy instruments, including carbon trading schemes, can pose greater institutional hurdles and implementation costs, or not be feasible.

Capacity building is therefore critical in creating mechanisms to support policy choices and implementation. Economic reform may also be needed in order to remove distortions in regulatory and pricing mechanisms and enable effective mitigation policies to be devised and implemented.

The opportunity cost of capital, and of government resources in particular, may be higher in developing countries than in developed countries. Consequently, the payoff from mitigation policies needs to be higher than in developed countries in order for mitigation investment to be judged worthwhile. Thus, developing countries may require international financial assistance in order to support their mitigation activities or make them economically viable.

is more transparent. This may of course lead to other problems associated with regulatory design.

3.8.7.2 Policy uncertainty

One aim of climate change mitigation policy is to promote emissions-reducing investments in sectors where assets have a long economic lifespan, such as energy (Chapter 7), buildings (Chapter 9) and transport (Chapter 8). Investment decisions are mainly based on expectations about future costs and revenues. Therefore, expectations about future policy settings can be more important than current policies in determining the nature and extent of investment for mitigation (Ulph, 2013).

Uncertainty over future policy directions, including changes in existing policies arising from, say, political change, can affect investment decisions and inhibit mitigation, as well as create economic costs (Weitzman, 1980; see also Chapter 2). To achieve cost-effective mitigation actions, a stable and predictable policy framework is required.

3.9 Metrics of costs and benefits

This section focuses on conceptual issues that arise in the quantification and measurement, using a common metric, of the pros and cons associated with mitigation and adaptation (i.e., benefits and costs). How costs are balanced against benefits in evaluating a climate policy is a matter for ethics, as has repeatedly been emphasized in this chapter. The discussion is largely based on the economic paradigm of balancing costs against benefits, with both measured in monetary units. But leaving aside how benefits and costs are monetized or balanced to develop policy, the underlying information can be helpful for policy makers who adopt other ethical perspectives. This section is also relevant for methods that reduce performance to a small number of metrics rather than a single one (such as MCA).

We begin with the chain of cause and effect. The chain starts with human activity that generates emissions that may be reduced with mitigation (recognizing that nature also contributes to emissions of GHGs). The global emissions of GHGs lead to changes in atmospheric concentrations, then to changes in radiative forcing, and finally to changes in climate. The latter affect biological and physical systems in good as well as bad ways (including through impacts on agriculture, forests, ecosystems, energy generation, fire, and floods). These changes in turn affect human wellbeing, negatively or positively, with both monetary and other consequences.[28] Each link in the chain has a time dimension, since emissions at a particular point in time lead to radiative forcing at future points in time, which later lead to more impacts and damages. The links also have spatial dimensions. Models play a key role in defining the relationships between the links in the chain. Global Climate Models (GCMs) translate emissions through atmospheric concentrations and radiative forcing into changes in climate. Other models—including crop, forest growth and hydrology models—translate

[28] We refer to effects on biological and physical systems as 'impacts', and effects of those impacts on human wellbeing as 'damages', whether positive or negative. These effects may include non-human impacts that are of concern to humans (see also Sections 3.4.1 and 3.4.3).

changes in climate into physical impacts. Economic models translate those impacts into measures that reflect a human perspective, typically monetary measures of welfare loss or gain. GCMs aggregate emissions of various gases into an overall level of radiative forcing; hydrology models aggregate precipitation at multiple locations within a watershed into stream flow at a given location; economic models aggregate impacts into an overall measure of welfare loss.

Much of the literature on impacts focuses on particular types of impacts at particular locations. Another aspect involves metrics that allow differential regulation of different GHGs, for instance, the relative weight that regulators should place on CH_4 and CO_2 in mitigation strategies. Because impacts and damages are so poorly known it has proved surprisingly difficult to provide a rigorous answer to that question.

3.9.1 The damages from climate change

The impacts of climate change may benefit some people and harm others. It can affect their livelihood, health, access to food, water and other amenities, and natural environment. While many non-monetary metrics can be used to characterize components of impacts, they provide no unambiguous aggregation methods for characterizing overall changes in welfare. In principle, the economic theory of monetary valuation provides a way, albeit an imperfect one, of performing this aggregation and supporting associated policy-making processes.

Changes that affect human wellbeing can be 'market' or 'non-market' changes. Market effects involve changes in prices, revenue and net income, as well as in the quantity, quality, or availability of market commodities. Key is the ability to observe both prices and how people respond to them when choosing quantities to consume. Non-market changes involve the quantity, quality, or availability of things that matter to people and which are not obtained through the market (e.g., quality of life, culture, and environmental quality). A change in a physical or biological system can generate both market and non-market damage to human wellbeing. For example, an episode of extreme heat in a rural area may generate heat stress in farm labourers and may dry up a wetland that serves as a refuge for migratory birds, while killing some crops and impairing the quality of others. From an economic perspective, damages would be conceptualized as a loss of income for farmers and farm workers, an increase in crop prices for consumers and a reduction in their quality; and non-market impacts might include the impairment of the ecosystem and human health (though some health effects may be captured in the wages of farm workers).

Economists define value in terms of a 'trade-off'. As discussed in Section 3.6.1, the economic value of an item, measured in money terms, is defined as the amount of income that would make a person whole, either in lieu of the environmental change or in conjunction with the environmental change; that is, its 'income equivalent'. This equivalence is evaluated through the Willingness To Pay (WTP) and Willingness To Accept (WTA) compensation measures (see also Willig, 1976; Hanemann, 1991). The item in question may or may not be a marketed commodity: it can be *anything* that the person values. Thus, the economic value of an item is *not* in general the same as its price or the total expenditure on it. The economic concept of value based on a trade-off has some critics. The item being valued may be seen as incommensurable with money, such that no trade-off is possible. Or, the trade-off may be deemed inappropriate or unethical (e.g., Kelman, 1981; see also Jamieson, 1992; Sagoff, 2008). In addition, while the economic concept of value is defined for an individual, it is typically measured for aggregates of individuals, and the issue of equity-weighting is often disregarded (Nyborg, 2012; see also Subsection 3.5.1.3).[29]

The methods used to measure WTP and WTA fall into two categories, known as 'revealed preference' and 'stated preference' methods. For a marketed item, an individual's purchase behaviour reveals information about their value of it. Observation of purchase behaviour in the marketplace is the basis of the revealed preference approaches. One can estimate a demand function from data on observed choice behaviour. Then, from the estimated demand function, one can infer the purchaser's WTP or WTA values for changes in the price, quantity, quality, or availability of the commodity. Another revealed preference approach, known as the hedonic pricing method, is based on finding an observed relationship between the quality characteristics of marketed items and the price at which they are sold (e.g., between the price of farmland and the condition and location of the farmland). From this approach, one can infer the 'marginal' value of a change in characteristics.[30] For instance, some have attempted to measure climate damages using an hedonic approach based on the correlation of residential house prices and climate in different areas (Cragg and Kahn, 1997; Maddison, 2001, 2003; Maddison and Bigano, 2003; Rehdanz and Maddison, 2009). The primary limitation of revealed preference methods is the frequent lack of a market associated with the environmental good being valued.

With stated preference, the analyst employs a survey or experiment through which subjects are confronted with a trade-off. With contingent valuation, for example, they are asked to choose whether or not to make a payment, such as a tax increase that allows the government to undertake an action that accomplishes a specific outcome (e.g., protecting a particular ecosystem). By varying the cost across subjects and then correlating the cost offered with the percentage of 'yes' responses, the analyst traces out a form of demand function from which the WTP (or WTA) measure can be derived. With choice experiments, subjects are asked to make repeated choices among alternative

29 The use of the term 'willingness' in WTP and WTA should not be taken literally. For instance, individuals may have a willingness to pay for cleaner air (the reduction in income that would be equivalent in welfare terms to an increase in air quality) but they may be very unwilling to make that payment, believing that clean air is a right that should not have to be purchased.

30 Details of these methods can be found in Becht (1995), chapters by McConnell and Bockstael (2006), Palmquist (2006), Phaneuf and Smith (2006), Mäler and Vincent (2005), or in textbooks such as Kolstad (2010), Champ, Boyle and Brown (2003), Haab and McConnell (2002) or Bockstael and McConnell (2007).

options that combine different outcomes with different levels of cost.[31] Although a growing number of researchers use stated preference studies to measure the public's WTP for climate change mitigation, one prominent criticism is the hypothetical nature of the choices involved.[32]

All these methods have been applied to valuing the damages from climate change.[33] AR2 contained a review of the literature on the economic valuation of climate change impacts. Since then, the literature has grown exponentially. The economic methodology has changed little (except for more coverage of non-market impacts and more use of stated preference). The main change is in the spatial representation of climate change impacts; whereas the older literature tended to measure the economic consequences of a uniform increase of, say 2.5 °C across the United States, the recent literature uses downscaling to measure impacts on a fine spatial scale. Most of the recent literature on the economic valuations of climate change has focused on market impacts, especially impacts on agriculture, forestry, sea level, energy, water, and tourism.[34]

The most extensive economic literature pertains to agriculture. The demand for many such commodities is often inelastic, so the short-run consequence of a negative supply shock is a price increase; while a benefit to producers, it is harmful for consumers (Roberts and Schlenker, 2010; Lobell et al., 2011). Some studies measure the effect of weather on current profits, rather than that of climate on long-term profitability (e.g., Deschênes and Greenstone, 2007), and some explore the effect of both weather and climate on current profits (Kelly et al., 2005). Examining weather and climate simultaneously leads to difficulties in identifying the separate effects of weather and climate (Deschênes and Kolstad, 2011), as well as in dealing with the confounding effects of price changes (Fisher et al., 2012). While some recent studies have found that extreme climate events have a disproportionate impact on agricultural systems (Schlenker and Roberts, 2009; Lobell et al., 2011; Deschênes and Kolstad, 2011; see also WGII, Section 7.3.2.1), the relatively high degree of spatial or temporal aggregation means that those events are not well captured in many existing economic analyses. Another difficulty is the welfare significance of shifts in location of agricultural production caused by climate. Markets for agricultural commodities are national or international in scope, so some economic analyses focus on aggregate international producer and consumer welfare. Under the potential Pareto criterion, transfers of income from one region to another are of no welfare significance, though of real policy significance.[35]

With other market sectors, the literature is both sparse and highly fragmented, but includes some estimates of economic impacts of climate change on energy, water, sea level rise, tourism, and health in particular locations. With regard to energy, climate change is expected to reduce demand for heating and increase demand for cooling (see WGII AR5, Chapter 10). Even if those two effects offset one another, the economic cost need not be negligible. With water supply, what matters in many cases is not total annual precipitation but the match between the timing of precipitation and the timing of water use (Strzepek and Boehlert, 2010). Those questions require analysis on a finer temporal or spatial scale than has typically been employed in the economic damage literature.

Estimates of the economic costs of a rise in sea level generally focus on either the property damage from flooding or on the economic costs of prevention, for example, sea wall construction (Hallegatte et al., 2007; Hallegatte, 2008; 2012). They sometimes include costs associated with the temporary disruption of economic activity. Estimates typically do not measure the loss of wellbeing for people harmed or displaced by flooding.[36] Similarly, the economic analyses of climate change impacts on tourism have focused on changes, for example, in the choice of destination and the income from tourism activities attributable to an increase in temperature, but not on the impacts on participants' wellbeing.[37]

The economic metrics conventionally used in the assessment of non-climate health outcomes have also been used to measure the impact of climate on health (e.g., Deschênes and Greenstone, 2011; Watkiss and Hunt, 2012). Measures to reduce GHGs may also reduce other pollutants associated with fossil fuel combustion, such as NO_x and particulates, which lead to time lost from work and reduced productivity (Östblom and Samakovlis, 2007). Exposure to high ambient tempera-

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31 Details can be found in Carson and Hanemann (2005), or in textbooks such as Champ, Boyle and Brown (2003), Haab and McConnell (2002), and Bennett and Blamey (2001).

32 Examples include Berrens et al. (2004), Lee and Cameron (2008), Solomon and Johnson (2009), and Aldy et al. (2012) for the U.S.; Akter and Bennett (2011) for Australia; Longo et al. (2012) for Spain; Lee et al. (2010) for Korea; Adaman et al. (2011) for Turkey; and Carlsson et al. (2012) for a comparative study of WTP in China, Sweden and the US.

33 Other economic measures of damage are sometimes used that may not be appropriate. The economic damage is, in principle, the lesser of the value of what was lost or the cost of replacing it (assuming a suitable and appropriate replacement exists). Therefore, the replacement cost itself may or may not be a relevant measure. Similarly, if the cost of mitigation is actually incurred, it is a lower bound on the value placed on the damage avoided. Otherwise, the mitigation cost is irrelevant if nobody is willing to incur it.

34 While there is a large literature covering physical and biological impacts, except for agriculture and forestry only a tiny portion of the literature carries the analysis to the point of measuring an economic value. However, the literature is expanding. A *Web of Knowledge* search on the terms ("climate change" or "global warming") and "damage" and "economic impacts" returns 39 papers for pre-2000, 136 papers for 2000–2009 and 209 papers for 2010 through September 2013.

35 The same issue arises with the effects on timber production in a global timber market; see for example, Sohngen et al. (2001).

36 Exceptions include Daniel et al. (2009) and Botzen and van den Bergh (2012). Cardoso and Benhin (2011) provide a stated preference valuation of protecting the Columbian Caribbean coast from sea level rise.

37 Exceptions include Pendleton and Mendelsohn (1998); Loomis and Richardson (2006); Richardson and Loomis (2004); Pendleton et al. (2011); Tseng and Chen (2008); and for commercial fishing, Narita et al. (2012).

tures is known to diminish work capacity and reduce labour productivity.[38]

3.9.2 Aggregate climate damages

This section focuses on the aggregate regional and global economic damages from climate change as used in IAMs to balance the benefits and costs of mitigation on a global scale.

The first estimates of the economic damage associated with a specific degree of climate change were made for the United States (Smith and Tirpak, 1989; Nordhaus, 1991; Cline, 1992; Titus, 1992; Fankhauser, 1994). These studies involved static analyses estimating the damage associated with a particular climate end-point, variously taken to be a 1 °C, 2.5 °C, or 3 °C increase in global average annual temperature. This approach gave way to dynamic analyses in IAMs that track economic output, emissions, atmospheric CO_2 concentration, and damages. Because some IAMs examine costs and benefits for different levels of emissions, they need damage 'functions' rather than point estimates.

Three IAMs have received most attention in the literature, all initially developed in the 1990s. The DICE model was first published in Nordhaus (1993a; b) but had its genesis in Nordhaus (1977); its regionally disaggregated sibling RICE was first published by Nordhaus and Yang (1996).[39] The FUND model was first published in Tol (1995). And the PAGE model, developed for European decision makers, was first published in Hope et al. (1993) and was used in the Stern (2007) review.[40] The models have undergone various refinements and updates.[41] While details have changed, their general structure has stayed the same, and questions remain about the validity of their damage functions (see Pindyck, 2013).

The IAMs use a highly aggregated representation of damages. The spatial unit of analysis in DICE is the entire world, whereas the worldis divided into 12 broad regions in RICE, 16 regions in FUND, and eight in PAGE. DICE and RICE have a single aggregate damage function for the change in global or regional GDP as a function of the increase in global average temperature, here denoted ΔT_t, and sea-level rise (which in turn is modelled as a function of ΔT_t). PAGE has four separate damage functions for different types of damages in each region: economic, non-economic, sea-level rise, and climate discontinuity (as a function of ΔT_t and the derivative rise in sea level). FUND has eight sectoral damage functions for each region, with each damage dependent on the regional ΔT_t and, in some cases, the rate of change in ΔT_t. Adaptation and catastrophic damage are included in a very simple way in some models (Greenstone et al., 2013).

Let D_{jkt} denote damages of type j in year t and region k, expressed as a proportion of per capita GDP in that year and region, Y_{kt}. The damage functions, say $D_{jkt} = D_{jkt}(\Delta T_t)$ are calibrated based on: (1) the modeller's choice of a particular algebraic formula for $D_{jkt}(\Delta T_t)$: (2) the common assumption of zero damage at the origin [$D_{jkt}(0) = 0$]; and (3) the modeller's estimate of damages at a benchmark change in global average temperature, ΔT^* (typically associated with a doubling of atmospheric CO_2). For example, in the original versions of PAGE and DICE the damage function resolves into a power function:

Equation 3.9.1 $D_{jt} = a_j[\Delta T_t/\Delta T^*]^b Y_t$

where b is a coefficient estimated or specified by the modeller, and a_j is the modeller's estimate of the economic damage for the benchmark temperature change.[42] In DICE, b = 2 is chosen.[43] In PAGE, b is a random variable between 1.5 and 3. In FUND, the damage functions are deterministic but have a slightly more complicated structure and calibration than in Equation 3.9.1.

Because each damage function is convex (with increasing marginal damage), the high degree of spatial and temporal aggregation causes the model to understate aggregate damages. This can be seen by representing the spatial or temporal distribution of warming by a mean and variance, and writing expected damages in a second order expansion around the mean.

A concern may be whether the curvature reflected in Equation 3.9.1 is adequate. The functions are calibrated to the typical warming associated with a doubling of CO_2 concentration, along with associated damage. The aggregate damage is based on heroic extrapolations to a regional or global scale from a sparse set of studies (some from the 1990s) done at particular geographic locations. The impacts literature is now paying somewhat more attention to higher levels of warming (New et al. (2011), World Bank (2012), and WGII Section 19.5.1), though estimates of monetary damage remain scarce (however, the literature is expanding rapidly). Another concern is the possibility of tipping points and extreme events (Lenton et al., 2008) (see also Box 3.9), possibly including increases in global temperature as large as 10–12 °C that are not always reflected in the calibration (Sherwood and Huber, 2010).

38 See Kjellstrom et al. (2009), Zivin and Neidell (2010), or Dunne et al. (2013). Some recent studies have focused on the correlation between high temperatures and poverty (Nordhaus, 2006), the link between fluctuations in temperature, cyclones and fluctuations in economic activity (Dell et al., 2009, 2012; Hsiang, 2010), and the connection between climate change and human conflict (Hsiang et al., 2013).

39 There are many extensions of DICE, including AD-DICE (de Bruin et al., 2009), with a more explicit treatment of adaptation.

40 Some other IAMs have damage functions, including the MERGE Model (Manne and Richels, 1992, 1995, 2004a); the CETA model (Peck and Teisberg, 1992, 1994); and, more recently, several IAMs developed by European researchers including the WITCH model (Bosetti et al., 2006), its extension the AD-WITCH model (Bosello et al., 2010), the ENVISAGE model (Roson and Mensbrugghe, 2012), and a model developed by Eboli et al. (2010) and Bosello et al. (2012).

41 The most recent versions are: DICE2013 (Nordhaus and Sztorc, 2013); RICE2010 (Nordhaus, 2010); PAGE 2009 (Hope, 2011, 2013); FUND 3.7 (Anthoff and Tol, 2013).

42 Typically, ΔT^* is 2.5 or 3 °C. When $\Delta T_t = \Delta T^*$ in this equation, then $D_{jt} = a_j Y_t$.

43 This formulation is also used by Kandlikar (1996) and Hammitt et al. (1996a) with b = 1, 2 or 3.

3

Box 3.9 | Uncertainty and damages: the fat tails problem

Weitzman (2009, 2011) has drawn attention to what has become known as the fat-tails problem. He emphasized the existence of a chain of structural uncertainties affecting both the climate system response to radiative forcing and the possibility of some resulting impacts on human wellbeing that could be catastrophic. Uncertainties relate to both means of distributions and higher moments. The resulting compounded probability distribution of possible economic damage could have a fat bad tail: i.e., the likelihood of an extremely large reduction in wellbeing does not go quickly to zero.[1] With or without risk aversion, the expected marginal reduction in wellbeing associated with an increment in emissions today could be very large, even infinite[2] See also Section 2.5.3.3.

A policy implication of the conditions described in the previous paragraph is that tail events can become much more important in determining expected damage than would be the case with probability distributions with thinner tails. Weitzman (2011) illustrates this for the distribution of temperature consequences of a doubling of atmospheric CO_2 (climate sensitivity), using WGI AR4 estimates to calibrate two distributions, one fat-tailed and one thin-tailed, to have a median temperature change of 3 °C and a 15 % probability of a temperature change in excess of 4.5 °C. With this calibration, the probability of temperatures in excess of 8 °C is nearly ten times greater with the fat-tailed distribution than the thin-tailed distribution. If high consequence, low probability events become more likely at higher temperatures, then tail events can dominate the computation of expected damages from climate change, depending on the nature of the probability distribution and other features of the problem (including timing and discounting).

At a more technical level, with some fat-tailed distributions and certain types of utility functions (constant relative risk aversion), the expectation of a marginal reduction in wellbeing associated with an increment in emissions is infinite. This is because in these cases, marginal utility becomes infinite as consumption goes to zero. This is a troubling result since infinite marginal damage implies all available resources should be dedicated to reducing the effects of climate change. But as Weitzman himself and other authors have pointed out, this extreme result is primarily a technical problem that can be solved by bounding the utility function or using a different functional form.

The primary conclusion from this debate is the importance of understanding the impacts associated with low probability, high climate change scenarios. These may in fact dominate the expected benefits of mitigation.

The policy implication of this conclusion is that the nature of uncertainty can profoundly change how climate policy is framed and analyzed with respect to the benefits of mitigation. Specifically, fatter tails on probability distributions of climate outcomes increase the importance in understanding and quantifying the impacts and economic value associated with tail events (such as 8 °C warming). It is natural to focus research attention on most likely outcomes (such as a 3 °C warming from a CO_2 doubling), but it may be that less likely outcomes will dominate the expected value of mitigation.

[1] Weitzman (2009) defines a fat-tailed distribution as one with an infinite moment generating function (a thin-tailed distribution has a finite moment generating function); more intuitively, for a fat-tailed distribution, the tail probability approaches zero more slowly than exponentially. For example, the normal (and any distribution with finite support) would be thin-tailed whereas the Pareto distribution (a power law distribution) would be fat-tailed.

[2] Weitzman (2007b, 2009) argued that the expected marginal reduction in wellbeing could be infinite. His results have been challenged by some as too pessimistic, e.g., Nordhaus (2011a), Pindyck (2011) and Costello et al. (2010).

The economic loss or gain from warming in a given year typically depends on the level of warming in that same year, with no lagged effects (at least for damages other than sea-level rise in DICE, the non-catastrophe component of damages in PAGE, and some sectors of FUND). Thus, impacts are (a) reversible, and (b) independent of the prior trajectory of temperatures. This assumption simplifies the computations, but some impacts and damages may actually depend on the rate of increase in temperature.[44] The optimal trajectory of mitigation and the level of damages could also depend on the cumulative amount of warming in previous years (measured, say, in degree years).

DICE, FUND and PAGE represent damage as equivalent to a change in production of market commodities that is proportional to output (a 'multiplicative' formulation). Weitzman (2010a) finds that this specification matters with high levels of warming because an additive formulation leads to more drastic emission reduction. Besides affecting current market production, climate change could damage natural, human, or physical capital (e.g., through wildfires or floods). Damage to capital stocks may last beyond a year and have lingering impacts that are not captured in current formulations (Wu et al., 2011). Economic consequences

[44] This rate of change was considered by Manne and Richels (2004a) in MERGE and by Peck and Teisberg (1994) in CETA. The latter found that it can have quite a large effect on the size of the optimal carbon tax.

depend on what is assumed about the elasticity of substitution in the utility function between market commodities and non-market climate impacts. An elasticity of substitution of unity is equivalent to the conventional multiplicative formulation, but a value less than unity, generates a more drastic trajectory of emission reductions (Krutilla, 1967; Sterner and Persson, 2008).

The utility function in these three IAMs does not distinguish between the welfare gains deriving from risk reduction when people are risk averse versus the gains from smoothing consumption over time when people have declining marginal utility of income: both preferences are captured by the curvature of the utility function as measured by η, in Equation 3.6.4. However, Kreps and Porteus (1978) and Epstein and Zin (1991) show that two separate functions can have separate parameters for risk aversion and inter-temporal substitution. This formulation is used successfully in the finance literature to explain anomalies in the market pricing of financial assets, including the equity premium (Campbell, 1996; Bansal and Yaron, 2004). The insight from this literature is that the standard model of discounted expected utility, used in DICE, FUND and PAGE, sets the risk premium too low and the discount rate too high, a result confirmed by Ackerman et al. (2013) and Crost and Traeger (2013).

Our general conclusion is that the reliability of damage functions in current IAMs is low. Users should be cautious in relying on them for policy analysis: some damages are omitted, and some estimates may not reflect the most recent information on physical impacts; the empirical basis of estimates is sparse and not necessarily up-to-date; and adaptation is difficult to properly represent. Furthermore, the literature on economic impacts has been growing rapidly and is often not fullyrepresented in damage functions used in IAMs. Some authors (e.g., WGII Chapter 19) conclude these damage functions are biased downwards. It should be underscored that most IAMs used in Chapter 6 of this volume do not consider damage functions so this particular criticism does not apply to Chapter 6 analyses.

3.9.3 The aggregate costs of mitigation

Reductions in GHG emission often impose costs on firms, households (see also Box 3.10), and governments as a result of changes in prices, revenues and net income, and in the availability or quality of commodities. GHG reduction requires not only technological but also behavioural and institutional changes, which may affect wellbeing. The changes in wellbeing are measured in monetary terms through a change in income that is equivalent to the impact on wellbeing. Changes in prices and incomes are often projected through economic models (see Chapter 6). In many cases, mitigation primarily involves improvements in energy efficiency or changes in the generation and use of energy from fossil fuels in order to reduce GHG emissions.

The models assessed in Chapter 6 are called IAMs (or Integrated Models—IMs) because they couple several systems together (such as the economy and the climate) in an integrated fashion, tracking the impact of changes in economic production on GHG emissions, as well as of emissions on global temperatures and the effect of mitigation policies on emissions. As discussed in Section 6.2, the IAMs used in Chapter 6 are heterogeneous. However, for most of the Chapter 6 IAMs, climate change has no feedback effects on market supply and demand, and most do not include damage functions.[45]

[45] Climate is assumed to be *separable* from market goods in the models' utility functions. If that assumption is incorrect, Carbone and Smith (2013) show that the welfare calculation may have significant error.

Box 3.10 | Could mitigation have a negative private cost?

A persistent issue in the analysis of mitigation options and costs is whether available mitigation opportunities can be privately profitable—that is, generate benefits to the consumer or firm that are in excess of their own cost of implementation—but which are not voluntarily undertaken. Absent another explanation, a negative private cost implies that a person is not fully pursuing his own interest. (By contrast, a negative social cost arises when the total of everybody's benefits exceeds costs, suggesting that some private decision-maker is not maximizing the interests of others.) The notion that available mitigation opportunities may have negative costs recently received attention because of analyses by McKinsey & Company (2009), Enkvist et al. (2007) and others that focused especially on energy use for lighting and heating in residential and commercial buildings, and on some agricultural and industrial processes. Much of this literature is in the context of the "energy efficiency gap,"[1] which dates to the 1970s, and the "Porter hypothesis".[2]

The literature suggesting that available opportunities may have negative cost often points to institutional, political, or social barriers as the cause. But other literature suggests economic

[1] The efficiency gap is defined as the difference between the socially desirable amount of energy efficiency (however defined) and what firms and consumers are willing to undertake voluntarily (see Meier and Whittier, 1983; Joskow and Marron, 1992, 1993; Jaffe and Stavins, 1994).

[2] Porter (1991) and Porter and van der Linde (1995) argued that unilateral reductions in pollution could stimulate innovation and improve firms' competitiveness as a by-product; see also Lanoie et al. (2008); Jaffe and Palmer (1997). The subsequent literature has obtained mixed finding (Ambec and Barla, 2006; Ambec et al., 2013).

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explanations. In addition, however, evidence indicates that the extent of such negative cost opportunities can be overstated, particularly in purely engineering studies.

Engineering studies may overestimate the energy savings, for example because they assume perfect installation and maintenance of the equipment (Dubin et al., 1986; Nadel and Keating, 1991) or they fail to account for interactions among different investments such as efficient lighting and cooling (Huntington, 2011). Engineering studies also may fail to account for all costs actually incurred, including time costs, scarce managerial attention and the opportunity cost of the money, time, or attention devoted to energy efficiency.[3] In some cases, the engineering analysis may not account for reductions in quality (e.g., CFL lighting is perceived as providing less attractive lighting services). Choices may also be influenced by uncertainty (e.g., this is an unfamiliar product, one doesn't know how well it will work, or what future energy prices will be). Another consideration sometimes overlooked in engineering analyses is the rebound effect—the cost saving induces a higher rate of equipment usage (see Section 3.9.5). The analyses may overlook heterogeneity among consumers: what appears attractive for the average consumer may not be attractive for all (or many) consumers, based on differences in their circumstances and preferences. One approach to validation is to examine energy efficiency programs and compare ex ante estimates of efficiency opportunities with ex post accomplishment; the evidence from such comparisons appears to be inconclusive, though more analysis may be fruitful.[4]

Economic explanations for the apparent failure to pursue profitable mitigation/energy saving opportunities include the following.[5] Given uncertainty and risk aversion, consumers may rationally desire a higher return as compensation. Price uncertainty and the irreversibility of investment may also pose additional economic barriers to the timing of adoption—it may pay to wait before making the investment (Hassett and Metcalf, 1993; Metcalf, 1994). Mitigation investments take time to pay off, and consumers act as if they are employing high discount rates when evaluating such investments (Hausman, 1979). These consumer discount rates might be much higher than those of commercial businesses, reflecting liquidity and credit constraints. The durability of the existing capital stock can be a barrier to rapid deployment of otherwise profitable new technologies. Also, a principal-agent problem arises when the party that pays for an energy-efficiency investment doesn't capture all the benefits, or vice versa. For example a tenant installs an efficient refrigerator, but the landlord retains ownership when the tenant leaves (split incentives). Or the landlord buys a refrigerator but doesn't care about its energy efficiency. Such problems can also arise in organizations where different actors are responsible, say, for energy bills and investment accounts.[6] Finally, energy users, especially residential users, may be uninformed, or poorly informed, about the energy savings they are forgoing. In some cases, the seller of the product has better information than the potential buyer (asymmetric information) and may fail to convey that information credibly (Bardhan et al., 2013).

Recently, some economists have suggested that systematic behavioral biases in decision-making can cause a failure to make otherwise profitable investment. These have been classified as non-standard beliefs (e.g., incorrect assessments of fuel savings—Allcott, 2013), non-standard preferences (e.g., loss aversion—Greene et al., 2009), and non-standard decision making (e.g., tax salience—Chetty et al., 2009). Such phenomena can give rise to what might be considered 'misoptimization' by decision makers, which in turn could create a role for efficiency-improving policy not motivated by conventional market failures (Allcott et al., forthcoming); see Section 3.10.1 for a fuller account.

In summary, whether opportunities for mitigation at negative private cost exist is ultimately an empirical question. Both economic and non-economic reasons can explain why they might exist, as noted in recent reviews (Huntington, 2011; Murphy and Jaccard, 2011; Allcott and Greenstone, 2012; Gillingham and Palmer, 2014). But, evidence also suggests that the occurrence of negative private costs is sometimes overstated, for reasons identified above. This remains an active area of research and debate.

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3 For example, Anderson and Newell (2004) examined energy audits for manufacturing plants and found that roughly half of the projects recommended by auditors were not adopted despite extremely short payback periods. When asked, plant managers responded that as much as 93 % of the projects were rejected for economic reasons, many of which related to high opportunity costs. Joskow and Marron (1992, 1993) show some engineering estimates understated actual costs.

4 Arimura et al. (2012) review US electricity industry conservation programmes (demand side management—DSM) and conclude that programmes saved energy at a mean cost of USD 0.05 per kWh, with a 90 % confidence interval of USD 0.003 to USD 0.010. Allcott and Greenstone (2012) conclude that this average cost is barely profitable. Although this may be true, one cannot conclude that on this evidence alone that ex ante engineering estimates of costs were too optimistic.

5 Allcott and Greenstone (2012) and Gillingham and Palmer (2014) provide excellent reviews.

6 Davis (2011) and Gillingham et al. (2012) provide evidence of principal-agent problems in residential energy, although amount of energy lost as a result was not large in the cases examined.

The calculation of cost depends on assumptions made (1) in specifying the model's structure and (2) in calibrating its parameters. The models are calibrated to actual economic data. While more validation is required, some models are validated by making and testing predictions of the response to observed changes (Valenzuela et al., 2007; Beckman et al., 2011; Baldos and Hertel, 2013). While some models do not address either the speed or cost of adjustment, many models incorporate adjustment costs and additional constraints to reflect deviations from full optimization (see Jacoby et al., 2006; Babiker et al., 2009; van Vuuren et al., 2009). Most models allow little scope for endogenous (price-induced) technical change (3.11.4) or endogenous non-price behavioural factors (3.10.1). It is a matter of debate how well the models accurately represent underlying economic processes (see Burtraw, 1996; Burtraw et al., 2005; Hanemann, 2010).

Besides estimating total cost, the models can be used to estimate Marginal Abatement Cost (MAC), the private cost of abating one additional unit of emissions. With a cap-and-trade system, emissions would theoretically be abated up to the point where MAC equals the permit price; with an emissions tax, they would be abated to the point where MAC equals the tax rate. It is common to graph the MAC associated with different levels of abatement. Under simplified conditions, the area under the MAC curve measures the total economic cost of emissions reduction, but not if it fails to capture some of the economy-wide effects associated with large existing distortions (Klepper and Peterson, 2006; Paltsev et al., 2007; Kesicki and Ekins, 2012; Morris et al., 2012). However, a MAC is a static approximation to the dynamic process involved in pollution abatement; it thus has its limitations.

3.9.4 Social cost of carbon

Although estimates of aggregate damages from climate change are useful in formulating GHG mitigation policies (despite the caveats listed in Section 3.9.2), they are often needed for more mundane policy reasons. Governments have to make decisions about regulation when implementing energy policies, such as on fuel or EE standards for vehicles and appliances. The social cost of carbon emissions can be factored into such decisions.

To calculate the social cost, consider a baseline trajectory of emissions ($E_0,\ldots,E_t$) that results in a trajectory of temperature changes, ΔT_t. Suppose a damage function for year *t* is discounted to the present and called $D(\Delta T_t)$, as discussed in Equation 3.9.2. These trajectories result in a discounted present value of damages:

Equation 3.9.2 $$PVD \equiv \int_0^\infty D(\Delta T_t)dt$$

Then take the derivative with respect to a small change in emissions at $t = 0$, E_0, to measure the extra cost associated with a one tonne increase in emissions at time 0 (that is, the increment in *PVD*):

Equation 3.9.3 $$MDCC = \frac{\partial PVD}{\partial E_0}$$

When applied to CO_2 this equation gives the marginal damage from the change in climate that results from an extra tonne of carbon. It is also called the social cost of carbon (SCC). It should be emphasized that the calculation of SCC is highly sensitive to the projected future trajectory of emissions and also any current or future regulatory regime.[46]

Because of its potential use in formulating climate or energy regulatory policy, governments have commissioned estimates of SCC. Since 2002, an SCC value has been used in policy analysis and regulatory impact assessment in the United Kingdom (Clarkson and Deyes, 2002). It was revised in 2007 and 2010. In 2010, a standardized range of SCC values based on simulations with DICE, FUND, and PAGE using alternative projections of emissions and alternative discount rates, was made available to all U.S. Government agencies.[47] It was updated in 2013 (US Interagency Working Group, 2013).

3.9.5 The rebound effect

Technological improvements in energy efficiency (EE) have direct effects on energy consumption and thus GHG emissions, but can cause other changes in consumption, production, and prices that will, in turn, affect GHG emissions. These changes are generally called 'rebound' or 'takeback' because in most cases they reduce the net energy or emissions reduction associated with the efficiency improvement. The size of rebound is controversial, with some research papers suggesting little or no rebound and others concluding that it offsets most or all reductions from EE policies (Greening et al., 2000; Binswanger, 2001; Gillingham et al., 2013, summarize the empirical research). Total EE rebound can be broken down into three distinct parts: substitution-effect, income-effect, and economy-wide.

In end-use consumption, substitution-effect rebound, or 'direct rebound' assumes that a consumer will make more use of a device if it becomes more energy efficient because it will be cheaper to use. Substitution-effect rebound extends to innovations triggered by the improved EE that results in new ways of using the device. To pay for that extra use, the individual must still consume less of something else, so net substitution-effect rebound is the difference between the energy expended in using more of the device and the energy saved from using whatever was previously used less (see Thomas and Azevedo, 2013).

[46] Some ambiguity regards the definition of the SCC and the correct way to calculate it in the context of an equilibrium IAM (in terms of distinguishing between a marginal change in welfare vs. a marginal change in damage only). See, for instance, an account of the initial U.S. Government effort (Greenstone et al., 2013).

[47] Obviously, estimates of the SCC are sensitive to the structural and data assumptions in the models used to compute the SCC. Weitzman (2013), for instance, demonstrates the significance of the discount rate in the calculation.

Income-effect rebound or 'indirect rebound', arises if the improvement in EE makes the consumer wealthier and leads them to consume additional products that require energy. Even if energy efficient light bulbs lead to no substitution-effect rebound (more lighting), income-effect rebound would result if the consumer spends the net savings from installing the bulbs on new consumption that uses energy. The income-effect rebound will reflect the size of the income savings from the EE improvement and the energy intensity of marginal income expenditures.

Analogous rebound effects for EE improvements in production are substitution towards an input with improved energy efficiency, and substitution among products by consumers when an EE improvement changes the relative prices of goods, as well as an income effect when an EE improvement lowers production costs and creates greater wealth.

Economy-wide rebound refers to impacts beyond the behaviour of the entity benefiting directly from the EE improvement, such as the impact of EE on the price of energy. For example, improved fuel economy lowers vehicle oil demand and prices leading some consumers to raise their consumption of oil products. The size of this energy price effect will be greater with less elastic supply and more elastic demand. Some argue that the macroeconomic multiplier effects of a wealth shock from EE improvement also create economy-wide rebound.

Rebound is sometimes confused with the concept of economic leakage, which describes the incentive for emissions-intensive economic activity to migrate away from a region that restricts GHGs (or other pollutants) towards areas with fewer or no restrictions on such emissions. Energy efficiency rebound will occur regardless of how broadly or narrowly the policy change is adopted. As with leakage, however, the potential for significant rebound illustrates the importance of considering the full equilibrium effects of a policy designed to address climate change.

3.9.6 Greenhouse gas emissions metrics

The purpose of emissions metrics is to establish an exchange rate, that is, to assign relative values between physically and chemically different GHGs and radiative forcing agents (Fuglestvedt et al., 2003; Plattner et al., 2009). For instance, per unit mass, CH_4 is a more potent GHG than CO_2 in terms of instantaneous radiative forcing, yet it operates on a shorter time scale. In a purely temporal sense, the impacts are different. Therefore, how should mitigation efforts be apportioned for emissions of different GHGs?[48]

GHG emissions metrics are required for generating aggregate GHG emissions inventories; to determine the relative prices of different GHGs in a multi-gas emissions trading system; for designing multi-gas mitigation strategies; or for undertaking life-cycle assessment (e.g., Peters et al., 2011b). Since metrics quantify the trade-offs between different GHGs, any metric used for mitigation strategies explicitly or implicitly evaluates the climate impact of different gases relative to each other.

The most prominent GHG emissions metric is the Global Warming Potential (GWP), which calculates the integrated radiative forcing from the emission of one kilogram of a component *j* out to a time horizon *T*:

Equation 3.9.4 $$AGWP_j(T) = \int_0^T RF_j(t)\, dt$$

The AGWP is an absolute metric. The corresponding relative metric is then defined as $GWP_j = AGWP_j / AGWP_{CO2}$.

The GWP with a finite time horizon *T* was introduced by the IPCC (1990). With a 100-year time horizon, the GWP is used in the Kyoto Protocol and many other scientific and policy applications for converting emissions of various GHGs into 'CO_2 equivalents'. As pointed out in WGI, no scientific argument favours selecting 100 years compared with other choices. Conceptual shortcomings of the GWP include: (a) the choice of a finite time horizon is arbitrary, yet has strong effects on metric value (IPCC, 1990); (b) the same CO_2-equivalent amount of different gases may have different physical climate implications (Fuglestvedt et al., 2000; O'Neill, 2000; Smith and Wigley, 2000); (c) physical impacts and impacts to humans (well-being) are missing; and (d) temporal aggregation of forcing does not capture important differences in temporal behaviour. Limitations and inconsistencies also relate to the treatment of indirect effects and feedbacks (see WGI, Chapter 8).

Many alternative metrics have been proposed in the scientific literature. It can be argued that the net impacts from different gases should be compared (when measured in the same units) and the relative impact used for the exchange rate. The Global Damage Potential (GDamP) follows this approach by using climate damages as an impact proxy, and exponential discounting for inter-temporal aggregation of impacts (Hammitt et al., 1996b; Kandlikar, 1996). Since marginal damages depend on the time at which GHGs are emitted, the GDamP is a time-variant metric. The GDamP accounts for the full causal chain from emissions to impacts. One advantage of the framework is that relevant normative judgements, such as the choice of inter-temporal discounting and the valuation of impacts, are explicit (Deuber et al., 2013). In practice, however, the GDamP is difficult to operationalize. The difficulties in calculating the GDamP and SCC are closely related (see Section 3.9.4).

The Global Cost Potential (GCP) calculates the time-varying ratio of marginal abatement costs of alternative gases arising in a cost-effective multi-gas mitigation strategy given a prescribed climate target (Manne and Richels, 2001), such as a cap on temperature change or

48 This issue is discussed in Chapter 8 of WGI.

Table 3.4 | Overview and classification of different metrics from the scientific literature.

Name of metric		Impact function	Atmospheric background	Time dimension	Reference
GWP	Global Warming Potential	*RF*	Constant	Constant temporal weighting over fixed time horizon	IPCC (1990)
GWP-LA	Global Warming Potential (discounting)	*RF*	Constant, average of future conditions	Exponential discounting	Lashof and Ahuja (1990)
GTP-H	Global Temperature Change Potential (fixed time horizon)	ΔT	Constant	Evaluation at a fixed time T after emission	Fuglestvedt et al., (2010), Shine et al. (2005)
GTP(t)	Time-dependent global temperature change potential	ΔT	Time-varying	Evaluation at a fixed end point time in the future	Shine et al. (2007)
CETP	Cost Effective Temperature Potential	ΔT	Exogenous scenario	Complex function of time when climate threshold is reached	Johannson (2012)
MGTP	Mean Global Temperature Change Potential	ΔT	Time-varying	Constant temporal weighting over fixed time horizon	Gillet and Mathews (2010), Peters et al. (2011a)
GCP	Global Cost Potential	Infinite damage above climate target	Time-varying	Exponential discounting	Manne and Richels (2001)
GDamP	Global Damage Potential	$D(\Delta T)$	Time-varying	Exponential discounting	Kandlikar (1996), Hammit et al. (1996a)

on GHG concentrations. While the GCP avoids the problems associated with damage functions, it still requires complex integrated energy-economy-climate models to calculate GHG price ratios, and is therefore less transparent to stakeholders than physical metrics.[49]

The time-dependant Global Temperature Change Potential (GTP) is a physical metric that does not involve integration of the chosen impact parameter over time (Shine et al., 2007). It is defined as the relative effect of different gases on temperature at a predefined future date from a unit impulse of those gases. Typically these are normalized to a base, such as same mass of CO_2 emitted. While the GWP and GTP were not constructed with a specific policy target in mind, the GCP is conceptually more consistent with a policy approach aiming at achieving climate objectives in a cost-effective way (Fuglestvedt et al., 2003; Manning and Reisinger, 2011; Tol et al., 2012).

Virtually all absolute metrics (AM_j) can be expressed in terms of a generalization of Equation 3.9.4 (Kandlikar, 1996; Forster et al., 2007):

Equation 3.9.5 $$AM_j = \int_0^{\infty} I_j(\Delta T(t), RF(t), \ldots) W(t)\, dt$$

where the *impact function* I_j links the metric to the change in a physical climate parameter, typically the global mean radiative forcing *RF* (e.g., in the case of the GWP) or the change in global mean temperature ΔT (e.g., GTP and most formulations of the GDamP). In some cases, the impact function also considers the rate of change of a physical climate parameter (Manne and Richels, 2001; Johansson et al., 2006).

The temporal 'weighting function, W(t)', determines how the metric aggregates impacts over time. It can prescribe a finite time horizon (GWP), evaluation at a discrete point in time (GTP), or exponential discounting over an infinite time horizon (GDamP), which is consistent with the standard approach to inter-temporal aggregation used in economics (see Section 3.6.2). The weighting used in the GWP is a weight equal to one up to the time horizon and zero thereafter.

The categorization according to their choice of impact and temporal weighting function (Table 3.4) serves to expose underlying explicit and implicit assumptions, which, in turn, may reflect normative judgements. It also helps to identify relationships between different metric concepts (Tol et al., 2012; Deuber et al., 2013). In essence, the choice of an appropriate metric for policy applications involves a trade-off between completeness, simplicity, measurability, and transparency (Fuglestvedt et al., 2003; Plattner et al., 2009; Deuber et al., 2013). The GDP and GCP are cost effective in implementing multi-gas mitigation policies, but are subject to large measurability, value-based, and scientific uncertainties. Simple physical metrics, such as the GWP, are easier to calculate and produce a more transparent result, but are inaccurate in representing the relevant impact trade-offs between different GHGs (Fuglestvedt et al., 2003; Deuber et al., 2013).

The choice of metric can have a strong effect on the numerical value of GHG exchange rates. This is particularly relevant for CH_4, which operates on a much shorter timescale than CO_2. In WGI, Section 8.7, an exchange ratio of CH_4 to CO_2 of 28 is given for GWP and of 4 for a time horizon of 100 years for GTP.[50] For a quadratic damage function and a

49 In the context of a multi-gas integrated assessment model which seeks to minimize the cost of meeting a climate target.

50 See WGI Chapter 8, Appendix 8A for GWP and GTP values for an extensive list of components.

discount rate of 2 %, Boucher (2012) obtained a median estimate of the GDamP exchange ratios of 24.3. This exchange rate obviously has very significant implications for relative emphasis a country may place on methane mitigation vs. carbon dioxide mitigation.

A small but increasing body of literature relates to the economic implications of metric choice. A limited number of model-based examinations find that, despite its conceptual short-comings, the GWP-100 performs roughly similarly to GTP or a cost-optimizing metric (such as the GCP) in terms of aggregate costs of reaching a prescribed climate target, although regional and sectoral differences may be significant (Godal and Fuglestvedt, 2002; Johansson et al., 2006; Reisinger et al., 2013; Smith et al., 2013; Ekholm et al., 2013). In other words, based on these few studies, the scope for reducing aggregate mitigation costs of reaching a particular climate target by switching to a metric other than the currently used GWP-100 may be limited, although there may be significant differences in terms of regional costs.

In the Kyoto Protocol, emission reductions of one GHG can be traded with reductions in all other GHGs. Such 'single-basket' approaches implicitly assume that the GHGs can linearly substitute each other in the mitigation effort. However, the same CO_2-equivalent amount of different GHGs can result in climate responses that are very different for transitional and long-term temperature change, chiefly due to different life-times of the substances (Fuglestvedt et al., 2000; Smith and Wigley, 2000). As an alternative, multi-basket approaches have been proposed, which only allow trading within groups of forcing agents with similar physical and chemical properties (Rypdal et al., 2005; Jackson, 2009; Daniel et al., 2012; Smith et al., 2013). Smith et al. (2013) propose a methodology for categorizing GHGs into two baskets of (a) long-lived species, for which the cumulative emissions determine the long-term temperature response, and (b) shorter-lived species for which sustained emissions matter. Applying separate emission equivalence metrics and regulations to each of the two baskets can effectively control the maximum peak temperature reached under a global climate policy regime. However, further research on the institutional requirements and economic implications of such an approach is needed, as it requires regulators to agree on separate caps for each basket and reduces the flexibility of emission trading systems to harvest the cheapest mitigation options.

3.10 Behavioural economics and culture

This section summarizes behavioural economics related to climate change mitigation. We focus on systematic deviations from the traditional neoclassical economic model, which assumes that preferences are complete, consistent, transitive, and non-altruistic, and that humans have unbounded computational capacity and rational expectations. In this context, social and cultural issues and conditions that frame our attitudes, as well as living conditions, are also addressed. Chapter 2 also considers behavioural questions, though primarily in the context of risk and uncertainty.

Although the focus is on the behaviour of individuals, some firms and organizations also take actions that appear to be inconsistent with the standard neoclassical model of the profit-maximizing firm (Lyon and Maxwell, 2007).

3.10.1 Behavioural economics and the cost of emissions reduction

Behavioural economics deals with cognitive limitations (and abilities) that affect people's economic decision-making processes. Choices can be affected and/or framed by perceived fairness, social norms, cooperation, selfishness, and so on.[51] Behavioural economics emphasizes the cognitive, social, and emotional factors that lead to apparently irrational choices. A growing number of documented systematic deviations from the neoclassical model help explain people's behaviour, but here we focus on several that we see as most relevant to climate change mitigation.[52]

3.10.1.1 Consumer undervaluation of energy costs

Consumers may undervalue energy costs when they purchase energy-using durables, such as vehicles, or make other investment decisions related to energy use.[53] By 'undervalue', we mean that consumers' choices systematically fail to maximize the utility they experience when the choices are implemented ('experienced' utility) (Kahneman and Sugden, 2005; see also, e. g., Fleurbaey, 2009). This misoptimization reduces demand for EE. Three potential mechanisms of undervaluation may be most influential (see also Box 3.10). First, when considering a choice with multiple attributes, evidence suggests that consumers are inattentive to add-on costs and ancillary attributes, such as shipping and handling charges or sales taxes (Hossain and Morgan, 2006; Chetty et al., 2009). It could be that EE is a similar type of ancillary product attribute and is thus less salient at the time of purchase. Second, significant evidence across many contexts also suggests that humans are 'present biased' (DellaVigna, 2009). If energy costs affect consumption in the future while purchase prices affect consumption in the present, this would lead consumers to be less energy efficient. Third, people's beliefs about the implications of different choices may

[51] See, e. g., Babcock and Loewenstein (1997), Shiv and Fedorikhin (1999), Asheim et al. (2006), Barrett (2007), Levati et al. (2007), Potters et al. (2007), Shogren and Taylor (2008) and Dannenberg et al. (2010).

[52] See Rachlinksi (2000), Brekke and Johansson-Stenmann (2008), Gowdy (2008) and the American Psychological Association (2010).

[53] This can even apply to cases that use sophisticated methods to support decisions (e. g., Korpi and Ala-Risku, 2008).

be systematically biased (Jensen, 2010; Bollinger et al., 2011; Kling et al., 2012; McKenzie et al., 2013). Attari et al. (2010) show that people systematically underestimate the energy savings from a set of household energy conserving activities, and Allcott (2013) shows that the average consumer either correctly estimates or systematically slightly underestimates the financial savings from more fuel-efficient vehicles. Each of these three mechanisms of undervaluation appears plausible based on results from other contexts. However, rigorous evidence of misoptimization is limited in the specific context of energy demand (Allcott and Greenstone, 2012).

Three implications arise for climate and energy policy if the average consumer who is marginal to a policy does, in fact, undervalue energy costs. The first is an 'internality dividend' from carbon taxes (or other policies that internalize the carbon externality into energy prices): a carbon tax can actually increase consumer welfare when consumers undervalue energy costs (Allcott et al., forthcoming). This occurs because undervaluation would be a pre-existing distortion that reduces demand for EE below consumers' private optima, and one that increasing carbon taxes helps to correct. Second, in addition to carbon taxes, other tax or subsidy policies that raise the relative purchase price of energy-inefficient durable goods can improve welfare (Cropper and Laibson, 1999; O'Donoghue and Rabin, 2008; Fullerton et al., 2011). Third, welfare gains are largest from policies that preferentially target consumers who undervalue energy costs the most. This effect is related to the broader philosophies of libertarian paternalism (Sunstein and Thaler, 2003) and asymmetric paternalism (Camerer et al., 2003), which advocate policies that do not infringe on freedom of choice but could improve choices by the subset of people who misoptimize. In the context of energy demand, such policies might include labels or programmes that provide information about, and attract attention to, energy use by durable goods.

3.10.1.2 Firm behaviour

Some of the phenomena described above may also apply to firms. Lyon and Maxwell (2004, 2008) examine in detail the tendency of firms to undertake pro-environment actions, such as mitigation, without being prompted by regulation. Taking a neoclassical approach to the problem, they find that firms view a variety of pro-environment actions as being to their advantage. However, evidence of a compliance norm has been found in other contexts where firms' responses to regulation have been studied (Ayres and Braithwaite, 1992; Gunningham et al., 2003).

The conventional economic model represents the firm as a single, unitary decision-maker, with a single objective, namely, profit maximization. As an alternative to this 'black-box' model of the firm (Malloy, 2002), the firm may be seen as an organization with a multiplicity of actors, perhaps with different goals, and with certain distinctive internal features (Coase, 1937; Cyert and March, 1963; Williamson, 1975).

3.10.1.3 Non-price interventions to induce behavioural change

Besides carbon taxes and other policies that affect relative prices, other non-price policy instruments can reduce energy demand, and, therefore, carbon emissions. Such interventions include supplying information on potential savings from energy-efficient investment, drawing attention to energy use, and providing concrete examples of energy-saving measures and activities (e.g., Stern, 1992; Abrahamse et al., 2005). They also include providing feedback on historical energy consumption (Fischer, 2008) and information on how personal energy use compares to a social norm (Allcott, 2011).[54]

In some cases, non-price energy conservation and efficiency programmes may have low costs to the programme operator, and it is therefore argued that they are potential substitutes if carbon taxes are not politically feasible (Gupta et al., 2007). However, it is questionable whether such interventions are appropriate substitutes for carbon taxes, for example, in terms of environmental and cost effectiveness, because their impact may be small (Gillingham et al., 2006) and unaccounted costs may reduce the true welfare gains. For example, consumers' expenditures on energy-efficient technologies and time spent turning lights off may not be observed.

Research in other domains (e.g., Bertrand et al., 2010) has shown that a person's choices are sometimes not consistent. They may be malleable by 'ancillary conditions'—non-informational factors that do not affect experienced utility. In the context of EE, this could imply that energy demand may be reduced with relatively low welfare costs through publicity aimed at changing consumer preferences. However, publicly-funded persuasion campaigns bring up important ethical and political concerns, and the effectiveness of awareness-raising programmes on energy and carbon will depend on how consumers actually use the information and the mix of policy instruments (Gillingham et al., 2006; Gupta et al., 2007; also Worrell et al., 2004; Mundaca et al., 2010).

3.10.1.4 Altruistic reductions of carbon emissions

In many contexts, people are altruistic, being willing to reduce their own welfare to increase that of others. For example, in laboratory 'dictator games', people voluntarily give money to others (Forsythe et al., 1994), and participants in public goods games regularly contribute more than the privately-optimal amount (Dawes and Thaler, 1988; Ledyard, 1993). Charitable donations in the United States amount to more than 2 % of GDP (List, 2011). Similarly, many individuals voluntarily contribute to environmental public goods, such as reduced carbon

[54] The efficacy of these interventions can often be explained within neoclassical economic models. From an expositional perspective, it is still relevant to cover them in this section.

emissions. For example, USD 387 million were spent in the U.S. on voluntary carbon offset purchases in 2009 (Bloomberg, 2010).

Pre-existing altruistic voluntary carbon emission reductions could moderate the effects of a new carbon tax on energy demand because the introduction of monetary incentives can 'crowd out' altruistic motivations (Titmuss, 1970; Frey and Oberholzer-Gee, 1997; Gneezy and Rustichini, 2000). Thus, a carbon tax could reduce voluntary carbon emission reductions even as it increases financially-motivated reductions. While this effect might not weaken the welfare argument for a carbon tax, it does reduce the elasticity of carbon emissions with respect to a carbon tax.

Reciprocity, understood as the practice of people rewarding generosity and castigating cruelty towards them, has been found to be a key driver of voluntary contributions to public goods. Positive reciprocity comes in the form of conditional cooperation, which is a tendency to cooperate when others do so too (Axelrod, 1984; Fischbacher et al., 2001; Frey and Meier, 2004). However, cooperation based on positive reciprocity is often fragile and is declining over time (Bolton et al., 2004; Fischbacher and Gächter, 2010). Incentives and penalties are fundamental to maintaining cooperation in environmental treaties (Barrett, 2003). Adding a strategic option to punish defectors often stabilizes cooperation, even when punishment comes at a cost to punishers (Ostrom et al., 1992; Fehr and Gächter, 2002). Yet, if agents are allowed to counter-punish, the effectiveness of reciprocity to promote cooperation might be mitigated (Nikiforakis, 2008). However, most laboratory studies have been conducted under symmetric conditions and little is known about human cooperation in asymmetric settings, which tend to impose more serious normative conflicts (Nikiforakis et al., 2012).

Experiments also reveal a paradox: actors can agree to a combined negotiated climate goal for reducing the risk of catastrophe, but behave as if they were blind to the risks (Barrett and Dannenberg, 2012). People are also often motivated by concerns about the fairness of outcomes and procedures; in particular, many do not like falling behind others (Fehr and Schmidt, 1999; Bolton and Ockenfels, 2000; Charness and Rabin, 2002; Bolton et al., 2005). Such concerns can both promote and hamper the effectiveness of negotiations, including climate negotiations, in overcoming cooperation and distributional problems (Güth et al., 1982; Lange and Vogt, 2003; Lange et al., 2007; Dannenberg et al., 2010).

Uncertainty about outcomes and behaviours also tends to hamper cooperation (Gangadharan and Nemes, 2009; Ambrus and Greiner, 2012). As a result, the information given to, and exchanged by, decision makers may affect social comparison processes and reciprocal interaction, and thus the effectiveness of mechanisms to resolve conflicts (Goldstein et al., 2008; Chen et al., 2010; Bolton et al., 2013). In particular, face-to-face communication has been proved to significantly promote cooperation (Ostrom, 1990; Brosig et al., 2003). Concerns about free-riding are perceived as a barrier to engaging in mitigation actions (Lorenzoni et al., 2007). The importance of fairness in promoting international cooperation (see also Chapter 4) is one of the few non-normative justifications for fairness in climate policy.

3.10.1.5 Human ability to understand climate change

So far, we have covered deviations from the neoclassical model that affect energy demand. Such deviations can also affect the policy-making process. The understanding of climate change as a physical phenomenon with links to societal causes and impacts is highly complex (Weber and Stern, 2011). Some deviations are behavioural and affect perceptions and decision making in various settings besides climate change. (See Section 2.4 for a fuller discussion). For example, perceptions of, and reactions to, uncertainty and risk can depend not only on external reality, as assumed in the neoclassical model, but also on cognitive and emotional processes (Section 2.4.2). When making decisions, people tend to overweight outcomes that are especially 'available' or salient (Kahneman and Tversky, 1974, 1979). They are more averse to losses than they are interested in gains relative to a reference point (Kahneman and Tversky, 1979). Because climate change involves a loss of existing environmental amenities, this can increase its perceived costs. However, if the costs of abatement are seen as a reduction relative to a reference rate of future economic growth, this can increase the perceived costs of climate change mitigation.

Some factors make it hard for people to think about climate change and lead them to underweight it: change happens gradually; the major effects are likely to occur in the distant future; the effects will be felt elsewhere; and their nature is uncertain. Furthermore, weather is naturally variable, and the distinction between weather and climate is often misunderstood (Reynolds et al., 2010). People's perceptions and understanding of climate change do not necessarily correspond to scientific knowledge (Section 2.4.3) because they are more vulnerable to emotions, values, views, and (unreliable) sources (Weber and Stern, 2011). People are likely to be misled if they apply their conventional modes of understanding to climate change (Bostrom et al., 1994).

3.10.2 Social and cultural issues

In recent years, the orientation of social processes and norms towards mitigation efforts has been seen as an alternative or complement to traditional mitigation actions, such as incentives and regulation. We address some of the concepts discussed in the literature, which, from a social and cultural perspective, contribute to strengthening climate change actions and policies.

3.10.2.1 Customs

In both developed and developing countries, governments, social organizations, and individuals have tried to change cultural attitudes

Box 3.11 | Gross National Happiness (GNH)

The Kingdom of Bhutan has adopted an index of GNH as a tool for assessing national welfare and planning development (Kingdom of Bhutan, 2008). According to this concept, happiness does not derive from consumption, but rather from factors such as the ability to live in harmony with nature (Taplin et al., 2013). Thus, GNH is both a critique of, and an alternative to, the conventional global development model (Taplin et al., 2013). The GNH Index measures wellbeing and progress according to nine key domains (and 72 core indicators) (Uddin et al., 2007). The intention is to increase access to health, education, clean water, and electrical power (Pennock and Ura, 2011) while maintaining a balance between economic growth, environmental protection, and the preservation of local culture and traditions. This is seen as a 'Middle Way' aimed at tempering the environmental and social costs of unchecked economic development (Frame, 2005; Taplin et al., 2013).

towards emissions, energy use, and lifestyles (European Commission, 2009). For example, household energy-use patterns for space and water heating differ significantly between Japan and Norway because of lifestyle differences (Wilhite et al., 1996; Gram-Hanssen, 2010). Some have argued that the bio-cultural heritage of indigenous peoples is a resource that should be valued and preserved as it constitutes an irreplaceable bundle of teachings on the practices of mitigation and sustainability (Sheridan and Longboat, 2006; Russell-Smith et al., 2009; Kronik and Verner, 2010). Sometimes local strategies and indices have metamorphosed into national policies, as in the case of '*Buen Vivir*' in Ecuador (Choquehuanca, 2010; Gudynas, 2011) and 'Gross National Happiness' (GNH), described in Box 3.11. In rich countries, and among social groups with high levels of environmental awareness, interest in sustainability has given rise to cultural movements promoting change in modes of thought, production, and consumption. Including the cultural dimension in mitigation policies facilitates social acceptability.

3.10.2.2 Indigenous peoples

Indigenous peoples number millions across the globe (Daes, 1996). Land and the natural environment are integral to their sense of identity and belonging and to their culture, and are essential for their survival (Gilbert, 2006; Xanthaki, 2007). The ancestral lands of indigenous peoples contain 80 % of the earth's remaining healthy ecosystems and global biodiversity priority areas, including the largest tropical forests (Sobrevila, 2008). Because they depend on natural resources and inhabit biodiversity-rich but fragile ecosystems, indigenous peoples are particularly vulnerable to climate change and have only limited means of coping with such change (Henriksen, 2007; Permanent Forum on Indigenous Issues, 2008). They are often marginalized in decision making and unable to participate adequately in local, national, regional, and international climate-change mechanisms. Yet, it is increasingly being recognized that indigenous peoples can impart valuable insights into ways of managing mitigation and adaptation (Nakashima et al., 2012), including forest governance and conserving ecosystems (Nepstad et al., 2006; Hayes and Murtinho, 2008; Persha et al., 2011).

3.10.2.3 Women and climate change

Women often have more restricted access to, and control of, the resources on which they depend than men. In many developing countries, most small-scale food producers are women. They are usually the ones responsible for collecting water and fuel and for looking after the sick. If climate change adversely affects crop production and the availability of fuel and water, or increases ill health, women may bear a disproportionate burden of those consequences (Dankelman, 2002; UNEP, 2011).[55] On the other hand, they may be better at adapting to climate change, both at home and in the community. But given their traditional vulnerability, the role of women across society will need to be re-examined in a gender-sensitive manner to ensure they have equal access to all types of resources (Agostino and Lizarde, 2012).

3.10.2.4 Social institutions for collective action

Social institutions shape individual actions in ways that can help in both mitigation and adaptation. They promote trust and reciprocity, establish networks, and contribute to the evolution of common rules. They also provide structures through which individuals can share information and knowledge, motivate and coordinate behaviour, and act collectively to deal with common challenges. Collective action is reinforced when social actors understand they can participate in local solutions to a global problem that directly concerns them.

As noted in Sections 3.10.1.5 and 2.4, public perceptions of the cause and effect of climate change vary, in both developed and developing countries, with some erroneous ideas persisting even among well-educated people. Studies of perceptions (O'Connor et al., 1999; Corner et al., 2012) demonstrate that the public is often unaware of the roles that individuals and society can play in both mitigation and adaptation. The concepts of social and policy learning can be used in stimu-

[55] Natural disasters over the period 1981–2002 revealed evidence of a gender gap: natural disasters lowered women's life expectancy more than men's: the worse the disaster and the lower the woman's socio-economic status the bigger the disparity (Neumayer and Plümper, 2007).

lating and organizing collective action. Social learning involves participation by members of a group in discourse, imitation, and shared collective or individual actions. The concept of policy learning describes the process of adaptation by organizations to external change while retaining or strengthening their own objectives and domination over existing socio-economic structures (Adger and Kelly, 1999). The task of an educational programme in mitigating and adapting to climate change is to represent a collective global problem in individual and social terms. This will require the strategies for disseminating scientific information to be reinforced and the practical implications advertised in ways that are understandable to diverse populations (González Gaudiano and Meira Cartea, 2009).

3.11 Technological change

Mitigation scenarios aim at significant reductions in current emission levels that will be both difficult and costly to achieve with existing technological options. However, cost-reducing technological innovations are plausible. The global externality caused by climate change compounds market failures common to private sector innovations. Appropriate policy interventions are accordingly needed to encourage the type and amount of climate-friendly technological change (TC) that would lead to sizable reductions in the costs of reducing carbon emissions. This section reviews theories, concepts, and principles used in the study of environmentally oriented TC, and highlights key lessons from the literature, in particular, the potential of policy to encourage TC. Examples of success and failure in promoting low carbon energy production and consumption technologies are further evaluated in Chapters 6–16.

3.11.1 Market provision of TC

As pollution is not fully priced by the market, private individuals lack incentives to invest in the development and use of emissions-reducing technologies in the absence of appropriate policy interventions. Market failures other than environmental pollution include what is known as the 'appropriability problem'. This occurs when inventors copy and build on existing innovations, and reap part of the social returns on them. While the negative climate change externality leads to over use of the environment, the positive 'appropriability' externality leads to an under-supply of technological innovation.[56] Indeed, empirical research provides ample evidence that social rates of return on R&D are higher than private rates of return (Griliches, 1992). Thus, the benefits of new knowledge may be considered as a public good (see, e.g., Geroski, 1995).

Imperfections in capital markets often distort the structure of incentives for financing technological development. Information about the potential of a new technology may be asymmetrically held, creating adverse selection (Hall and Lerner, 2010). This may be particularly acute in developing countries. The issue of path dependence, acknowledged in evolutionary models of TC, points to the importance of transformative events in generating or diverting technological trajectories (see Chapters 4 and 5). Even endogenously induced transformative events may not follow a smooth or predictable path in responding to changing economic incentives, suggesting that carbon-price policy alone may not promote the desired transformative events.

3.11.2 Induced innovation

The concept of 'induced innovation' postulates that investment in R&D is profit-motivated and responds positively to changes in relative prices[57] (Hicks, 1932; Binswanger and Ruttan, 1978; Acemoglu, 2002).[58] Initial evidence of induced TC focused on the links between energy prices and innovation and revealed the lag between induced responses and the time when price changes came into effect, which is estimated at five years by Newell et al. (1999) and Popp (2002) (see Chapter 5). Policy also plays an important role in inducing innovation, as demonstrated by the increase in applications for renewable energy patents within the European Union in response to incentives for innovation provided by both national policies and international efforts to combat climate change (Johnstone et al., 2010). Recent evidence also suggests that international environmental agreements provide policy signals that encourage both innovation (Dekker et al., 2012) and diffusion (Popp et al., 2011). With the exception of China, most climate-friendly innovation occurred in developed countries (Dechezlepretre et al., 2011).[59]

3.11.3 Learning-by-doing and other structural models of TC

An extensive literature relates to rates of energy cost reduction based on the concept of 'experience' curves (see Chapter 6). In economics, this concept is often described as learning-by-doing (LBD)—to describe the decrease in costs to manufacturers as a function of cumulative output—or 'learning-by-using', reflecting the reduction in costs

56 For incremental innovations, the net technology externality can be negative. Depending on market structure and intellectual property rules, the inventor of an incremental improvement on an existing technology may be able to appropriate the entire market, thereby earning profits that exceed the incremental value of the improvement.

57 It should be pointed out that in economics, 'induced innovation' typically means innovation induced by relative price differences. The IPCC uses a different definition: innovation induced by policy.

58 In economics, 'induced innovation' typically means innovation induced by relative price differences. The IPCC uses a different definition: innovation induced by policy.

59 Global R&D expenditures amounted to USD 1.107 trillion in 2007, with OECD nations accounting for 80 %, and the U.S. and Japan together accounting for 46 % (National Science Board, 2010).

(and/or increase in benefits) to consumers as a function using a technology. While learning curves are relatively easy to incorporate into most climate integrated assessment models (IAMs), the application of LBD has limitations as a model of TC (Ferioli et al., 2009). Learning curves ignore potential physical constraints. For example, while costs may initially fall as cumulative output expands, if renewable energy is scaled up, the use of suboptimal locations for production would increase costs. Ferioli et al. (2009) also provide evidence that learning can be specific to individual components, so that the savings from learning may not fully transfer from one generation of equipment to the next. They therefore suggest caution when extrapolating cost savings from learning curves to long-term frames or large-scale expansions. Similarly, in a study on cost reductions associated with photovoltaic cells, Nemet (2006) finds that most efficiency gains come from universities, which have little traditional LBD through production experience. Hendry and Harborne (2011) provide examples of the interaction of experience and R&D in the development of wind technology.

3.11.4 Endogenous and exogenous TC and growth

Within climate policy models, TC is either treated as exogenous or endogenous. Köhler et al. (2006), Gillingham et al. (2008) and Popp et al. (2010) provide reviews of the literature on TC in climate models.

Exogenous TC (most common in models) progresses at a steady rate over time, independently of changes in market incentives. One drawback of exogenous TC is that it ignores potential feedback between climate policy and the development of new technologies. Models with endogenous TC address this limitation by relating technological improvements in the energy sector to changes in energy prices and policy. These models demonstrate that ignoring induced innovation overstates the costs of climate control.

The Nordhaus (1977, 1994) DICE model is the pioneering example of a climate policy model incorporating TC into IAMs. In most implementations of DICE, TC is exogenous. Efforts to endogenize TC have been difficult, mainly because market-based spillovers from R&D are not taken into account when deciding how much R&D to undertake. Recent attempts to endogenize TC include WITCH model (Bosetti et al., 2006) and Popp's (2004) ENTICE model. Popp (2004) shows that models that ignore directed TC do indeed significantly overstate the costs of environmental regulation (more detailed discussion on TC in these and more recent models is provided in Chapter 6).

An alternative approach builds on new growth theories, where TC is by its nature endogenous, in order to look at the interactions between growth and the environment. Policies like R&D subsidies or carbon taxes affect aggregate growth by affecting entrepreneurs' incentives to innovate. Factoring in firms' innovations dramatically changes our view of the relationship between growth and the environment. More recent work by Acemoglu et al. (2012) extends the endogenous growth literature to the case where firms can choose the direction of innovation (i.e., they can decide whether to innovate in more or less carbon-intensive technologies or sectors).[60]

In contrast, LBD models use learning curve estimates to simulate falling costs for alternative energy technologies as cumulative experience with the technology increases. One criticism of these models is that learning curve estimates provide evidence of correlation, but not causation. While LBD is easy to implement, it is difficult to identify the mechanisms through which learning occurs. Goulder and Mathai (2000) provide a theoretical model that explores the implications of modelling technological change through R&D or LBD (several empirical studies on this are reviewed in more detail in Chapter 6).

3.11.5 Policy measures for inducing R&D

Correcting the environmental externality or correcting knowledge market failures present two key options for policy intervention to encourage development of climate-friendly technologies. Patent protection, R&D tax credits, and rewarding innovation are good examples of correcting failures in knowledge markets and promoting higher rates of innovation. On the other hand, policies regulating environmental externalities, such as a carbon tax or a cap-and-trade system, influence the direction of innovation.

Chapter 15 discusses in more detail how environmental and technology policies work best in tandem (e.g., Popp, 2006; Fischer, 2008; Acemoglu et al., 2012). For instance, in evaluating a broad set of policies to reduce CO_2 emissions and promote innovation and diffusion of renewable energy in the United States electricity sector, Fischer & Newell (2008) find that a portfolio of policies (including emission pricing and R&D) achieves emission reductions at significantly lower cost than any single policy (see Chapters 7 to 13). However, Gerlagh and van der Zwaan (2006) note the importance of evaluating the trade-off between cost savings from innovation and Fischer and Newell (2008) assumptions of decreasing returns to scale due to space limitations for new solar and wind installations.

3.11.6 Technology transfer (TT)

Technology transfer (TT) has been at the centre of the scholarly debate on climate change and equity in economic development as a way for developed countries to assist developing countries access new low carbon technologies. Modes of TT include, trade in products, knowledge and technology, direct foreign investment, and international move-

[60] Other works investigating the response of technology to environment regulations include Grübler and Messner (1998), Manne and Richels (2004b), Messner (1997), Buonanno et al. (2003), Nordhaus (2002), Di Maria and Valente (2008), Bosetti et al. (2008), Massetti et al. (2009), Grimaud and Rouge (2008), and Aghion et al. (2009).

ment of people (Hoekman et al., 2005). Phases and steps for TT involve absorption and learning, adaptation to the local environment and needs, assimilation of subsequent improvements, and generalization. Technological learning or catch-up thus proceeds in stages: importing foreign technologies; local diffusion and incremental improvements in process and product design; and marketing, with different policy measures suited to different stages of the catch-up process.

'Leapfrogging', or the skipping of some generations of technology or stages of development, is a useful concept in the climate change mitigation literature for enabling developing countries to avoid the more emissions-intensive stages of development (Watson and Sauter, 2011). Examples of successful low-carbon leapfrogging are discussed in more detail in Chapter 14.

Whether proprietary rights affect transfers of climate technologies has become a subject of significant debate. Some technologies are in the public domain; they are not patented or their patents have expired. Much of the debate on patented technologies centres on whether the temporary monopoly conferred by patents has hampered access to technology. Proponents of strong intellectual property (IP) rights believe that patents enhance TT as applicants have to disclose information on their inventions. Some climate technology sectors, for example, those producing renewable energy, have easily available substitutes and sufficient competition, so that patents on these technologies do not make them costly or prevent their spread (Barton, 2007). In other climate-related technology sectors, IP protection could be a barrier to TT (Lewis, 2007). (The subject is further discussed in Chapters 13 and 15.)

Various international agreements on climate change, trade, and intellectual property include provisions for facilitating the transfer of technology to developing countries. Climate change agreements encourage participation by developing countries and address barriers to the adoption of technologies, including financing. However, some scholars have found these agreements to be ineffective because they do not incorporate mechanisms for ensuring technology transfers to developing countries (Moon, 2008). (The literature on international cooperation on TT is further discussed in Chapters 13, 14 and 16.)

3.12 Gaps in knowledge and data

As this chapter makes clear, many questions are not completely answered by the literature. So it is prudent to end our assessment with our findings on where research might be directed over the coming decade so that the AR6 (should there be one) may be able to say more about the ethics and economics of climate change.

- To plan an appropriate response to climate change, it is important to evaluate each of the alternative responses that are available. How can we take into account changes in the world's population? Should society aim to promote the total of people's wellbeing in the world, or their average wellbeing, or something else? The answer to this question will make a great difference to the conclusions we reach.

- The economics and ethics of geoengineering is an emerging field that could become of the utmost importance to policymakers. Deeper analysis of the ethics of this topic is needed, as well as more research on the economic aspects of different possible geoengineering approaches and their potential effects and side-effects.

- To develop better estimates of the social cost of carbon and to better evaluate mitigation options, it would be helpful to have more realistic estimates of the components of the damage function, more closely connected to WGII assessments of physical impacts. Quantifying non-market values, that is, measuring valuations placed by humans on nature and culture, is highly uncertain and could be improved through more and better methods and empirical studies. As discussed in Section 3.9, the aggregate damage functions used in many IAMs are generated from a remarkable paucity of data and are thus of low reliability.

- The development of regulatory mechanisms for mitigation would be helped by more ex-post evaluation of existing regulations, addressing the effectiveness of different regulatory approaches, both singly and jointly. For instance, understanding, retrospectively, the effectiveness of the European Union Emissions Trading Scheme (EU ETS), the California cap-and-trade system, or the interplay between renewable standards and carbon regulations in a variety of countries.

- Energy models need to provide a more realistic portrait of microeconomic decision-making frameworks for technology-choice (energy-economy models).

- A literature is emerging in economics and ethics on the risk of catastrophic climate change impacts, but much more probing into the ethical dimensions is needed to inform future economic analysis.

- More research that incorporates behavioural economics into climate change mitigation is needed. For instance, more work on understanding how individuals and their social preferences respond to (ambitious) policy instruments and make decisions relevant to climate change is critical.

- Despite the importance of the cost of mitigation, the aggregate cost of mitigating x tonnes of carbon globally is poorly understood. To put it differently, a global carbon tax of x dollars per tonne would yield y(t) tonnes of carbon abatement at time, t. We do not understand the relationship between x and y(t).

- The choice of the rate at which future uncertain climate damages are discounted depends on their risk profile in relation to other risks in the economy. By how much does mitigating climate change reduce the aggregate uncertainty faced by future generations?

- As has been recently underscored by several authors (Pindyck, 2013; Stern, 2013) as well as this review, integrated assessment models have very significant shortcomings for CBA, as they do not fully represent climate damages, yet remain important tools for investigating climate policy. They have been widely and successfully applied for CEA analysis (Paltsev et al., 2008; Clarke et al., 2009; Krey and Clarke, 2011; Fawcett et al., 2013). Research into improving the state-of-the-art of such models (beyond just updating) can have high payoff.

3.13 Frequently Asked Questions

FAQ 3.1 The IPCC is charged with providing the world with a clear scientific view of the current state of knowledge on climate change. Why does it need to consider ethics?

The IPCC aims to provide information that can be used by governments and other agents when they are considering what they should do about climate change. The question of what they should do is a normative one and thus has ethical dimensions because it generally involves the conflicting interests of different people. The answer rests implicitly or explicitly on ethical judgements. For instance, an answer may depend on a judgement about the responsibility of the present generation towards people who will live in the future or on a judgement about how this responsibility should be distributed among different groups in the present generation. The methods of ethical theory investigate the basis and logic of judgements such as these.

FAQ 3.2 Do the terms justice, fairness and equity mean the same thing?

The terms 'justice', 'fairness' and 'equity' are used with subtly different meanings in different disciplines and by different authors. 'Justice' and 'equity' commonly have much the same meaning: 'justice' is used more frequently in philosophy; 'equity' in social science. Many authors use 'fairness' as also synonymous with these two. In reporting on the literature, the IPCC assessment does not impose a strictly uniform usage on these terms. All three are often used synonymously. Section 3.3 describes what they refer to, generally using the term 'justice'.

Whereas justice is broadly concerned with a person receiving their due, 'fairness' is sometimes used in the narrower sense of receiving one's due (or 'fair share') in comparison with what others receive. So it is unfair if people do not all accept an appropriate share of the burden of reducing emissions, whereas on this narrow interpretation it is not unfair—though it may be unjust—for one person's emissions to harm another person. Fairness is concerned with the distribution of goods and harms among people. 'Distributive justice'—described in Section 3.3—falls under fairness on the narrow interpretation.

FAQ 3.3 What factors are relevant in considering responsibility for future measures that would mitigate climate change?

It is difficult to indicate unambiguously how much responsibility different parties should take for mitigating future emissions. Income and capacity are relevant, as are ethical perceptions of rights and justice. One might also investigate how similar issues have been dealt with in the past in non-climate contexts. Under both common law and civil law systems, those responsible for harmful actions can only be held liable if their actions infringe a legal standard, such as negligence or nuisance. Negligence is based on the standard of the reasonable person. On the other hand, liability for causing a nuisance does not exist if the actor did not know or have reason to know the effects of its conduct. If it were established that the emission of GHGs constituted wrongful conduct within the terms of the law, the nature of the causal link to the resulting harm would then have to be demonstrated.

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4 Sustainable Development and Equity

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Executive Summary

Since the first assessment report, the Intergovernmental Panel on Climate Change (IPCC) has considered issues of sustainable development (SD) and equity: acknowledging the importance to climate decision making, and progressively expanding the scope to include: the co-benefits of climate actions for SD and equity, the relevance of lifestyle and behaviour, the relevance of technological choices, the relevance of procedural equity to effective decision making, and the relevance of ethical frameworks and equitable burden sharing in assessing climate responses. This Assessment Report further explores key dimensions of SD and equity, highlighting the significance of disparities across different regions and groups, and the ways in which designing a climate policy is a component of a wide-ranging societal choice of a development path. [Section 4.1, 4.2]

Sustainable development, a central framing issue in this Assessment Report, is intimately connected to climate change (*high confidence*). SD is variably conceived as development that preserves the interests of future generations, that preserves the ecosystem services on which continued human flourishing depends, or that harmonizes the co-evolution of three pillars (economic, social, environmental) [4.2]. First, the climate threat constrains possible development paths, and sufficiently disruptive climate change could preclude any prospect for a sustainable future (*medium evidence, high agreement*). Thus, a stable climate is one component of SD. Second, there are synergies and tradeoffs between climate responses and broader SD goals, because some climate responses generate co-benefits for human and economic development, while others can have adverse side-effects and generate risks (*robust evidence, high agreement*). These co-benefits and risks are studied in the sector chapters of this report, along with measures and strategies to optimize them. Options for equitable burden sharing can reduce the potential for the costs of climate action to constrain development (*medium evidence, high agreement*). Third, at a more fundamental level, the capacities underlying an effective climate response overlap strongly with capacities for SD (*medium evidence, high agreement*) and designing an effective climate policy involves 'mainstreaming' climate in the design of comprehensive SD strategies and thinking through the general orientation of development (*medium evidence, medium agreement*). [4.2, 4.5]

Equity is an integral dimension of SD (*high confidence*). First, intergenerational equity underlies the concept of sustainability. Intragenerational equity is also often considered an intrinsic component of SD. In the particular context of international climate policy discussions, several arguments support giving equity an important role: a moral justification that draws upon ethical principles; a legal justification that appeals to existing treaty commitments and soft law agreements to cooperate on the basis of stated equity principles; and an effectiveness justification that argues that a fair arrangement is more likely to be agreed internationally and successfully implemented domestically (*medium evidence, medium agreement*). A relatively small set of core equity principles serve as the basis for most discussions of equitable burden sharing in a climate regime: responsibility (for GHG emissions), capacity (ability to pay for mitigation, but sometimes other dimensions of mitigative capacity), the right to development, and equality (often interpreted as an equal entitlement to emit). [4.2, 4.6]

While it is possible to envision an evolution toward equitable and sustainable development, its underlying determinants are also deeply embedded in existing societal patterns that are unsustainable and highly inertial (*high confidence*). A useful set of determinants from which to examine the prospects for and impediments to SD and equity are: the legacy of development relations; governance and political economy; population and demography; values and behaviour; human and social capital; technology; natural resource endowments; and finance and investment. The evolution of each of these determinants as a driver (rather than barrier) to a SD transition is conceivable, but also poses profound challenges (*medium evidence, medium agreement*). [4.3]

Governing a transition toward an effective climate response and SD pathway is a challenge involving rethinking our relation to nature, accounting for multiple generations and interests (including those based on endowments in natural resources), overlapping environmental issues, among actors with widely unequal capacities, resources, and political power, and divergent conceptions of justice (*high confidence*). Key debated issues include articulating top-down and bottom-up approaches, engaging participation of diverse countries and actors, creating procedurally equitable forms of decentralization and combining market mechanisms with government action, all in a particular political economic context (*robust evidence, high agreement*). [4.3]

Technology and finance both are strong determinants of future societal paths, and while society's current systems of allocating resources and prioritizing efforts toward investment and innovation are in many ways robust and dynamic, there are also some fundamental tensions with the underlying objectives of SD (*high confidence*). First, the technological innovation and financial systems are highly responsive to short-term motivations, and are sensitive to broader social and environmental costs and benefits only to the—often limited—extent that these costs and benefits are internalized by regulation, taxation, laws and social norms. Second, while these systems are quite responsive to market demand that is supported by purchasing power, they are only indirectly responsive to needs, particularly of those of the world's poor, and they operate with a time horizon that disregards potential needs of future generations (*medium evidence, medium agreement*). [4.3]

Enhancing human capital based on individual knowledge and skills, and social capital based on mutually beneficial formal and informal relationships is important for facilitating a transition toward sustainable development (*medium evidence, high agreement*). 'Social dilemmas' arise in which short-term individual

interests conflict with long-term social interests, with altruistic values being favourable to SD. However, the formation of values and their translation into behaviours is mediated by many factors, including the available set of market choices and lifestyles, the tenor of dominant information sources (including advertisements and popular culture), the culture and priorities of formal and civil institutions, and prevailing governance mode (*medium evidence, medium agreement*). The demographic transition toward low fertility rates is usually viewed favorably, though an ageing population creates economic and social challenges, and migrations due to climate impacts may exacerbate tensions (*medium evidence, medium agreement*). [4.3, 4.4]

The global consumption of goods and services has increased dramatically over the last decades, in both absolute and per capita terms, and is a key driver of environmental degradation, including global warming (*high confidence*). This trend involves the spread of high-consumption lifestyles in some countries and subregions, while in other parts of the world large populations continue to live in poverty. There are high disparities in consumption both between and within countries (*robust evidence, high agreement*). [4.4]

Two basic types of decoupling are often invoked in the context of a transition toward sustainable development: the decoupling of material resource consumption (including fossil fuels) and environmental impact (including climate change) from economic growth, and the decoupling of economic growth from human well-being (*high confidence*). The first type—the dematerialization of the economy, i.e., of consumption and production—is generally considered crucial for meeting SD and equity goals, including mitigation of climate change. Production-based (territorial) accounting suggests that some decoupling of impacts from economic growth has occurred, especially in industrialized countries, but its extent is significantly diminished based on a consumption-based accounting (*robust evidence, medium agreement*). Consumption-based emissions are more strongly associated with Gross Domestic Product (GDP) than production-based emissions, because wealthier countries generally satisfy a higher share of their final consumption of products through net imports compared to poorer countries. Ultimately, absolute levels of resource use and environmental impact—including GHG emissions—generally continue to rise with GDP (*robust evidence, high agreement*), though great variations between countries highlight the importance of other factors such as geography, energy system, production methods, waste management, household size, diet and lifestyle. The second type of decoupling—of human well-being from economic growth—is a more controversial goal than the first. There are ethical controversies about the measure of well-being and the use of subjective data for this purpose (*robust evidence, medium agreement*). There are also empirical controversies about the relationship between subjective well-being and income, with some recent studies across countries finding a clear relationship between average levels of life satisfaction and per capita income, while the evidence about the long-term relationship between satisfaction and income is less conclusive and quite diverse among countries (*medium evidence, medium agreement*). Studies of emotional well-being do identify clear satiation points beyond which further increases in income no longer enhance emotional well-being (*medium evidence, medium agreement*). Furthermore, income inequality has been found to have a marked negative effect on average subjective well-being, due to perceived unfairness and undermined trust of institutions among low income groups (*medium evidence, medium agreement*). [4.4]

Understanding the impact of development paths on emissions and mitigative capacity, and, more generally, how development paths can be made more sustainable and more equitable in the future requires in-depth analysis of the mechanisms that underpin these paths (*high confidence*). Of particular importance are the processes that may generate path dependence and lock-ins, notably 'increasing returns' but also use of scarce resources, switching costs, negative externalities or complementarities between outcomes (*robust evidence, high agreement*). [4.5, 4.6] The study of transitions between pathways is an emerging field, notably in the context of technology transitions. Yet analyzing how to transition to a sustainable, low-emission pathway remains a major scientific challenge. It would be aided by models with a holistic framework encompassing the economy, society (in particular the distribution of resources and well-being), and the environment, that take account of relevant technical constraints and trends, and explore a long-term horizon while simultaneously capturing processes relevant for the short-term and the key uncertainties (*medium evidence, medium agreement*). [4.5, 4.7]

Mitigation and adaptation measures can strongly affect broader SD and equity objectives, and it is thus useful to understand their broader implications (*high confidence*). Building both mitigative capacity and adaptive capacity relies to a profound extent on the same factors as those that are integral to equitable and sustainable development (*medium evidence, high agreement*), and equitable burden sharing can enhance these capacities where they are most fragile [4.6]. This chapter focuses on examining ways in which the broader objectives of equitable and sustainable development provide a policy frame for an effective, robust, and long-term response to the climate problem. [4.8]

4.1 Introduction

4.1.1 Key messages of previous IPCC reports

This chapter seeks to place climate change, and climate change mitigation in particular, in the context of equity and SD. Prior IPCC assessments have sought to do this as well, progressively expanding the scope of assessment to include broader and more insightful reflections on the policy-relevant contributions of academic literature.

The IPCC First Assessment Report (FAR) (IPCC, 1990) underscored the relevance of equity and SD to climate policy. Mandated to identify "possible elements for inclusion in a framework convention on climate change", the IPCC prominently put forward the "endorsement and elaboration of the concept of sustainable development" for negotiators to consider as part of the Convention's Preamble. It noted as key issues "how to address equitably the consequences for all" and "whether obligations should be equitably differentiated according to countries' respective responsibilities for causing and combating climate change and their level of development". This set the stage for the ensuing United Nations Framework Convention on Climate Change (UNFCCC) negotiations, which ultimately included explicit appeals to equity and SD, including in its Preamble, its Principles (Article 2), its Objective (Article 3), and its Commitments (Article 4).

The IPCC Second Assessment Report (SAR) (IPCC, 1995), published after the UNFCCC was signed, maintained this focus on equity and SD. It reflected a growing appreciation for the prospects for SD co-benefits and reiterated the policy relevance of equity and SD. It did this most visibly in a special section of the Summary for Policymakers presenting "Information Relevant to Interpreting Article 2 of the UNFCCC", including "Equity and social considerations" and "Economic development to proceed in a sustainable manner". Notably, the SAR added an emphasis on procedural equity through a legitimate process that empowers all actors to effectively participate, and on the need to build capacities and strengthen institutions, particularly in developing countries.

The IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2000) demonstrated that broader SD goals can contribute indirectly, yet substantially, to reducing emissions. This IPCC contribution reflected a change in the scientific literature, which had in recent years expanded its discussion of SD to encompass analyses of lifestyles, culture, and behaviour, complementing its traditional techno-economic analyses. It also reflected a recognition that economic growth (especially as currently measured) is not the sole goal of societies. The SRES thus provided insights into how policy intervention can decouple economic growth from emissions and well-being from economic growth, showing that both forms of decoupling are important elements of a transition to a world with low greenhouse gas (GHG) emissions.

The IPCC Third Assessment Report (TAR) (IPCC, 2001) deepened the consideration of broader SD objectives in assessing response strategies. Perhaps owing to a growing appreciation for the severity of the climate challenge, the TAR stressed the need for an ambitious and encompassing response, and was thus more attentive to the risk of climate-focused measures conflicting with basic development aspirations. It thus articulated the fundamental equity challenge of climate change as ensuring "that neither the impact of climate change nor that of mitigation policies exacerbates existing inequities both within and across nations", specifically because "restrictions on emissions will continue to be viewed by many people in developing countries as yet another constraint on the development process" (See Box 4.1 for further discussion of the relationship between climate change and development challenges in developing countries.). The TAR recognized the need to deepen the analysis of equitable burden sharing in order to avoid undermining prospects for SD in developing countries. More generally, the TAR observed that equitable burden sharing is not solely an ethical matter. Even from a rational-actor game-theoretic perspective, an agreement in which the burden is equitably shared is more likely to be signed by a large number of countries, and thus to be more effective and efficient.

The IPCC Fourth Assessment Report (AR4) (IPCC, 2007) further expanded the consideration of broader SD objectives. It stressed the importance of civil society and other non-government actors in designing climate policy and equitable SD strategies generally. The AR4 focused more strongly on the distributional implications of climate policies, noting that conventional climate policy analysis that is based too narrowly on traditional utilitarian or cost-benefit frameworks will neglect critical equity issues. These oversights include human rights implications and moral imperatives; the distribution of costs and benefits of a given set of policies, and the further distributional inequities that arise when the poor have limited scope to influence policy. This is particularly problematic, the AR4 notes, in integrated assessment model (IAM) analyses of 'optimal' mitigation pathways, because climate impacts do not affect the poor exclusively through changes in incomes. Nor do they satisfactorily account for uncertainty and risk, which the poor treat differently than the rich. The poor have higher risk aversion and lower access to assets and financial mechanisms that buffer against shocks. The AR4 went on to outline alternative ethical frameworks including rights-based and capabilities-based approaches, suggesting how they can inform climate policy decisions. In particular, the AR4 discussed the implications of these different frameworks for equitable international burden sharing.

The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (IPCC, 2011) deepened the consideration of broader SD objectives in assessing renewable energy options, noting particularly that while synergies can arise (for example, helping to expand access to energy services, increase energy security, and reduce some environmental pressures), there can also be tradeoffs (such as increased pressure on land resources, and affordability) and these must be negotiated in a manner sensitive to equity considerations.

The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) (IPCC 2012a) highlighted key further dimensions of SD and equity, including the distinction and interplay between incremental and transformative changes—both of which are necessary for an effective climate policy response, and emphasized the diversity of values that underlie decision making, e.g., a human rights framework vs. utilitarian cost-benefit analysis.

4.1.2 Narrative focus and key messages

In keeping with the previous IPCC assessments, this chapter considers SD and equity as matters of policy relevance for climate change decision makers. The chapter examines the ways in which climate change is in fact inextricably linked with SD and equity, and it does so with the aim of drawing policy-relevant conclusions regarding equitable and sustainable responses to climate change.

In one direction, the link is self-evident: an effective climate response is necessary for equitable and sustainable development to occur. The disruptions that climate change would cause in the absence of an effective societal response are sufficiently severe (see Working Group (WG) I and II contributions to the IPCC Fifth Assessment Report (AR5)) to severely compromise development, even taking into account future societies' ability to adapt (Shalizi and Lecocq, 2010). Nor is this development likely to be equitable, as an increasingly inhospitable climate will most seriously undermine the future prospects of those nations, communities, and individuals that are in greatest need of development. Without an effective response to climate change, including both timely mitigation and proactive adaptation, development can be neither sustainable nor equitable.

In recent years, the academic community has come increasingly to appreciate the extent to which SD and equity are also needed as frameworks for assessing and prioritizing climate responses: given the strong tradeoffs and synergies between the options for a climate response and SD, the design of an effective climate response must accord with the objectives for development and equity and exploit the synergies. A climate strategy that does not do so runs the risk either of being ineffective for lack of consensus and earnest implementation or of jeopardizing SD just as would unabated climate change. Therefore, a shift toward more equitable and sustainable modes of development may provide the only context in which an effective climate response can be realized.

The scientific community is coming to understand that climate change is but one example of how humankind is pressing up against its planetary limits (Millennium Ecosystem Assessment, 2005; Rockström et al., 2009a). Technical measures can certainly help in the near-term to alleviate climate change. However, the comprehensive and durable strategies society needs are those that recognize that climate change shares its root causes with other dimensions of the global sustainability crisis, and that without addressing these root causes, robust solutions may not be accessible.

This chapter, and many parts of this report, uncovers ways in which a broader agenda of SD and equity may support and enable an effective societal response to the climate challenge, by establishing the basis by which mitigative and adaptive capacity can be built and sustained. In examining this perspective, this chapter focuses on several broad themes.

4.1.2.1 Consumption, disparities, and well-being

The first theme relates to well-being and consumption. The relationship between consumption levels and environmental pressures, including GHG emissions, has long been a key concern for SD, with a growing focus on high-consumption lifestyles in particular and consumption disparities. A significant part of the literature develops methodologies for assessing the environmental impacts across national boundaries of consumption, through consumption-based accounting and GHG footprint analysis. Important research is now also emerging on the relationship between well-being and consumption, and how to moderate consumption and its impacts without hindering well-being—and indeed, while enhancing it. More research is now available on the importance of behaviour, lifestyles, and culture, and their relationship to over-consumption (Sections 4.3, 4.4).

Research is emerging to help understand 'under-consumption', i.e., poverty and deprivation, and its impacts on well-being more broadly, and specifically on the means by which it undermines mitigative and adaptive capacity (WGII Chapter 20). Energy poverty is one critical example, linked directly to climate change, of under-consumption that is well-correlated with weakened livelihoods, lack of resilience, and limited mitigative and adaptive capacity. Overcoming under-consumption and reversing over-consumption, while maintaining and advancing human well-being, are fundamental dimensions of SD, and are equally critical to resolving the climate problem (Sections 4.5, 4.6).

4.1.2.2 Equity at the national and international scales

Given the disparities evident in consumption patterns, the distributional implications of climate response strategies are critically important. As recent history shows, understanding how policies affect different segments of the population is essential to designing and implementing politically acceptable and effective national climate response strategies. A transition perceived as just would attract a greater level of public support for the substantial techno-economic, institutional, and lifestyle shifts needed to reduce emissions substantially and enable adaptive responses.

At the international level, an equitable regime with fair burden sharing is likely to be a key condition for an effective global response (Sections 4.2, 4.6). Given the urgency of the climate challenge, a rather rapid transition will be required if the global temperature rise is to remain below the politically discussed targets, such as 1.5 °C or 2 °C over pre-industrial levels, with global emissions possibly peaking as soon as 2020 (see WGI, Figure 6.25). Particularly in a situation calling for a concerted global effort, the most promising response is a cooperative approach "that would quickly require humanity to think like a society of people, not like a collection of individual states" (Victor, 1998).

While scientific assessments cannot define what equity is and how equitable burden sharing should be implementing the Convention and climate policies in general, they can help illuminate the implications of alternative choices and their ethical basis (Section 4.6, also Sections 3.2, 3.3, 6.3.6, 13.4.3).

Box 4.1 | Sustainable development and climate change mitigation in developing countries

The interconnectedness of climate change, sustainable development, and equity poses serious challenges for developing countries but it also presents opportunities.

Developing countries are confronted by a daunting mitigation challenge in the midst of pressing development needs. Developing country emissions comprised more than half of global emissions in 2010, and grew during the preceding decade by an amount that accounted for the total global emissions rise (JRC/PBL (2013), IEA (2012a), see Annex II.9; see Section 5.2). In the absence of concerted mitigation actions, the coming decades would see this trend prolonged, with a continued growth in global emissions driven predominantly by developing countries' rising emissions (see Section 6.3). This trend is the unsurprising outcome of the recent economic growth in many developing countries. The increase in emissions coincided with a number of positive developments: over the past decade, the overall poverty rate has declined, maternal and child mortality have fallen, the prevalence of several preventable diseases has decreased, and access to safe drinking water and sanitation has expanded, while the Human Development Index (HDI) across nations has risen and its convergence has become more pronounced. This "rise of the South" has been termed "unprecedented in its speed and scale [...] affecting a hundred times as many people as the Industrial Revolution" and setting in motion a "dramatic rebalancing" of economic and geopolitical forces (United Nations, 2011a; United Nations Development Programme, 2013).

Notwithstanding these gains, further developmental progress is urgently needed throughout the developing world. More than 1.5 billion people remain in multi-dimensional poverty, energy insecurity is still widespread, inequality of income and access to social services is persistently high, and the environmental resource base on which humans rely is deteriorating in multiple ways (Millennium Ecosystem Assessment, 2005; Bazilian et al., 2010; United Nations Development Programme, 2013). Moreover, unavoidable climate change will amplify the challenges of development: climate impacts are expected to slow economic growth and exacerbate poverty, and current failures to address emerging impacts are already eroding the basis for sustainable development (WGII SPM).

Thus, the challenge confronting developing countries is to preserve and build on the developmental achievements to date, sharing them broadly and equitably across their populations, but to do so via a sustainable development pathway that does not reproduce the fossil-fuel based and emissions-intensive conventional pathway by which the developed world moved from poverty to prosperity. Faced with this dilemma, developing countries have sought evidence that such alternative development pathways exist, looking in particular to developed countries to take the lead during the two decades since the UNFCCC was negotiated. Some such evidence has emerged, in the form of a variety of incipient climate policy experiments (see Section 15.6, 15.7) that appear to have generated some innovation in low-carbon technologies (see Section 4.4) and modestly curbed emissions in some countries (see Section 5.3).

Developing countries have stepped forward with significant actions to address climate change, but will need to build mitigative and adaptive capacity if they are to respond yet more effectively (see Section 4.6). More broadly, the underlying determinants of development pathways in developing countries are often not aligned toward a sustainable pathway (see Sections 4.3, 4.5). At the same time, developing countries are in some ways well-positioned to shift toward sustainable pathways: most developing countries are still in the process of building their urban and industrial infrastructure and can avoid lock-in (see Sections 4.5, 5.6). Many are also in the process of establishing the cultural norms and lifestyles of an emerging middle class, and can do so without reproducing the consumerist values of many developed countries (4.3, 4.4). Some barriers, such as lack of access to financial and technological resources, can be overcome through international cooperation based on principles of equity and fair burden sharing (see Sections 4.6, 6.3).

4.1.2.3 Building institutions and capacity for effective governance

While there is strong evidence that a transition to a sustainable and equitable path is technically feasible (see Sections 6.1.2, 6.3), charting an effective and viable course through the climate challenge is not merely a technical exercise. It will involve myriad and sequential decisions, among states and civil society actors, supported by the broadest possible constituencies (Section 4.3). Such a process benefits from the education and empowerment of diverse actors to participate in systems of decision making that are designed and implemented with procedural equity as a deliberate objective. This applies at the national as well as international levels, where effective governance relating to global common resources, in particular, is not yet mature.

Any given approach to addressing the climate challenge has potential winners and losers. The political feasibility of that approach will depend strongly on the distribution of power, resources, and decision-making authority among the potential winners and losers. In a world characterized by profound disparities, procedurally equitable systems of engagement, decision making, and governance appear needed to enable a polity to come to equitable and sustainable solutions to the sustainable development challenge.

4.2 Approaches and indicators

This section maps out the various conceptual approaches to the issues of SD (4.2.1), equity (4.2.2), and their linkages to climate change and climate policy.

4.2.1 Sustainability and sustainable development (SD)

4.2.1.1 Defining and measuring sustainability

The most frequently quoted definition of SD is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", from the Brundtland Report (World Commission on Environment and Development, 1987). This definition acknowledges a tension between sustainability and development (Jabareen, 2006), and that development objectives aim at meeting basic needs for all citizens and securing them in a sustainable manner (Murdiyarso, 2010). One of the first definitions of SD (Prescott-Allen, 1980) refers to a development process that is compatible with the preservation of ecosystems and species.

A popular conceptualization of SD goes beyond securing needs and preserving the environment and involves three 'pillars' or three 'bottom-lines' of sustainability: environmental, economic, and social aspects (Dobson, 1991; Elkington, 1998; Flint and Danner, 2001; Pope et al., 2004; Sneddon et al., 2006; Murdiyarso, 2010; Okereke, 2011). There is some variation in the articulation of the three spheres, with some scholars arguing for an equal appraisal of their co-evolution and mutual interactions, and others positing a hierarchy with economic activities embedded in the social matrix, which is itself grounded in the ecosphere (Levin, 2000; Fischer et al., 2007). This broad SD framework is equally relevant for rich countries concerned with growth, well-being, human development, and lifestyles.

A well-known distinction opposes weak sustainability to strong sustainability approaches (Neumayer, 2010). The former relies on the assumption that human-made capital can replace natural resources and ecosystem services with a high degree of substitutability. Strong sustainability, in contrast, takes the view that certain critical natural stocks—such as the climate system and biodiversity—cannot be replaced by human-made capital and must be maintained. Weak sustainability is often believed to be inherent to economic modelling that aggregates all forms of capital together (Dietz and Neumayer, 2007), but economic models and indicators can accommodate any degree of substitutability between different forms of capital (Fleurbaey and Blanchet, 2013). The linkage between strong sustainability and IAMs is discussed in Sathaye et al. (2011). A different but related issue is whether one should evaluate development paths only in terms of human well-being, which depends on the environment services (Millennium Ecosystem Assessment, 2005), or also account for natural systems as intrinsically valuable (McShane, 2007; Attfield, 2008).

Sustainability is closely related to resilience (WII AR5 2.5 and 20.2–20.6; Folke et al., 2010; Gallopin, 2006; Goerner et al., 2009) and vulnerability (Kates, 2001; Clark and Dickson, 2003; IPCC, 2012a). A key premise of this direction of research is that social and biophysical processes are interdependent and co-evolving (Polsky and Eakin, 2011). The biosphere itself is a complex adaptive system, the monitoring of which is still perfectible (Levin, 2000; Thuiller, 2007). Critical perspectives on these concepts, when applied to SD analysis, can be found in Turner (2010) and Cannon and Müller-Mahn (2010).

Although there are various conceptions of sustainability in the literature, there are internationally agreed principles of SD adopted by heads of states and governments at the 1992 UN Conference on Environment and Development (UNCED) and reaffirmed at subsequent review and implementation conferences (United Nations, 1992a, 1997, 2002, 2012a). A key guiding principle is: "The right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations" (1992 Rio Declaration Principle 3). The Rio principles were reaffirmed at the June 2012 summit level UN Conference on SD.

Box 4.2 | Sustainable development indicators (SDI)

When SD became a prominent consideration in policymaking in the early 1990s, SDI initiatives flourished. Pressure-state-response (PSR) and capital accounting-based (CAB) frameworks, in particular, were widely used to assess sustainability. The PSR approach was further modified as driving force-state-response (DSR) by the United Nations Conference on Sustainable Development (UNCSD) (2001) and driving force-pressure-state-impact-response (DPSIR) by the United Nations Environment Programme (UNEP) (UNEP, 1997, 2000, 2002). The System of Integrated Environmental-Economic Accounting (SEEA) of the United Nations offers a wealth of information about the state of ecosystems and is currently under revision and expansion.[1] The CAB approach is embodied in the Adjusted Net Savings indicator of the World Bank (2003, 2011), which is mentioned in Section 4.3 and 14.1 of this report. It is based on the economic theory of 'genuine savings' (understood as the variation of all natural and man-made capital stocks, evaluated at certain specific accounting prices), which shows that on a path that maximizes the discounted utilitarian sum, a negative value for genuine savings implies that the current level of well-being is not sustainable (Hamilton and Clemens, 1999; Pezzey, 2004).

General presentations and critical assessments of SDIs can be found in a large literature (Daly, 1996; Aronsson et al., 1997; Pezzey and Toman, 2002; Lawn, 2003; Hamilton and Atkinson, 2006; Asheim, 2007; Dietz and Neumayer, 2007; Neumayer, 2010; Martinet, 2012; Mori and Christodoulou, 2012; Fleurbaey and Blanchet, 2013). This literature is pervaded by a concern for comprehensiveness—i. e., recording all important aspects of well-being, equity, and nature preservation for current and future generations—and accuracy—i. e., avoiding arbitrary or unreliable weighting of the relevant dimensions when synthesizing multidimensional information. The general conclusion of this literature is that there is currently no satisfactory empirical indicator of sustainability.

A limitation of the PSR model is that it fails to identify causal relations, and it oversimplifies the links between dimensions. It is moreover based upon aggregate indices, which lose much information contained in the underlying indicators. An important limitation of the SEEA is that social and institutional issues are essentially left out, and its stock-and-flow approach is problematic with respect to environmental and social aspects that do not have a market price. Similarly, computing CAB indicators compounds the difficulty of comprehensively estimating the evolution of capital stocks with the difficulty of computing the accounting prices. Market prices do provide relevant information for valuing capital stocks in a perfectly managed economy (as shown by Weitzman, 1976), but may be very misleading in actual conditions (Dasgupta and Mäler, 2000; Arrow et al., 2012).

[1] Documentation is available at http://unstats.un.org/unsd/envaccounting/seea.asp.

4.2.1.2 Links with climate change and climate policy

The literature on the complex relations between climate change, climate policies, and SD is large (Swart et al., 2003; Robinson et al., 2006; Bizikova et al., 2007; Sathaye et al., 2007; Thuiller, 2007; Akimoto et al., 2012; Janetos et al., 2012). The links between SD and climate issues are examined in detail in WGII Chapter 20. Mapping out these links is also important in this WGIII report, and is done in this section.

Three main linkages can be identified, each of which contains many elements. First, the climate threat constrains possible development paths, and sufficiently disruptive climate change could preclude any prospect for sustainable future (WGII Chapter 19). In this perspective, an effective climate response is necessarily an integral objective of an SD strategy.

Second, there are tradeoffs between climate responses and broader SD goals, because some climate responses can impose other environmental pressures, have adverse distributional effects, draw resources away from other developmental priorities, or otherwise impose limitations on growth and development (Sections 4.6, 7.11, 8.9, 9.9, 10.10, 11.9, 12.8). Section 4.4 examines how to avoid such tradeoffs by changing behavioural patterns and decoupling emissions and growth, and/or decoupling growth and well-being.

Third, there are multiple potential synergies between climate responses and broader SD objectives. Climate responses may generate co-benefits for human and economic development (Sections 3.6, 4.8, 6.6, 7.9, 8.7, 9.7, 10.8, 11.7). At a more fundamental level, capacities underlying an effective climate response overlap strongly with capacities for SD (Sections 4.6, 5.3).

A key message of this report is that designing a successful climate policy may require going beyond a narrow focus on mitigation and adaptation, beyond the analysis of a few co-benefits of climate policy, and may instead require 'mainstreaming' climate issues into the design of comprehensive SD strategies, including at local and regional levels. Figure 4.1 illustrates the different perspectives from which climate policy can be envisioned. In the broadest, boldest perspective, the choice of the development path (see Sections 4.5, 6.1) is at stake.

4.2.2 Equity and its relation to sustainable development and climate change

Equity is prominent in research and policy debates about SD and climate, both as distributive equity (distribution of resources in contexts such as burden sharing, distribution of well-being in the broader context of social justice, see Sections 3.3, 4.4, 4.6) and procedural equity (participation in decision making, see Section 4.3). Various aspects of the general concept, as developed in social ethics, are introduced in Section 3.2 under the name of fairness and justice. (In this chapter the terms equity, fairness, and justice are not distinguished but are used according to common usage depending on context). The aim of this subsection is to analyze the links between equity, SD, and climate issues.

Equity *between* generations underlies the very notion of SD. Figure 4.2, a variant of a figure from Howarth and Norgaard (1992), illustrates sustainability as the possibility for future generations to reach at least the same level of well-being as the current generation. It shows in particular that sustainability is a matter of distributive equity, not of efficiency, even if eliminating inefficiencies affecting future sustainable well-being may improve sustainability, as stressed in Grubb et al. (2013).

There has been a recent surge of research on intergenerational equity, motivated by dissatisfaction with the tradition of discounting the utility of future generations in the analysis of growth paths (see, e.g., Asheim (2007), Roemer and Suzumura (2002) for recent syntheses). The debate on discounting is reviewed in Section 3.6.2. Recent literature presents new arguments deriving the imperative of sustaining well-being across generations from more basic equity principles (Asheim et al., 2001, 2012).

Equity *within* every generation is often considered an intrinsic component of SD linked to the social pillar. The Millennium Development Goals (MDGs) may be seen as one indication of a more explicit global commitment to the social pillar (United Nations, 2000). Yet, the relation between equity within generations and SD is complex. Attempting to meet the needs of the world's poor by proliferating the consumption patterns and production processes of the world's richest populations would be unsustainable (Millennium Ecosystem Assessment, 2005; Rockström et al., 2009b; Steffen et al., 2011; IPCC, 2014). Such a scenario would not likely play out well for the world's poor. Environmental issues are interwoven with the fabric of racial, social, and economic injustice. Environmental costs and benefits are often distributed so that those who already suffer other socio-economic disadvantages tend to bear the greatest burden (Okereke, 2011).

Figure 4.3 illustrates the normative framework in which a SD path can be grounded on certain values (well-being, equity) and interrelated goals (development and conservation), and the synergies and tradeoffs between SD and climate policy, with procedural equity and iterative learning nurturing each step, from conceptualization to implementation.

In the rest of this section, we focus on one key dimension of equity that is of central importance to international negotiations toward an effective global response to climate change. As in many other contexts, fundamental questions of resource allocation and burden sharing arise in climate change, and therefore equity principles are invoked and debated. Three lines of argument have been put forward to justify a reference to equity in this context (Section 4.6 examines the details of burden sharing principles and frameworks in a climate regime.)

The first justification is the normative claim that it is morally proper to allocate burdens associated with our common global climate challenge according to ethical principles. The broad set of ethical arguments for ascribing moral obligations to individual nations has been reviewed in Section 3.3, drawing implicitly upon a cosmopolitan view of justice, which posits that some of the basic rights and duties that arise between people within nations also hold between people of different nations.

The second justification is the legal claim that countries have accepted treaty commitments to act against climate change that include the commitment to share the burden of action equitably. This claim derives from the fact that signatories to the UNFCCC have agreed that: "Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities" (UNFCCC, 2002). These commitments are consistent with a body of soft law and norms such as the no-harm rule according to which a state must prevent, reduce or control the risk of serious environmental harm to other states (Stockholm Convention (UNEP, 1972), Rio declaration (United Nations, 1992b), Stone, 2004). In addition, it has been noted that climate change adversely affects a range of human rights that are incorporated in widely ratified treaties (Aminzadeh, 2006; Humphreys, 2009; Knox, 2009; Wewerinke and Yu III, 2010; Bodansky, 2010).

Figure 4.1 | Three frameworks for thinking about mitigation.

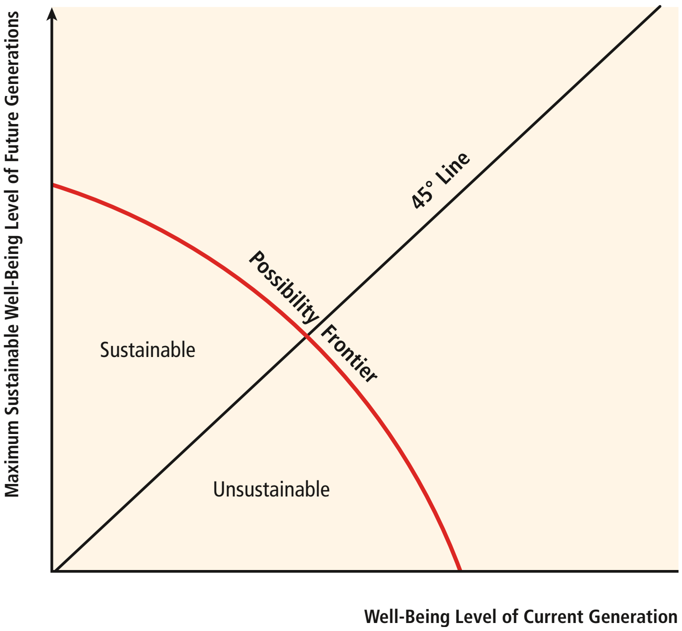

Figure 4.2 | The well-being level of the current generation is sustainable if it does not exceed the maximum sustainable well-being level of the future generations—independently of whether one is or is not on the possibility frontier. Modified from Howarth and Norgaard (1992).

The third justification is the positive claim that equitable burden sharing will be necessary if the climate challenge is to be effectively met. This claim derives from the fact that climate change is a classic commons problem (Hardin, 1968; Soroos, 1997; Buck, 1998; Folke, 2007) (also see Section 13.2.1.1). As with any commons problem, the solution lies in collective action (Ostrom, 1990). This is true at the global scale as well as the local, only more challenging to achieve (Ostrom et al., 1999). Inducing cooperation relies, to an important degree, on convincing others that one is doing one's fair share. This is why notions of equitable burden-sharing are considered important in motivating actors to effectively respond to climate change. They are even more important given that actors are not as equal as the proverbial 'commoners', where the very name asserts homogeneity (Milanović et al., 2007). To the contrary, there are important asymmetries or inequalities between stakeholders (Okereke et al., 2009; Okereke, 2010): asymmetry in contribution to climate change (past and present), in vulnerability to the impacts of climate change, in capacity to mitigate the problem, and in power to decide on solutions. Other aspects of the relation between intragenerational equity and climate response include the gender issues noted in 4.3, and the role of virtue ethics and citizen attitudes in changing lifestyles and behaviours (Dobson, 2007; Lane, 2012), a topic analyzed in Section 4.4.

Young (2013) has identified three general conditions—which apply to the climate context—under which the successful formation and eventual effectiveness of a collective action regime may hinge on equitable burden sharing: the absence of actors who are powerful enough to coercively impose their preferred burden sharing arrangements; the inapplicability of standard utilitarian methods of calculating costs and benefits; and the fact that regime effectiveness depends on a long-term commitment of members to implement its terms. With respect to climate change, it has long been noted that a regime that many members find unfair will face severe challenges to its adoption or be vulnerable to festering tensions that jeopardize its effectiveness (Harris, 1996; Müller, 1999; Young, 2012). Specifically, any attempt to protect the climate by keeping living standards low for a large part of the world population will face strong political resistance, and will almost certainly fail (Roberts and Parks, 2007; Baer et al., 2009). While costs of participation may provide incentives for non-cooperation or defection in the short-term, the climate negotiations are not a one-shot game, and they are embedded in a much broader global context; climate change is only one of many global problems—environmental, economic, and social—that will require effective cooperative global governance if development—and indeed human welfare—is to be sustained in the long term (Singer, 2004; Jasanoff, 2004; Speth and Haas, 2006; Kjellen, 2008).

Despite these three lines of justification, the question of the role that equity does or should play in the establishment of global climate policy and burden sharing in particular is nonetheless controversial (Victor, 1998). The fact that there is no universally accepted global authority to enforce participation is taken by some to mean that sovereignty, not equity is the prevailing principle. Such a conception implies that the bottom-line criterion for a self-enforcing (Barrett, 2005) cooperative agreement would be simply that everyone is no worse off than at the status quo. This has been termed "International Paretianism" (Posner and Weisbach, 2010), and its ironic, even perverse results have been pointed out: "an optimal climate treaty could well require side payments to rich countries like the United States and rising countries like China, and indeed possibly from very poor countries which are extremely vulnerable to climate change—such as Bangladesh." (Posner and Weisbach, 2010).

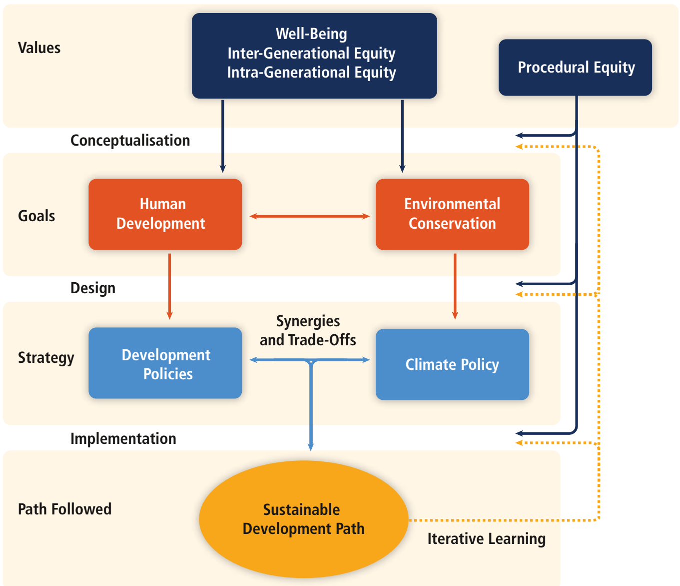

Figure 4.3 | Links between SD, equity, and climate policy.

However, both critics and advocates of the importance of equity in the climate negotiations acknowledge that governments can choose to act on moral rather than purely self-interested principles (DeCanio and Fremstad, 2010; Posner and Weisbach, 2010, 2012; Baer, 2013; Jamieson, 2013) (see also Section 3.10). Whether or not states behave as rational actors, given the significant global gains to be had from cooperation, this leaves ample room for discussion of the role of equity in the distribution of those global gains, while still leaving all parties better off (Stone, 2004).

While the above discussion focuses on equity among nations, equally relevant concerns regarding equity within nations also arise, and indeed can be overriding determinants of the prospects for climate policy to be adopted. Demands for equity have been articulated by labour communities primarily in terms of a just transition (International Labour Office, 2010; Newell and Mulvaney, 2013), and often by marginalized populations and racial minorities in terms of environmental justice and just sustainability (Agyeman and Evans, 2004; Walker and Bulkeley, 2006; Shiva, 2008). While the particular demands are highly location- and context-specific, the broad concerns are procedural and about distributive justice with reduced power asymmetries, as underscored throughout this chapter.

4.3 Determinants, drivers and barriers

This section explores the determinants of SD, emphasizing how each influences the extent to which societies can balance the economic, social, and environmental pillars of SD, while highlighting potential synergies and tradeoffs for the building of mitigative and adaptive capacity and the realization of effective and equitable mitigation and adaptation strategies. Determinants refer to social processes, properties, and artefacts, as well as natural resources, which together condition and mediate the course of societal development, and thus the prospects for SD. When determinants facilitate SD they act as drivers and when they constrain it they act as barriers.

The determinants discussed include: the legacy of development relations; governance and political economy; population and demography; human and social capital; behaviour, culture, and values; technology and innovation processes; natural resources; and finance and investment. These determinants are interdependent, characterized by feedbacks that blur the distinction between cause and effect, and their relative importance depends on context—see analogous discussion in the context of GHG emission drivers in Section 5.3. They are not unique, and other determinants such as leadership (Jones and Olken, 2005), randomness (Holling, 1973; Arthur, 1989), or human nature (Wilson, 1978) could be added to the list, but they are less amenable to deliberate intervention by policy-makers and other decision makers and have therefore been excluded. What follows lays the foundations for understanding concepts that recur throughout this chapter and those that follow.

4.3.1 Legacy of development relations

Following World War II, security, economic, and humanitarian relations between rich nations and poor nations were comingled and addressed under the umbrella of 'development' (Truman, 1949; Sachs, Wolfgang, 1999). Differing perspectives on the mixed outcomes of six decades of development, and what the outcomes may indicate about underlying intentions and capabilities, inform different actors in different ways as to what will work to address climate change and the transition to SD. During the 1950s and 1960s, for example, expectations were that poverty would be reduced dramatically by the end of the century (Rist, 2003). It was widely believed that economic development could be instigated through aid from richer nations, both financial and in kind. Development was seen as a process of going through stages starting with transforming traditional agriculture through education, the introduction of new agricultural technologies, improved access to capital for farm improvements, and the construction of transportation infrastructure to facilitate markets. Improved agriculture would release workers for an industrial stage and thereby increase opportunities for education and commercial development in cities. As development proceeded, nations would increasingly acquire their own scientific capabilities and, later, sophisticated governance structures to regulate finance and industry in the public good, becoming well-rounded, well-governed economies comparable to those of rich nations.

By the 1970s, however, it was clear that development was not on a path to fulfilling these linear expectations because: 1) contributions of aid from the rich nations were not at levels anticipated; 2) technological and institutional changes were only partially successful, proved inappropriate, or had unpredicted, unfortunate consequences; 3) requests for military aid and the security and economic objectives of richer nations in the context of the Cold War were frequently given priority over poverty reduction; and 4) graft, patronage, and the favouring of special interests diverted funds from poverty reduction. The general belief that nations naturally went through stages of development to become well-rounded economies faded by the early 1980s. Greater participation in global trade, with its implied specialization, was invoked as the path to economic growth. Diverse other efforts were made to improve how development worked, but with only modest success, leaving many in rich and poor nations concerned about development process and prospects (United Nations, 2011a).

Layering the goal of environmental sustainability onto the goal of poverty reduction further compounded the legacy of unmet expectations (World Commission on Environment and Development, 1987). There have been difficulties determining, shifting to, and governing for sustainable pathways (Sanwal, 2010)—see Section 4.3.2 below. The negotiation of new rules for the mobility of private capital and the drive for globalization of the economy also came with new expectations for development (Stiglitz, 2002). The Millennium Development Goals (MDG) established in 2000 to be met by 2015 are an example of how such expectations were thought to be realizable in the rapidly evolving times of the global financial economy. In retrospect and after the 2008 financial sector induced recession, significant improvements are largely in China and India where economic growth accelerated through private capital flows independent of the MDG process. Excluding these countries, the record is mixed at best and still poor in most of Africa (Keyzer and Wesenbeeck, 2007; Easterly, 2009; United Nations, 2011a). Additionally, since the 1990s, greenhouse gas emissions became another focus of contention (Roberts and Parks, 2007; Penetrante, 2011; Dryzek et al., 2011). The developed nations became rich through the early use of fossil fuels and land transformations that put GHGs in the atmosphere, imposing costs on all people, rich and poor, through climate impacts that will persist over centuries (Srinivasan et al., 2008). Connections between causal and moral responsibility arose, complicating the legacy of development.

Such legacy of unmet development and sustainability expectations is open to multiple interpretations. In richer nations, the evidence can be interpreted to support the views of fiscal conservatives who oppose aid, libertarians who oppose humanitarian and environmental interventions, progressives who urge that more needs to be done to reach social and environmental goals, and some environmentalists who urge dematerialization and degrowth among the rich as necessary to meet the needs of the poor. In poorer nations, the legacy similarly supports various views including a distrust of rich nations for not delivering development and environmental assistance as promised, cynicism toward the intentions and conceptual rationales when it is provided, and also a wariness of development's unpredicted outcomes.

In both developed and developing nations these diverse sentiments among the public, policy makers, and climate negotiators contribute to what philosopher Gardiner (2011b) refers to as the "perfect moral storm" of climate policy. Some analysts argue that the legacy of development and interrelated issues of equity so cloud global climate negotiations that *ad hoc* agreements and voluntary pledges are the most that can be achieved (Victor, 2004) and considerations of development and equity are better left aside (Posner and Weisbach, 2010), although this leaves open whether such arrangements could provide an adequately ambitious climate response consistent with the UNFCCC's objectives. (See Section 4.6.2 for further discussion of perspectives on equity in a climate regime, and Section 13.4.3 for further discussion of regime architectures).

4.3.2 Governance and political economy

Governance and political economy are critical determinants for SD, equity, and climate change mitigation because they circumscribe the process through which these goals and how to attain them are articulated and contested. The quest for equity and climate change mitigation in the context of SD thus necessitates an improved understanding and practice of governance (Biermann et al., 2009; Okereke et al., 2009). Governance in the broadest sense refers to the processes of interaction and decision making among actors involved in a common problem (Kooiman, 2003; Hufty, 2011). It goes beyond notions of formal government or political authority and integrates other actors, networks, informal institutions, and incentive structures operating at various levels of social organization (Rosenau, 1990; Chotray and Stoker, 2009). In turn, climate governance has been defined as the mechanisms and measures "aimed at steering social systems towards preventing, mitigating or adapting to the risks posed by climate change" (Jagers and Stripple, 2003). From this definition, it can be seen as a broad phenomenon encompassing not only formal policymaking by states, but all the processes through which authority is generated and exerted to affect climate change and sustainability. This includes policymaking by states but also by many other actors -NGOs, TNCs, municipalities, for example—operating across various scales (Okereke et al., 2009).

Many scholars have highlighted the challenges associated with governing for SD and climate change (Adger and Jordan, 2009; Levin et al., 2012). First, it involves rethinking the ways society relates to nature and the underlying biophysical systems. This is relevant in the context of the growing evidence of the impact of human activity on the planet and the understanding that extraordinary degrees of irreversible damage and harm are distinct possibilities if the right measures are not taken within an adequate timescale (Millennium Ecosystem Assessment, 2005; Rockström et al., 2009a). Second, governing climate change involves complex intergenerational considerations. On the one hand, cause and effect of some environmental impacts and climate change are separated by decades, often generations, and on the other hand, those who bear the costs of remediation and mitigation may not be the ones to reap the benefits of avoided harm (Biermann, 2007).

Third, effective response to climate change may require a fundamental restructuring of the global economic and social systems, which in turn would involve overcoming multiple vested interests and the inertia associated with behavioural patterns and crafting new institutions that promote sustainability (Meadows et al., 2004; Millennium Ecosystem Assessment, 2005). This challenge is exacerbated by the huge mismatch between the planning horizon needed to address global environmental problems and climate change and the tenure of decision makers (Hovi et al., 2009).

Fourth, and finally, SD governance cuts across several realms of policy and organization. Particularly, the governance of mitigation and adaptation is an element of a complex and evolving arena of global environmental governance, which deals with other, and often overlapping, issues such as biodiversity loss, desertification, water management, trade, energy security, and health, among others (Adger and Jordan, 2009; Brown, 2009; Bell et al., 2010; Balsiger and Debarbieux, 2011; da Fonseca et al., 2012; Bark et al., 2012). Sites of climate change governance and policymaking are thus multiple and are not confined to the UNFCCC and national rule-making processes, a situation which raises challenges in relation to coordination, linkages, and synergies (Ostrom, 2010; Zelli, 2011; Jinnah, 2011)—see Sections 13.4, 13.13, 14.1, 15.2, notably Figure 13.1 for a visual summary.

These considerations explain why climate governance has attracted more political controversy than other issues in relation to global sustainability and its equity considerations. Some of the main aspects of this controversy include: who should participate in decision making; how to modulate power asymmetry among stakeholders; how to share responsibility among actors; what ideas and institutions should govern response measures; and where should interventions focus? Questions of justice are embedded throughout, aggravated by the high stakes involved and the stark asymmetry among states and others actors in terms of cause, effect, and capability to respond to the problem (Okereke and Dooley, 2010; Okereke, 2010; Schroeder et al., 2012).

Scholars have long analyzed the above issues within climate governance, offering a multitude of possible solutions. Concerning participation, a departure from the top-down approach implied in the Kyoto Protocol towards a more voluntary and bottom-up approach has been suggested (Rayner, 2010). Some argue that limiting participation to the "most capable, responsible and vulnerable" countries can foster progress toward more stringent mitigation policy (Eckersley, 2012). However, the latter has been opposed on the basis that it would further exacerbate issues of inequity (Aitken, 2012; Stevenson and Dryzek, 2012). Others have discussed the need to create spaces for collaborative learning to debate, legitimize, and potentially overcome knowledge divides between experts and lay people in sectoral climate policy development (Swanson et al., 2010; Armitage et al., 2011; Colfer, 2011; Larsen et al., 2012)—see Sections 13.3.1 and 13.5 for further detail. On allocation of responsibility, a global agreement has been elusive not merely because parties and other key actors have differing conceptions of a fair allocation (Okereke, 2008), but because the pertinent policies are highly contentious given the combination of factors at play, prominent among which are finance, politics, ineffective institutions, and vested interests.

A defining image of the climate governance landscape is that key actors have vastly disproportionate capacities and resources, including the political, financial, and cognitive resources that are necessary to steer the behaviour of the collective within and across territorial boundaries (Dingwerth and Pattberg, 2009). A central element of governance therefore relates to huge asymmetry in such resources and the ability to exercise power or influence outcomes. Some actors, including governments, make use of negotiation power and/or lobbying activities to influence policy decisions at multiple scales and, by doing so, affect the design and the subsequent allocation and distribution of benefits and costs resulting from such decisions (Markussen and Svendsen, 2005; Benvenisti and Downs, 2007; Schäfer, 2009; Sandler, 2010)—see e.g., Section 15.5.2. The problem, however, also resides in the fact that those that wield the greatest power either consider it against their interest to facilitate rapid progress towards a global low carbon economy or insist that the accepted solutions must be aligned to increase their power and material gains (Sæverud and Skjærseth, 2007; Giddens, 2009; Hulme, 2009; Lohmann, 2009, 2010; Okereke and McDaniels, 2012; Wittneben et al., 2012). The most notable effect of this is that despite some exceptions, the prevailing organization of the global economy, which confers significant power on actors associated with fossil fuel interests and with the financial sector, has provided the context for the sorts of governance practices of climate change that have dominated to date (Newell and Paterson, 2010).

Many specific governance initiatives, described in Sections 13.13 and 15.3, whether organized by states or among novel configurations of actors, have focused on creating new markets or investment opportunities. This applies, for example, to carbon markets (Paterson, 2009), carbon offsetting (Bumpus and Liverman, 2008; Lovell et al., 2009; Corbera and Schroeder, 2011; Corbera, 2012), investor-led governance initiatives such as the Carbon Disclosure Project (CDP) (Kolk et al., 2008) or partnerships such as the Renewable Energy and Energy Efficiency Partnership (REEEP) (Parthan et al., 2010). Some scholars find that carbon markets can contribute to achieving a low fossil carbon transition, but require careful designs to achieve environmental and welfare gains (Wood and Jotzo, 2011; Pezzey and Jotzo, 2012; Springmann, 2012; Bakam et al., 2012). Others note that such mechanisms are vulnerable to 'capture' by special interests and against the original purposes for which they are conceived. Several authors have discussed this problem in the context of the Clean Development Mechanism (CDM) and the European Union Emissions Trading Scheme (EU-ETS) (Lohmann, 2008; Clò, 2010; Okereke and McDaniels, 2012; Böhm et al., 2012).

Governing for SD and climate change requires close attention to three key issues. First, there is a need to understand current governance as encompassing more than the actors within formal government structures, and to understand how choices are driven by more than optimal decision making theory. Second effective governance requires understanding the dynamics that determine whether and how policy options are legitimized, and then formally deliberated and adopted (or not). Consequently, it is necessary to examine how these modes of governance are defined and established in the first place, by whom and for whose benefit, thus illuminating the relationship and tensions between effective governance and existing trends in political economy. Third, there is a need to explore how different modes of governance translate into outcomes, affecting the decisions and actions of actors at multiple scales, and to draw lessons about their environmental effectiveness and distributional implications. While some argue that states should still be regarded as key agents in steering such transitions (Eckersley, 2004; Weale, 2009), most decision making relevant to SD and climate remains fundamentally decentralized. A key challenge of governance is thus to recognize the political economy context of these decision makers, to ensure procedurally equitable processes that address the allocation of responsibilities and ensure transparency and accountability in any transition towards SD.

4.3.3 Population and demography

Population variables, including size, density, and growth rate, as well as age, sex, education, and settlement structures, play a determinant role in countries' SD trajectories. Their drivers, in particular fertility, mortality, and migration, are reciprocally influenced by development pathways, including evolving policies, socio-cultural trends, as well as by changes in the economy (Bloom, 2011). In the climate change context, population trends have been shown to matter both for mitigation efforts as well as for societies' adaptive capacities to climate change (O'Neill et al., 2001).

Current demographic trends show distinct patterns in different parts of the world. While population sizes are on a declining trajectory in Eastern Europe and Japan, they are set for significant further increase in many developing countries (particularly in Africa and south-western Asia) due to a very young population age structure and continued high levels of fertility. As most recent projections show, the world's population is almost certain to increase to between 8 and 10 billion by mid-century. After that period, uncertainty increases significantly, with the future trend in birth rates being the key determinant, but it is also amplified by the uncertainty about future infectious disease mortality and the still uncertain consequences of climate change on future mortality trajectories (O'Neill et al., 2001; Lutz and KC, 2010; United Nations, 2011b; Lee, 2011; Scherbov et al., 2011). The population of Sub-Saharan Africa will almost certainly double and could still increase by a factor of three or more depending on the course of fertility over the coming decades, which depends primarily on progress in female education and the availability of reproductive health services (Bongaarts, 2009; Bloom, 2011; Bongaarts and Sinding, 2011).

Declining fertility rates, together with continued increases in life-expectancy, result in significant population ageing around the world, with the current low fertility countries being most advanced in this process. Population ageing is considered a major challenge for the solvency of social security systems. For populations still in the process of fertility decline, the expected burden of ageing is a more distant prospect, and the declining birth rates are expected to bring some near term benefits. This phase in the universal process of any demographic transition, when the ratio of children to adults is already declining and the proportion of elderly has not yet increased, is considered a window of opportunity for economic development, which may also result in an economic rebound effect leading to higher per capita consumption and emissions (Bloom and Canning, 2000).

Low development is widely understood to contribute to high population growth, which declines only after the appearance of widespread access to key developmental needs such as perinatal and maternal healthcare, and female education and empowerment. Conversely, high population growth is widely regarded as an obstacle to SD because it tends to make efforts such as the provision of clean drinking water and agricultural goods and the expansion of health services and school enrollment rates difficult (Dyson, 2006; Potts, 2007; Pimentel and Paoletti, 2009). This has given rise to the fear of a vicious circle of underdevelopment and gender inequity yielding high population growth and environmental degradation, in turn inhibiting the development necessary to bring down fertility (Caole and Hoover, 1958; Ehrlich and Holdren, 1971; Dasgupta, 1993). However, history shows that countries can break this vicious circle with the right social policies, with an early emphasis on education and family planning; prominent examples include South Korea and Mauritius, which were used in the 1950s as textbook examples of countries trapped in such a vicious circle (Meade, 1967).

With respect to adaptation to climate change, the literature on population and environment has begun to explore more closely people's vulnerability to climate stressors, including variability and extreme events, and to analyze their adaptive capacity and reliance on environmental resources to cope with adversities and adapt to gradual changes and shocks (Bankoff et al., 2004; Adger et al., 2009)—see also Section 4.6.1 and WGII AR5. Generally speaking, not only does the number of people matter, but so does their composition by age, gender, place of residence, and level of education, as well as the institutional context that influences people's decision making and development opportunities (Dyson, 2006). One widely and controversially discussed form of adaptation can be international migration induced by climate change. There is often public concern that massive migration of this sort could contribute to political instability and possibly conflict. However, a major recent review of our knowledge in this field has concluded that much environmentally induced migration is likely to be internal migration and there is very little science-based evidence for assessing possible consequences of environmental change on large international migration streams (UK Government Office for Science, 2011).

4.3.4 Values and behaviours

Research has identified a range of individual and contextual predictors of behaviours in favour or against climate change mitigation, ranging from individuals' psychological needs to cultural and social orientations towards time and nature (Swim et al., 2009)—see Sections 2.4, 3.10, and 5.5. Below we discuss some of these factors, focusing on human values that influence individual and collective behaviours and affect our priorities and actions concerning the pursuit of SD, equity goals, and climate mitigation. Values have been defined as "enduring beliefs that pertain to desirable end states or behaviours, transcend specific situations, guide selection or evaluation of behaviour and events and are ordered by importance" (Pepper et al., 2009; citing Schwartz and Bilsky, 1987). Values provide "guides for living the best way possible for individuals, social groups and cultures" (Pepper et al., 2009; citing Rohan, 2000) and so influence actions at all levels of society—including the individual, the household, the firm, civil society, and government. Individuals acquire values through socialization and learning experience (Pepper et al., 2009) and values thus relate to many of the other determinants discussed in this section. Values may be rooted in cultural, religious, and other belief systems, which may sometimes conflict with scientific understandings of environmental risks. In particular, distinct values may influence perceptions and interpretations of climate impacts and hence climate responses (Wolf et al., 2013).

The relevance of values to SD and, particularly, to ecologically conscious (consumer) behaviour, is related to the nature of environmental issues as 'social dilemmas', where short-term narrow individual interests conflict with the longer term social interest (Pepper et al., 2009). Researchers have highlighted the role of non-selfish values that promote the welfare of others (including nature), noting that some but not all indigenous societies are known to focus on 'collective' as opposed to 'individual' interests and values, which often result in positive resource conservation strategies and wellbeing (Gadgil et al., 1993; Sobrevila, 2008; Watson et al., 2011). However, it is well known that a range of factors also mediate the impact of values on behaviour so that the link from values to ecologically conscious behaviour is often loose (Pepper et al., 2009).

In fact, this 'value-action' gap suggests that pursuing climate change mitigation and SD globally may require substantial changes in behaviour in the short term along with a transformation of human values in the long term, e.g., progressively changing conceptions and attitudes toward biophysical systems and human interaction (Gladwin et al., 1995; Leiserowitz et al., 2005; Vlek and Steg, 2007; Folke et al., 2011a). Changing human values would require a better understanding of cross-cultural behavioural differences that in turn relate to environmental, economic, and political histories (Norenzayan, 2011).

Behavioural change can be induced by changes in formal and civil institutions and governance, human values (Jackson, 2005a; Folke et al., 2011a; Fischer et al., 2012), perceptions of risk and causality, and economic incentives. Removing perverse subsidies for environmentally harmful products, favouring greener consumption and technologies, adopting more comprehensive forms of biophysical and economic accounting, and providing safer working conditions are considered central for achieving pro-SD behavioural change (Lebel and Lorek, 2008; Le Blanc, 2010; Thøgersen, 2010). Yet behaviour experiments (Osbaldiston and Schott, 2012) suggest there is no 'silver bullet' for fostering ecologically conscious behaviour, as favourable actions (e.g., to conserve energy) are triggered by different stimuli, including information, regulation or economic rewards, and influenced by the nature of the issue itself. Furthermore, people are able to "express both relatively high levels of environmental concern and relatively high levels of materialism simultaneously" (Gatersleben et al., 2010). This suggests the need to be issue, context, and culturally aware when designing specific actions to foster pro-SD behaviour, as both environmental and materialistic concerns must be addressed. These complexities underscore the challenges in changing beliefs, preferences, habits, and routines (Southerton, 2012)—see Sections 4.4 and 5.5.2.

4.3.5 Human and social capital

Levels of human and social capital also critically influence a transition toward SD and the design and implementation of mitigation and adaptation strategies. Human capital results from individual and collective investments in acquiring knowledge and skills that become useful for improving wellbeing (Iyer, 2006). Such knowledge and skills can be acquired through formal schooling and training, as well as informally through customary practices and institutions, including communities and families. Human capital can thus be viewed as a critical component of a broader-encompassing human capability, i.e., a person's ability to achieve a given list of 'functionings' or achievements, which depend on a range of personal and social factors, including education, age, gender, health, income, nutritional knowledge, and environmental conditions, among others (Sen, 1997, 2001). See Clark (2009) and Schokkaert (2009) for a review of Sen's capability approach and its critiques.

Economists have long considered improvements in human capital a key explanatory reason behind the evolution of economic systems, in terms of growth and constant innovation (Schultz, 1961; Healy and Cote, 2001). Macro-economic research shows a strong correlation between levels of economic development and levels of human capital and vice versa (Schultz, 2003; Iyer, 2006), while micro-economic studies reveal a positive relationship between increases in the quantity and quality of formal education and future earnings (Duflo, 2001). Gains in human capital can be positively correlated to economic growth and efficiency, but also to nutritional, health, and education standards (Schultz, 1995). As such, improvements in human capital provide a basis for SD, as they shape countries' socio-economic systems and influence people's ability to make informed choices. Seemingly, human capital often also explains the development and survival of business ventures (Colombo and Grilli, 2005; Patzelt, 2010; Gimmon and Levie, 2010), which are an important source of innovation and diffusion of principles and technologies that can contribute to SD and to ambitious mitigation and adaptation goals (Marvel and Lumpkin, 2007; Terjesen, 2007).

Additionally, a growing body of literature in economics, geography, and psychology (reviewed in Sections 2.4, 2.6.6 and 3.10 as well as in WGII Chapter 2) has shown that the diversity of environmental, socio-economic, educational and cultural contexts in which individuals make decisions shape their willingness and/or ability to engage in mitigation and adaptation action (Lorenzoni et al., 2007). It is important to distinguish between formally acquired knowledge on climate change—often based on scientific developments—and traditional knowledge on climate-related issues (Smith and Sharp, 2012), as well as to recognize that the relative validity of both types of knowledge to different audiences, and the meaning and relevance of personal engagement, will be influenced by individual perceptions, preferences, values, and beliefs. Therefore, knowledge on climate issues does not alone explain individual and collective responses to the climate challenge (Whitmarsh, 2009; Sarewitz, 2011; Wolf and Moser, 2011; Berkhout, 2012). There is evidence of cognitive dissonance and strategic behaviour in both mitigation and adaptation. Denial mechanisms that overrate the costs of changing lifestyles, blame others, and that cast doubt on the effectiveness of individual action or the soundness of scientific knowledge are well documented (Stoll-Kleemann et al., 2001; Norgaard, 2011; McCright and Dunlap, 2011), as is the concerted effort by opponents of climate action to seed and amplify those doubts (Jacques et al., 2008; Kolmes, 2011; Conway and Oreskes, 2011).

Among the different definitions of social capital, one of the most influential was proposed by Fukuyama (2002): the shared norms or values that promote social cooperation, which are founded in turn on actual social relationships, including trust and reciprocity. Social capital appears in the form of family bonds, friendship and collective networks, associations, and other more or less institutionalized forms of collective action. Social capital is thus generally perceived as an asset for both the individuals that recognize and participate in such norms and networks and for the respective group/society, insofar as they derive benefits from information, participating in decision making and belonging to the group. Social capital can be linked to successful outcomes in education, employment, family relationships, and health (Gamarnikow and Green, 1999), as well as to economic development and participatory, democratic governance (Woolcock, 1998; Fukuyama, 2002; Doh and McNeely, 2012). Indeed, social capital can also be sustained on unfair social norms and institutions that perpetuate an inequitable access to the benefits provided by social organization (Woolcock and Narayan, 2000), through social networks of corruption or criminal organizations, for example, that perpetuate the uneven distribution of public resources, and undermine societies' cohesion and physical security.

Scholarship suggests that social capital is supportive for SD (Rudd, 2000; Bridger and Luloff, 2001; Tsai, 2008; Ostrom, 2008; Jones et al., 2011), having shown that it can be instrumental to address collective action problems (Ostrom, 1998; Rothstein, 2005), combat injustices and conditions of poverty and vulnerability (Woolcock and Narayan, 2000), and benefit from resources (Bebbington, 1999; Diaz et al., 2002), and to foster mitigation and adaptation (Adger, 2003; Wolf et al., 2010).

4.3.6 Technology

Technology has been a central element of human, social, and economic development since ancient times (Jonas, 1985; Mokyr, 1992). It can be a means to achieving equitable SD, by enabling economic and social development while using environmental resources more efficiently. The development and deployment of the overwhelming majority of technologies is mediated by markets, responding to effective demand of purchasers (Baumol, 2002), and carried out by private firms, where the pre-requisites of technological capacity and investment resources tend to be found. However, this process does not necessarily address the basic needs of those members of society with insufficient market demand to influence the decisions of innovators and investors, nor does it provide an incentive to reduce externalized costs, such as the costs of GHG pollution (Jaffe et al., 2005).

Fundamental objectives of equity and SD are still unmet. For example, the basic energy and nutritional needs of large parts of the world's population remain unfulfilled. An estimated 1.3 billion people lacked access to electricity in 2010 and about 3 billion people worldwide relied on highly polluting and unhealthy traditional solid fuels for household cooking and heating (Pachauri et al., 2012; IEA, 2012b) (see Section 14.3.2.1). Similarly, the Food and Agricultural Organization (FAO) indicates that almost 870 million people (mostly in developing countries) were chronically undernourished in 2010–12 (FAO, 2012). Achieving the objectives of equitable SD demands the fulfilment of such basic and other developmental needs. The challenge is therefore to design, implement, and provide support for technology innovation and diffusion processes that respond to social and environmental goals, which at present do not receive adequate incentives through conventional markets.

Scholars of technological change have, in recent years, begun to highlight the 'systemic' nature of innovation processes as well as the fundamental importance of social and technical interactions in shaping technological change (see Section 4.5.2.2). Accordingly, as a first step toward understanding how innovation could help meet social and environmental goals, a systematic assessment of the adequacy and performance of the relevant innovation systems would be helpful, including an examination of the scale of innovation investments, the allocation among various objectives and options, the efficiency by which investments yield outputs, and how effectively the outputs are utilized for meeting the diffusion objectives (Sagar and Holdren, 2002; Sanwal, 2011; Aitken, 2012). For example, many reports and analyses have suggested that investments in innovation for public goods such as clean energy and energy access are not commensurate with the nature and scale of these challenges (Nemet and Kammen, 2007; AEIC, 2010; Bazilian et al., 2010). Innovation in and diffusion of new technologies also require skills and knowledge from both developers and users, as well as different combinations of enabling policies, institutions, markets, social capital, and financial means depending on the type of technology and the application being considered (Bretschger, 2005; Dinica, 2009; Blalock and Gertler, 2009; Rao and Kishore, 2010; Weyant, 2011; Jänicke, 2012). Appropriately harnessing these kinds of capabilities and processes themselves may require novel mechanisms and institutional forms (Bonvillian and Weiss, 2009; Sagar et al., 2009).

At the same time, the role of public policy in creating demand for technologies that have a public goods nature cannot be overstated (see also Section 3.11), although these policies need to be designed carefully to be effective. In the case of renewables, for example, it has been shown that intermittent policy subsidies, governments' changing R&D support, misalignments between policy levels, sectors, and institutions can greatly impede the diffusion of these technologies (Negro et al., 2012). Similarly, in agriculture, while there are many intersections between mitigation and SD through options such as 'sustainable agriculture', the potential for leveraging these synergies is contingent on appropriate and effective policies (Smith et al., 2007)—see also Sections 4.6.1 and 11.10.

Sometimes there may be a clear alignment between achieving equitable SD benefits and meeting climate goals such as the provision of clean energy to the rural poor. But in meeting multiple objectives, potential for conflicts and tradeoffs can also arise. For example, our likely continued reliance on fossil fuels (IEA 2012b) underlies the current exploration of new or well-established GHG mitigation options, such as biofuels or nuclear power, and other approaches like carbon dioxide capture and storage (CCS) and geo-engineering, including solar radiation management techniques, to avoid a dangerous increase of the Earth's temperature (Crutzen, 2006; Rasch et al., 2008; IPCC, 2012b). While such technological options may help mitigate global warming, they also pose potential adverse environmental and social risks, and thus give rise to concerns about their regulation and governance (Mitchell, 2008; Pimentel et al., 2009; de Paula Gomes and Muylaert de Araujo, 2011; Shrader-Frechette, 2011; Jackson, 2011b; Scheidel and Sorman, 2012; Scott, 2013; Diaz-Maurin and Giampietro, 2013)—see Sections 7.9 and 11.7.

The public perception and acceptability of technologies is country and context-specific, mediated by age, gender, knowledge, attitudes towards environmental risks and climate change, and policy procedures (Shackley et al., 2005; Pidgeon et al., 2008; Wallquist et al., 2010; Corner et al., 2011; Poumadere et al., 2011; Visschers and Siegrist, 2012) and therefore resolution of these kinds of tradeoffs and conflicts may not be easy. Yet the tradeoffs and synergies between the three dimensions of SD, as well as the impacts on socio-ecological systems across geographical scales will need to be systematically considered, which in turn will require the acknowledgement of multiple stakeholder perspectives. Assessment of energy technology options, for example, will need to include impact on landscapes' ecological and social dimensions—accounting for multiple values—and on energy distribution and access (Wolsink, 2007; Zografos and Martinez-Alier, 2009).

There are also some crosscutting issues, such as regimes for technology transfer (TT) and intellectual property (IP) that are particularly relevant to international cooperation in meeting the global challenge of pursuing equitable SD and mitigation, although progress under the UNFCCC has been incomplete. For example, TT under the CDM has been limited to selective conditions and mainly to a few countries (Dechezleprêtre et al., 2009; Seres et al., 2009; Wang, 2010). IP rights and patent laws have been shown as promoting innovation in some countries (Khan, 2005), although recent work suggests a more nuanced picture (Moser, 2013; Hudson and Minea, 2013). In fact, IP protection has also been regarded as a precondition for technology transfer but, again, reality has proven more complex (United Nations Environment Programme et al., 2010). A recent study shows that in the wind sector, there are 'patent thickets', which might restrain the extent and scope of dissemination of wind power technologies (Wang et al., 2013). In part, there are such divergent views on this issue since IP and TT also touch upon economic competitiveness (Ockwell et al., 2010). As noted earlier, perspectives are shaped by perceived national circumstances, capabilities, and needs, yet these issues do need to be resolved—in fact, there may be no single approach that will meet all needs. Different IP regimes, for example, are required to meet development objectives at different stages of development (Correa, 2011). The importance of this issue and the lack of consensus provide impetus for further analysis of the evidence and for exploration to develop IP and TT regimes that further international cooperation to meet climate, SD, and equity objectives.

4.3.7 Natural resources

Countries' level of endowment with renewable and/or non-renewable resources influences but does not determine their development paths. The location, types, quantities, long-term availability and the rates of exploitation of non-renewable resources, including fossil fuels and minerals, and renewable resources such as fertile land, forests, or freshwater affect national economies (e.g., in terms of GDP, trade balance, and rent potential), agricultural and industrial production systems, the potential for civil conflict, and countries' role in global geo-political and trade systems (Krausmann et al., 2009; Muradian et al., 2012; Collier and Goderis, 2012). Economies can evolve to reflect changes in economic trends, in policies or in consumption patterns, both nationally and internationally. In the context of climate change, natural resource endowments affect the level and profile of GHG emissions, the relative cost of mitigation, and the level of political commitment to climate action.

Resource-rich countries characterized by governance problems, including rent-seeking behaviour and weak judiciary and political institutions, have more limited capacity to distribute resource extraction rents and increase incomes (Mehlum et al., 2006; Pendergast et al., 2011; Bjorvatn et al., 2012). Some have negative genuine savings, i.e., they do not fully reinvest their resource rents in foreign assets or productive capital, which in turn impoverishes present and future generations and undermines both natural capital and human development prospects (Mehlum et al., 2006; van der Ploeg, 2011). Furthermore, these countries also face risks associated with an over-specialization on agriculture and resource-based exports that can undermine other productive sectors, e.g., through increases in exchange rates and a reliance on importing countries economic growth trajectories (Muradian et al., 2012). In some countries, an increase in primary commodity exports can lead to the rise of socio-environmental conflicts due to the increasing exploitation of land, mineral, and other resources (Martinez-Alier et al., 2010; Mitchell and Thies, 2012; Muradian et al., 2012).

Scholars have not reached definitive conclusions on the inter-relationships between resource endowment and development paths, including impacts on social welfare and conflict, and prospects for SD. Recent reviews, for example, note the need to continue investigating current resource booms and busts and documenting the latter's effect on national economies, policies, and social well-being, and to draw historical comparisons across countries and different institutional contexts (Wick and Bulte, 2009; Deacon, 2011; van der Ploeg, 2011). It is clear though that the state and those actors involved in natural resources use play a determining role in ensuring a fair distribution of any benefits and costs (Banai et al., 2011). Further, economic valuation studies have noted that systematic valuations of both positive and negative externalities can inform policymaking relating to resource exploitation, in some cases showing that the exploitation of land and mineral resources may not always be socially optimal, i.e., the social and environmental costs of action may be higher than the economic benefits of exploitation (de Groot, 2006; Thampapillai, 2011).

These considerations are relevant for mitigation policy for at least three reasons. First, they raise questions about if and how countries invest resource rents across economic, social, and environmental sectors for SD (see Section 4.3.8). Second, they suggest that nations or sub-national actors with abundant fossil fuel reserves have, in principle, strong economic interest in exploiting them, and thus in opposing the adoption of policies that constrain such exploitation. The timeliness of this issue is underscored by the growing financial sector attention (although not yet academic attention) to the potential impact of a global carbon constraint on the fossil sector (Grantham Institute and CTI 2013; HSBC Global Research, 2013; Standard & Poor's, 2013). This raises the issue of how to compensate resource-rich countries for forgone benefits if necessary to win their participation in international mitigation efforts (Rival, 2010; Waisman et al., 2013). It similarly raises the issue of compensating (or circumventing) sub-national actors who are politically powerful enough to impede domestic climate efforts. And third, they suggest that, if any given resource-rich country faces increased exposure to climate variability and extreme events, the forgone benefits of resource rents may undermine its ability to absorb increasing adaptation costs. In this regard, a recent analysis of the relationship between countries' adoption of mitigation policies and their vulnerability to climate change confirms that countries that may suffer considerable impacts of climate change in the future, which include many resource-rich developing countries, do not show a strong commitment to either mitigation or adaptation, while countries exhibiting strong political commitment and action towards mitigation are also active in promoting adaptation policies (Tubi et al., 2012).

4.3.8 Finance and investment

The financial system, comprising a large set of private and public institutions and actors, is the medium by which households, firms, and collectivities manage insurable risks and fund investments to secure future returns, thereby laying the foundations for future well-being. As such, it is a key determinant of society's development pathway and thus its prospects for an SD transition.

The financial system is characterized by four structural tensions with the ideals of SD. First, its dominant private component (banks and financial markets) is focused on commercial returns and cannot spontaneously internalize environmental and social spillovers, even if some investors' interest in 'sustainable investment' is growing (UNPRI, 2012). Climate change, identified as the "greatest and widest-ranging market failure ever seen" (Stern and Treasury, 2007), is but one obvious example of a large societally important cost that is neglected by capital markets. Second, the private component of the financial system is also largely unattuned to distributive issues and particularly insensitive to "the essential needs of the world's poor, to which overriding priority should be given" (World Commission on Environment and Development, 1987), even if foreign direct investments have contributed to overall growth in emerging economies. Third, the interests of future generations may be neglected (although over-investment is also possible—see Gollier, 2013) and within a generation, there are various governance, organizational and sociological mechanisms contributing to short-termism (Tonello, 2006; Marginson and McAulay, 2008). Fourth, the recent crisis has led some to conclude that the financial system itself is a source of economic instability (Farmer et al., 2012), an issue reinforced by the recent financialization of the global economy, with accelerated growth of the financial sector relative to the 'real' economy, and an increasing role of the financial system in mediating short-term speculation as distinct from long-term investment (Epstein, 2005; Krippner, 2005; Palley, 2007; Dore, 2008).

These inherent problems in the financial system are sometimes compounded by hurdles in the economic and institutional environment. The challenges are felt especially in many developing countries, which face several investment barriers that affect their capacity to mobilize private sector capital toward SD objectives and climate change mitigation and adaptation. These barriers include the comparatively high overall cost of doing business; market distortionary policies such as subsidies for conventional fuels; absence of credit-worthy off-takers; low access to early-stage financing; lower public R&D spending; too few wealthy consumers willing to pay a premium for 'green products'; social and political instability; poor market infrastructure; and weak enforcement of the regulatory frameworks. Establishing better mechanisms for leveraging private sector finance through innovative financing can help (EGTT, 2008), but there are also risks in relying on the private sector as market-based finance focuses on short term lending, and private financing during episodes of abundant liquidity may not constitute a source of stable long-term climate finance (Akyüz, 2012) –see Section 16.4 for further discussion and references on barriers, risks, and innovative mechanisms.

While some developing countries are able to mobilize domestic resources to finance efforts toward SD, the needs for many developing countries exceed their financial capacity. Consequently, their ability to pursue SD, and climate change mitigation and adaptation actions in particular, can be severely constrained by lack of finance. The international provision of finance, alongside technology transfer, can help to alleviate this problem, as well as accord with principles of equity, international commitments, and arguments of effectiveness—see Sections 4.2.2 and 4.6.2. Under international agreements, in particular Agenda 21 and the Rio Conventions of 1992, and reaffirmed in subsequent UN resolutions and programs including the 2012 UN Conference on Sustainable Development (United Nations, 2012a), developed countries have committed to provide financial resources to developing countries that are new and additional to conventional development assistance.

4.4 Production, trade, consumption and waste patterns

The previous section has highlighted the role of behaviours and lifestyles and the complex interaction of the values, goals, and interests of many actors in the political economy of SD and equity. In order to better understand the possibilities and difficulties to equitably sustain well-being in the future, this section examines the consumption of goods and services by households, consumption trends and disparities, and the relationship between consumption and GHG emissions. It also discusses the components and drivers of consumption, efforts to make consumption (and production) more sustainable, and how consumption affects well-being. In order to shed light on important debates about equity in mitigation, this chapter also reviews approaches to consumption-based accounting of GHG emissions (carbon footprinting) and their relationship to territorial approaches. So while subsequent chapters analyze GHG emissions associated with specific sectors and transformation pathways, this chapter focuses on a particular group (consumers) and examines their emissions in an integrated way.

The possibility of a SD pathway for the world hinges on 'decoupling' (von Weizsäcker et al., 1997, 2009; Jackson, 2005b, 2009). We consider two types of decoupling at the global scale and in the long term: the decoupling of material resource consumption (including fossil carbon) and environmental impact (including climate change) from economic growth ('dematerialization'); and the decoupling of human well-being from economic growth and consumption. The first type (see Sections 4.4.1 and 4.4.3) involves an increased material efficiency and environmental efficiency of production and is generally considered crucial for meeting SD and equity goals (UNEP, 2011); yet while some dematerialization has occurred, absolute levels of resource use and environmental impact have continued to rise, highlighting the important distinction between relative and absolute decoupling (Krausmann et al., 2009). This has inspired examination of the second type of decoupling (Jackson, 2005b, 2009; Assadourian, 2010), including the reduction of consumption levels in wealthier countries. We address this topic (in Section 4.4.4) by examining how income and income inequality affect dimensions of well-being. While the second type of decoupling represents a 'stronger' form than the first, it is also a more controversial goal, even though the unsustainability of excessive consumption was highlighted by Chapter 4 of Agenda 21 (United Nations, 1992c).

4.4.1 Consumption patterns, inequality and environmental impact

4.4.1.1 Trends in resource consumption

Global levels of resource consumption and GHG emissions show strong historical trends, driven primarily by developments in industrialized countries and emerging economies (see Sections 5.2 and 14.3). The global annual use (extraction) of material resources—i.e., ores and industrial minerals, construction materials, biomass, and fossil energy carriers—increased eightfold during the 20th century, reaching about 55 Gt in 2000, while the average resource use per capita (the metabolic rate) doubled, reaching 8.5–9.2 tonnes per capita per year in 2005 (Krausmann et al., 2009; UNEP, 2011). The value of the global consumption of goods and services (the global GDP) has increased sixfold since 1960 while consumption expenditures per capita have almost tripled (Assadourian, 2010). Consumption-based GHG emissions ('carbon footprints'—see Section 4.4.2.2) increased between 1990 and 2009 in the world's major economies, except the Russian Federation, ranging from 0.1–0.2 % per year in the EU27, to 4.8–6.0 % per year in China (Peters et al., 2012) (see Section 5.2.1).

Global resource consumption has risen slower than GDP, especially after around 1970, indicating some decoupling of economic development and resource use, and signifying an aggregate increase in resource productivity of about 1–2 % annually (Krausmann et al., 2009; UNEP, 2011). While dematerialization of economic activity has been most noticeable in the industrialized countries, metabolic rates across countries remain highly unequal, varying by a factor of 10 or more due largely to differences in level of development, although there is also significant cross-country variation in the relation between GDP and resource use (Krausmann et al., 2009; UNEP, 2011).

4.4.1.2 Consumerism and unequal consumption levels

The spread of material consumption with rising incomes is one of the 'mega-drivers' of global resource use and environmental degradation (Assadourian, 2010). While for the world's many poor people, consumption is driven mainly by the need to satisfy basic human needs, it is increasingly common across cultures that people seek meaning, contentment and acceptance in consumption. This pattern is often referred to as 'consumerism', defined as a cultural paradigm where "the possession and use of an increasing number and variety of goods and services is the principal cultural aspiration and the surest perceived route to personal happiness, social status and national success" (Assadourian, 2010, p. 187).

Consumerist lifestyles in industrialized countries seem to be imitated by the growing elites (Pow, 2011) and middle-class populations in developing countries (Cleveland and Laroche, 2007; Gupta, 2011), exemplified by the increased demand for space cooling in emerging economies (Isaac and van Vuuren, 2009). Together with the unequal distribution of income in the world, the spread of consumerism means that a large share of goods and services produced are 'luxuries' that only the wealthy can afford, while the poor are unable to afford even basic goods and services (Khor, 2011).

A disproportionate part of the GHG emissions arising from production are linked to the consumption of products by a relatively small portion of the world's population, illustrated by the great variation in the per capita carbon footprint between countries and regions at different income levels (Hertwich and Peters, 2009; Davis and Caldeira, 2010; Peters et al., 2011) (see Section 14.3.1). The carbon footprint is strongly correlated with consumption expenditure. Across countries, Hertwich and Peters (2009) found an expenditure elasticity of 0.57 for all GHGs: as nations become wealthier, the per capita carbon footprint increases by 57 % for each doubling of consumption. Within countries, similar relationships have been found between household expenditure and carbon footprint (Druckman and Jackson, 2009; Hertwich, 2011). Because wealthier countries meet a higher share of their final demand from (net) imports than do less wealthy countries, consumption-based emissions are more closely associated with GDP than are territorial emissions, the difference being the emissions embodied in trade (see Section 4.4.2 as well as 5.2 and 14.3).

4.4.1.3 Effect of non-income factors on per capita carbon footprint

Non-income factors such as geography, energy system, production methods, waste management (GAIA, 2012; Corsten et al., 2013), household size, diet, and lifestyle also affect per capita carbon footprints and other environmental impacts (Tukker et al., 2010a) so that the effects of increasing income varies considerably between regions and countries (Lenzen et al., 2006; Hertwich, 2011; Homma et al., 2012), cities (Jones and Kammen, 2011) and between rural and urban areas (Lenzen and Peters, 2010). In this regard, the environmental impact of specific consumption patterns has been studied intensely in recent years (Druckman and Jackson, 2009; Davis and Caldeira, 2010; Tukker et al., 2010a; Hertwich, 2011). At the global level, Hertwich and Peters (2009) found that food is the consumption category with the greatest climate impact, accounting for nearly 20 % of GHG emissions, followed by housing/shelter, mobility, services, manufactured products, and construction (see Sections 8.2, 9.2, 10.3, 11.2, 12.2). Food and services were a larger share in poor countries, while at high expenditure levels, mobility and the consumption of manufactured goods caused the largest GHG emissions (Hertwich and Peters, 2009). The factors responsible for variations in carbon footprints across households at different scales are further discussed in Sections 5.3, 5.5, 12.2 and 14.3.4.

4.4.2 Consumption patterns and carbon accounting

4.4.2.1 Choice of GHG accounting method

New GHG accounting methods have emerged and proliferated in the last decade, in response to interest in 1) determining whether nations are reducing emissions (Bows and Barrett, 2010; Peters et al., 2011, 2012), 2) allocating GHG responsibility (Peters and Hertwich, 2008a; b; Bows and Barrett, 2010), 3) assuring the accountability of carbon markets (Stechemesser and Guenther, 2012), 4) determining the full implications of alternative energy technologies (von Blottnitz and Curran, 2007; Martínez et al., 2009; Cherubini et al., 2009; Soimakallio et al., 2011) and of outsourcing of industrial production (see Section 4.4.3.3) helping corporations become greener (Wiedmann et al., 2009), and 6) encouraging consumers to reduce their carbon footprints (Bolwig and Gibbon, 2010; Jones and Kammen, 2011). Methods differ on whether consumers or producers of products are responsible; whether emissions embedded in past or potential replacement of capital investments are included; and whether indirect emissions, for example, through global land-use change resulting from changing product prices, are included (Finkbeiner, 2009; Plevin et al., 2010; Plassmann et al., 2010). These methodological differences have normative implications.

Systems of GHG emissions accounting are constructed according to certain conventions and purposes (Davis and Caldeira, 2010). Better ways may be excessively expensive given the plausible importance of the value of better information in the decision process. Some interests will plead for standardized techniques based on past data because it favours them. Others will argue for tailored approaches that make their technologies or products look good. Producers favour responsibility being assigned to consumers, as do nations that are net exporters of industrial goods. Controversies over GHG emissions accounting approaches play into the broader issue of mitigation governance (see Section 4.4.2.4). And whether carbon markets are effective or not depends on good accounting and enforcement—but what will be enforced will depend on the accounting measures agreed upon. The next section discusses consumption-based GHG emissions accounting.

4.4.2.2 Carbon footprinting (consumption-based GHG emissions accounting)

Carbon (or GHG) accounting refers to the calculation of the GHG emissions associated with economic activities at a given scale or with respect to a given functional unit—including products, households, firms, cities, and nations (Peters, 2010; Pandey et al., 2011). GHG accounting has traditionally focused on emission sources, but recent years have seen a growing interest in analyzing the drivers of emissions by calculating the GHG emissions that occur along the supply chain of different functional units such as those just mentioned (Peters, 2010). The result of this consumption-based emissions accounting is often referred to as 'carbon footprint' even if it involves other GHGs along with CO_2. Carbon footprinting starts from the premise that the GHG emissions associated with economic activity are generated at least partly as a result of people's attempts to satisfy certain functional needs and desires (Lenzen et al., 2007; Druckman and Jackson, 2009; Bows and Barrett, 2010). These needs and desires carry the consumer demand for goods and services, and thereby the production processes that consume resources and energy and release pollutants. Emission drivers are not limited to individuals' consumption behaviour, however, but include also the wider contexts of consumption such as transport infrastructure, production and waste systems, and energy systems (see below and Sections 7.3, 8.2, 9.2, 10.3, 11.2, 12.2).

There is no single accepted carbon footprinting methodology (Pandey et al., 2011), nor is there one widely accepted definition of carbon footprint. Peters (2010) proposes this definition, which allows for all possible applications across scales: "[t]he 'carbon footprint' of a functional unit is the climate impact under a specific metric that considers all relevant emission sources, sinks and storage in both consumption and production within the specified spatial and temporal system boundary" (pp. 245). The emissions associated with the functional unit (but physically not part of the unit) are referred to as 'embodied carbon', 'carbon flows' or similar terms. (Annex II of this report discusses different carbon footprint methodologies, including Life Cycle Assessment (LCA) and environmentally-extended input-output (EIO) models.) Carbon footprints have been estimated with respect to different functional units at different scales. Most relevant to the analysis of consumption patterns and mitigation linkages are the carbon footprints of products and nations, discussed in turn.

4.4.2.3 Product carbon footprinting

A product carbon footprint includes all emissions generated during the lifecycle of a good or service—from production and distribution to end-use and disposal or recycling. Carbon footprinting of products (and firms) can enable a range of mitigation actions and can have co-benefits (Sinden, 2009; Bolwig and Gibbon, 2010). Informing consumers about the climate impact of products through labelling or other means can influence purchasing decisions in a more climate-friendly direction and at the same time enable product differentiation (Edwards-Jones et al., 2009; Weber and Johnson, 2012). Carbon footprinting can also help companies reduce GHG emissions cost-effectively by identifying the various emission sources within the company and along the supply chain (Sinden, 2009; Sundarakani et al., 2010; Lee, 2012). Those emissions can be reduced directly, or by purchasing offsets in carbon markets. There is both theoretical and empirical evidence of a positive relationship between a company's environmental and financial performance (Delmas and Nairn-Birch, 2011; Griffin et al., 2012). The specific effect of carbon footprinting on company financial performance and investor valuation is not well researched, however, and the results are ambiguous: in the United Kingdom, Sullivan and Gouldson (2012) found limited investor interest in the climate change-related data provided by retailers, while a study from North America concludes that investors do care about companies' GHG emission disclosures, whether these occur through a voluntary scheme or informal estimates (Griffin et al., 2012).[1] (See also Section 15.3.3)

There are also risks associated with product carbon footprinting. It can affect competitiveness and trade by increasing costs and reduce demand for products made abroad, including in developing countries, and it may violate World Trade Organization (WTO) trade rules (Brenton et al., 2009; Edwards-Jones et al., 2009; Erickson et al., 2012). A one-sided focus on GHG emissions in product development and consumer choice could also involve tradeoffs with other sustainability dimensions (Finkbeiner, 2009; Laurent et al., 2012). So there are reasons to adopt more broadly encompassing concepts and tools to assess and manage sustainability in relation to the consumption of goods and services.

4.4.2.4 Consumption-based and territorial approaches to GHG accounting

Consumption-based accounting of GHG emissions (carbon footprinting) at national level differs from the production-based or territorial framework because of imports and exports of goods and services that, directly or indirectly, involve GHG emissions (Davis and Caldeira, 2010; Peters et al., 2011, 2012). The territorial framework allocates to a nation (or other jurisdiction) those emissions that are physically produced within its territorial boundaries. The consumption-based framework assigns the emissions released through the supply chain of goods and services consumed within a nation irrespective of their territorial origin. The difference in inventories calculated based on the two frameworks are the emissions embodied in trade (Peters and Hertwich, 2008b; Bows and Barrett, 2010). We emphasize that territorial and consumption-based accounting of emissions as such represent pure accounting identities measuring the emissions embodied in goods and services that are produced or consumed, respectively, by an individual, firm, country, region, etc. Responsibility for these emissions only arises once it is assigned within a normative or legal framework, such as a climate agreement, specifying rights to emit or obligations to reduce emission based on one of these metrics. As detailed below, the two approaches function differently in a global versus a fragmented climate policy regime.

Steckel et al. (2010) show that within a global regime that internalizes a cost of GHG emissions, the two approaches are theoretically equivalent in terms of their efficiency in inducing mitigation. For example, with a global cap-and-trade system with full coverage (i. e., an efficient global carbon market) and given initial emission allocations, countries exporting goods benefit from export revenues, with costs related to GHG emissions and any other negative impacts of production of those goods priced in, such that the choice of accounting system has no influence on the efficiency of production. Nor will it influence the welfare of countries, irrespective of being net exporters or importers of emissions, since costs associated with these emissions are fully internalized in product prices and will ultimately be borne by consumers. In practice, considerations such as transaction costs and information asymmetries would influence the relative effectiveness and choice of accounting system.

[1] In the United States, increasing carbon emissions was found to positively impact the financial performance of firms when using accounting-based measures, while the impact was negative when using market-based performance measures (Delmas and Nairn-Birch, 2011).

In the case of a fragmented climate policy regime, one argument put in favour of a consumption-based framework is that, unlike the territorial approach, it does not allow current emission inventories to be reduced by outsourcing production or relying more on imports to meet final demand. Hence, some authors (e.g., Peters and Hertwich, 2008b; Bows and Barrett, 2010) argue that this approach gives a fairer illustration of responsibility for current emissions. Carbon footprinting also increases the range of mitigation options by identifying the distribution of GHG emissions among different activities, final uses, locations, household types, etc. This enables a better targeting of policies and voluntary actions (Bows and Barrett, 2010; Jones and Kammen, 2011).

On the other hand, reducing emissions at the 'consumption end' of supply chains requires changing deeply entrenched lifestyle patterns and specific behaviours among many actors with diverse characteristics and preferences, as opposed to among the much fewer actors emitting GHGs at the source. It has also been pointed out that—identical to the accounting of production-based emissions—there is no direct one-to-one relationship between changes in consumption-based and global emissions (Jakob and Marschinski, 2012). That is, if some goods or services were not consumed in a given country, global emissions would not necessarily decrease by the same amount of emissions generated for their production, as this country's trade partners would adjust their consumption—as well as production—patterns in response to price changes resulting from its changed demand profile. This has been shown for China (Peters et al., 2007) and India (Dietzenbacher and Mukhopadhyay, 2007): while these countries are large net exporters of embodied carbon, territorial emissions would remain roughly constant or even increase if they were to withdraw from international trade (and produce their entire current consumption domestically instead). Hence, without international trade, consumption-based emissions of these countries' trade partners would likely be reduced, but not global emissions.

It is for this reason that Jakob and Marschinski (2012) argue that a more detailed understanding of the underlying determinants of emissions is needed than what is currently provided by either territorial or consumption-based accounts, in order to guide policies that will effectively reduce global emissions in a fragmented climate policy regime. In particular, a better understanding of system interrelationships in a global economy is required in order to be able to attribute how, e.g., policy choices in one region affect global emissions by transmission via world market prices and associated changes in production and consumption patterns in other regions. Furthermore, as market dynamics and resource use are driven by both demand and supply, it is conceivable to rely on climate policies that target the consumption as well as the production side of emissions, as is done in some other policy areas

4.4.3 Sustainable consumption and production—SCP

The concepts of 'sustainable consumption' and 'sustainable production' represent, respectively, demand- and supply-side perspectives on sustainability. The efforts by producers to improve the environmental or social impact of a product are futile if consumers do not buy the good or service (Moisander et al., 2010). Conversely, sustainable consumption behaviour depends on the availability and affordability of such products in the marketplace. The idea of sustainable consumption and production (SCP) was first placed high on the international policy agenda at the 1992 UN Conference on Environment and Development and was made part of Agenda 21. In 2003, a 10-year Framework of Programmes on SCP was initiated, which was formalized in a document adopted by the 2012 UN Conference on Sustainable Development (United Nations, 2012b, p. 2). A great variety of public and private SCP policies and initiatives have developed alongside the UN-led initiatives (see Section 10.11.3), as has a large body of research that we report on below.

4.4.3.1 Sustainable consumption and lifestyle

A rich research literature on sustainable consumption has developed over the past decade, including several special issues of international journals (Tukker et al., 2010b; Le Blanc, 2010; Kilbourne, 2010; Black, 2010; Schrader and Thøgersen, 2011). Several books, such as *Prosperity without Growth* (Jackson, 2009), discuss the unsustainable nature of current lifestyles, development trajectories, and economic systems, and how these could be changed in more sustainable directions. Several definitions of sustainable consumption have been proposed within policy, business, and academia (Pogutz and Micale, 2011). At a meeting in Oslo in 2005, a group of scientists agreed on the following broad and integrating conceptualization of sustainable consumption:

> *The future course of the world depends on humanity's ability to provide a high quality of life for a prospective nine billion people without exhausting the Earth's resources or irreparably damaging its natural systems … In this context, sustainable consumption focuses on formulating strategies that foster the highest quality of life, the efficient use of natural resources, and the effective satisfaction of human needs while simultaneously promoting equitable social development, economic competitiveness, and technological innovation.*
> *(Tukker et al., 2006)*

This perspective encompasses both demand-side and production issues, and addresses all three pillars of SD (social, economic, and environmental) as well as equity and well-being, illustrating the complexity of sustainable consumption and its connections to other issues.

Research has demonstrated that consumption practices and patterns are influenced by a range of economic, informational, psychological, sociological, and cultural factors, operating at different levels or spheres in society—including the individual, the family, the locality, the market, and the work place (Thøgersen, 2010). Furthermore, consumers' preferences are often constructed in the situation (rather than pre-existing) and their decisions are highly contextual (Weber and Johnson, 2009) and often inconsistent with values, attitudes, and perceptions of themselves as responsible and green consumers and citizens (Barr, 2006; de Barcellos et al., 2011) (see below, as well as Sections 2.6.6 and 3.10).

The sustainable consumption of goods and services can be viewed in the broader context of lifestyle and everyday life. Conversely, sustainable consumption practices are bound up with perceptions of identity, ideas of good life, and so on, and considered alongside other concerns such as affordability and health. Ethical consumption choices are also negotiated among family members with divergent priorities and interpretations of sustainability. Choosing a simpler lifestyle ('voluntary simplifying') seems to be related to environmental concern (Shaw and Newholm, 2002; Huneke, 2005), but frugality, as a more general trait or disposition, is not (Lastovicka et al., 1999; Pepper et al., 2009).

Other research draws attention to the constraints placed on consumption and lifestyle choices by factors beyond the influence of the individual, family or community, which tends to lock consumption into unsustainable patterns by reducing 'green agency' at the micro level (Thøgersen, 2005; Pogutz and Micale, 2011). These structural issues include product availability, cultural norms and beliefs, and working conditions that favour a 'work-and-spend' lifestyle (Sanne, 2002). Brulle and Young (2007) found that the growth in personal consumption in the United States during the 20th century is partly explained by the increase in advertising. According to this study, the effect of advertising on spending is concentrated on luxury goods (household appliances and supplies and automobiles) while it is nonexistent in the field of basic necessities (food and clothes), while Druckman and Jackson (2010) found that in the UK, expenditures on food and clothes clearly exceeded 'necessary' levels.

The strength and pervasiveness of political economy factors such as those just mentioned, and the inadequate attention to them by policy, is an important cause of the lack of real progress towards more sustainable consumption patterns (Thøgersen, 2005; Tukker et al., 2006; Le Blanc, 2010). Furthermore, the unsustainable lifestyles in industrialized countries are being replicated by the growing elites (Pow, 2011) and middle-class populations in developing countries (Cleveland and Laroche, 2007; Gupta, 2011). Finally, most Sustainable Consumption (SC) studies are done in a consumer culture context, which limits discussion of instances where sustainable consumption has pre-empted consumerism.

4.4.3.2 Consumer sustainability attitudes and the relation to behaviour

Despite the overwhelming impact of structural factors on consumer practices, choices and behaviour, it is widely agreed that the achievement of more sustainable consumption patterns also depends on how consumers value environmental quality and other dimensions of sustainability (Jackson, 2005a; Thøgersen, 2005; Bamberg and Möser, 2007). It also depends on whether people believe that their consumption practices make a difference to sustainability (Frantz and Mayer, 2009; Hanss and Böhm, 2010), which in turn is influenced by their value priorities and how much they trust the environmental information provided to them by scientists, companies, and public authorities (Kellstedt et al., 2008). The motivational roots of sustainable consumer choices seem to be substantially the same, although not equally salient in different national and cultural contexts (Thøgersen, 2009; Thøgersen and Zhou, 2012).

In a survey of European attitudes towards sustainable consumption and production (Gallup Organisation, 2008a), 84 % of EU citizens said that the product's impact on the environment is "very important" or "rather important" when making purchasing decisions. This attitude is rarely reflected in behaviour, however. There is plenty of evidence demonstrating the presence of an 'attitude-behaviour' or 'values-action' gap whereby consumers expressing 'green' attitudes fail to adopt sustainable consumption patterns and lifestyles (Barr, 2006; Young et al., 2010; de Barcellos et al., 2011). To a large measure, this gap can be attributed to many other goals and concerns competing for the person's limited attention (Weber and Johnson, 2009). This observation is reflected in the substantial difference in the level of environmental concern that Europeans express in opinion polls when the issue is treated in isolation, and when the environment is assessed in the context of other important societal issues. For example, in 2008, 64 % of Europeans said protecting the environment was "very important" to them personally when the issue was presented in isolation (Gallup Organisation, 2008b) while only 4 % pointed at environmental pollution as one of the two most important issues facing their country at the moment (Gallup Organisation, 2008a). When there are many important issues competing for the person's limited attention and resources, those that appear most pressing in everyday life are likely to prevail.

The likelihood that a person will act on his or her environmental concern is further diminished by factors affecting everyday decisions and behaviour, including the structural factors mentioned above, but also more specific factors such as habit, high transactions costs (i. e., time for information search and processing and product search), availability, affordability, and the influence of non-green criteria such as quality, size, brand, and discounts (Young et al., 2010). Some of these factors vary across different product categories and within sectors (McDonald et al., 2009). The impact of all of these impeding factors is substantial, calling into question the capacity of 'the green consumer' to effectively advance sustainable consumption and production (Csutora, 2012) and, more generally, the individualistic view of the consumer as a powerful market actor (Moisander et al., 2010).

Third-party eco-labels and declarations have proven to be an effective tool to transform consumer sustainability attitudes into behaviour in many cases (Thøgersen, 2002). One of the reasons is that a trusted label can function as a choice heuristic in the decision situation, allowing the experienced consumer to make sustainable choices in a fast and frugal way (see Section 2.6.5 and Thøgersen et al., 2012). Labeling products with their carbon footprint may help to create new goals (e.g., to reduce CO_2 emissions) and to attract and keep attention on those goals, in the competition between goals (Weber and Johnson, 2012). In Europe, 72 % of EU citizens thought that carbon labelling should be mandatory (Gallup Organisation, 2008a). In Australia, Vanclay et al. (2010) found a strong purchasing response of 20 % when a green-labelled product (indicating relatively low lifecycle CO_2 emissions) was also the cheapest, and a much weaker response when green-labelled products were not the cheapest. Hence, consumers, at least in developed countries, show interest in product carbon footprint information and many consumers would prefer carbon-labelled products and firms over others, other things being equal (Bolwig and Gibbon, 2010). Yet the impeding factors and the related 'attitude-behaviour' gap limit how far one can get towards sustainable consumption with labelling and other information-based means alone.

Research on these topics in the developing world is lacking. Considering the notion of a hierarchy of needs (Maslow, 1970; Chai and Moneta, 2012) and the challenges facing consumers in developing countries, carbon footprints and other environmental declarations might be seen as a luxury concern that only developed countries can afford. Countering this view, Kvaløy et al. (2012) find environmental concern in developing countries at the same level as in developed countries. Furthermore, eco-labelled products increasingly appear at retail level in developing countries (Roitner-Schobesberger et al., 2008; Thøgersen and Zhou, 2012).

4.4.3.3 Sustainable production

Research and initiatives on sustainable production have been concerned with increasing the resource efficiency of, and reducing the pollution and waste from, the production of goods and services through technological innovations in process and product design at the plant and product levels, and, more lately, through system-wide innovations across value chains or production networks (Pogutz and Micale, 2011). Policies that incentivize certain product choices have also been developed (see Section 10.11.3). Eco-efficiency (Schmidheiny and WBSCD, 1992) is the main management philosophy guiding sustainable production initiatives among companies (Pogutz and Micale, 2011) and is expressed as created value or provided functionality per caused environmental impact. Moving towards a more eco-efficient production thus means creating the same or higher value or functionality while causing a lower environmental impact (relative or even absolute decoupling). This involves consideration of multiple impacts across scales, ranging from global impacts like climate change over regional impacts associated with air and water pollution, to local impacts caused by use of land or water.

A strong increase in the eco-efficiency of production is a pre-requisite for developing a sustainable society (Pogutz and Micale, 2011). The I=PAT equation expresses the environmental impact I as a product of the population number P, the affluence A (value created or consumed per capita), and a technology factor T perceived as the reciprocal of eco-efficiency. Considering the foreseeable growth in P and A, and the current unsustainable level of I for many environmental impacts it is clear that the eco-efficiency (1/T) must increase many times (a factor 4 to 20)[2] to ensure a sustainable production. While a prerequisite, even this kind of increases in eco-efficiency may not be sufficient since A and T are not mutually independent due to the presence of rebound—including market effects; indeed, sometimes a reduction in T (increased eco-efficiency) is accompanied by an even greater growth in A, thereby increasing the overall environmental impact I (Pogutz and Micale, 2011). (A related concept to I=PAT is the Kaya identity, see Section 5.3)

With its focus on the provided function and its broad coverage of environmental impacts, LCA is frequently used for evaluation of the eco-efficiency of products or production activities (Hauschild, 2005; Finnveden et al., 2009) (see Annex II.4.2). LCA has been standardized by the International Organization for Standardization (ISO 14040 and ISO 14044) and is a key methodology underlying standards for eco-labelling and environmental product declarations. LCA is also the analytical tool underlying DFE (design for environment) methods (Bhander et al., 2003; Hauschild et al., 2004).

With the globalization and outsourcing of industrial production, analyzing the entire product lifecycle (or product chain)—from resource extraction to end-of-life—gains increased relevance when optimizing the energy and material efficiency of production. A lifecycle approach will reveal the potential problem shifting that is inherent in outsourcing and that may lead to increased overall resource consumption and GHG emissions of the product over its lifecycle in spite of reduced impacts of the mother company (Shui and Harriss, 2006; Li and Hewitt, 2008; Herrmann and Hauschild, 2009). This is why a lifecycle perspective is applied when calculating the carbon footprint. Indeed, a lifecycle-based assessment is generally needed to achieve resource and emissions optimization across the product chain. The use stage can be especially important for products that use electricity or fuels to function (Wenzel et al., 1997; Samaras and Meisterling, 2008; Yung et al., 2011; Sharma et al., 2011). Improvement potentials along product chains can be large, in particular when companies shift from selling only products to delivering product-service systems, often increasing the number of uses of the individual product (Manzini and Vezzoli, 2003). Exchange of flows of waste materials or energy can also contribute to increasing eco-efficiency. Under the heading of 'industrial symbiosis', such mutually beneficial relationships between independent industries have emerged at multiple locations, generally leading to savings of energy and sometimes also materials and resources (Chertow and Lombardi, 2005; Chertow, 2007; Sokka et al., 2011) (See Section 10.5).

While the broad coverage of environmental impacts supported by LCA is required to avoid unnoticed problem shifting between impacts, a narrower focus on climate change mitigation in relation to produc-

[2] Factor 4 to factor 20 increases can be calculated depending on the expected increases in P and A and the needed reduction in I (von Weizsäcker et al., 1997; Schmidt-Bleek, 2008).

tion would be supported by considering energy efficiency, which can be addressed at different levels: the individual process, the production facility, the product chain, and the industrial system (industrial symbiosis). At the process level, the operation of the individual process and consideration of the use-stage energy efficiency in the design of the machine tools and production equipment can be addressed (see Section 10.4). Improvements in energy efficiency in manufacturing have focused on both the design and operation of a variety of processes (Gutowski et al., 2009; Duflou et al., 2010; Herrmann et al., 2011; Kara and Li, 2011), finding improvement potentials at the individual process level of up to 70 % (Duflou et al., 2012), and at the plant level by re-using e.g., waste heat from one process for heating in another (Hayakawa et al., 1999). Exergy analysis and energy pinch analysis can be used to identify potentials for reutilization of energy flows in other processes (Creyts and Carey, 1999; Bejan, 2002).

Research on the social dimensions of production systems have addressed such issues as worker conditions (Riisgaard, 2009), farm income (Bolwig et al., 2009), small producer inclusion into markets and value chains (Bolwig et al., 2010; Mitchell and Coles, 2011) and the role of standards in fostering sustainability (Gibbon et al., 2010; Bolwig et al., 2013). Recently, the LCA methodology has been elaborated to include assessment of social impacts such as labour rights (Dreyer et al., 2010), in order to support the assessment of problem shifting and tradeoffs between environmental and social dimensions (Hauschild et al., 2008).

4.4.4 Relationship between consumption and well-being

As noted earlier, global material resource consumption continues to increase despite substantial gains in resource productivity or eco-efficiency, causing further increases in GHG emissions and overall environmental degradation. In this light it is relevant to discuss whether human well-being or happiness can be decoupled from consumption or growth (Ahuvia and Friedman, 1998; Jackson, 2005b; Tukker et al., 2006). We do this here by examining the relationship between different dimensions of well-being and income (and income inequality) across populations and over time.

Happiness is an ambiguous concept that is often used as a catchword for subjective well-being (SWB). SWB is multidimensional and includes both cognitive and affective components (Kahneman et al., 2003). Cognitive well-being refers to the evaluative judgments individuals make when they think about their life and is what is reported in life satisfaction or ladder-of-life data, whereas affective or emotional well-being refers to the emotional quality of an individual's everyday experience as captured by surveys about the intensity and prevalence of feelings along the day (Kahneman and Deaton, 2010). Emotional well-being has been defined as "the frequency and intensity of experiences of joy, fascination, anxiety, sadness, anger, and affection that makes one's life pleasant or unpleasant" (Kahneman and Deaton, 2010, p. 16489).

Camfield and Skevington (2008) examine the relationship between SWB and quality of life (QoL) as used in the literature. They find that SWB and QoL are virtually synonymous; that they both contain a substantial element of life satisfaction, and that health and income are key determinants of SWB or QoL, while low income and high inequality are both associated with poor health and high morbidity.

The "Easterlin paradox" refers to an emerging body of literature suggesting that while there is little or no relationship between SWB and the aggregate income of countries or long-term GDP growth, *within* countries people with more income are happier (Easterlin, 1973, 1995). Absolute income is, it is argued, only important for happiness when income is very low, while relative income (or income equality) is important for happiness at a wide range of income levels (Layard, 2005; Clark et al., 2008). These insights have been used to question whether economic growth should be a primary goal of government policy (for rich countries), instead of, for example, focusing on reducing inequality within countries and globally, and on maximizing subjective well-being. For instance, Assadourian (2010) argues against consumerism on the grounds that increased material wealth above a certain threshold does not contribute to subjective well-being.

The Easterlin paradox has been contested in comparisons across countries (Deaton, 2008) and over time (Stevenson and Wolfers, 2008; Sacks et al., 2010), on the basis of the World Gallup survey of well-being. These works establish a clear linear relationship between average levels of ladder-of-life satisfaction and the logarithm of GDP per capita across countries, and find no satiation threshold beyond which affluence no longer enhances subjective well-being. Their time series analysis also suggests that economic growth is on average associated with rising happiness over time. On this basis they picture a strong role for absolute income and less for relative income comparisons in determining happiness.

These results contrast with studies of emotional well-being, which generally find a weak relationship between income and well-being at higher income levels. In the United States, for example, Kahneman and Deaton (2010) find a clear satiation effect: beyond around USD_{2010} 75,000 annual household income (just above the mean United States household income) "further increases in income no longer improve individuals' emotional well-being (including aspects such as spending time with people they like, avoiding pain and disease, and enjoying leisure)" (p. 16492).[3] But even for life satisfaction, there is contrasting evidence. In particular, Deaton (2008) finds much variation of SWB between countries at the same level of development, and Sacks et al. (2010) finds the long term positive relationship between income and life satisfaction to be weakly significant and sensitive to the sample of countries (see also Graham, 2009; Easterlin et al., 2010; Di Tella and MacCulloch, 2010). An important phenomenon is that all components of SWB, in various degrees, adapt to most changes in objective conditions of life, except a

3 This result is based on cross-sectional data and do not refer to the effects of a *change* in a person's income.

few things, such as physical pain (Kahneman et al., 2003; Layard, 2005; Clark et al., 2008; Graham, 2009; Di Tella and MacCulloch, 2010).

The great variability of SWB data across individuals and countries and the adaptation phenomenon suggest that these data do not provide indices of well-being that are comparable across individuals and over time. Respondents have different standards when they answer satisfaction questions at different times or in different circumstances. Therefore, the weakness of the observed link between growth and SWB is not only debated, but it is quite compatible with a strong and firm desire in the population for ever-growing material consumption (Fleurbaey, 2009). Decoupling growth and well-being may be more complicated than suggested by raw SWB indicators.

Decoupling individual well-being from consumption may be fraught with controversies, but decoupling social welfare from average consumption might be possible via inequality reduction. It has been found that inequality in society has a marked negative effect on average SWB. For example, Oishi et al. (2011) found that over a 37-year period, Americans were less happy on average during years with greater income inequality. This was explained by the fact that lower-income respondents "trusted other people less and perceived other people to be less fair in the years with more national income inequality" (Oishi et al., 2011, p. 1095). The potential decoupling of social welfare from average consumption is even more obvious if social welfare is defined in a way that gives priority to those who are less well-off (Atkinson, 1970).

4.5 Development pathways

Sustainable development provides a framework for the evaluation of climate policies. This is particularly useful in view of the fact that a given concentration pathway or climate objective can typically be achieved through various policies and development pathways inducing different impacts on the economy, the society, and other aspects of the environment. Integrated models provide valuable tools for the analysis of pathways, though most models suffer from limitations analyzed in this section.

4.5.1 Definition and examples

Though widely used in the literature, the concept of development pathway has rarely been defined.[4] According to AR4, a development path is "an evolution based on an array of technological, economic, social, institutional, cultural, and biophysical characteristics that determine the interactions between human and natural systems, including consumption and production patterns in all countries, over time at a particular scale" (WGIII, AR4, Glossary, p. 813). AR4 also indicates that "alternative development paths refer to different possible trajectories of development, the continuation of current trends being just one of the many paths". Though AR4 defines development pathways as global, the concept has also been used at regional (e.g., Li and Zhang, 2008), national (e.g.,Poteete, 2009) and subnational scales (e.g. Dusyk et al., 2009) at provincial scale and (Yigitcanlar and Velibeyoglu, 2008) at city scale. In the present report, a development pathway characterizes all the interactions between human and natural systems in a particular territory, regardless of scale.

The concept of development pathway is holistic. It is broader than the development trajectory of a particular sector, or of a particular group of people within a society. Thus, a wide range of economic, social, and environmental indicators are necessary to describe a development pathway, not all of which may be amenable to quantitative representation. As defined by AR4, however, a "pathway" is not a random collection of indicators. It has an internal narrative and causal consistency that can be captured by the *determinants* of the interactions between human and natural systems. The underlying assumption is that the observed development trajectory—as recorded by various economic, social, and environmental indicators—can be explained by identifiable drivers. This roots the concept of development pathway in the (dominant) intellectual tradition according to which history has some degree of intelligibility (while another tradition holds that history is a chaotic set of events that is essentially not intelligible (Schopenhauer, 1819).

The literature on development pathways has two main branches. A 'backward-looking' body of work describes past and present development trajectories for given territories and explores their determinants. For example, most of the growth literature as well as a large part of the (macro) development literature fall into this category.[5] This body of work is discussed in Section 4.3 as well as in several other chapters. In particular, Section 5.3.1 reviews the determinants of GHG emissions, Section 12.2 reviews past trajectories of human settlements, and Section 14.3 discusses past trajectories of development at regional scale. In addition, 'forward-looking' studies construct plausible development pathways for the future and examine the ways by which development might be steered towards one pathway or another. Box 4.3 briefly reviews the main forward-looking development pathways published since AR4. Most of Chapter 6 is devoted to forward-looking studies.

[4] Development path and development pathway are synonymous.

[5] This literature can itself be divided in two main groups: papers aimed at identifying individual mechanisms that drive development trajectories, and papers aimed at identifying broad patterns of development. One example of the former is the literature on the relationships between GDP and emissions, discussed in Chapter 5, and in Section 4.4. One example of the latter is the so-called "investment development path" literature, which, following Dunning (1981), identifies stages of development for countries based on the direction of foreign direct investment flows and the competitiveness of domestic firms on international markets.

Box 4.3 | Forward-Looking Development Pathways: new developments since AR4

Forward-looking development pathways aim at illuminating possible futures, and at providing a sense of how these futures might be reached (or avoided). Forward-looking pathways can be constructed using various techniques, ranging from simulations with numerical models to qualitative scenario construction or group forecasting exercises (van Notten et al., 2003).

New sets of forward-looking development pathways have been proposed since the AR4 review (in Sathaye et al. (2007), Section 12.2.1.2). At the global scale, they include, inter alia, the climate smart pathway (World Bank, 2010), the Tellus Institute scenarios (Raskin et al., 2010), and degrowth strategies (Martínez-Alier et al., 2010) or the scenarios developed under the Integrated Assessment Modelling Consortium (IAMC) umbrella (Moss et al., 2010) to update the 2000 SRES scenarios (IPCC, 2000). Pathways have also been proposed for specific sectors, such as health (Etienne and Asamoa-Baah, 2010), agriculture (Paillard et al., 2010), biodiversity (Leadley et al., 2010; Pereira et al., 2010), and energy (Ayres and Ayres, 2009).

At the national and regional levels, the emergence of the "green growth" agenda (OECD, 2011) has spurred the development of many short- to medium-term exercises (e.g. Republic of Korea, 2009; Jaeger et al., 2011); as well as renewed discussions on SD trajectories (e.g. Jupesta et al., 2011). Similarly, there is growing research on the ways by which societies can transition towards a "low carbon economy", considering not only mitigation and adaptation to climate change, but also the need for social, economic, and technological (Shukla et al., 2008) (see Section 6.6.2 for a broader review). For instance, studies in China show that controlling emissions without proper policies to counteract the negative effects will have an adverse impact on the country's economic development, reducing its per capita income and the living standards of both urban and rural residents (Wang Can et al., 2005; Wang Ke, 2008). China is developing indicators for low-carbon development and low-carbon society (UN (2010), with many citations) with specific indicators tested on selected cities and provinces (Fu, Jiafeng et al., 2010), providing useful data on challenges and gaps as well as the need for clearly defined goals and definitions of "low-carbon" and its SD context.

4.5.2 Transition between pathways

Backward-looking studies reveal that past development pathways have differed in many respects, notably in terms of GHG emissions because of differences in, inter alia, fuel supply mix, location patterns, structure of economic activity, composition of household demand, etc.—even across countries with otherwise very similar economic characteristics. Similarly, forward-looking studies point to very contrasted, yet equally plausible, futures in terms of GHG emissions. Shifting from a high- to a low-emissions development pathway requires modifying the trajectory of the system that generates (among others) GHG emissions. It thus requires time as well as action over multiple dimensions of development (location, technology, lifestyles, etc.). Yet, shifting from a high- to a low-emissions development pathway could potentially be as important for climate change mitigation as implementing 'climate' policies (Halsnaes et al., 2011).

A central theme of the present report is to explore the conditions of a transition towards development pathways with lower emissions, globally (Chapter 6), sectorally (Chapters 7–12), and regionally (Chapters 13–15). To frame these subsequent discussions, the present section does two things. First, it discusses the obstacles to changing course by introducing the key notions of path dependence and lock-ins (4.5.2.1). Second, examples and lessons from the technology transition literature are discussed (4.5.2.2). The policy and institutional aspects of building strategies to transition between pathways are discussed in the subsequent chapters.[6]

4.5.2.1 Path dependence and lock-ins

Path dependence is the tendency for past decisions and events to self-reinforce, thereby diminishing and possibly excluding the prospects for alternatives to emerge. Path dependence is important for analyzing transitions between development pathways. For example, development of inter-city highways may make further extension of the road network more likely (if only for feeder roads) but also make further extension of rail networks less cost-effective by drawing out traffic and investment financing (see Section 12.5), thereby diminishing the prospects for alternative transportation investments.

Chief among the mechanisms that underlie path-dependence are 'increasing returns' mechanisms (Page, 2006)—in which an outcome in one period increases the probability of generating that same outcome in the next period. Increasing returns is a large group that com-

[6] The key point, as emphasized in AR4, is that a development pathway results from the interactions of decisions by multiple agents, at all levels. Thus in general public policies alone cannot trigger changes in pathways, and cooperation between governments, markets, and civil societies are necessary (Sathaye et al., 2007).

prises, inter alia, increasing returns to scale, learning by doing, induced technological change, or agglomeration economies. As Shalizi and Lecocq (2013) note, the concept of increasing returns has a long tradition in economic history, and the implications of increasing returns mechanisms have been systematically explored over the past three decades or so, notably around issues of monopolistic competition (Dixit and Stiglitz, 1977), international trade (Krugman, 1979), economic geography (Fujita et al., 1999), economic growth (Romer, 1990), industrial organizations, or adoption of technologies (Arthur, 1989).

Yet increasing returns are neither sufficient nor necessary to generate path-dependence. They are not sufficient because competing increasing returns can cancel out. And they are not necessary because other mechanisms might generate path-dependence. For example, decisions that involve the use of scarce resources, such as land, labour or exhaustible natural resources constrain future agents' options, either temporarily (for labour) or permanently (for exhaustible resources). Similarly, in the presence of switching costs—e.g., costs attached to premature replacement of long-lived capital stock—decisions made at one point in time can partially or totally lock-in decision makers' subsequent choices (Farrell and Klemperer, 2007). Also, path-dependence can emerge from coordination failures in complex systems that require high degree of articulation between actors (Yarime, 2009). The key message is that it is essential to look broadly for mechanisms that may generate path-dependence when analyzing the determinants of pathways (past or anticipated) (Shalizi and Lecocq, 2013).

Lock-in is the most extreme manifestation of path dependence, when it becomes extremely costly or impossible to shift away from the current pathway. Lock-ins can emerge in many domains, with examples ranging from end-use technology standards (e.g. the competition between the AZERTY and the QWERTY keyboards, or between the VHS and BETAMAX video standards), energy supply networks to expansion pathways of regions once initial choices are made (Fujita et al., 1999). Lock-ins are not 'good' or 'bad' per se (Shalizi and Lecocq, 2013), but identifying risks of 'bad' lock-ins and taking advantage of possible 'good' lock-ins matters for policymaking, so that ex ante decisions are not regretted ex post (Liebowitz and Margolis, 1995). The literature, however, underlines that lock-ins do not stem only from lack of information. There are also many cases in which rational agents might make decisions based only on part of the information available, because of, inter alia, differences between local and global optimum, time and resource constraints on the process or information symmetry (Foray, 1997); which points to the process of decision making (see Section 4.3.2 on Governance and Political Economy).

4.5.2.2 Examples and lessons from the technology transition literature

Part of the literature on innovation (reviewed in Sections 3.11 and 4.3.6; technological change is reviewed in Section 5.6) adopts a broad, systemic perspective to try to explain how new technologies emerge. It thus provides examples of, and insights on how transition between pathways can occur. In fact, changes in technologies, their causes, and their implications for societies have been actively studied in social sciences since the late 18th century by historians, economists, and sociologists. A common starting point is the observation that "technological change is not a haphazard process, but proceeds in certain directions" (Kemp, 1994). For example, processors tend to become faster, planes to become lighter, etc. To characterize these regularities, scholars have developed the concepts of *technological regime* (Nelson and Winter, 2002) and *technological paradigms* (Dosi, 1982; Dosi and Nelson, 1994). Technological regimes refer to shared beliefs among technicians about what is feasible. Technological paradigms refer to the *selected* set of objects engineers are working on, and to the *selected* set of problems they choose to address. How technological regimes may change (such as with the development of information technologies) is a subject of intense research. Radical innovations (e.g., the steam engine) are seen as a necessary condition. But the drivers of radical innovation themselves are not clearly understood. In addition, once an innovation is present, the shift in technological regime is not a straightforward process: the forces that maintain technological regimes (e.g., increasing returns to scale, vested interests, network externalities) are not easy to overcome—all the more so that new technologies are often less efficient, in many respects, than existing ones, and competing technologies may coexist for a while. History thus suggests that the diffusion of new technologies is a slow process (Kemp, 1994; Fouquet, 2010).

More recent research over the past 20 years has yielded two major perspectives on technology transitions (Truffer and Coenen, 2012): the multi-level perspective on socio-technical systems (Geels, 2002) and the concept of technological innovations systems (Bergek et al., 2008). The multi-level perspective distinguishes three levels of analysis: niche innovations, socio-technical regimes, and socio-technical landscape (Geels, 2002). A technological niche is the micro-level where radical innovations emerge. Socio-technical regimes correspond to an extended version of the technological regime discussed above. The socio-technical landscape corresponds to the regulatory, institutional, physical, and behavioural environment within which innovations emerge. There is considerable inertia at this third level. Changes in socio-technical regimes emerge from the interactions between these three levels. According to Geels and Schot's typology (2007), changes in socio-technical regimes can follow four different paths. *Transformation* corresponds to cases in which moderate changes in the landscape occur at a time when niche innovations are not yet developed, thus resulting in a relatively small change of direction of the development pathway. An example of transformation occurred when municipal sewer systems were implemented in Dutch cities (Geels, 2006). *De-alignment* and *realignment* correspond to sudden changes in the landscape that cause actors to lose faith in the regime. If no clear replacement is ready yet, a large range of technologies may compete until one finally dominates and a new equilibrium is reached. One example is the transition from horse-powered vehicles to cars. If new technologies are already available, on the other hand, a *transition substitution* might occur, as in the case of the replacement of sailing ships by steamships between 1850 and 1920. Finally, a *reconfiguration* occurs when innovations initially adopted as part of the current regime progressively subvert it into a new one, an example of which is the transition from traditional factories to mass production in the United States.

The technological innovation systems approach (Bergek et al., 2008) adopts a systemic perspective by considering all relevant actors, their interactions, and the institutions relevant for innovation. Early work in this approach argues that beside market failures, 'system failures' such as, inter alia, actor deficiencies, coordination deficits or conflicts with existing institutional structures (institutional deficits) can explain unsuccessful innovation (Jacobsson and Bergek, 2011). More recent analysis focuses on core processes critical for innovation, such as presence of entrepreneurial activities, learning, knowledge diffusion through networks, etc. The technological innovation systems concept was developed to inform public policy on how to better support technologies deemed sustainable with an increasing focus on 'system innovations' as opposed to innovation in single technologies or products (Truffer and Coenen, 2012).

4.5.2.3 Economic modelling of transitions between pathways

As noted above (4.5.1), economic modelling is a major tool for analyzing future development pathways. Models provide different types of information about transition, depending on their features and on how they are used. The present sub-section reviews the use of models for studying transitions. See Section 6.2 for a review of modelling tools for integrated assessment.

There are four increasingly complex ways of using economic models to analyze transitions between development pathways. The first option—*static modelling*—consists of building plausible images of the future at a given date and comparing them (comparative statics). The focus is on the internal consistency of each image, and on the distance between them. Models without explicit representation of time (e.g., input-output, partial equilibrium, or static general equilibrium models) are sufficient. Static models can provide insights on the sustainable character of the long-term images, to the extent that the model captures critical variables for sustainability such as natural resources use or impact of economic activity on the environment (e.g., GHG emissions). However, national accounts typically add up multiple products with very different material content, very different energy contents, and very different prices. Thus, constructing robust relationships between aggregate monetary indicators and physical flows requires in-depth analysis. Similarly, static models can provide insights on the social components of sustainability to the extent they include some form of representation of the *distribution* of economic activity within the society, notably across income groups (see Section 4.4.1). Again, the associated data challenge is significant. By construction, on the other hand, static models do not provide insights on the pathways from the present on to each possible future, let alone on the transitions between pathways.

Dynamic models are needed to depict the pathway towards desirable (or undesirable) long-term futures. Still, the relevance of dynamic models for discussing transitions depends on their structure, content, and way they are used. A large part of the modelling literature on climate change mitigation relies on neoclassical growth models with exogenous (Swan, 1956; Solow, 1956) or endogenous (Koopmans, 1965; Cass, 1965) savings rate. In those models, long-term growth is ultimately driven by the sum of population growth and exogenous total factor productivity growth (exogenous technical change). In the simplest version of the neoclassical model, there is thus only one 'pathway' to speak of, as determined by human fertility and human ingenuity. Any departure from this pathway resorbs itself endogenously through adjustment of the relative weights of capital and labour in the production function, and through adjustment of the savings rate (when endogenous). Empirically, neoclassical growth models have limited ability to explain observed short-term growth patterns (e.g., Easterly, 2002).

Modelling of *processes* is needed to enrich discussions about transitions by differentiatiating short-term economic processes from long-term processes. The general point is that the technical, economic, and social processes often exhibit more rigidities in the short- than in the long-run. As Solow (2000) suggests, at short-term scales, "something sort of 'Keynesian' is a good approximation, and surely better than anything straight 'neoclassical'. At very long time scales, the interesting questions are best studied in a neoclassical framework and attention to the Keynesian side of things would be a minor distraction". There is a long tradition of debates in economics on the degree to which production technologies and wages should be considered flexible or rigid in the short- and medium-run, with potentially very different results for the assessment of mitigation policies (Rezai et al., 2013), (Guivarch et al., 2011). Other important rigidities include, inter alia, long-lived physical capital, the premature replacement of which is typically very costly, and the dynamics of which have important implications for the costs, timing, and direction of climate policies (e.g. Lecocq et al., 1998; Wing, 1999); rigidities associated with the location of households and firms, changes of which take time; or rigidities associated with preferences of individuals and with institutions. Presence of rigidities may also lead to bifurcations towards different long-term outcome (i.e., equilibrium-dependence and not just path-dependence as in section 4.5.2) (See e.g. Hallegatte et al., 2007).

Recognizing *uncertainty* is a further key element for enriching the analysis of transitions, relaxing the full information hypothesis under which many models are run. If information increases over time, there is a rationale for a sequential decision making framework (Arrow et al., 1996), in which choices made at one point can be re-considered in light of new information. Thus, the issue is no longer to select a pathway once and for all, but to make the best first-step (or short-term) decision, given the structure of uncertainties and the potential for increasing information over time—factors which are especially relevant in the context of climate change. Inertia plays an especially important role in this context, as the more choices made at one point constrain future opportunity sets, the more difficult it becomes to make advantage of new information (e.g.,Ha-Duong et al., 1997). Another way by which uncertainty can be captured in models is to abandon the intertemporal optimization objective altogether and use simulation models instead, with decisions made at any time based on imperfect expectations (Scrieciu et al., 2013). Such shift has major implications for the transition pathway (Sassi et al., 2010), but results strongly depend on how expectations and decisions under uncertainty are represented.

Ideally, models that produce development pathways should thus (1) be framed in a consistent macroeconomic framework (since a pathway is holistic), (2) impose relevant technical constraints in each sector, such as assumptions about the process of technical change, (3) capture the key relationships between economic activity and the environment, e.g., energy and natural resources consumption or greenhouse gases emissions, (4) have a horizon long enough to assess 'sustainability'—a long-term horizon which also implies, incidentally, that the model must be able to represent structural and technical change—yet (5) recognize short-term economic processes critical for assessing transition pathways, such as market imbalance and rigidities, all this while (6) providing an explicit representation of how economic activity is distributed within the society, and how this retrofits into the growth pattern, and (7) representing key uncertainties.

No model today meets all these specifications. Current models can be classified along two major fault lines: bottom-up vs. top-down, and long-term vs. short-term. By design, computable general equilibrium (CGE) models provide a comprehensive macroeconomic framework, and they can be harnessed to analyze distributional issues, at least amongst income groups, but they typically fail to incorporate key technical constraints. Conversely, bottom-up engineering models provide a detailed account of technical potentials and limitations, but their macro-engine, if at all, is most often rudimentary. Emerging 'hybrid' models developed in the context of climate policy assessment are steps towards closing this gap (Hourcade et al., 2006). A similar rift occurs with regard to time horizon. Growth models like Solow's are designed to capture key features of long-term development pathways, but they do not include short- or medium-term economic processes such as market rigidities. On the other hand, short-term models (econometric or structural) will meet this requirement but are not designed to look deep in the future. Again, emerging models include short-/medium-term processes into analysis of growth in the long-run (see e.g., Barker and Serban Scrieciu, 2010), but this pretty much remains an open research field.

4.6 Mitigative capacity and mitigation, and links to adaptive capacity and adaptation

4.6.1 Mitigation and adaptation measures, capacities, and development pathways

Even though adaptation and mitigation are generally approached as distinct domains of scientific research and practice (Biesbroek et al., 2009) (as reflected, for example, in the IPCC separate Working Groups II and III), a recognition of the deep linkages between mitigation and adaptation has gradually emerged. Initially, mitigation and adaptation were analyzed primarily in terms of techno-economic considerations. But growing attention has been directed at the underlying capacities, first with respect to adaptation, and later -and less fully- with respect

Box 4.4 | Characterizing the sustainability of development pathways

Constructing and modelling forward-looking development pathways is one thing, evaluating how they fare in terms of sustainability within and beyond the time horizon of the modelling is another. Two questions can actually be distinguished (Asheim, 2007). One is to predict whether the current situation (welfare, environment) will be preserved in the future: are we on a sustained development pathway, i.e., a pathway without downturn in welfare or environmental objectives? This question is answered by looking at the evolution of the target variables within the time horizon of the scenario, and what happens beyond the horizon remains undetermined. Another question is to determine whether the current generation's decisions leave it possible for future generations to achieve a sustained pathway: is a sustained development pathway possible given what the current generation does? Unlike the former question, the latter does not require predicting the future generations' decisions, only their future constraints and opportunities. Showing the existence of a sustained pathway is then an argument in favour of the compatibility of current decisions with future sustainability. Some indicators of sustainability such as genuine savings (see Box 4.2) are meant to provide an answer based on the current evolution of (economic, social, environmental) capital stocks and can also be used for the evaluation of scenarios that depict these stocks. In practice, sustainability analysis (of either type) is not frequent in the scenario-building community, though multi-criteria analysis of scenarios has been gaining ground in recent years (see e.g.,GEA, 2012).

to mitigation, (Grothmann and Patt, 2005; Burch and Robinson, 2007; Winkler et al., 2007; Goklany, 2007; Pelling, 2010).

This attention has necessitated a broadening of the scope of analysis well beyond narrow techno-economic considerations, to the social, political, economic, and cultural domains, as ultimately, this is where the underlying determinants of mitigative and adaptive capacity lie. Following the literature enumerated above, a non-exhaustive list of these underlying determinants include: the level and distribution of wealth, robustness and legitimacy of institutions, availability of credible information, existence and reliability of infrastructure, access to and adequacy of technologies and systems of innovation, effective governance, social cohesion and security, distribution of decision-making power among actors, conditions of equity and empowerment among citizens, and the opportunity costs of action, as well as individual cognitive factors, including relevant skills, knowledge and cultural framings. The fact that mitigative and adaptive capacities share and are similarly affected by these underlying determinants highlights their similarity, blurring the distinction between them and leading some scholars to argue that there is simply 'response capacity' (Tompkins and Adger, 2005; Wilbanks, 2005; Burch and Robinson, 2007). Because response capacity is directly shaped by these underlying technological, economic, institutional, socio-cultural, and political determinants, it is in other words directly shaped by the overall development pathway, which is the combined product of those same inter-related determinants. This dependence of response capacity on development pathway is underscored by the strong parallel between its determinants (outlined above) and the defining dimensions of a development pathway (discussed in Sections 4.3 and 4.5). Indeed, response capacity is determined much more by the overall development pathway than by targeted climate-specific policies. The academic consensus on this point has been clearly reflected in the AR4 (IPCC, 2007), in WGI Chapter 12 in the case of mitigative capacity, and WGII Chapter 18 in the case of adaptive capacity. Of course, more nuanced and site-specific assessments of the determinants of such capacity can provide further useful insight (see e.g., Keskitalo et al, 2011).

Moreover, there is consensus that an effective transition toward a SD pathway in particular can more effectively foster response capacity (IPCC, 2007; Matthew and Hammill, 2009; Parry, 2009; Halsnaes et al., 2011; Harry and Morad, 2013). There are various elements of fostering a transition toward SD that naturally accord with the creation of mitigative and adaptive capacity, including, for example, the establishment of innovation systems that are supportive of environmental and social priorities, the support for adaptive ecosystem management and conservation, the strengthening of institutions and assets to support food and water security and public health, and the support for procedurally equitable systems of governance (Banuri, 2009; Barbier, 2011; Bowen et al., 2011; Bowen and Friel, 2012). Mitigation and adaptation outcomes can of course still be expected to depend on the extent to which explicit efforts are taken to implement and mainstream climate change policies and measures, as well as on the manner in which a particular SD approach may evolve—with more or less emphasis on economic, social, or environmental objectives (Giddings et al., 2002; Beg et al., 2002; Grist, 2008; Halsnæs et al., 2008).

The centrality of mitigative and adaptive capacity to SD is highlighted by the growing attention to the idea that the Earth system has moved from the Holocene into the Anthropocene (Steffen et al., 2011), where societies are the most important drivers of the Earth's dynamics. Mitigative and adaptive capacity can be seen in general terms, i.e., not just with respect to GHG emissions and climate impacts, but all anthropogenic environmental pressures and impacts from ecosystem degradation. In this view, mitigative and adaptive capacity are central to sustainable ecosystem management (Holling, 1978; Walters and Holling, 1990; McFadden et al., 2011; Williams, 2011), and thus fundamental to SD (Chapin et al., 2010; Folke et al., 2011b; Polasky et al., 2011; Biermann et al., 2012). Some scholars interpret this as a fundamental redefinition of development calling for transformational shifts based on re-imagining possibilities for future development pathways (Pelling, 2010; Jackson, 2011a; Kates et al., 2012; Ehrlich et al., 2012).

Scholarship exploring the links between mitigation, adaptation, socio-ecological resilience and SD more generally, has generally pointed toward the existence of (potential) synergies and tradeoffs within and across policy sectors and across implementation measures (Gallopín, 2006; Rosenzweig and Tubiello, 2007; Vogel et al., 2007; Boyd et al., 2009; Thornton and Gerber, 2010; Adger et al., 2011; Warren, 2011; Lal et al., 2011; Vermeulen et al., 2012; Denton and Wilbanks, 2014; Hill, 2013). These studies show that, in spite of mitigative and adaptive *capacities* being so closely intertwined with each other and with SD, the relationship between mitigation and adaptation *measures* is more ambiguous and, in line with the AR4, suggest that outcomes are highly dependent on the measures and the context in which they are undertaken, with some policy sectors being more conducive to synergies than others.

In the agricultural sector, for example, scholars have for many years highlighted the potential of fostering both mitigation and adaptation by supporting traditional and biodiverse agro-ecological systems around the world (Campbell, 2011; Altieri and Nicholls, 2013, and see Section 11.5). A recent modelling exercise suggests that investing substantially in adapting agriculture to climate change in some regions—Asia and North America—can result in substantial mitigation co-benefits, while the latter may be insignificant in Africa (Lobell et al., 2013). There are empirical studies where interventions in agricultural systems have led to positive mitigation and adaptation outcomes—or vice versa—(Kenny, 2011; Wollenberg, 2012; Bryan et al., 2012), or where synergies between adaptation and mitigation have not materialized due to, for example, limited scientific and policy knowledge, as well as institutional and farmers' own financial and cognitive constraints (Haden et al., 2012; Arbuckle Jr. et al., 2013; Bryan et al., 2013). In forestry, the links between fostering mitigation strategies, e.g., through planting trees, developing agro-forestry systems or conserving diverse ecosystems, and the adaptation of both forests and people to climate change have been widely acknowledged and the possibility of effective linkages in policy and action have also been identified (Locatelli et al., 2011; Schoeneberger et al., 2012; Mori et al., 2013). Methods for identifying tradeoffs between mitigation and adaptation at policy and implementation levels and to foster legitimate decision making have also been recently developed (Laukkonen et al., 2009; Janetos et al., 2012).

This evolving literature highlights the need to examine adaptation and mitigation for their SD implications, and ultimately to mainstream them in broader development policy. It also explains the parallel emergence of environmental governance research about reforming existing or developing institutions in different policy domains to meet this need (Folke et al., 2005; Folke, 2007; Brunner and Lynch, 2010). Recent studies highlight the organizational, institutional, financial, and knowledge barriers to the development of effective governance for mitigation and adaptation in general government policy (Picketts et al., 2012), as well as in particular policy sectors, e.g., in forestry (Johnston and Hesseln, 2012); in health (Bowen et al., 2013); or in urban planning (Barton, 2013). Others identify the multi-scale, inter-connected, and dynamic nature of many climate issues and their associated responses as a key barrier to action, particularly at local level (Romero-Lankao, 2012). Analyses of the effectiveness of public-private partnerships and other forms of multi-actor cooperation to mainstream both mitigation and adaptation measures in a given sector and context also reveal the challenging nature of such endeavour (Pattberg, 2010; Pinkse and Kolk, 2012).

There is ample scope to improve response capacity in nations and communities by putting SD at the core of development priorities, despite the considerable governance challenges to mainstreaming mitigation and adaptation measures across policy sectors, collective and individual behaviour, and to exploit possible synergies and confront tradeoffs. Nonetheless, it remains the case that the variation of mitigative and adaptive capacity between different nations—and communities within them—is a function of the vast disparities in the determinants of such capacity. These differences in capacity are in turn driven to a significant degree by differences in development pathways and, specifically, level of development. This is a primary reason why the issue of burden sharing among nations features so prominently in consideration of international cooperation on climate change generally, and the UNFCCC in particular, as discussed further in the following section.

4.6.2 Equity and burden sharing in the context of international cooperation on climate

Chapter 3 (Sections 3.2 to 3.5) introduced the general equity principles in the philosophical literature and their relevance to climate change including burden sharing. This section briefly reviews the extensive literature regarding burden sharing in a global climate regime. If focuses first on the equity principles as they are invoked in the literature, which emphasises those laid out in the UNFCCC. It then reviews several categories of burden sharing frameworks. While the academic literature uses the term 'burden sharing', it is understood that mitigation action entails not only burdens but also benefits.

4.6.2.1 Equity principles pertinent to burden sharing in an international climate regime

The UNFCCC clearly invokes the vision of equitable burden sharing among Parties toward achieving the Convention's objective. While Parties had not articulated a specific burden sharing arrangement in quantified detail, they had established an initial allocation of obligations among countries with explicit references to the need for equitable contributions. All Parties adopted general commitments to mitigate, adapt, and undertake other climate-related actions, but distinct categories of countries reflecting level of development were identified and assigned specific obligations. Developed countries (listed in Annex I) were distinguished from developing countries and obliged to "take the lead on combating climate change and the adverse effects thereof" (Article 3.1), noting "the need for equitable and appropriate contributions by each of these Parties to the global effort regarding [the UNFCCC] objective" (Article 4.2(a)). A subset of Annex I countries consisting of the wealthier developed countries (listed in Annex II) were further obliged to provide financial and technological support "to developing countries to enable them to effectively implement their UNFCCC commitments" (Article 4.7), noting that they "shall take into account … the importance of appropriate burden sharing among the developed country Parties".

While Parties' equitable contributions are elaborated further in subsequent UNFCCC decisions and under the Durban Platform for Enhanced Action, an explicit arrangement for equitable burden sharing remains unspecified. Because there is no absolute standard of equity, countries (like people) will tend to advocate interpretations which tend to favour their (often short term) interests (Heyward, 2007; Lange et al., 2010; Kals and Maes, 2011). It is thus tempting to say that no reasoned resolution is possible and to advocate a purely procedural resolution (Müller, 1999). However, there is a basic set of shared ethical premises and precedents that apply to the climate problem, and impartial reasoning (as behind a Rawlsian (Rawls, 2000) "veil of ignorance") can help put bounds on the plausible interpretations of equity in the burden sharing context. Even in the absence of a formal, globally agreed burden sharing framework, such principles are important in establishing expectations of what may be reasonably required of different actors. They influence the nature of the public discourse, the concessions individuals are willing to grant, the demands citizens are inclined to impose on their own governments, and the terms in which governments represent their negotiating positions both to other countries and to their own citizens. From the perspective of an international climate regime, many analysts have considered principles for equitable burden sharing, (Rose 1990; Hayes and Smith 1993; Baer et al. 2000; B. Metz et al. 2002; Ringius, Torvanger, and Underdal 2002; Aldy, Barrett, and Stavins 2003;

Ghersi, Hourcade, and Criqui 2003; Gardiner 2004; Caney 2005; Caney 2009; Caney 2010; Heyward 2007; E.A. Page 2008; Vanderheiden 2008; Klinsky and Dowlatabadi 2009; Winkler et al. 2011). Equitable burden sharing has been most frequently applied to costs of mitigation, though similar issues arise with regard to adaptation (Baer, 2006; Paavola and Adger, 2006; Adger, 2006; Jagers and Duus-Otterstrom, 2008; Dellink et al., 2009; Grasso, 2010; Hartzell-Nichols, 2011). Here these equity principles are given along four key dimensions—responsibility, capacity, equality, and the right to sustainable development, expanding on the philosophical arguments in Sections 3.2–3.4.

Responsibility

In the climate context, responsibility is widely taken as a fundamental principle relating responsibility for contributing to climate change (via emissions of GHGs) to the responsibility for solving the problem. The literature extensively discusses it, distinguishing moral responsibility from causal responsibility, and considering the moral significance of knowledge of harmful effects (Neumayer, 2000; Caney, 2005; Müller et al., 2009). Common sense ethics (and legal practice) hold persons responsible for harms or risks they knowingly impose or could have reasonably foreseen, and, in certain cases, regardless of whether they could have been foreseen. The notion of responsibility is thus closely connected to the Polluter Pays Principle (PPP), and burden sharing principles that derive from it hold that countries should be accountable for their greenhouse gas emissions. This is a common interpretation of the UNFCCC phrase "common but differentiated responsibilities" (Harris, 1999; Rajamani, 2000), given its similarity to the more explicit Rio Declaration (see Section 4.1).

Responsibility is taken by some to include present and past emissions (Grübler and Fujii, 1991; Smith, 1991; Neumayer, 2000; Rive et al., 2006; Wei et al., 2012). This has been justified on three main grounds. First, climate change results from the stock of accumulated historic emissions. Second, the total amount of greenhouse gases that can be emitted to the atmosphere must be constrained (to a level determined by society's choice of global climate stabilization goal (see WGI AR5), and thus constitutes a finite common resource (often loosely referred to as the 'atmospheric space' or the 'carbon budget'). Users of this resource—whether current or historical—should be accountable for depleting the resource and precluding the access of others. Third, historical emissions reflect the use of a resource from which benefits have been derived, i.e., wealth, fixed capital, infrastructure, and other assets. These benefits constitute a legacy based in part on consuming a common resource that (1) should be paid for, and (2) provides a basis for mitigative capacity (Shue, 1999; Caney, 2006, 2010). The latter argument carries the notion of responsibility further back in time, assigning responsibility for the emissions of previous generations, to the extent that present generations have inherited benefits. This argument links responsibility with the capacity principle discussed below (Meyer and Roser, 2010; Gardiner, 2011a; Meyer, 2012). If conventional development continues, the relative responsibility of some nations that currently have relatively low cumulative emissions would match and exceed by mid-century the relative responsibility of some nations who currently have high responsibility (Höhne and Blok, 2005; Botzen et al., 2008), on an aggregate—if not per capita—basis. Such projections illustrate that the relative distribution of responsibility among countries can vary substantially over time, and that a burden sharing framework must dynamically reflect evolving realities if they are to faithfully reflect ethical principles. They also may provide a basis for understanding *where* mitigation might productively be undertaken, though not necessarily *who* should be obliged to bear the costs.

Each nation's responsibility for emissions is typically defined (as in IPCC inventory methodologies) in terms of emissions within the nation's territorial boundary. An alternative interpretation (Fermann, 1994), which has become more salient as international trade has grown more important, is to include emissions embodied in internationally traded goods consumed by a given nation. Recent studies (Lenzen et al., 2007; Pan et al., 2008; Peters et al., 2011) have provided a quantitative basis for better understanding the implications of a consumption-based approach to assessing responsibility. In general, at the aggregate level, developed countries are net importers of emissions, and developing countries are net exporters (see Sections 5.3.3.2 and 14.3.4). The relevance of this to burden sharing may depend on further factors, such as the distribution between the exporting and importing countries of the benefits of carbon-intensive production, and the presence of other climate policies such as border carbon tariffs (see Section 13.8.1 and 14.4.1), as well as the development of the relevant data sources (see also Sections 3.9 and 4.4). Many analysts have suggested that all emissions are not equivalent in how they translate to responsibility, distinguishing the categories of 'survival emissions', 'development emissions', and 'luxury' emissions (Agarwal and Narain, 1991; Shue, 1993; Baer et al., 2009; Rao and Baer, 2012).

Determining responsibility for emissions in order to allocate responsibility raises methodological questions. In addition to the standard questions about data availability and reliability, there are also equity-related questions. For instance, there are various rationales for determining how far in the past to include historical emissions. One rationale is that the 1990s should be the earliest date, reflecting the timing of the FAR and the creation of a global regime that imposed obligations to curb emissions (Posner and Sunstein, 2007). Some argue that the date should be earlier, corresponding to the time that climate change became reasonably suspected of being a problem, and greenhouse gas emissions thus identifiable as a pollutant worthy of policy action. For example, one might argue for the 1970s or 1960s, based on the published warnings issued by scientific advisory panels to the United States presidents Johnson (U.S. National Research Council Committee on Atmospheric Sciences, 1966) and Carter (MacDonald et al., 1979), and the first G7 Summit Declaration highlighting climate change as a problem and seeking to prevent further increases of carbon dioxide in the atmosphere (Group of 7 Heads of State, 1979). Others argue that a still earlier date is appropriate because the damage is still caused, the stock depleted, and the benefits derived, regardless of whether there is a legal requirement or knowledge.

Another issue is the question of accounting for the residence time of emissions into the atmosphere, as an alternative to simply considering cumulative emissions over time. In the case of carbon dioxide, responsibility could include past emissions even when they are no longer resident in the atmosphere, on the grounds that those emissions (1) have contributed to the warming and climate damages experienced so far, and upon which further warming and damages will be additive, and (2) have been removed from the atmosphere predominantly to the oceans, where they are now causing ocean acidification, which is itself an environmental problem (See WGI AR5, Chapters 3 and 6).

Capacity (or, Ability to Pay)

A second principle for allocating effort arises from the capacity to contribute to solving the climate problem (Shue, 1999; Caney, 2010). Generally, capacity is interpreted to mean that the more one can afford to contribute, the more one should, just as societies tend to distribute the costs of preserving or generating societal public goods; i. e., most societies have progressive income taxation. This view can be applied at the level of countries, or at a lower level, recognizing inequalities between individuals. Smith et al. (1993) suggested GDP as an income-based measure of ability-to-pay, subject to a threshold value, determined by an indicator of quality of life. This was developed in Kartha et al. (2009) and Baer et al. (2010), taking into account intra-national disparities.

As discussed in Section 4.6.1, response capacity refers to more than just financial wherewithal, encompassing also other characteristics that affect a nation's ability to contribute to solving the climate problem. It recognizes that effective responses require not only financial resources, but also technological, institutional, and human capacity. This issue has been treated by Winkler, Letete, and Marquard (2011) by considering the Human Development Index as a complement to income in considering capacity. Capacity, even in this broader sense, can be distinguished from mitigation potential, which refers to the presence of techno-economic opportunities for reducing emissions due to, for example, having renewable energy resources that can be exploited, a legacy of high-carbon infrastructure that can be replaced, or a rapidly growing capital stock that can be built based on low-carbon investments. Mitigation potential is a useful characteristic for determining where emissions reductions can be located geographically for reasons of cost-effectiveness, but this can be distinguished from burden sharing *per se*, in the sense of determining on normative grounds which country should pay for those reductions. This distinction is reflected in the economist's notion that economic efficiency can be decoupled from equity (Coase, 1960; Manne and Stephan, 2005).

Equality

Equality means many things, but a common understanding in international law is that each human being has equal moral worth and thus should have equal rights. Some argue this applies to access to common global resources, expressed in the perspective that each person should have an equal right to emit (Grubb, 1989; Agarwal and Narain, 1991). This equal right is applied by some analysts to current and future flows, and by some to the cumulative stock as well. (See further below.)

Some analysts (Caney, 2009) have noted, however, that a commitment to equality does not necessarily translate into an equal right to emit. Egalitarians generally call for equality of a total package of 'resources' (or 'capabilities' or 'opportunities for welfare') and thus may support inequalities in one good to compensate for inequalities in other goods (Starkey, 2011). For example, one might argue that poor people who are disadvantaged with respect to access to resources such as food or drinking water may be entitled to a greater than per capita share of emissions rights. Second, some individuals may have greater needs than others. For example, poorer people may have less access to alternatives to fossil fuels (or unsustainably harvested wood fuel) because of higher cost or less available technologies, and thus be entitled to a larger share of emission rights.

Others have suggested that equality can be interpreted as requiring equal sacrifices, either by all parties, or by parties who are equal along some relevant dimension. Then, to the extent that parties are not equal, more responsibility (Gonzalez Miguez and Santhiago de Oliveira, 2011) or capacity (Jacoby et al., 2009) would imply more obligation, all else being equal.

Right to development

The right to development appears in international law in the UN Declaration on the Right to Development, the Rio Declaration, and the Vienna Declaration, and is closely related to the notion of *need* as an equity principle, in that it posits that the interests of poor people and poor countries in meeting basic needs are a global priority (Andreassen and Marks, 2007). The UNFCCC acknowledges a right to promote sustainable development, and "the legitimate priority needs of developing countries for the achievement of sustained economic growth and the eradication of poverty" (UNFCCC, 2002) and recognizes that "economic and social development and poverty eradication are the first and overriding priorities of the developing country Parties" (p. 3).

In the context of equitable burden sharing, a minimalist interpretation of a right to development is a right to an exemption from obligations for poor Parties (Ringius et al., 2002) on the basis that meeting basic needs has clear moral precedence over the need to solve the climate problem, or, at the very least, it should not be hindered by measures taken to address climate change.

4.6.2.2 Frameworks for equitable burden sharing

There are various ways of interpreting the above equity principles and applying them to the design of burden sharing frameworks. It is helpful to categorize them into two broad classes. 'Resource-sharing' frameworks are aimed at applying ethical principles to establish a basis for sharing the agreed global 'carbon budget'. 'Effort-sharing' frameworks are aimed at sharing the costs of the global climate response. The resource-sharing frame is the natural point of departure if climate change is posed as a tragedy of the commons type of collective action problem; if it is posed as a free-rider type of collective action problem, the effort-sharing perspective is more natural. Neither of these framings is objectively the 'correct' one, just as neither collective action framing of the climate change problem is correct. Both can inform policymakers' judgments in different ways. Indeed, the two approaches are complementary: any given resource-sharing framework implies a particular distribution of the effort, and conversely the opposite is true. In either case, burden sharing frameworks are typically formulated as emission entitlements to be used in trading system or global climate fund, which enables a cost-effective distribution of the actual mitigation efforts. Through such mechanisms, countries with obligations greater than their domestic mitigation potential can fund reductions in countries with obligations that are less than their domestic mitigation potential (see Sections 6.3.6 and 13.4.3).

One important dimension along which both resource-sharing and effort-sharing proposals can be compared is the number of categories into which countries are grouped. The UNFCCC in fact had three categories—Annex I, Annex II (the OECD countries within Annex I), and non-Annex I. Many of the proposals discussed below reproduce these distinctions. Others increase the number of 'bins', to as many as six (Winkler et al., 2006). Finally, many others eliminate any qualitative categories, instead allocating emissions rights or obligations on the basis of a continuous index.

Resource sharing approaches

The resource-sharing approach starts by acknowledging that the global 'carbon budget' is bounded, with its size defined by the agreed climate stabilization target. The most straightforward resource-sharing approach is an equal per capita approach (Grubb, 1990; Agarwal and Narain, 1991; Jamieson, 2001), which is premised on the equal rights to the atmospheric commons to all individuals, and allocates emission allowances to each country in proportion to its population. In response to the concern that an equal per capita allocation would provide an incentive for more rapid population growth, some analysts have argued that the effect would be negligible in comparison to other factors affecting population, and others have proposed solutions such as holding population constant as of some agreed date (Jamieson, 2001), establishing standardized growth expectations (Cline, 1992), or allocating emission in proportion only to adult population (Grubb, 1990).

In response to the concern that unrealistically rapid reductions would be required in those countries whose current emissions are far above the global average, some have proposed a period of transition from grandfathered emission rights (i.e., allocated in proportion to current emissions) to equal per capita emission rights (Grubb and Sebenius, 1992; Welsch, 1993; Meyer, 2004). This rationale applies specifically to a framework intended to determine actual emission pathways, in which case an immediate per capita distribution would impose unrealistically abrupt changes from present emission levels. For a framework intended to assign transferable rights to emit, rather than actual emissions, the rationale is questionable: the opportunity to acquire additional allocations through emissions trading or some other transfer system would allow a cost-effective transition and lessen, though not eliminate, the political challenges of an immediate equal per capita allocation.

A variant on the above that aims to address the concern that many developing countries would have to reduce their emissions from already very low levels is "Common but Differentiated Convergence" (Höhne et al., 2006), under which a developing country is required to begin converging only once its per capita emissions exceed a specified (and progressively declining) threshold. Chakravarty et al. (2009) put forward a variant that looked beyond average national indicators of emissions by examining the distribution of emissions across individuals at different income levels within countries.

Extending the concept of equal per capita rights to include both the historical and future carbon budget gives the "equal cumulative per capita emission rights" family of frameworks (Bode, 2004; den Elzen et al., 2005; German Advisory Council on Global Change, 2009; Oberheitmann, 2010; Höhne et al., 2011; CASS/DRC Joint Project Team, 2011; Jayaraman et al., 2011; Pan et al., 2013). These frameworks vary, for example, in their choice of the initial date for historical emissions, the way they deal with growing populations, their treatment of luxury versus survival emissions, and their way of distributing a budget over time. As some countries (which tend to be higher income countries that industrialized earlier) have consumed more than their equal per capita share of the historical global budget, this excess use is offered as an argument for obliging them to provide financial and technological resources to other countries that have used less than their historical share. This obligation has been linked to the notion of a 'carbon debt' or 'climate debt' (Pickering and Barry, 2012), and framed as a subset of a larger 'ecological debt' (Roberts and Parks, 2009; Goeminne and Paredis, 2010), which some analyses have attempted to quantify (Smith, 1991; Srinivasan et al., 2008; Cranston et al., 2010).

Effort sharing approaches

'Effort sharing' frameworks seek to fairly divide the costs of reducing emissions to an agreed level. (Effort sharing approaches can also be applied to adaptation costs whereas resource sharing approaches cannot.) Many of the philosophers engaged with the question of burden sharing in the climate regime have argued that obligations should be proportional in some fashion to responsibility and capacity (see, for example the analyses of Shue, 1993; or Caney, 2005).

An early effort-sharing approach was the Brazilian proposal using historic responsibility for emissions and thus global temperature rise as a basis for setting Kyoto targets. This approach has been quantitatively analyzed (Höhne and Blok, 2005) and recently discussed in the global political context (Gonzalez Miguez and Santhiago de Oliveira, 2011). Other approaches have used capacity based on indicators such as GDP per capita (Wada et al., 2012) as a basis for effort-sharing, or have combined capacity and responsibility (Winkler et al., 2006). Some have included minimal form of a right to development by identifying a threshold of development below which income and emissions are not included in a nation's capacity or responsibility (Cao, 2008; Kartha et al., 2009; Yue and Wang, 2012).

The quantitative implications of a number of burden sharing frameworks are presented for several regions in Section 6.3.6.6. The frameworks are grouped into six categories, corresponding either to one of the underlying burden sharing principles (responsibility, capability, equality, right to development), or a combination of them. It is important to note that several of the approaches are based on considerations other than equity principles. For example, several allocate allowances based on grandfathered emissions levels, with a transition to an equity-based allocation only over several decades or in some cases with no such transition. Others allocate allowances in proportion to GDP, while others include mitigation potential as one basis in addition to equity principles.

4.7 Integration of framing issues in the context of sustainable development

Chapters 2 and 3 of this report review the framing issues related to risk and uncertainty (Chapter 2) and social, economic, and ethical considerations guiding policy (Chapter 3). They examine how these issues bear on climate policy, both on the mitigation and on the adaptation side of our response to the challenge of climate change. Their general analysis is also directly relevant to the understanding of SD and equity goals. This section briefly examines how the concepts reviewed in these chapters shed light on the topic of the present chapter.

4.7.1 Risk and uncertainty in sustainability evaluation

The sustainability ideal seeks to minimize risks that compromise future human development (Sections 4.2 and 4.5). This objective is less ambitious than maximizing an expected value of social welfare over the whole future. It focuses on avoiding setbacks on development, and is therefore well in line with Chapter 2 (Section 2.5.1) highlighting the difficulty of applying the standard decision model based on expected utility in the context of climate policy. It is directly akin to the methods of risk management listed there (Sections 2.5.2–2.5.7), in particular those focusing on worst-case scenarios. The literature on adaptation has similarly emphasized the concept of resilience, which is the ability of a system to preserve its functions in a risky and changing environment (WGII Section 2.5 and Sections 20.2–20.6; Folke et al., 2010; Gallopin, 2006).

This chapter has reviewed the actors and determinants of support for policies addressing the climate challenge (Sections 4.3 and 4.6). Among the relevant considerations, one must include how risk perceptions shape the actors' understanding of threats to sustainability and willingness to take action. Chapter 2 (Section 2.4) has described how framing and affective associations can be effective and manipulative, how absence or presence of a direct experience of climate extremes makes individuals distort probabilities, and how gradual changes are easy to underestimate.

Risk and uncertainty are also relevant to the dimension of equity, in relation to sustainability, because various regions of the world and communities within those regions experience unequal degrees of climate risk and uncertainty. Better information about the distribution of risks between regions and countries would affect the policy response and negotiations. Lecocq and Shalizi (2007) argue that the absence of information about the location and extent of impacts raises incentives for mitigation, and Lecocq and Hourcade (2012) show that the optimal level of mitigation may also increase.

Incorporating risk in the evaluation of sustainability of a development pathway is challenging and has been analyzed in a small literature. In particular, Baumgärtner and Quaas (2009) and Martinet (2011) propose to define thresholds for well-being or for various natural or man-made stocks and to assess sustainability by the probability that thresholds will be crossed in the foreseeable future. However, a decision maker may not find it sufficient to check that the risk of unsustainability is below a given threshold, and may also want to know the likelihood of the bad scenarios and the harm incurred by the population in these scenarios.

4.7.2 Socio-economic evaluation

Chapter 3 has reviewed the principles of social and economic evaluation and equity in a general way. In 3.6.1 it recalls that there is now a consensus that methods of cost-benefit analysis that simply add up monetary-equivalent gains and losses are consistent and applicable only under very specific assumptions (constant marginal utility of income and absence of priority for the worse off) which are empirically dubious and ethically controversial. It is thus necessary to introduce weights in such summations (see Equation 3.6.2) that embody suitable ethical concerns and restore consistency of the evaluation. Adler (2011) makes a detailed argument in favour of this 'social welfare function' approach to cost-benefit analysis. This approach is followed by Anthoff et al. (2009), refining previous use of equity weights by Fankhauser et al. (1997) and Tol (1999). An advantage of a well-specified methodology for the choice of equity weights is the ability to reach more precise conclusions than when all possible weights are spanned. It also makes it possible to transparently relate conclusions to ethical assumptions such as the degree of priority to the worse off.

Chapter 3 (Section 3.4) describes the general concepts of social welfare and individual well-being. In applications to the assessment of development paths and sustainability, empirical measures are needed.

Several methods are discussed in Stiglitz et al. (2009) and Adler (2011). In particular, the capability approach (Sen, 2001, 2009) is well known for its broad measure of well-being that synthesizes multiple dimensions of human life and incorporates considerations of autonomy and freedom. Most applications of it do not directly rely on individual preferences (Alkire, 2010). Fleurbaey and Blanchet (2013) defend an approach that relies on individual preferences, in a similar fashion as money-metric utilities. Some authors (e.g., Layard et al., 2008) even propose to use satisfaction levels obtained from happiness surveys directly as utility numbers. This is controversial because different individuals use different standards when they answer questions about their satisfaction with life (Graham, 2009).

One reason why well-being may be useful as a guiding principle in the assessment of sustainability, as opposed to a more piecemeal analysis of each pillar, is that it helps evaluate the weak versus strong sustainability distinction. As explained in Section 4.2, weak sustainability assumes that produced capital can replace natural capital, whereas strong sustainability requires natural capital to be preserved. From the standpoint of well-being, the possibility to substitute produced capital for natural capital depends on the consequences on living beings. If the well-being of humans depends directly on natural capital, if there is option value in preserving natural capital because it may have useful properties that have yet to be discovered, or if non-human living beings depend on natural capital for their flourishing, this gives powerful reasons to support a form of strong sustainability.

Additionally, Chapter 3 (in particular Sections 3.3 and 3.5) mentions other aspects of equity that are relevant to policy debates and international negotiations on climate responses. Chapter 3 discusses these issues at the level of ethical principles, and given the importance of such issues in policy debates about mitigation efforts, Section 4.6 develops how these principles have been applied to the issue of burden sharing in climate regime.

4.8 Implications for subsequent chapters

The primary implication of this chapter as a framing for subsequent chapters is to underscore the importance of explicitly scrutinizing the candidate mitigation technologies, measures, and policies for their broader equity and sustainability implications. Indeed, the relevant stakeholders and decision makers have various priorities, in particular regarding economic and human development, which may align or conflict with prospective climate actions. Equitable and sustainable development provides a broader overarching framework within which to examine climate strategies as one of the multiple interacting challenges confronting society. Ultimately, it is a framework within which society can consider the fundamental question of its development pathway.

4.8.1 Three levels of analysis of sustainability consequences of climate policy options

Various definitions and indicators of SD have been introduced in this chapter (in particular in Section 4.2, 4.5). This subsection offers a simple taxonomy of approaches for the assessment of sustainability.

Long-term evolution of the three pillars. The outcomes of climate policy options can generally be observed in the three spheres related to the three pillars of SD: the economic, the social, and the environmental sphere. Sustainability in the economy refers to the preservation of standards of living and the convergence of developing economies toward the level of developed countries. Sustainability in the social sphere refers to fostering the quality of social relations and reducing causes of conflicts and instability, such as excessive inequalities and poverty, lack of access to basic resources and facilities, and discriminations. Sustainability in the environmental sphere refers to the conservation of biodiversity, habitat, natural resources, and to the minimization of ecosystem impacts more generally.

Long-term evolution of well-being. The way the three spheres (and pillars) flourish can be viewed as contributing to sustaining well-being for humans as well as for other living creatures. Human well-being depends on economic, social, and natural goods, and the other living beings depend on the quality of the ecological system. It may therefore be convenient to summarize the multiple relevant considerations by saying that the ultimate end result, for sustainability assessment, is the well-being of all living beings. Measuring well-being is considered difficult for humans because there are controversies about how best to depict individual well-being, and about how to aggregate over the whole population. However, as explained in Sections 3.4 and 4.7, many of the difficulties have been exaggerated in the literature, and practical methodologies have been developed. Truly enough, it still remains difficult to assess the well-being of all living beings, humans and non-humans together.

But, even if current methodologies fall short of operationalizing comprehensive measures of well-being of that sort, it is useful for experts who study particular sectors to bear in mind that a narrow notion of living standards for humans does not cover all the aspects of well-being for the purposes of assessing sustainability. It is also useful to try to assess how various interactions between the three spheres can impact on well-being. When there are tradeoffs between different aspects of the economic, social, and ecological dimensions, one has to make an assessment of their relative priorities. Well-being is the overarching notion that helps thinking about such issues.

Current evolution of capacities. Sustainability can also be assessed in terms of capital or capacities, as suggested by some indicators such as genuine savings (Section 4.2). Preserving the resources transmitted to the future generation is a key step in guaranteeing a sustainable path. Again, it is useful to think of the capacities underlying the functioning of the three spheres: economic, social, environmental. The economic sphere needs various forms of productive capital and raw materials, infrastructures, and a propitious environment, but also human capital, institutions, governance, and knowledge. The social sphere needs various forms of institutions and resources for sharing goods and connecting people, which involve certain patterns of distribution of economic resources, transmission of knowledge, and forms of interaction, coordination, and cooperation. The ecological sphere needs to keep the bases of its health, including habitat, climate, and biological integrity. In general, climate policy options can affect capacities in all of these spheres, to varying degrees.

4.8.2 Sustainability and equity issues in subsequent chapters

As discussed in this chapter (Sections 4.2 and 4.5), sustainability is a property of a development pathway as a whole. And some of the literature reviewed in the subsequent chapters (6–16) actually discusses development pathways and the sustainability thereof. In addition, Chapters 6–16 discuss individual issues relevant to SD and equity. Based on a detailed description of SD and equity issues (rooted in the 'three pillars' approach for SD, see Section 4.8.1), this section provides

Table 4.1 | Overview of SD and equity issues as addressed in Chapters 5–16 of the WGIII AR5.

SD and equity issues	Chapter											
	5	6	7	8	9	10	11	12	13	14	15	16
EQUITY												
• Distribution (within and between countries and generations)	5.3.3	6.3.6.6	7.9.1	8.10.1	9.7.1		11.7.1	12.6	13.2.2.3 13.4.2.4 13.13.1.2	14.1.3	15.5.2.3 15.5.2.4	
• Procedural equity (Participation / involvement, including institutional issues)		6.3.6.6					11.7.1 11.8.2 11.9.3	12.5.2.3 12.6.1	13.2.2.4		15.2.1	
ECONOMIC												
• Employment	5.7.2	6.6.2.4	7.9.1	8.7.1	9.7.2.1	10.8.1	11.7.1 11.13.6	12.4.2 12.5.2.1		14.1.3		
• Standards of living	5.3.3	6.3.1.2	7.10.2	8.2.2.1	9.7.2.5	10.8.1	11.7.1	12.5.2.1				
• Financing			7.10.2		9.10.3.3		11.7.1	12.6.2	13.11.1	14.3.7 14.4.4		16.8
• Innovation	5.6.1	6.5.1	7.9.1	8.7.3		10.8.4	11.3.1 11.13.6	12.2.1.3	13.9	14.3.6	15.6	
• Path-dependence and lock-ins	5.6.3	6.3.6.4 6.4.3	7.9,1 7.10.5	8.4	9.4.3		11.3.2	12.3.2.1 12.4.1		14.3.2		
• Energy Security	5.3.4	6.6.2.2	7.9.1	8.7.1	9.7.2.2	10.8.1	11.13.6	12.8.2		14.4.3		
SOCIAL												
• Poverty (alleviation)		6.6.2.3	7.9,1 7.10.3	8.7.1	9.7.2.5		11.7.1 11.8.1 11.13.6			14.1.3		
• Access to and affordability of basic services		6.6.2.3	7.9.1	8.7.1	9.7.1		11.A.6	12.4.2.4 12.5.2.1		14.3.2.1		
• Food security	5.3.5 5.7.2	6.3.5	7.9.4				11.7.1 11.13.6/7					
• Education and learning			7.9.1						13.10		15.10	16.3
• Health	5.7.1	6.6.2.1	7.9.2; 7.9.3	8.7.1	9.7.3.1 9.7.3.2	10.8.1	11.7.1 11.13.6	12.8.1 12.8.3/4				
• Displacements			7.9.4			10.8.1	11.7.1 11.13.6					
• Quality of life			7.9.4	8.7.1	9.7.1	10.8.1	11.A.6	12.8.2/3				
• Gender Impacts			7.9.1 (Box)		9.7.1		11.7 11.13.5					
ENVIRONMENTAL												
• Ecosystem impacts and biodiversity conservation	5.7.2	6.6.2.6	7.9.2	8.7.1	9.7.1	10.8.1	11.7.2 11.13.6/7	12.5.1 12.8.1/4		14.3.5	15.5.6	
• Water, soils, and other natural resources	5.5.2	6.6.2.5	7.9.2; 7.9.3	8.7.2	9.7.3.3	10.8.1	11.7.2 11.8.3 11.13.6	12.6.1 12.8.4				

a map and a reader's guide for the report from the SD and equity perspective. Table 4.1 shows where those issues are addressed throughout the report. It is supplemented in this section by a brief outline of how each chapter from 6–16 deals with them.

The present section is broader than, and a complement to, Section 6.6 and Table 6.7, which sum up and discuss key co-benefits and adverse side-effects in Chapters 7–12. It is broader in two ways. First, the present section covers all chapters, not just the sectoral chapters. Second, the present section reviews not only where co-benefits and adverse side-effects are discussed (the "development in the climate lens" approach as in Sathaye et al., 2007), but also where the implications of key development policies for mitigation and mitigative capacity are discussed ("climate in the development lens"), and where integrated development paths, including but not limited to climate mitigation, are analyzed. On the other hand, Section 6.6 and Table 6.7 provide a more detailed description of many sorts of co-benefits and adverse side-effects (not all of which directly bear on SD).

The review conducted in the present section leads to three key messages. First, SD and equity issues are pervasive throughout the chapters, reflecting growing literature and attention paid to the topic. Second, a large part of the discussion remains framed within the framework of co-benefits and adverse side-effects. Although extremely important and useful, it has been noted above (Section 4.2) that co-benefits and adverse side-effects are only a building block towards a full SD assessment—which is about integrating the different dimensions in a comprehensive pathway framework. Third, while some topics, such as health co-benefits and adverse side-effects associated with mitigation policies, appear already well covered in the literature, others remain scarcely addressed. In particular, distributional issues (both distributional implications of mitigation policies and implications of different distributional settings for climate policies), employment, and social cohesiveness, have limited coverage—despite being among the key SD goals that policymakers will consider.

The following paragraphs briefly describe how each chapter (from 5 to 16) deals with SD and equity issues. Chapter 5 analyzes the drivers of GHG emissions, and many of these drivers have to do with basic characteristics of the development pathway (population, economic growth, behaviours, technology) that impact sustainability perspectives (5.3, 5.5, 5.6). It also provides a brief overview of co-benefits (in particular in health) and adverse side-effects (5.7) and takes a system perspective to understand the linkages between emissions and the various drivers (5.8)—such a systemic view is congenial to the comprehensive approach to SD discussed in 4.2.

Chapter 6 analyzes distributional consequences of different international burden sharing regimes (6.3.6.6). This chapter also highlights the contrast between the literature suggesting that mitigation might increase the rural-urban gap and deteriorate the living standards of large sections of the population in developing countries, and the SD literature stating that policy and measures aligned to 'development' and 'climate' objectives can deliver substantial co-benefits (Box 6.2). Section 6.5.2 discusses underlying factors that enable or prevent mitigation. Section 6.6.1 summarizes Chapters 7–12 information on co-benefits and adverse side-effects, while 6.6.2 attempts to link transformation pathway studies with other key development priorities, including air pollution and health (6.6.2.1), energy security (6.6.2.2), energy access (6.6.2.3), employment (6.6.2.4), biodiversity (6.6.2.5), water use (6.6.2.6). Section 6.6.2.7 reviews scenario studies analyzing the interactions between mitigation, air quality, and energy security objectives.

Chapter 7 reviews the literature on the co-benefits, risks, and spillovers of mitigation in the energy sector, with emphasis on employment, energy security and energy access (7.9.1), and health and environmental issues (7.9.2). It also puts energy mitigation options into a broader development context, notably by examining how special mechanisms such as microfinance can help lifting rural populations out of the energy poverty trap and increase the deployment of low carbon energy technologies (7.10.2). It stresses that poverty itself is shaping energy systems in Least Developed Countries (LDCs) and creating obstacles (e.g., legal barriers, or vandalism, in informal settlements) to the distribution of electricity (7.10.3). It also highlights the implications of the long life duration of energy supply fixed capital stock (7.10.5).

Chapter 8 emphasizes the importance of the transport sector both for human development and for mitigation (8.1.1). There are many potential co-benefits associated with mitigation actions in the transport sector, with respect to equitable mobility access, health and local air pollution, traffic congestion, energy security, and road safety (8.7.1). It is, however, difficult to assess the social value of such benefits, and there are risks and uncertainties (8.7.2). The chapter analyzes the special uncertainties and concerns of developing countries, where efforts are made to develop or improve institutional effectiveness to support integrated planning (involving transportation, land use, energy, agriculture and public health authorities) that uses transportation as a driver for developing economic and social resilience (8.9.2). Finally, Chapter 8 mentions the concerns with market-based policies having differential impacts across population groups (8.10.1).

Chapter 9 lists the co-benefits and adverse side-effects associated with buildings, notably in terms of employment (9.7.2.1), energy security (9.7.2.2), fuel poverty alleviation (9.7.2.5), and health (9.7.3.1 and 9.7.3.2). Detailed analysis is also conducted on path dependence and lock-in effects associated with the building stock (9.4.2) and with financing issues, as they relate to the particular situations of developing countries (9.10.4).

Chapter 10 discusses the co-benefits and adverse side-effects associated with mitigation actions in the industry sector, focusing mostly on macroeconomic and health benefits (10.8.1). The chapter also focuses on employment impacts of eco-innovation and investment, noting that substantial impacts require job support mechanisms, and that the distributional effects of these policies and across different countries remain unclear (10.10.2).

Chapter 11 frames the discussion of mitigation options in the Agriculture, Forestry, and Other Land Use (AFOLU) sector within a systemic development context (11.4.1). It thoroughly examines the socio-economic impacts of changes in land use (11.7.1). Increasing land rents and food prices due to a reduction in land availability for agriculture, and increasing inequity and land conflicts are serious concerns (11.7.1). Special care for small holders and equity issues, including gender, should accompany mitigation projects (Box 11.6). Bioenergy deployment can have strong distributional impacts, mediated by global market dynamics, including policy regulations and incentives, the production model and deployment scale, and place-specific factors such as land tenure security, labour and financial capabilities. It can raise and diversify farm incomes and increase rural employment, but can also cause smallholders, tenants and herders to lose access to productive land, while other social groups such as workers, investors, company owners, biofuels consumers, would benefit (bioenergy appendix).

Chapter 12 naturally adopts a systemic perspective in dealing with human settlements (12.1, 12.4, 12.5.1), and discusses procedural equity issues in the context of city governance (12.6). It notes that a high-density city, depending heavily upon land-based public-private financing, faces issues of real estate speculation and housing affordability (12.6.2). Adapted tax policies can help integrate market incentives with policy objectives such as sustainable transit financing, affordable housing, and environmental protection. Section 12.8 focuses more specifically on the co-benefits of mitigation options in human settlements, notably in terms of improved health, but also regarding quality of life (noise, urban heat island effect) and energy security and efficiency.

Chapter 13 provides a detailed examination of various international agreements and mechanisms through the lens of distributional impacts, noting the complex interaction between equity and participation in voluntary cooperation processes (13.2). The chapter discusses the distributional impacts of the Kyoto Protocol as well as various proposals for multilateral systems (global permit market, global tax, technology-oriented schemes) (13.13), linkages (13.7.2), and more decentralized initiatives such as trade sanctions (13.8) and geo-engineering (13.4.4). Chapter 13 further discusses advantages and limitations of linking negotiations on mitigation and negotiations on other development objectives (13.3.3). Links with policies and institutions related to other development goals are not discussed, except for relationships between mitigation and international trade regulation (13.8). Finally, human rights and rights of nature are discussed in so far as they might support legal challenges to greenhouse gases emissions (13.5.2.2).

Chapter 14 firmly embeds its analysis of climate policies at the regional level within the context of possible development paths, highlighting significant regional differences (14.1.2, 14.1.3). Given heterogeneity of capacities between countries, it argues that regional cooperation on climate change can help to foster mitigation that considers distributional aspects. In particular, high inequalities in poor regions raise difficult distributional questions regarding the costs and benefits of mitigation policies (14.1.3). Mitigation opportunities are discussed in the context of the broader development objectives, with regard to energy access (14.3.2), urbanization (14.3.3), consumption patterns (14.3.4), agriculture and land-use (14.3.5), and technological development (14.3.6). Relationships between mitigation options and regional trade agreements—not a development objective per se but an instrument for achieving economic growth—are also examined (14.4.2). Finally, Chapter 14 examines the geographical concentration of CDM projects (14.3.7).

In analyzing policies at the national and subnational level, Chapter 15 provides a detailed analysis of the relationships between climate change mitigation and other development goals. While it notes the practical importance of co-benefits in the design of climate policies (15.2.4), it also shows that certain measures set up with primarily other development objectives have important implications for climate change mitigation, either directly in terms of emission reductions, or indirectly in terms of provision of public goods necessary for mitigation policies to be effective (15.3.4, 15.5.2, 15.5.6). In addition, the chapter highlights the importance of designing policy packages that jointly address different development objectives, and discusses in depth the opportunities but also the difficulties of such association (15.7.2, 15.11). Chapter 15 insists on the fact that whether a policy is adopted or not, and what outcome it finally has strongly depends on local circumstances (notably institutions), and on the process by which the decision is made (15.8.2, 15.9). Finally, this chapter notes that while the distributional incidence of taxes has been studied quite extensively, much less is known about the distributional incidence of other policies (15.13).

Availability of resources for investment is critical for supporting any development path. The literature reviewed in Chapter 16 notes that there are barriers to investment in many countries, not specific to mitigation—although mitigation activities have specific characteristics (size, perceived risks, etc.) that make their financing even more difficult (16.8). However, Chapter 16 notes that the literature on financing remains limited, and focuses quite narrowly on energy mitigation policies. There is very little evaluation, both at the micro and macro level, of how investment flows in other sectors (such as transportation or housing), could be redirected in relation with mitigation.

4.9 Gaps in knowledge and data

The current literature and data in the area of sustainable development and equity has gaps that could be better addressed. The points below highlight questions and connections that may serve as openings for future research.

- The relationship between countries' human capital levels and their national and international engagement in climate change policy would benefit from additional studies.

- There are many open questions about how developing countries can best pull together the resources and capabilities to achieve SD and mitigation objectives and how to leverage international cooperation to support this process.

- Not much is known about the desirability and feasibility of various economic and policy frameworks for the compensation of foregone benefits from exploiting fossil fuels in resource-rich countries.

- In the efforts made toward an evaluation of funding necessary to implement UNFCCC mitigation and adaptation activities, harmonized and clear methodologies and processes are still missing as a basis for accurate estimates.

- It is still difficult to assess the unrealized potential for reducing the environmental impact of economic activity and to understand how this potential can be realized.

- For technology transitions, knowledge remains insufficient for a comparative assessment of alternative innovation and diffusion systems and an assessment of the interplay between property rights, markets and government action, taking account of local circumstances and constraints.

- The relative importance in a SD transition of changes in values, as opposed to standard economic instruments influencing behaviours and economic activity, remains hard to assess.

- Not much is known about the relative potential of frugality (lifestyles and consumption patterns involving lower expenditures on goods and services) versus ecologically-conscious behaviour (lifestyles and consumption patterns involving fewer material resources and less environmental harm without necessarily reducing expenditure) for promoting SD and equity.

- The non-economic motivations for climate-friendly behaviours are not well understood, particularly with regard to the respective role of social considerations or values (e.g. universalism regarding fellow human beings) versus ecological considerations (universalism regarding the environment), and the extent to which these drivers can be separated.

- The predictive power of values regarding ecologically conscious consumer behaviour is often low, typically less than 20 %, due to a range of factors operating at different levels. The causes of this 'value-action gap' regarding, especially, behaviours that increase or limit GHG emissions are not well understood.

- The measurement of well-being, for the purpose of public policy, remains a controversial field, which suggests a need to further explore the potential uses of subjective data, and also seek ways to improve the quality of data on well-being.

- The empirical economic models used in the context of climate policy could substantially improve by integrating transition issues (short-medium term) into long-term analysis, and also by adopting a sequential structure compatible with the resolution of uncertainty over time.

- The current methodologies for the construction of scenarios do not yet deliver sufficiently detailed and sufficiently long-term data in order to assess development paths at the bar of sustainability and equity. The studies of SD impacts of sectoral measures in terms of co-benefits are seldom integrated into a comprehensive assessment of sustainability of the general development path.

- A better understanding of the distributional impacts of prospective climate policies would provide guidance for designing equitable policies, and insight into the present political economic landscape wherein some actors support climate action and others oppose it.

4.10 Frequently Asked Questions

FAQ 4.1 Why does the IPCC need to think about sustainable development?

Climate change is one among many (some of them longstanding) threats to SD, such as the depletion of natural resources, pollution hazards, inequalities, or geopolitical tensions. As policymakers are concerned with the broader issues of SD, it is important to reflect on how climate risks and policies fit in the general outlook. This report studies the interdependence between policy objectives via the analysis of co-benefits and adverse side-effects. More broadly, it examines how climate policy can be conceived as a component of the transition of nations toward SD pathways (Sections 4.2, 4.6, 4.8). Many factors determine the development pathway. Among the main factors that can be influenced by policy decisions, one can list governance, human and social capital, technology, and finance. Population size, behaviours and values are also important factors. Managing the transition toward SD also requires taking account of path dependence and potential favourable or unfavourable lock-ins (e.g., via infrastructures), and attention to the political economy in which all of these factors are embedded (Sections 4.3, 4.4, 4.5).

FAQ 4.2 The IPCC and UNFCCC focus primarily on GHG emissions within countries. How can we properly account for all emissions related to consumption activities, even if these emissions occur in other countries?

For any given country, it is possible to compute the emissions embodied in its consumption or those emitted in its productive sector. The consumption-based framework for GHG emission accounting allocates the emissions released during the production and distribution (i.e., along the supply chain) of goods and services to the final consumer and the nation (or another territorial unit) in which they resides, irrespective of the geographical origin of these products. The territorial or production-based framework allocates the emissions physically produced within a nation's territorial boundary to that nation. The difference in emissions inventories calculated based on the two frameworks are the emissions embodied in trade. Consumption-based emissions are more strongly associated with GDP than are territorial emissions. This is because wealthier countries satisfy a higher share of their final consumption of products through net imports compared to poorer countries. (Section 4.4)

FAQ 4.3 What kind of consumption has the greatest environmental impact?

The relationship between consumer behaviours and their associated environmental impacts is well understood. Generally, higher consumption lifestyles have greater environmental impact, which connects distributive equity issues with the environment. Beyond that, research has shown that food accounts for the largest share of consumption-based GHG emissions (carbon footprints) with nearly 20 % of the global carbon footprint, followed by housing, mobility, services, manufactured products, and construction. Food and services are more important in poor countries, while mobility and manufactured goods account for the highest carbon footprints in rich countries. (Section 4.4)

FAQ 4.4 Why is equity relevant in climate negotiations?

The international climate negotiations under the UNFCCC are working toward a collective global response to the common threat of climate change. As with any cooperative undertaking, the total required effort will be allocated in some way among countries, including both domestic action and international financial support. At least three lines of reasoning have been put forward to explain the relevance of equity in allocating this effort: (1) a *moral* justification that draws upon widely applied ethical principles, (2) a *legal* justification that appeals to existing treaty commitments and soft law agreements to cooperate on the basis of stated equity principles, and (3) an *effectiveness* justification that argues that an international collective arrangement that is perceived to be fair has greater legitimacy and is more likely to be internationally agreed and domestically implemented, reducing the risks of defection and a cooperative collapse. (Sections 4.2, 4.6)

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5

Drivers, Trends and Mitigation

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Executive Summary

Chapter 5 analyzes the anthropogenic greenhouse gas (GHG) emission trends until the present and the main drivers that explain those trends. The chapter uses different perspectives to analyze past GHG-emissions trends, including aggregate emissions flows and per capita emissions, cumulative emissions, sectoral emissions, and territory-based vs. consumption-based emissions. In all cases, global and regional trends are analyzed. Where appropriate, the emission trends are contextualized with long-term historic developments in GHG emissions extending back to 1750.

GHG-emissions trends

Anthropogenic GHG emissions have increased from 27 (±3.2) to 49 (±4.5) $GtCO_2$eq/yr (+80 %) between 1970 and 2010; GHG emissions during the last decade of this period were the highest in human history *(high confidence)*.[1] GHG emissions grew on average by 1 $GtCO_2$eq (2.2 %) per year between 2000 and 2010, compared to 0.4 $GtCO_2$eq (1.3 %) per year between 1970 and 2000. [Section 5.2.1]

CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78 % of the total GHG emission increase from 1970 to 2010, with similar percentage contribution for the period 2000–2010 (*high confidence*). Fossil fuel-related CO_2 emissions for energy purposes increased consistently over the last 40 years reaching 32 (±2.7) $GtCO_2$/yr, or 69 % of global GHG emissions in 2010.[2] They grew further by about 3 % between 2010 and 2011 and by about 1–2 % between 2011 and 2012. Agriculture, deforestation, and other land use changes have been the second-largest contributors whose emissions, including other GHGs, have reached 12 $GtCO_2$eq/yr (*low confidence*), 24 % of global GHG emissions in 2010. Since 1970, CO_2 emissions increased by about 90 %, and methane (CH_4) and nitrous oxide (N_2O) increased by about 47 % and 43 %, respectively. Fluorinated gases (F-gases) emitted in industrial processes continue to represent less than 2 % of anthropogenic GHG emissions. Of the 49 (±4.5) $GtCO_2$eq/yr in total anthropogenic GHG emissions in 2010, CO_2 remains the major anthropogenic GHG accounting for 76 % (38±3.8 $GtCO_2$eq/yr) of total anthropogenic GHG emissions in 2010. 16 % (7.8±1.6 $GtCO_2$eq/yr) come from methane (CH_4), 6.2 % (3.1±1.9 $GtCO_2$eq/yr) from nitrous oxide (N_2O), and 2.0 % (1.0±0.2 $GtCO_2$eq/yr) from fluorinated gases. [5.2.1]

Over the last four decades GHG emissions have risen in every region other than Economies in Transition, though trends in the different regions have been dissimilar (*high confidence*). In Asia, GHG emissions grew by 330 % reaching 19 $GtCO_2$eq/yr in 2010, in Middle East and Africa (MAF) by 70 %, in Latin America (LAM) by 57 %, in the group of member countries of the Organisation for Economic Co-operation and Development (OECD-1990) by 22 %, and in Economies in Transition (EIT) by 4 %.[3] Although small in absolute terms, GHG emissions from international transportation are growing rapidly. [5.2.1]

Cumulative fossil CO_2 emissions (since 1750) more than tripled from 420 $GtCO_2$ by 1970 to 1300 $GtCO_2$ (±8 %) by 2010 (*high confidence*). Cumulative CO_2 emissions associated with agriculture, deforestation, and other land use change (AFOLU) have increased from about 490 $GtCO_2$ in 1970 to approximately 680 $GtCO_2$ (±45 %) in 2010. Considering cumulative CO_2 emissions from 1750 to 2010, the OECD-1990 region continues to be the major contributor with 42 %; Asia with 22 % is increasing its share. [5.2.1]

In 2010, median per capita emissions for the group of high-income countries (13 tCO_2eq/cap) is almost 10 times that of low-income countries (1.4 tCO_2eq/cap) (*robust evidence, high agreement*). Global average per capita GHG emissions have shown a stable trend over the last 40 years. This global average, however, masks the divergence that exists at the regional level; in 2010 per capita GHG emissions in OECD-1990 and EIT are between 1.9 and 2.7 times higher than per capita GHG emissions in LAM, MAF, and Asia. While per capita GHG emissions in LAM and MAF have been stable over the last four decades, in Asia they have increased by more than 120 %. [5.2.1]

The energy and industry sectors in upper-middle income countries accounted for 60 % of the rise in global GHG emissions between 2000 and 2010 (*high confidence*). From 2000–2010, GHG emissions grew in all sectors, except in AFOLU where positive and negative emission changes are reported across different databases and uncertainties in the data are high: energy supply (+36 %, to 17 $GtCO_2$eq/yr), industry (+39 %, to 10 $GtCO_2$eq/yr), transport (+18 %, to 7.0 $GtCO_2$eq/yr), buildings (+9 %, to 3.2 $GtCO_2$eq/yr), AFOLU (+8 %, to 12 $GtCO_2$eq/yr).[4] Waste GHG emissions increased substantially but remained close to 3 % of global GHG emissions. [5.3.4, 5.3.5]

In the OECD-1990 region, territorial CO_2 emissions slightly decreased between 2000 and 2010, but consumption-based CO_2 emissions increased by 5 % (*robust evidence, high agreement*). In most developed countries, both consumption-related emissions and GDP are growing. There is an emerging gap between territorial,

[1] Values with ± provide uncertainty ranges for a 90 % confidence interval.

[2] Unless stated otherwise, all emission shares are calculated based on global warming potential with a 100-year time horizon. See also Section 3.9.6 for more information on emission metrics.

[3] The country compositions of OECD-1990, EIT, LAM, MAF, and ASIA are defined in Annex II.2 of the report. In Chapter 5, both 'ASIA' and 'Asia' refer to the same group of countries in the geographic region Asia. The region referred to excludes Japan, Australia and New Zealand; the latter countries are included in the OECD-1990 region.

[4] These numbers are from the Emissions Database for Global Atmospheric Research (EDGAR) database (JRC/PBL, 2013). These data have high levels of uncertainty and differences between databases exist.

production-related emissions, and consumption-related emissions that include CO_2 embedded in trade flows. The gap shows that a considerable share of CO2 emissions from fossil fuels combustion in developing countries is released in the production of goods exported to developed countries. By 2010, however, the developing country group has overtaken the developed country group in terms of annual CO_2 emissions from fossil fuel combustion and industrial processes from both production and consumption perspectives. [5.3.3]

The trend of increasing fossil CO_2 emissions is robust (*very high confidence*). Five different fossil fuel CO_2 emissions datasets—harmonized to cover fossil fuel, cement, bunker fuels, and gas flaring—show ±4 % differences over the last three decades. Uncertainties associated with estimates of historic anthropogenic GHG emissions vary by type of gas and decrease with the level of aggregation. Global CO_2 emissions from fossil fuels have relatively low uncertainty, assessed to be ±8 %. Uncertainty in fossil CO_2 emissions at the country level reaches up to 50 %. [5.2.1, 5.2.3]

GHG-emissions drivers

Per capita production and consumption growth is a major driver for worldwide increasing GHG emissions (*robust evidence, high agreement*). Global average economic growth, as measured through GDP per capita, grew by 100 %, from 4800 to 9800 $Int\$_{2005}$/cap yr between 1970 and 2010, outpacing GHG-intensity improvements. At regional level, however, there are large variations. Although different in absolute values, OECD-1990 and LAM showed a stable growth in per capita income of the same order of magnitude as the GHG-intensity improvements. This led to almost constant per capita emissions and an increase in total emissions at the rate of population growth. The EIT showed a decrease in income around 1990 that together with decreasing emissions per output and a very low population growth led to a decrease in overall emissions until 2000. The MAF showed a decrease in GDP per capita, but a high population growth rate led to an increase in overall emissions. Emerging economies in Asia showed very high economic growth rates at aggregate and per capita levels leading to the largest growth in per capita emissions despite also having the highest emissions per output efficiency improvements. [5.3.3]

Reductions in the energy intensity of economic output during the past four decades have not been sufficient to offset the effect of GDP growth (*high confidence*). Energy intensity has declined in all developed and large developing countries due mainly to technology, changes in economic structure, the mix of energy sources, and changes in the participation of inputs such as capital and labour used. At the global level, per capita primary energy consumption rose by 30 % from 1970–2010; due to population growth, total energy use has increased by 130 % over the same period. Countries and regions with higher income per capita tend to have higher energy use per capita; per capita energy use in the developing regions is only about 25 % of that in the developed economies on average. Growth rates in energy use per capita in developing countries, however, are much higher than those in developed countries. [5.3.4]

The decreasing carbon intensity of energy supply has been insufficient to offset the increase in global energy use (*high confidence*). Increased use of coal since 2000 has reversed the slight decarbonization trends exacerbating the burden of energy-related GHG emissions. Estimates indicate that coal, and unconventional gas and oil resources are large, suggesting that decarbonization would not be primarily driven by the exhaustion of fossil fuels, but by economics and technological and socio-political decisions. [5.3.4, 5.8]

Population growth aggravates worldwide growth of GHG emissions (*high confidence*). Global population has increased by 87 % from 1970 reaching 6.9 billion in 2010. The population has increased mainly in Asia, Latin America, and Africa, but the emissions increase for an additional person varies widely, depending on geographical location, income, lifestyle, and the available energy resources and technologies. The gap in per capita emissions between the top and bottom countries exceeds a factor of 50. The effects of demographic changes such as urbanization, ageing, and household size have indirect effects on emissions and smaller than the direct effects of changes in population size. [5.3.2]

Technological innovation and diffusion support overall economic growth, and also determine the energy intensity of economic output and the carbon intensity of energy (*medium confidence*). At the aggregate level, between 1970 and 2010, technological change increased income and resources use, as past technological change has favoured labour-productivity increase over resource efficiency [5.6.1]. Innovations that potentially decrease emissions can trigger behavioural responses that diminish the potential gains from increased efficiency, a phenomenon called the 'rebound effect' [5.6.2]. Trade facilitates the diffusion of productivity-enhancing and emissions-reducing technologies [5.4].

Infrastructural choices have long-lasting effects on emissions and may lock a country in a development path for decades (*medium evidence, medium agreement*). As an example, infrastructure and technology choices made by industrialized countries in the post-World War II period, at low-energy prices, still have an effect on current worldwide GHG emissions. [5.6.3]

Behaviour affects emissions through energy use, technological choices, lifestyles, and consumption preferences (*robust evidence, high agreement*). Behaviour is rooted in individuals' psychological, cultural, and social orientations that lead to different lifestyles and consumption patterns. Across countries, strategies and policies have been used to change individual choices, sometimes through changing the context in which decisions are made; a question remains whether such policies can be scaled up to macro level. [5.5]

Co-benefits may be particularly important for policymakers because the benefits can be realized faster than can benefits from reduced climate change, but they depend on assumptions about future trends (*medium evidence, high agreement*). Policies addressing fossil fuel use may reduce not only CO_2 emissions but also sulphur dioxide (SO_2) emissions and other pollutants that directly affect human health, but this effect interacts with future air pollution policies. Some mitigation policies may also produce adverse side-effects, by promoting energy supply technologies that increase some forms of air pollution. A comprehensive analysis of co-benefits and adverse side-effects is essential to estimate the actual costs of mitigation policies. [5.7]

Policies can be designed to act upon underlying drivers so as to decrease GHG emissions (*limited evidence, medium agreement*). Policies can be designed and implemented to affect underlying drivers. From 1970–2010, in most regions and countries, policies have proved insufficient in influencing infrastructure, technological, or behavioural choices at a scale that curbs the upward GHG-emissions trends. [5.6, 5.8]

5.1 Introduction and overview

The concentration of greenhouse gases, including CO_2 and methane (CH_4), in the atmosphere has been steadily rising since the beginning of the Industrial Revolution (Etheridge et al., 1996, 2002; NRC, 2010). Anthropogenic CO_2 emissions from the combustion of fossil fuels have been the main contributor to rising CO_2-concentration levels in the atmosphere, followed by CO_2 emissions from land use, land use change, and forestry (LULUCF).

Chapter 5 analyzes the anthropogenic greenhouse gas (GHG)-emission trends until the present and the main drivers that explain those trends. This chapter serves as a reference for assessing, in following chapters, the potential future emissions paths, and mitigation measures.

For a systematic assessment of the main drivers of GHG-emission trends, this and subsequent chapters employ a decomposition analysis based on the IPAT and Kaya identities (see Box 5.1).

Chapter 5 first considers the immediate drivers, or factors in the decomposition, of total GHG emissions. For energy, the factors are population, gross domestic product (GDP) (production) and gross national expenditure (GNE) (expenditures) per capita, energy intensity of production and expenditures, and GHG-emissions intensity of energy. For other sectors, the last two factors are combined into GHG-emissions intensity of production or expenditures. Secondly, it considers the underlying drivers defined as the processes, mechanisms, and characteristics of society that influence emissions through the factors, such as fossil fuels endowment and availability, consumption patterns, structural and technological changes, and behavioural choices.

Underlying drivers are subject to policies and measures that can be applied to, and act upon them. Changes in these underlying drivers, in turn, induce changes in the immediate drivers and, eventually, in the GHG-emissions trends.

The effect of immediate drivers on GHG emissions can be quantified through a straight decomposition analysis; the effect of underlying drivers on immediate drivers, however, is not straightforward and, for that reason, difficult to quantify in terms of their ultimate effects on GHG emissions. In addition, sometimes immediate drivers may affect underlying drivers in a reverse direction. Policies and measures in turn affect these interactions. Figure 5.1 reflects the interconnections among GHG emissions, immediate drivers, underlying drivers, and policies and measures as well as the interactions across these three groups through the dotted lines.

Past trends in global and regional GHG emissions from the beginning of the Industrial Revolution are presented in Section 5.2, *Global trends in greenhouse gases and short-lived species*; sectoral breakdowns of emissions trends are introduced later in Section 5.3.4, *Energy demand and supply,* and Section 5.3.5, *Other key sectors,* which includes transport, buildings, industry, forestry, agriculture, and waste sectors.

The decomposition framework and its main results at both global and regional levels are presented in Section 5.3.1, *Drivers of global emissions*. Immediate drivers or factors in the decomposition identity are discussed in Section 5.3.2, *Population and demographic structure*, Section 5.3.3, *Economic growth and development*, and Section 5.3.4, *Energy demand and supply*. Past trends of the immediate drivers are identified and analyzed in these sections.

At a deeper level, the underlying drivers that influence immediate drivers that, in turn, affect GHG emissions trends, are identified and discussed in Section 5.4, *Production and trade patterns*, Section 5.5, *Consumption and behavioural change*, and Section 5.6, *Technological change*. Underlying drivers include individual and societal choices as well as infrastructure and technological changes.

Section 5.7, *Co-benefits and adverse side-effects of mitigation actions,* identifies the effects of mitigation policies, measures or actions on other development aspects such as energy security, and public health.

Section 5.8, *The system perspective: linking sectors, technologies and consumption patterns,* synthesizes the main findings of the chapter and highlights the relevant interactions among and across immediate and underlying drivers that may be key for the design of mitigation policies and measures.

Finally, Section 5.9, *Gaps in knowledge and data,* addresses shortcomings in the dataset that prevent a more thorough analysis or limit the time span of certain variables. The section also discussed the gaps in the knowledge on the linkages among drivers and their effect on GHG emissions.

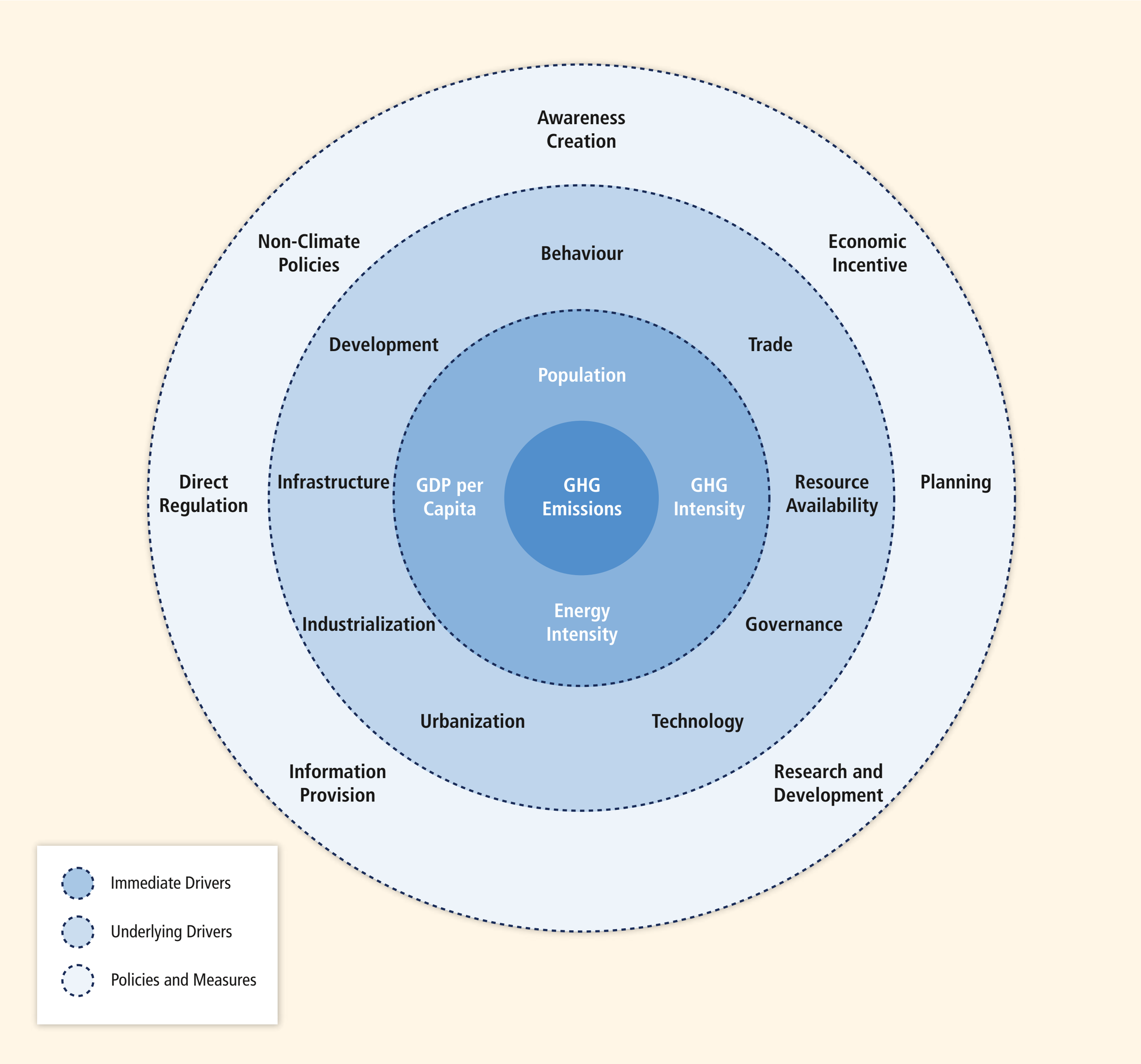


Figure 5.1 | Interconnections among GHG emissions, immediate drivers, underlying drivers, and policies and measures. Immediate drivers comprise the factors in the decomposition of emissions. Underlying drivers refer to the processes, mechanisms, and characteristics that influence emissions through the factors. Policies and measures affect the underlying drivers that, in turn, may change the factors. Immediate and underlying drivers may, in return, influence policies and measures.

5.2 Global trends in stocks and flows of greenhouse gases and short-lived species

5.2.1 Sectoral and regional trends in GHG emissions

Between 1970 and 2010, global warming potential (GWP)-weighted territorial GHG emissions increased from 27 to 49 $GtCO_2eq$, an 80 % increase (Figure 5.2). Total GHG emissions increased by 8 $GtCO_2eq$ over the 1970s, 6 $GtCO_2eq$ over the 1980s, and by 2 $GtCO_2$ over the 1990s, estimated as linear trends. Emissions growth accelerated in the 2000s for an increase of 10 $GtCO_2eq$. The average annual GHG-growth rate over these decadal periods was 2.0 %, 1.4 %, 0.6 %, and 2.2 %.[5] The main regional changes underlying these global trends were the reduction in GHG emissions in the Economies in Transition (EIT) region

[5] Note that there are different methods to calculate the average annual growth rate. Here, for convenience of the reader, we take the simple linear average of the annual growth rates g_t within the period considered.

starting in the 1990s and the rapid increase in GHG emissions in Asia in the 2000s. Emissions values in Section 5.2 are from the Emissions Database for Global Atmospheric Research (EDGAR) (JRC/PBL, 2013) unless otherwise noted. As in previous assessments, the EDGAR inventory is used because it provides the only consistent and comprehensive estimate of global emissions over the last 40 years. The EDGAR emissions estimates for specific compounds are compared to other results in the literature below.

Similar trends were seen for fossil CO_2 emissions, where a longer record exists. The absolute growth rate over the last decade was 8 $GtCO_2$/decade, which was higher than at any point in history (Boden et al., 2012). The relative growth rate for per capita CO_2 emissions over the last decade is still smaller than the per capita growth rates at previous points in history, such as during the post-World War II economic expansion. Absolute rates of CO_2 emissions growth, however, are higher than in the past due to an overall expansion of the global economy due to population growth.

Carbon dioxide (CO_2) is the largest component of anthropogenic GHG emissions (Figure 1.3 in Chapter 1). CO_2 is released during the combustion of fossil fuels such as coal, oil, and gas as well as the production of cement (Houghton, 2007). In 2010, CO_2, including net land-use-change emissions, comprised over 75 % (38±3.8 $GtCO_2$eq/yr) of 100-year GWP-weighted anthropogenic GHG emissions (Figure 1.3). Between 1970–2010, global anthropogenic fossil CO_2 emissions more than doubled, while methane (CH_4) and nitrous oxide (N_2O) each increased by about 45 %, although there is evidence that CH_4 emissions may not have increased over recent decades (see Section 5.2.3). In 2010, their shares in total GHG emissions were 16 % (7.8±1.6 $GtCO_2$eq/yr) and 6.2 % (3.1±1.9 $GtCO_2$eq/yr) respectively. Fluorinated gases, which represented about 0.4 % in 1970, increased to comprise 2 % (1.0±0.2 $GtCO_2$eq/yr) of GHG emissions in 2010. Some anthropogenic influences on climate, such as chlorofluorocarbons and aviation contrails, are not discussed in this section, but are assessed in the Intergovernmental Panel on Climate Change (IPCC) Working Group I (WGI) contribution to the Fifth Assessment Report (AR5) (Boucher and Randall, 2013; Hartmann et al., 2013). Forcing from aerosols and ozone precursor compounds are considered in the next section.

Following general scientific practice, 100-year GWPs from the IPCC Second Assessment Report (SAR) (Schimel et al., 1996) are used as the index for converting GHG emission estimates to common units of CO_2-equivalent emissions in this section (please refer to Annex II.9.1 for the exact values). There is no unique method of comparing trends for different climate-forcing agents (see Sections 1.2.5 and 3.9.6). A change to 20- or 500-year GWP values would change the trends by ±6 %. Similarly, use of updated GWPs from the IPCC Fourth Assessment Report (AR4) or AR5, which change values by a smaller amount, would not change the overall conclusions in this section. The largest absolute

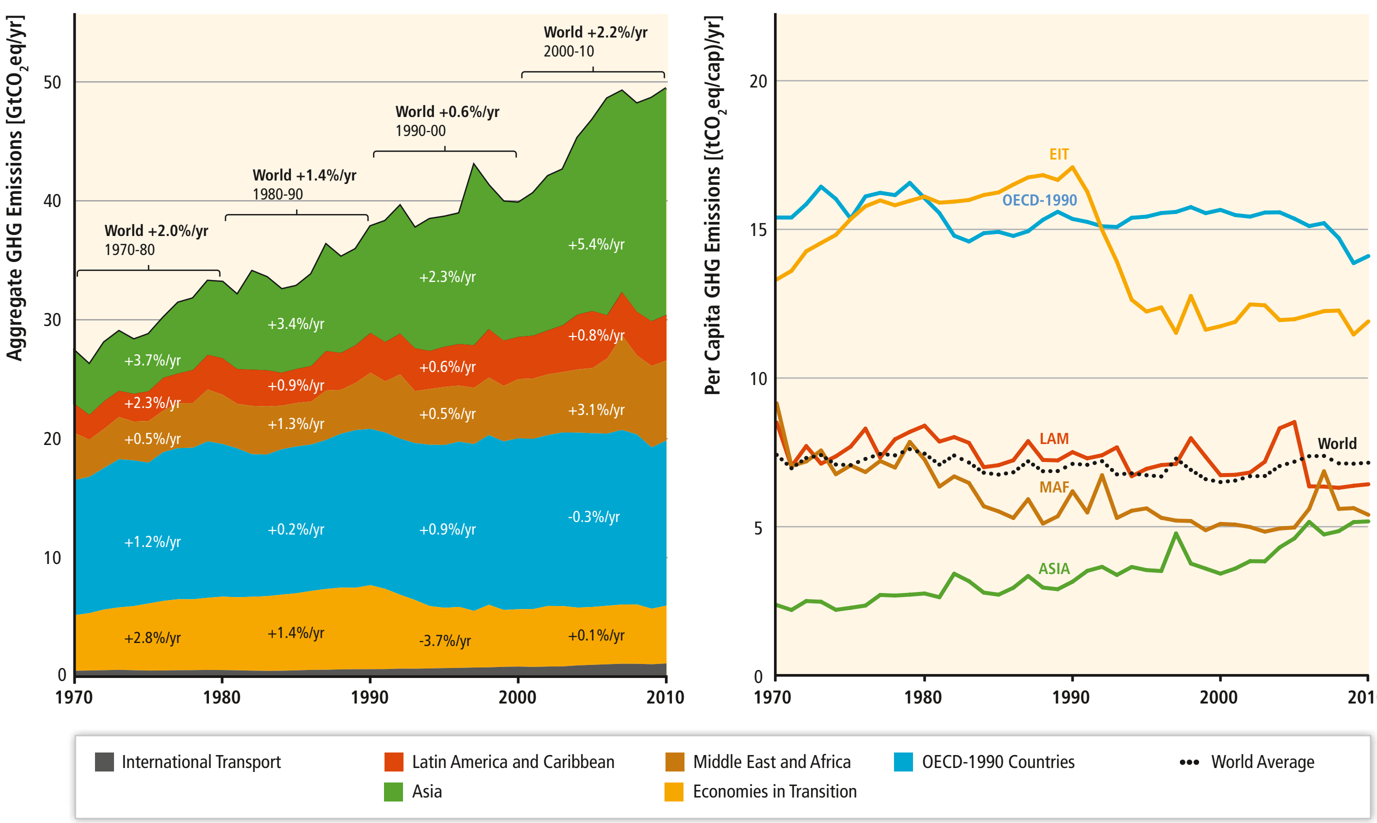


Figure 5.2 | Left panel: GHG emissions per region over 1970 – 2010. Emissions include all sectors, sources and gases, are territorial (see Box 5.2), and aggregated using 100-year GWP values. Right panel: The same data presented as per capita GHG emissions. Data from JRC/PBL (2013) and IEA (2012). Regions are defined in Annex II.2.

impact of a change in index values is on the weight given to methane, whose emission trends are particularly uncertain (Section 5.2.3; Kirschke et al., 2013).

Global per capita GHG emissions (Figure 5.2, right panel) have shown little trend over the last 40 years. The most noticeable regional trend over the last two decades in terms of per capita GHG emissions is the increase in Asia. Per capita emissions in regions other than EIT were fairly flat until the last several years when per capita emissions have decreased slightly in Latin America (LAM) and the group of member countries of the Organisation for Economic Co-operation and Development in 1990 (OECD-1990).

Fossil CO_2 emissions have grown substantially over the past two centuries (Figure 5.3, left panels). Fossil CO_2 emissions over 2002–2011 were estimated at 30 ±8 % $GtCO_2$/yr (Andres et al., 2012), (90 % confidence interval). Emissions in the 2000s as compared to the 1990s were higher in all regions, except for EIT, and the rate of increase was largest in ASIA. The increase in developing countries is due to an industrialization process that historically has been energy-intensive; a pattern similar to what the current OECD countries experienced before 1970. The figure also shows a shift in relative contribution. The OECD-1990 countries contributed most to the pre-1970 emissions, but in 2010 the developing countries and ASIA in particular, make up the major share of emissions.

CO_2 emissions from fossil fuel combustion and industrial processes made up the largest share (78 %) of the total emission increase from 1970 to 2010, with a similar percentage contribution between 2000 and 2010. In 2011, fossil CO_2 emissions were 3 % higher than in 2010, taking the average of estimates from Joint Research Centre (JRC)/ Netherlands Environmental Assessment Agency (PBL) (Olivier et al., 2013), U.S. Energy Information Administration (EIA), and Carbon Dioxide Information Analysis Center (CDIAC) (Macknick, 2011). Preliminary estimates for 2012 indicate that emissions growth has slowed to 1.4 % (Olivier et al., 2013) or 2 % (BP, 2013), as compared to 2012.

Land-use-change (LUC) emissions are highly uncertain, with emissions over 2002–2011 estimated to be 3.3 ±50–75 % $GtCO_2$/yr (Ciais et al., 2013). One estimate of LUC emissions by region is shown in Figure 5.3, left panel (Houghton et al., 2012), disaggregated into sub-regions using Houghton (2008), and extended to 1750 using regional trends from Pongratz et al. (2009). LUC emissions were comparable to or greater than fossil emissions for much of the last two centuries, but are of the order of 10 % of fossil emissions by 2010. LUC emissions appear to be declining over the last decade, with some regions showing net carbon uptake, although estimates do not agree on the rate or magnitude of these changes (Figure 11.6). Uncertainty estimates in Figure 5.3 follow Le Quéré et al.(2012) and WGI (Ciais et al., 2013).

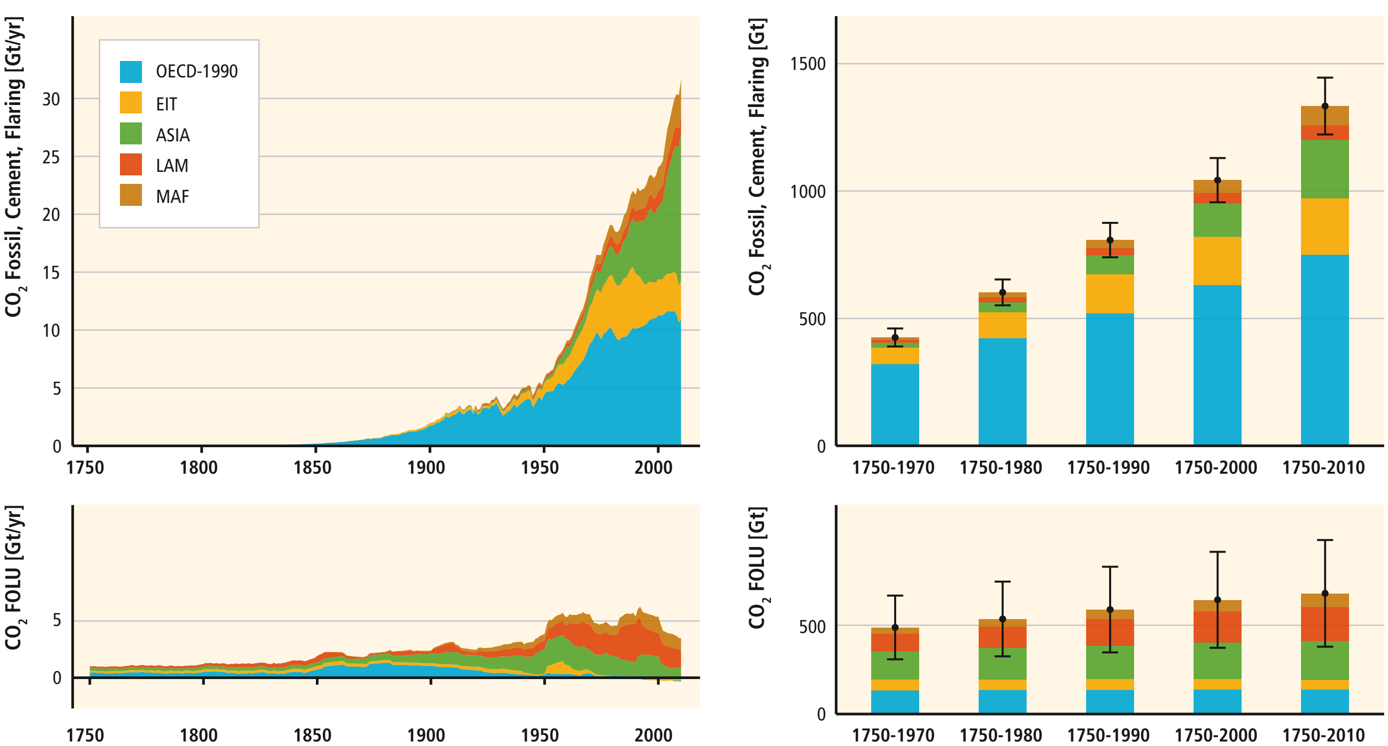


Figure 5.3 | Upper-left panel: CO_2 emissions per region over 1750–2010, including emissions from fossil fuel combustion, cement production, and gas flaring (territorial, Boden et al., 2012). Lower-left panel: an illustrative estimate of CO_2 emissions from AFOLU over 1750–2010 (Houghton e al., 2012). Right panels show cumulative CO_2 emissions over selected time periods by region. Whisker lines give an indication of the range of emission results. Regions are defined in Annex II.2.

Cumulative CO_2 emissions, which are a rough measure of the impact of past emissions on atmospheric concentrations, are also shown in Figure 5.3 (right panels). About half of cumulative fossil CO_2 emissions to 2010 were from the OECD-1990 region, 20 % from the EIT region, 15 % from the ASIA region, and the remainder from LAM, MAF, and international shipping (not shown). The cumulative contribution of LUC emissions was similar to that of fossil fuels until the late 20th century. By 2010, however, cumulative fossil emissions are nearly twice that of cumulative LUC emissions. Note that the figures for LUC are illustrative, and are much more uncertain than the estimates of fossil CO_2 emissions. Cumulative fossil CO_2 emissions to 2011 are estimated to be 1340 ± 110 $GtCO_2$, while cumulative LUC emissions are 680 ± 300 $GtCO_2$ (WGI Table 6.1). Cumulative uncertainties are, conservatively, estimated across time periods with 100 % correlation across years. Cumulative per capita emissions are another method of presenting emissions in the context of examining historical responsibility (see Chapters 3 and 13; Teng et al., 2011).

Methane is the second most important greenhouse gas, although its apparent impact in these figures is sensitive to the index used to convert to CO_2 equivalents (see Section 3.9.6). Methane emissions are due to a wide range of anthropogenic activities including the production and transport of fossil fuels, livestock, and rice cultivation, and the decay of organic waste in solid waste landfills. The 2005 estimate of CH_4 emissions from JRC/PBL (2013) of 7.3 $GtCO_2eq$ is 7 % higher than the 6.8 $GtCO_2eq$ estimates of US EPA (2012) and Höglund-Isaksson et al. (2012), which is well within an estimated 20 % uncertainty (Section 5.2.3).

The third most important anthropogenic greenhouse gas is N_2O, which is emitted during agricultural and industrial activities as well as during combustion and human waste disposal. Current estimates are that about 40 % of total N_20 emissions are anthropogenic. The 2005 estimate of N_2O emissions from JRC/PBL (2013) of 3.0 $GtCO_2eq$ is 12 % lower than the 3.4 $GtCO_2$ estimate of US EPA (2012), which is well within an estimated 30 to 90 % uncertainty (Section 5.2.3).

In addition to CO_2, CH_4, and N_2O, the F-gases are also greenhouse gases, and include hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride. These gases, sometimes referred to as High Global Warming Potential gases ('High GWP gases'), are typically emitted in smaller quantities from a variety of industrial processes. Hydrofluorocarbons are mostly used as substitutes for ozone-depleting substances (i. e., chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and halons). Emissions uncertainty for these gases varies, although for those gases with known atmospheric lifetimes, atmospheric measurements can be inverted to obtain an estimate of total global emissions. Overall, the uncertainty in global F-gas emissions have been estimated to be 20 % (UNEP, 2012, appendix), although atmospheric inversions constrain emissions to lower uncertainty levels in some cases (Section 5.2.3).

Greenhouse gases are emitted from many societal activities, with global emissions from the energy sector consistently increasing the most each decade over the last 40 years (see also Figure 5.18). A notable change over the last decade is high growth in emissions from the industrial sector, the second highest growth by sector over this period. Subsequent sections of this chapter describe the main trends and drivers associated with these activities and prospects for future mitigation options.

5.2.2 Trends in aerosols and aerosol/tropospheric ozone precursors

In addition to GHGs, aerosols and tropospheric ozone also contribute to trends in climate forcing. Because these forcing agents are shorter lived and heterogeneous, their impact on climate is not discussed in terms of concentrations, but instead in terms of radiative forcing, which is the change in the radiative energy budget of the Earth (Myhre et al., 2014). A positive forcing, such as that due to increases in GHGs, tends to warm the system while a negative forcing represents a cooling effect. Trends for the relevant emissions are shown in the Figure 5.4.

Aerosols contribute a net negative, but uncertain, radiative forcing (IPCC, 2007a; Myhre et al., 2014) estimated to total -0.90 W/m^2 (5–95 % range: -1.9 to -0.1 W/m^2). Trends in atmospheric aerosol loading, and the associated radiative forcing, are influenced primarily by trends in primary aerosol, black carbon (BC) and organic carbon (OC), and precursor emissions (primarily sulphur dioxide (SO_2)), although trends in climate and land-use also impact these forcing agents.

Sulphur dioxide is the largest anthropogenic source of aerosols, and is emitted by fossil fuel combustion, metal smelting, and other industrial processes. Global sulphur emissions peaked in the 1970s, and have generally decreased since then. Uncertainty in global SO_2 emissions over this period is estimated to be relatively low (±10 %), although regional uncertainty can be higher (Smith et al., 2011).

A recent update of carbonaceous aerosol emissions trends (BC and OC) found an increase from 1970 through 2000, with a particularly notable increase in BC emissions from 1970 to 1980 (Lamarque et al., 2010). A recent assessment indicates that BC and OC emissions may be underestimated (Bond et al., 2013). These emissions are highly sensitive to combustion conditions, which results in a large uncertainty (+100 %/–50 %; Bond et al., 2007). Global emissions from 2000 to 2010 have not yet been estimated, but will depend on the trends in driving forces such as residential coal and biofuel use, which are poorly quantified, and petroleum consumption for transport, but also changes in technology characteristics and the implementation of emission reduction technologies.

Because of the large uncertainty in aerosol forcing effects, the trend in aerosol forcing over the last two decades is not clear (Shindell et al., 2013).

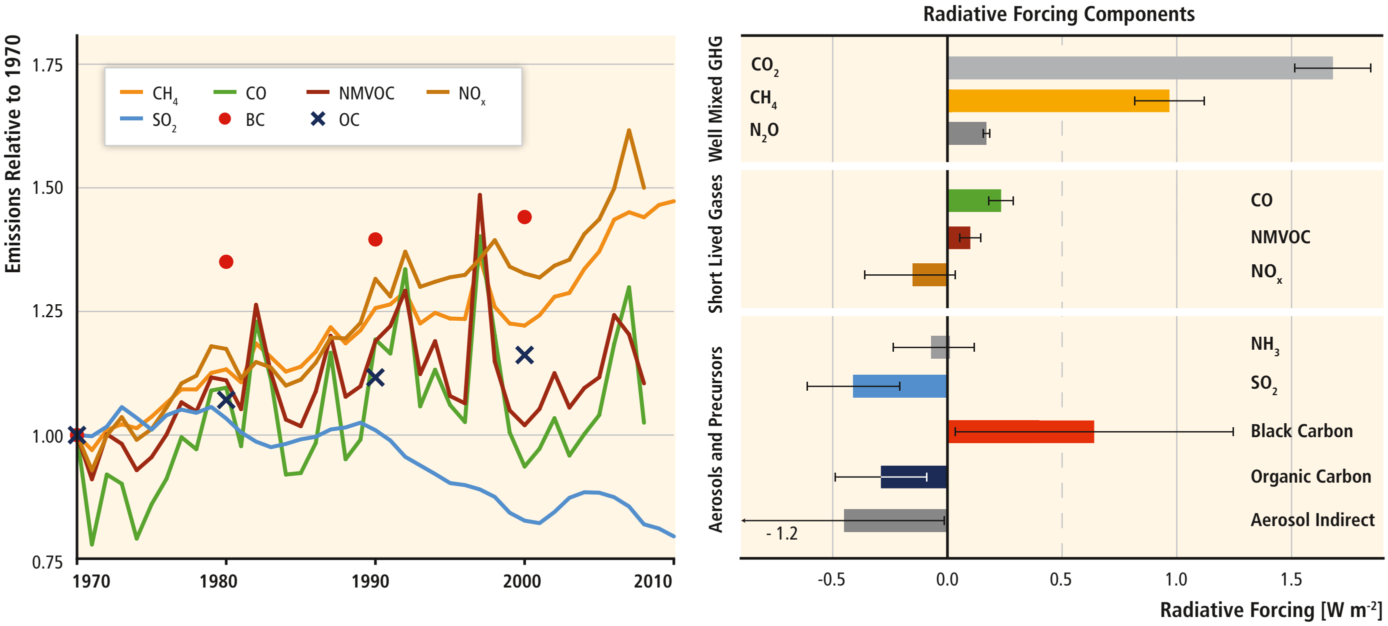


Figure 5.4 | Left panel: Global trends for air pollutant and methane emissions from anthropogenic and open burning, normalized to 1970 values. Short-timescale variability, in carbon monoxide (CO) and non-methane volatile organic compounds (NMVOC) in particular, is due to grassland and forest burning. Data from JRC/PBL (2013), except for SO_2 (Smith et al., 2011; Klimont et al., 2013), and BC/OC (Lamarque et al., 2010). Right panel: contribution of each emission species in terms of top of the atmosphere radiative forcing (adapted from Myhre et al., 2014, Figure 8.17). The aerosol indirect effect is shown separately as there is uncertainty as to the contribution of each species. Species not included in the left panel are shown in grey (included for reference).

Tropospheric ozone contributes a positive forcing and is formed by chemical reactions in the atmosphere. Ozone concentrations are impacted by a variety of emissions, including CH_4, nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic hydrocarbons (VOC) (Myhre et al., 2014). Global emissions of ozone precursor compounds are also thought to have increased over the last four decades. Global uncertainty has not been quantified for these emissions. An uncertainty of 10–20 % for 1990 NO_x emissions has been estimated in various European countries (Schöpp et al., 2005).

5.2.3 Emissions uncertainty

5.2.3.1 Methods for emissions uncertainty estimation

There are multiple methods of estimating emissions uncertainty (Marland et al., 2009), although almost all methods include an element of expert judgement. The traditional uncertainty estimation method, which compares emissions estimates to independent measurements, fails because of a mismatch in spatial and temporal scales. The data required for emission estimates, ranging from emission factors to fuel consumption data, originate from multiple sources that rarely have well characterized uncertainties. A potentially useful input to uncertainty estimates is a comparison of somewhat independent estimates of emissions, ideally over time, although care must be taken to assure that data cover the same source categories (Macknick, 2011; Andres et al., 2012). Formal uncertainty propagation can be useful as well (UNEP, 2012; Elzen et al., 2013) although one poorly constrained element of such analysis is the methodology for aggregating uncertainty between regions. Uncertainties in this section are presented as 5–95 % confidence intervals, with values from the literature converted to this range where necessary assuming a Gaussian uncertainty distribution.

Total GHG emissions from EDGAR as presented here are up to 5–10 % lower over 1970–2004 than the earlier estimates presented in AR4 (IPCC, 2007a). The lower values here are largely due to lower estimates of LUC CO_2 emissions (by 0–50 %) and N_2O emissions (by 20–40 %) and fossil CO_2 emissions (by 0–5 %). These differences in these emissions are within the uncertainty ranges estimated for these emission categories.

5.2.3.2 Fossil carbon dioxide emissions uncertainty

Carbon dioxide emissions from fossil fuels and cement production are considered to have relatively low uncertainty, with global uncertainty recently assessed to be 8 % (Andres et al., 2012). Uncertainties in fossil-fuel CO_2 emissions arise from uncertainty in fuel combustion or other activity data and uncertainties in emission factors, as well as assumptions for combustion completeness and non-combustion uses. Default uncertainty estimates (two standard deviations) suggested by the IPCC (2006) for fossil fuel combustion emission factors are lower for fuels that have relatively uniform properties (−3 %/+5 % for motor gasoline, −2 %/+1 % for gas/diesel oil) and higher for fuels with more diverse properties (–15 %/+18 % petroleum coke, –10 %/+14 % for lignite). Some emissions factors used by country inventories, however, differ from the suggested defaults by amounts that are outside the stated uncertainty range because of local fuel practices (Olivier et al., 2011). In a study examining power plant emissions in the United States, measured CO_2 emissions were an average of 5 % higher than calculated emissions, with larger deviations for individual plants (Ackerman and Sundquist, 2008). A comparison of five different fossil fuel CO_2 emissions datasets, harmonized to cover most of the same sources (fossil fuel, cement, bunker fuels, gas flaring) shows ±4 % differences over the last three decades (Macknick, 2011). Uncertainty in underlying energy production and consumption statistics, which are drawn from similar sources for existing emission estimates, will contribute further to uncertainty (Gregg et al., 2008; Guan et al., 2012).

Uncertainty in fossil CO_2 emissions increases at the country level (Marland et al., 1999; Macknick, 2011; Andres et al., 2012), with differences between estimates of up to 50 %. Figure 5.5 compares five estimates of fossil CO_2 emissions for several countries. For some countries the estimates agree well while for others more substantial differences exist. A high level of agreement between estimates, however, can arise due to similar assumptions and data sources and does not necessarily imply an equally low level of uncertainty. Note that differences in treatment of biofuels and international bunker fuels at the country level can contribute to differences seen in this comparison.

Figure 5.5 | Upper panels: five estimates of CO_2 emissions for the three countries with the largest emissions (and complete time series), including fossil fuel combustion, cement production, and gas flaring. Middle panels: the three countries with the largest percentage variation between estimates. Lower panel: global emissions ($MtCO_2$). Emissions data are harmonized data from Macknick (2011; downloaded Sept 2013), IEA (2012) and JRC / PBL (2013). Note that the vertical scales differ significantly between plots.

5.2.3.3 Other greenhouse gases and non-fossil fuel carbon dioxide

Uncertainty is particularly large for sources without a simple relationship to activity factors, such as emissions from LUC (Houghton et al., 2012; see also Chapter 11 for a comprehensive discussion), fugitive emissions of CH_4 and fluorinated gases (Hayhoe et al., 2002), and biogenic emissions of CH_4 and N_2O, and gas flaring (Macknick, 2011). Formally estimating uncertainty for LUC emissions is difficult because a number of relevant processes are not characterized well enough to be included in estimates (Houghton et al., 2012).

Methane emissions are more uncertain than CO_2, with fewer global estimates (US EPA, 2012; Höglund-Isaksson et al., 2012; JRC/PBL, 2013). The relationship between emissions and activity levels for CH_4 are highly variable, leading to greater uncertainty in emission estimates. Leakage rates, for example, depend on equipment design, environmental conditions, and maintenance procedures. Emissions from anaerobic decomposition (ruminants, rice, landfill) also are dependent on environmental conditions.

Nitrogen oxide emission factors are also heterogeneous, leading to large uncertainty. Bottom-up (inventory) estimates of uncertainty of 25 % (UNEP, 2012) are smaller than the uncertainty of 60 % estimated by constraining emissions with atmospheric concentration observation and estimates of removal rates (Ciais et al., 2013).

Unlike CO_2, CH_4, and N_2O, most fluorinated gases are purely anthropogenic in origin, simplifying estimates. Bottom up emissions, however, depend on assumed rates of leakage, for example, from refrigeration units. Emissions can be estimated using concentration data together with inverse modelling techniques, resulting in global uncertainties of 20–80 % for various perfluorocarbons (Ivy et al., 2012), 8–11 % for sulphur hexafluoride (SF_6) (Rigby et al., 2010), and ±6–11 % for HCFC-22 (Saikawa et al., 2012).[6]

5.2.3.4 Total greenhouse gas uncertainty

Estimated uncertainty ranges for GHGs range from relatively low for fossil fuel CO_2 (±8 %), to intermediate values for CH_4 and the F-gases (±20 %), to higher values for N_2O (±60 %) and net LUC CO_2 (50–75 %). Few estimates of total GHG uncertainty exist, and it should be noted that any such estimates are contingent on the index used to convert emissions to CO_2 equivalent values. The uncertainty estimates quoted here are also not time-dependent. In reality, the most recent data is generally more uncertain due to the preliminary nature of much of the information used to calculate estimates. Data for historical periods can also be more uncertain due to less extensive data collection infrastructure and the lack of emission factor measurements for technologies no longer in use. Uncertainty can also change over time due to changes in regional and sector contributions.

An illustrative uncertainty estimate of around 10 % for total GHG emissions can be obtained by combining the uncertainties for each gas assuming complete independence (which may underestimate actual uncertainty). An estimate of 7.5 % (90 percentile range) was provided by the United Nations Environment Programme (UNEP) Gap Report (UNEP, 2012, appendix), which is lower largely due to a lower uncertainty for fossil CO_2.

5.2.3.5 Sulphur dioxide and aerosols

Uncertainties in SO_2 and carbonaceous aerosol (BC and OC) emissions have been estimated by Smith et al. (2011) and Bond et al. (2004, 2007). Sulphur dioxide emissions uncertainty at the global level is relatively low because uncertainties in fuel sulphur content are not well correlated between regions. Uncertainty at the regional level ranges up to 35 %. Uncertainties in carbonaceous aerosol emissions, in contrast, are high at both regional and global scales due to fundamental uncertainty in emission factors. Carbonaceous aerosol emissions are highly state-dependent, with emissions factors that can vary by over an order of magnitude depending on combustion conditions and emission controls. A recent assessment indicated that BC emissions may be substantially underestimated (Bond et al., 2013), supporting the literature estimates of high uncertainty for these emissions.

5.2.3.6 Uncertainties in emission trends

For global fossil CO_2, the increase over the last decade as well as previous decades was larger than estimated uncertainties in annual emissions, meaning that the trend of increasing emissions is robust. Uncertainties can, however, impact the trends of fossil emissions of specific countries if increases are less rapid and uncertainties are sufficiently high.

Quantification of uncertainties is complicated by uncertainties not only in annual uncertainty determinations but also by potential year-to-year uncertainty correlations (Ballantyne et al., 2010, 2012). For fossil CO_2, these correlations are most closely tied to fuel use estimates, an integral part of the fossil CO_2 emission calculation. For other emissions, errors in other drivers or emission factors may have their own temporal trends as well. Without explicit temporal uncertainty considerations, the true emission trends may deviate slightly from the estimated ones.

In contrast to fossil-fuel emissions, uncertainties in global LUC emissions are sufficiently high to make trends over recent decades uncertain in direction and magnitude (see also Chapter 11).

While two global inventories both indicate that anthropogenic methane emissions have increased over the last three decades, a recent

[6] HCFC-22 is regulated under the Montreal Protocol but not included in fluorinated gases totals reported in this chapter as it is not included in the Kyoto Protocol.

assessment combining atmospheric measurements, inventories, and modelling concluded that anthropogenic methane emissions are likely to have been flat or have declined over this period (Kirschke et al., 2013). The EDGAR inventory estimates an 86-Mt-CH_4 (or 30 %) increase over 1980–2010 and the EPA (2012) historical estimate has a 26-Mt-CH_4 increase from 1990–2005 (with a further 18-Mt-CH_4 projected increase to 2010). (Kirschke et al., 2013) derives either a 5-Mt increase or a net 15-Mt decrease over this period, which indicates the inventories may be overestimating the increase in anthropogenic methane emissions. These results suggest that estimates of methane emission uncertainties of 20 % (UNEP, 2012; Kirschke et al., 2013) for anthropogenic emissions may be too low, since the differences in trend between inventories and the inversion synthesis are of this magnitude.

Overall, global SO_2 emissions have decreased over the last two decades, decreasing again in recent years following an increase from about 2000–2005 (Klimont et al., 2013). Global trends in carbonaceous aerosols over the past decade have not been estimated, however, BC and OC emissions from fuel combustion in China and India were estimated to have increased over 2000–2010 (Lu et al., 2011).

5.2.3.7 Uncertainties in consumption-based carbon dioxide emission accounts

Consumption-based CO_2 emission accounts reallocate part of the territorial CO_2 emissions associated with the production of exports to the countries where they are eventually consumed (Peters, 2008; Minx et al., 2009). Different techniques and assumptions have been applied in modelling consumption-based CO_2 emissions including aggregation or disaggregation of production sectors (Lenzen, 2011; Lindner et al., 2012, 2013); consideration of price and deflation effects (Dietzenbacher and Hoen, 1998; Dietzenbacher and Wagener, 1999); use of balancing techniques for data discrepancies (Rey et al., 2004; Lenzen et al., 2009, 2010); simplifying multi-regional input-output models (Nansai et al., 2009a); and use of domestic production structure as a proxy for imports (Suh, 2005). Different models and assumptions result in substantially different estimates of consumption-based CO_2 emissions, but a direct comparison between these remains a gap in the literature.

Uncertainties in consumption-based emission accounts arise from various sources (Lenzen et al., 2010) including (1) uncertainty in the territory-based emission estimates (see previous sections); (2) uncertainties in input-output and international trade statistics (Lenzen et al., 2010); and (3) uncertainties in the definitions, level of aggregation, and assumptions underlying the model (Peters and Solli, 2010; Kanemoto et al., 2012; Andres et al., 2012).

There has been little quantitative analysis of this at the global level, with only a few comparisons across different versions of the same dataset (Andrew and Peters, 2013) and direct comparisons between studies (Andres et al., 2012). However, there have been detailed studies at the country level (Lenzen et al., 2010) and many of the mechanisms of uncertainty are understood.

The few quantitative studies on the uncertainty and model spread in global analyses confirm that the uncertainty in consumption-based emissions are larger than territorial emissions, though trends over time are likely to be robust (Andres et al., 2012). The uncertainty in territorial emission estimates is a key driver for the uncertainty in consumption-based emissions, and differences in definition and system boundaries can lead to important differences (Peters and Solli, 2010). A detailed assessment of the uncertainty due to different supply chain models is lacking, and this remains a large gap in the literature. Based on model comparisons, particularly for large countries or regions, the uncertainties may be less important than the uncertainties in territorial emission estimates used as inputs.

5.3 Key drivers of global change

5.3.1 Drivers of global emissions

This section analyzes drivers of the global trends in GHG emissions that were discussed in Section 5.2. In general, drivers are the elements that directly or indirectly contribute to GHG emissions. While there is no general consensus in the literature, some researchers distinguish proximate versus underlying or ultimate drivers (see e.g., Angel et al., 1998; Geist and Lambin, 2002), where proximate drivers are generally the activities that are directly or closely related to the generation of GHGs and underlying or ultimate drivers are the ones that motivate the proximate drivers.

There is neither a unique method to identify the drivers of climate change, nor can the drivers always be objectively defined: human activities manifest themselves through a complex network of interactions, and isolating a clear cause-and-effect for a certain phenomenon purely through the lens of scientific observation is often difficult. Therefore, the term, 'driver' may not represent an exact *causality* but is used to indicate an *association* to provide insights on what constitutes overall changes in global GHG emissions.

In the literature, studies recognize various factors as main drivers to GHG emissions including consumption (Morioka and Yoshida, 1995; Munksgaard et al., 2001; Wier et al., 2001; Hertwich and Peters, 2009), international trade (Weber and Matthews, 2007; Peters and Hertwich, 2008; Li and Hewitt, 2008; Yunfeng and Laike, 2010; Peters et al., 2011; Jakob and Marschinski, 2013), population growth (Ehrlich and Holdren, 1971; O'Neill et al., 2010), economic growth (Grossman and Krueger, 1994; Arrow et al, 1996; Stern et al., 1996; Lim et al., 2009; Blodgett and Parker, 2010; Carson, 2010), structural change to a service econ-

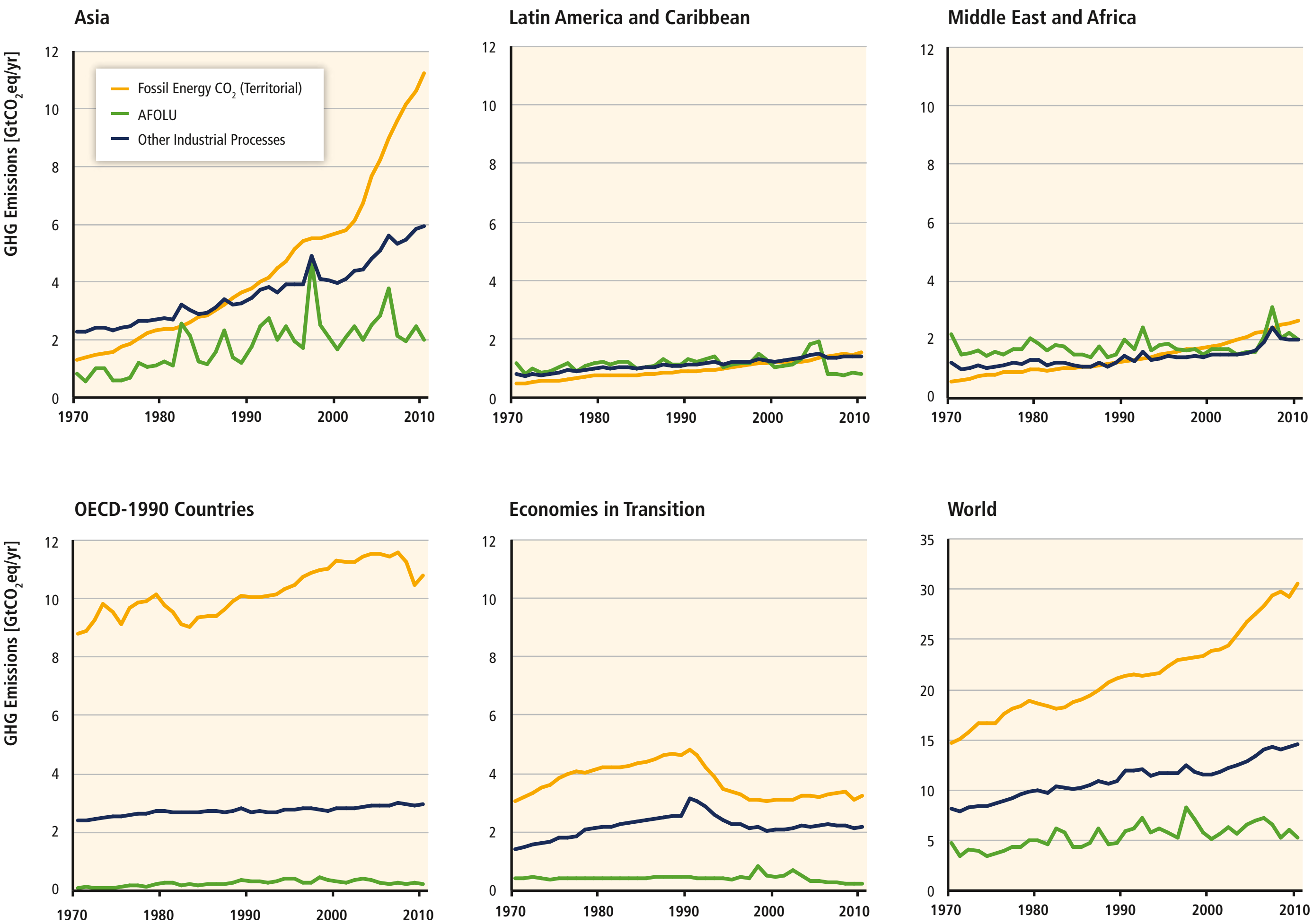


Figure 5.6 | Territorial GHG emissions per region over 1970–2010. Note that only the bottom-right panel for the World has a different scale for its vertical axis. Fossil energy CO_2 indicates emissions from fossil fuel combustion. Emissions are aggregated using 100-year GWP values. Data from JRC/PBL (2013) and IEA (2012). Regions are defined in Annex II.2 | The direct emission data from JRC/PBL (2013) (see Annex II.9) represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthropogenic emission sources in the FOLU sub-sector. For a more detailed representation of Agriculture and FOLU (AFOLU) GHG flux, see Section 11.2 and Figures 11.2 and 11.6.

omy (Suh, 2006; Nansai et al., 2009b), and energy consumption (Wier, 1998; Malla, 2009; Bolla and Pendolovska, 2011). Each of these topics will be discussed in more depth, starting in Section 5.3.2.

Obviously many drivers of GHG emissions are interlinked with each other, and furthermore, many of these drivers can be further decomposed into various subcomponents. For example, transportation emissions are an important driver of increasing GHG emissions globally. But there is a wide regional variation in its significance. Furthermore, the increase in vehicle miles driven per capita or changes in fuel economy of average vehicle fleet can also be referred to as a driver, while these drivers are underlying to the higher-level driver, namely changes to transportation emissions. Therefore, drivers to GHG emissions can only be understood in the context of scale, level of detail, and the framework under which the factors contributing to GHG emissions are analyzed.

5.3.1.1 Key drivers

Figure 5.6 shows that, globally AFOLU emissions have increased by 12 % between 1970 and 2010. The AFOLU emissions have been more pronounced in non-OECD-1990 regions and dominate total GHG emissions from MAF and LAM regions. Major increases in global GHG emission have been, however, associated with CO_2 emissions from fossil energy (+108 % between 1970 and 2010), which has been growing more rapidly since AR4 (IPCC, 2007b).

Figure 5.7 shows this increase in fossil energy CO_2 decomposed into changes in population (+87 %), per capita GDP adjusted with Purchasing Power Parity (PPP) (+103 %), energy intensity in GDP (–35 %) and CO_2 intensity of energy (–15 %) between 1970 and 2010. Over the last decade, however, the long trend of decreasing carbon intensity in energy has been broken, and it increased by 1.7 %. In short, the

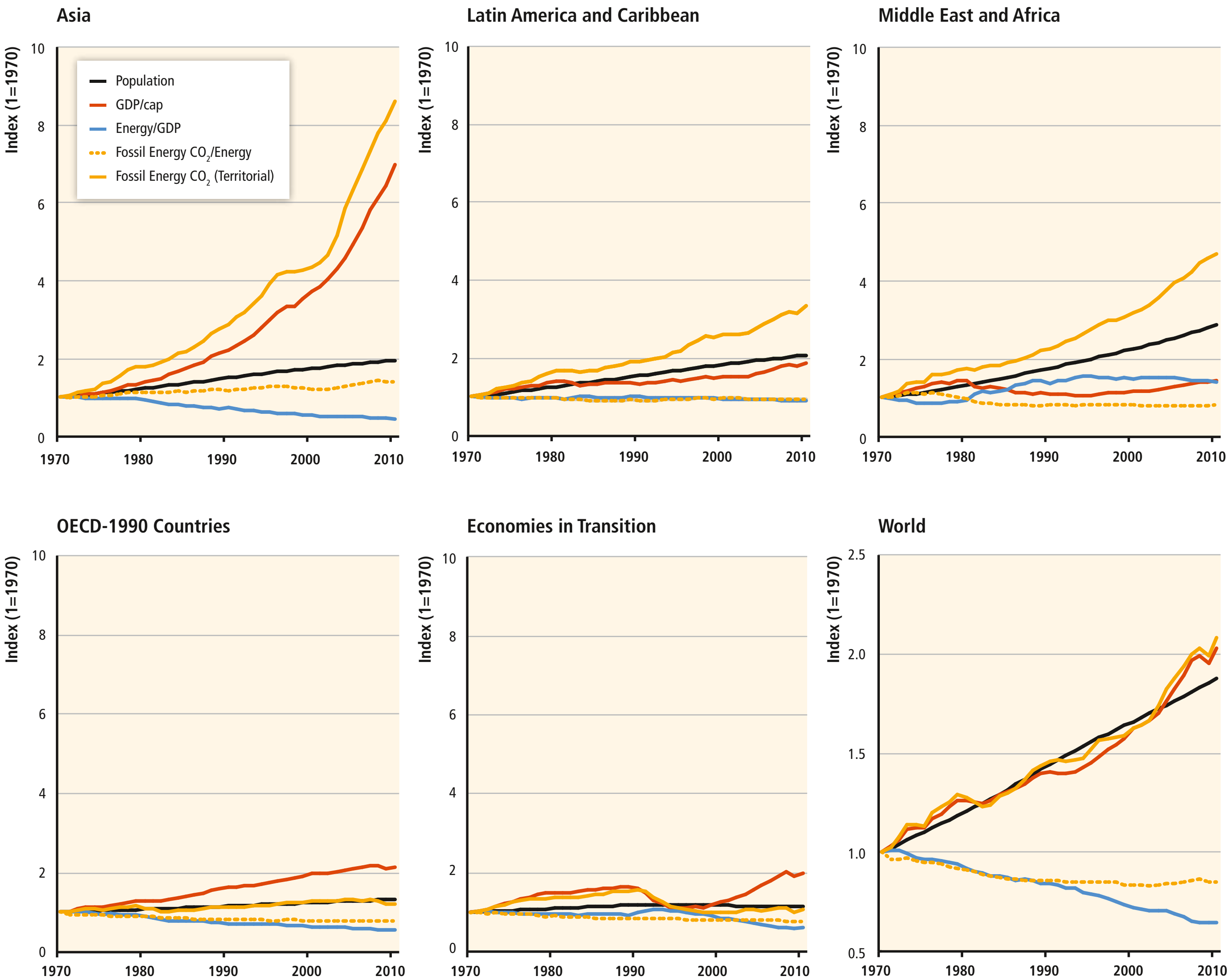


Figure 5.7 | Four factor decomposition of territorial CO_2 emission from fossil fuel combustion at regional level over 1970–2010. Note that only the bottom-right panel for the World has a different scale for its vertical axis. Data from IEA (2012) and JRC/PBL (2013); based on PPP-adjusted GDP. Regions are defined in Annex II.2.

improvements in energy intensity of GDP that the world has achieved over the last four decades could not keep up with the continuous growth of global population resulting in a closely synchronous behaviour between GDP per capita and CO_2 emission during the period.

At a regional scale, all regions but Asia show 5 % to 25 % reduction in CO_2 intensity of energy consumption, while Asia increased CO_2 intensity of energy consumption by 44 % between 1970 and 2010. Energy intensity of GDP declined significantly in the EIT, ASIA, and OECD-1990 (39 %–55 %) and moderately in LAM (9 %), while in MAF it increased by 41 %. Energy intensity of GDP may increase as an economy enters into an industrialization process, while it generally decreases as the industrialization process matures and as the share of service sector in the economy grows (Nansai et al., 2007; Henriques and Kander, 2010). In all regions, population growth has been a persistent trend. The EIT region showed the lowest population growth rate over the last four decades (16 %), whereas MAF marked 188 % increase in population during the same period. ASIA gained the most to its population from 1.9 billion to 3.7 billion during the period. Purchasing Power Parity (PPP-) adjusted GDP also grew in all regions ranging from 43 % (MAF), about two-fold (OECD-1990, EIT, and LAM) to a remarkable six-fold increase (ASIA) over the last four decades. In general, the use of PPP-adjusted GDP instead of Market Exchange Rate (MER)-based GDP gives more weight to developing economies and their GDP growth (Raupach et al., 2007).

In summary, the improvements in energy intensity in GDP over the last four decades could not keep up with the stable and persistent upward trends in GDP per capita and population. In particular, a strong growth in GDP per capita in ASIA combined with its population growth has been the most significant factors to the increase in GHG emissions during the period.

Global CO_2 emissions from fossil energy are decomposed into three factors using territorial and consumption accounts. Figure 5.8 high-

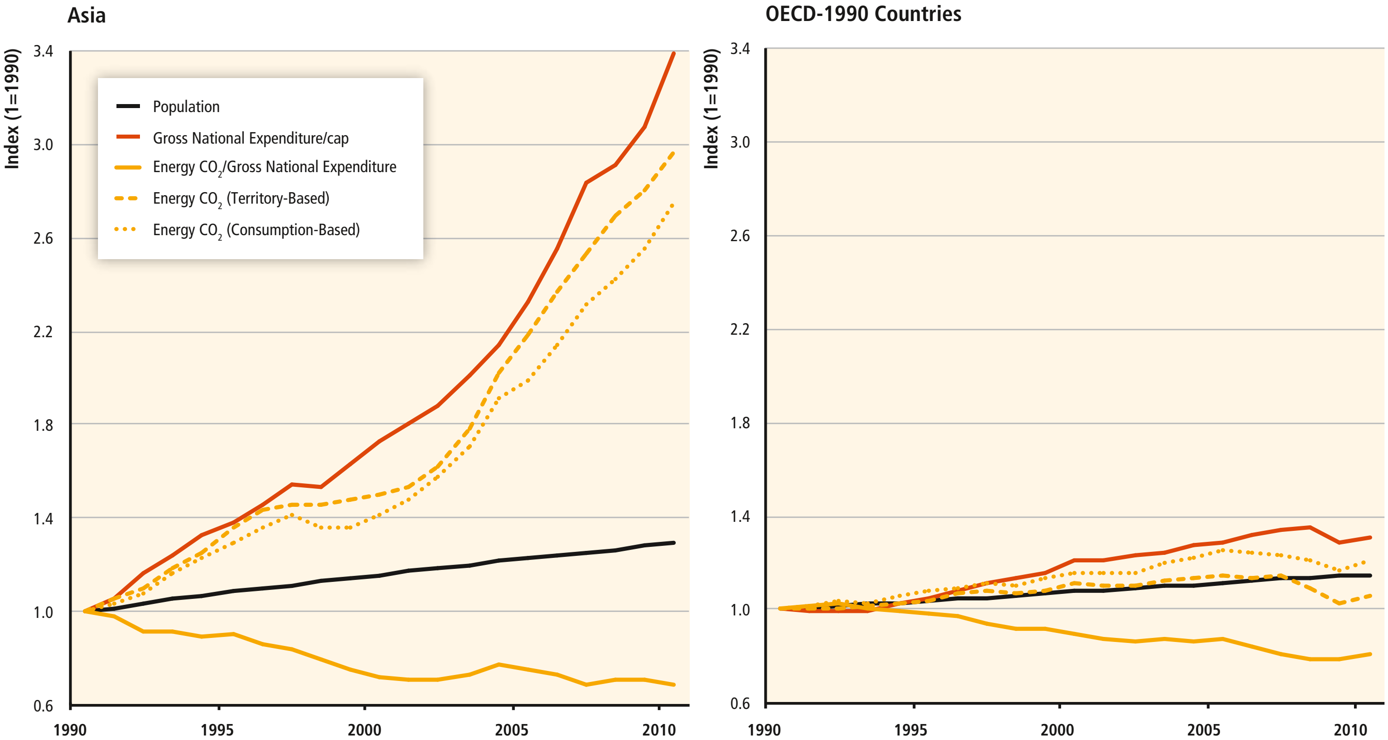


Figure 5.8 | Three factor decomposition of consumption-based and territorial CO_2 emission from fossil fuel combustion for Asia (left) and OECD (right) over 1990–2010. Data from IEA (2012) and JRC/PBL (2013). Regions are defined in Annex II.2.

lights the case of ASIA and OECD-1990, where the gap between the two approaches is largest, over the 1990–2010 period. Based on a territorial accounting, OECD-1990 increased its CO_2 emissions from fossil energy only by 6 % from 1990 to 2010. The increase in CO_2 emission from fossil energy embodied in consumption by OECD-1990, however, is more significant (22 %) during the period. On the other hand, CO_2 emission embodied in consumption by ASIA increased by 175 % during the period, while its territorial emissions increased by 197 % during the period. Increasing international trade played an important role in this result, which will be elaborated in Section 5.4.

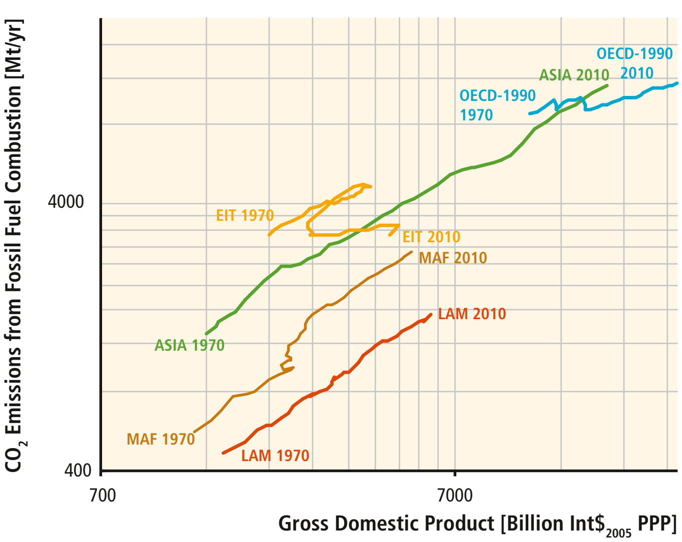


Figure 5.9 | Regional trajectories of territorial CO_2 emissions from fossil fuel combustion versus GDP over 1970–2010. Data from IEA (2012) and JRC/PBL (2013). Regions are defined in Annex II.2.

The strong correlation between GDP and CO_2 emissions can be identified from the historical trajectories of CO_2 emissions and GDP (Figure 5.9). Although there are notable exceptions (EIT), regional CO_2 emission trajectories are closely aligned with the growth in GDP. On average, 1 % of world GDP increase has been associated with 0.39 % increase in fossil energy CO_2 emission during the 1970–2010 period. Over the last two decades, however, 1 % of world GDP increase has been accompanied with 0.49 % increase in fossil energy CO_2 emission (1990–2010) due largely to the rapid growth of the energy-intensive non-OECD Asian economy.

Overall, the growth in production and consumption outpaced the reduction in CO_2 emissions intensity of production and that embodied in consumption. Together with the growth in population, global CO_2 emissions from fossil energy maintained a stable upward trend, which characterizes the overall increase in global GHG emissions over the last two decades.

Box 5.1 | IPAT and Kaya decomposition methods

The IPAT (Ehrlich and Holdren, 1971) and Kaya (Kaya, 1990) identities provide two common frameworks in the literature for analyzing emission drivers by decomposing overall changes in GHG emissions into underlying factors. The Kaya identity is a special case of the more general IPAT identity (Ehrlich and Holdren, 1971). The IPAT identity decomposes an impact (I, e.g., total GHG emissions) into population (P), affluence (A, e.g., income per capita) and technology (T, e.g., GHG emission intensity of production or consumption). The Kaya identity deals with a subset of GHG emissions, namely CO_2 emissions from fossil fuel combustion, which is the dominant part of the anthropogenic GHG emissions and their changes at a global level (Figure 5.6). While global GHG emissions measured in GWP 100 have increased in all three categories, namely fossil energy CO_2, AFOLU, and other over the last four decades, fossil energy CO_2 dominates the absolute growth of GHG emissions in all regions and the world during the period. Two approaches to GHG accounting are distinguished in the literature, namely territorial and consumption accounts (see Box 5.2 for the definition). The Kaya identity for territorial CO_2 emissions can be written as:

(1) Territorial CO_2 emissions =

$$\text{population} \times \frac{\text{GDP}}{\text{population}} \times \frac{\text{Energy}}{\$\text{GDP}} \times \frac{CO_2\text{ emission}}{\text{Energy}}$$

In other words, CO_2 emissions are expressed as a product of four underlying factors: (1) population, (2) per capita GDP (GDP/population), (3) energy intensity of GDP (Energy/GDP), and (4) CO_2 intensity of energy (CO_2 emissions/energy) (Raupach et al., 2007; Steckel et al., 2011). Also even simpler decomposition forms can be found in the literature (Raupach et al., 2007). They are obtained when any two or three adjoining factors in the four-factor Kaya identity in equation (1) are merged. For example, merging energy intensity of GDP and CO_2 intensity of energy into CO_2 intensity of GDP, a three-factor decomposition can be written as:

(2) Territorial CO_2 emissions =

$$\text{population} \times \frac{\text{GDP}}{\text{population}} \times \frac{CO_2\text{ emission}}{\text{GDP}}$$

Similarly, consumption-based CO_2 emissions can be decomposed such that

(3) Consumption – based CO_2 emissions =

$$\text{population} \times \frac{\text{GNE}}{\text{population}} \times \frac{\text{consumption} - \text{based } CO_2\text{ emission}}{\text{GNE}}$$

In this case, consumption-based CO_2 emissions are decomposed into (1) population, (2) per capita consumption (GNE/population; GNE = Gross National Expenditure), and (3) embodied CO_2 intensity of consumption (consumption-based CO_2 emission/GNE). The Kaya identity can also be expressed as a ratio between two time periods to show relative change in CO_2 emissions and its contributing factors (Raupach et al., 2007).

5.3.2 Population and demographic structure

5.3.2.1 Population trends

In the second half of the 19th century, global population increased at an average annual rate of 0.55 %, but it accelerated after 1900. Population size and age composition are driven by fertility and mortality rates, which in turn depend on a range of factors, including income, education, social norms, and health provisions that keep changing over time, partly in response to government policies. Section 4.3.1 discusses these processes in depth. Figure 5.10 presents the main outcomes. Between 1970 and 2010, global population has increased by 87 %, from 3.7 billion to 6.9 billion (Wang et al., 2012a). The underlying process is the demographic transition in which societies move from a relatively stable population level at high fertility and mortality rates, through a period of declined mortality rates and fast population growth, and only at a later stage followed by a decline in fertility rates with a more stable population size.

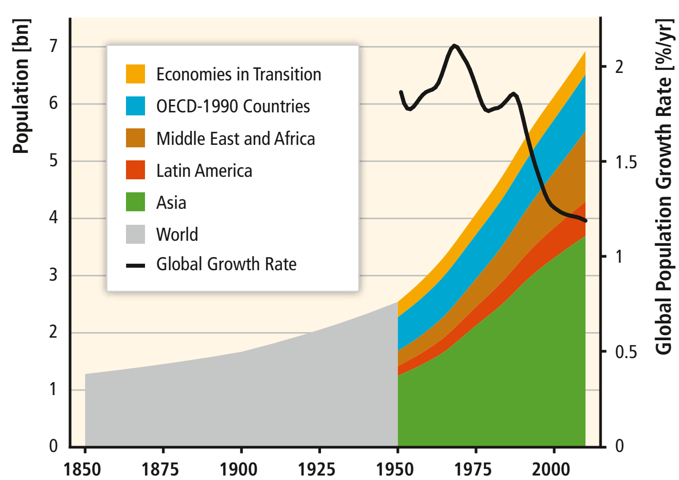


Figure 5.10 | Trends in regional and global population growth 1850–2010 | Global data up to 1950 (grey from (UN, 1999). Regional data from 1950 onwards from UN WPP (2012). Regions are defined in Annex II.2.

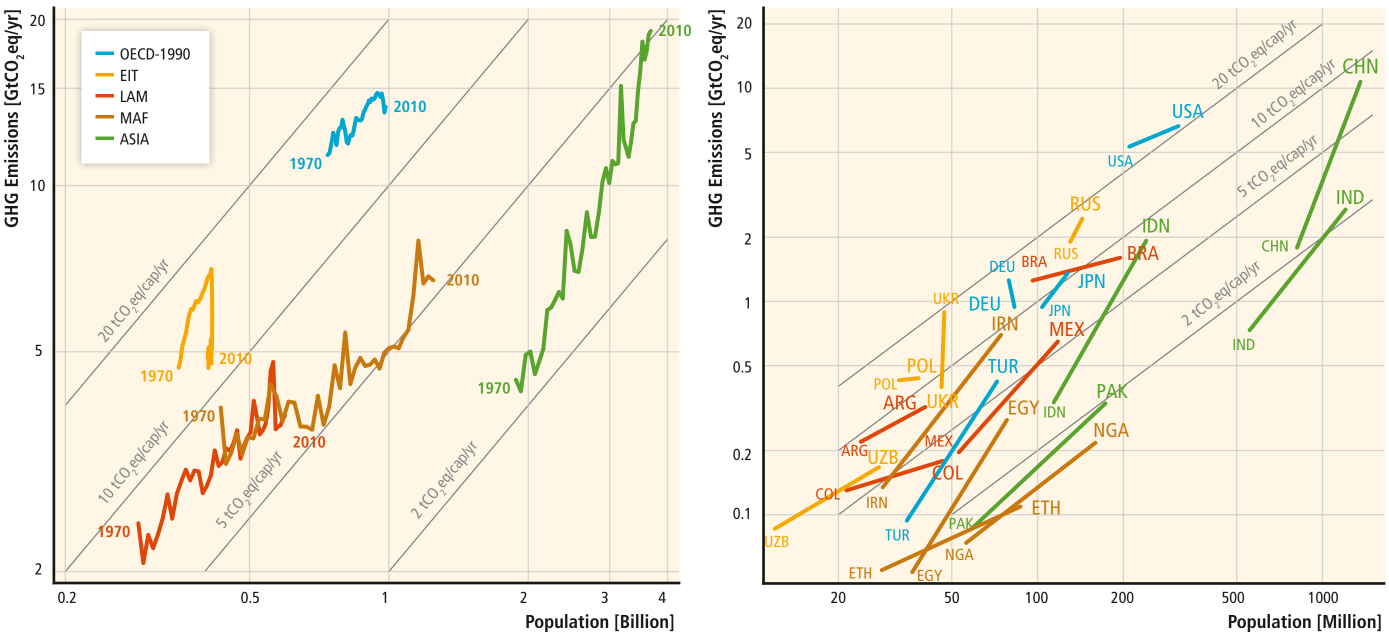


Figure 5.11 | Regional trends in population and GHG emissions (left panel) and for each region the four most populous countries in 2010 (right panel). Regions are defined in Annex II.2 | Grey diagonals connect points with constant emission intensity. Major GHG-emitting regions or countries are in the upper half. A shift to the right presents population growth. A steep line presents a growth in per capita emissions, while a flat line presents decreasing per capita emissions between 1971 and 2010 | Right panel: The small labels refer to 1970, the large labels to 2010 | Data from JRC/PBL (2013) and IEA (2012). (Note the log-log plot.)

Each person added to the global population increases GHG emissions, but the additional contribution varies widely depending on the socio-economic and geographic conditions of the additional person. There is a 91-fold difference in per capita CO_2 emissions from fossil fuels between the highest and lowest emitters across the nine global regions analyzed by Raupach et al. (2007). Global CO_2 emissions from fossil fuel combustion have been growing at about the growth rate of global population in most of the 1970–2010 period, but emissions growth accelerated toward the end of the period (Figure 5.7).

Aggregating population and GHG emissions data according to the five IPCC Representative Concentration Pathways (RC) regions (see Annex II.2), Figure 5.11 shows that between 1971 and 2010 population growth was fastest in the MAF; GHG emissions have increased most in ASIA while changes in population and emissions were modest in OECD-1990 and EIT. The evolution of total population and per capita GHG emissions in the same period is shown in Figure 5.11. With some fluctuations, per capita emissions have declined slightly from rather high levels in the OECD-1990 countries and the EIT, decreased somewhat from relatively lower levels in LAM and especially in the MAF, while more than doubled in ASIA. These trends raise concerns about the future: per capita emissions decline slowly in high-emission regions (OECD-1990 and EIT) while fast increasing per capita emissions are combined with relatively fast population and per capita income growth in ASIA (JRC/PBL, 2013).

There is a substantial number of empirical econometric studies that assess the role of various demographic attributes; an early example is (Dietz and Rosa, 1997). Those reviewed by O'Neill et al. (2012) confirm earlier observations that GHG emissions increase with the population size, although the elasticity values (percent increase in emissions per 1 % increase in population size) vary widely: from 0.32 (Martínez-Zarzoso and Maruotti, 2011) to 2.78 (Martínez-Zarzoso et al., 2007) (for the eight new European Union countries of Central Europe). Differences in statistical estimation techniques and data sets (countries included, time horizon covered, the number and kind of variables included in the regression model and their possible linkages to excluded variables) explain this wide range. Most recent studies find more than proportional increase of emissions triggered by the increase in population. Yet the literature presents contradicting results concerning whether population growth in rich or poor countries contributes more to increasing GHG emissions: Poumanyvong and Kaneko (2010) estimate elasticities ranging from 1.12 (high-income) to 1.23 (middle-income) to 1.75 (low-income) countries while Jorgenson and Clark (2010) find a value of 1.65 for developed and 1.27 for developing groups of countries.

5.3.2.2 Trends in demographic structure

Urbanization

Income, lifestyles, energy use (amount and mix), and the resulting GHG emissions differ considerably between rural and urban populations. The global rate of urbanization has increased from 13 % (1900) to 36 % (1970) to 52 % (2011), but the linkages between urbanization and GHG-emissions trends are complex and involve many factors including the level of development, rate of economic growth, availability of energy resources and technologies, and urban form and infrastructure.

Comparable direct measures of the effect of urbanization on emissions remain difficult due to challenges of defining consistent system boundaries, including administrative or territorial, functional or economic, and morphological or land use boundaries. Moreover, because urban areas are typically much smaller than the infrastructure (e.g., transport, energy) in which they are embedded, strict territorial emissions accounting such as that used for nations, omits important emissions sources such as from energy production (Chavez and Ramaswami, 2013). An alternative is to measure the effect of urbanization indirectly, through statistical analysis of national emission data and its relation to national urbanization trends. An analysis of the effects of urbanization on energy use and CO_2 emissions over the period 1975–2005 for 99 countries, divided into three groups based on GDP per capita, and explicitly considering the shares of industry and services and the energy intensity in the CO_2 emissions, concludes that the effects depend on the stage of development. The impact of urbanization on energy use is negative (elasticity of −0.132) in the low-income group, while positive (0.507) in the medium-income group, and strongly positive (0.907) in the high-income group. Emissions (for given energy use) are positively affected in all three income groups (between 0.358 and 0.512) (Poumanyvong and Kaneko, 2010). Consistent with this conclusion, a set of multivariate decomposition studies reviewed by O'Neill et al. (2012) estimate elasticity values between 0.02 and 0.76, indicating almost negligible to significant but still less than proportional increases in GHG emissions as a result of urbanization. In China, between 1992 and 2007, urbanization and the related lifestyle changes contributed to increasing energy-related CO_2 emissions (Minx et al., 2011).

Many studies observe that GHG emissions from urban regions vary significantly between cities, but that measurements are also widely dispersed due to differences in accounting methods, the coverage of GHGs and their sources, and the definition of urban areas (Dhakal, 2009). A comparison of GHG emissions in 10 global cities by considering geophysical characteristics (climate, resources, gateway status (port of entry and distribution centre for larger regions due to its geographic location), and technical features (urban design, electricity generation, waste processing) finds various outstanding determinants. For example, the level of household income is important because it affects the threshold temperature for heating and cooling of the residential area. The use of high versus low-carbon sources for electricity production, such as nuclear power, is an important determinant of urban GHG emissions in several global cities in the examined sample. Other determinants include connectivity, accessibility of destination and origin, and ability to use alternative transportation modes including mass transit, bicycling, or walking. GHG emissions associated with aviation and marine fuels reflect the gateway status of cities that, in turn, is linked to the overall urban economic activity (Kennedy et al., 2009).

An extended analysis of the urbanization-emissions linkage in 88 countries between 1975 and 2003 finds a diverse picture. In 44 countries, urbanization is found to be not a statistically significant contributor to emissions. In the other 44 countries, all other things equal, in the early phase of urbanization (at low-urbanization levels) emissions increased, while further urbanization at high-urbanization levels was associated with decreasing emissions (Martínez-Zarzoso and Maruotti, 2011). This also confirms that in fast-growing and urbanizing developing countries, urban households tend to be far ahead of rural households in the use of modern energy forms and use much larger shares of commercial energy. Urbanization thereby involves radical increases in household electricity demand and in CO_2 emissions as long as electricity supply comes from fossil fuelled, especially coal based power plants. Transition from coal to low-carbon electricity could mitigate the fast increasing CO_2 emissions associated with the combination of fast urbanization and the related energy transition in these countries.

The literature is divided about the contribution of urbanization to GHG emissions. Most top-down studies find increasing emissions as urbanization advances, while some studies identify an inverted U-shaped relationship between the two. Bottom-up studies often identify economic structure, trade typology, and urban form as central determinants that are more important than the fraction of people in urban areas (see Chapter 12). These findings are important to consider when extrapolating past emission trends, based on past urbanization, to the future, together with other related aspects.

Age structure and household size

Studies of the effect of age structure (especially ageing) on GHG emissions fall into two main categories with seemingly contradicting results: overall macroeconomic studies, and household-level consumption and energy use patterns of different age groups. A national-scale energy-economic growth model calculates for the United States that ageing tends to reduce long-term CO_2 emissions significantly relative to a baseline path with equal population levels (Dalton et al., 2008). Lower labour force participation and labour productivity would slow economic growth in an ageing society, leading to lower energy consumption and GHG emissions (O'Neill et al., 2010). In contrast, studies taking a closer look at the lifestyles and energy consumption of different age groups find that older generations tend to use more energy and emit above average GHGs per person. A study of the impacts of population, incomes, and technology on CO_2 emissions in the period 1975–2000 in over 200 countries and territories finds that the share of the population in the 15–64 age group has a different impact on emissions between different income groups: the impact is negative for high-income countries and positive for lower-income levels (Fan et al., 2006). This is consistent with the finding that (in the United States) energy intensity associated with the lifestyles of the 20–34 and the above 65 retirement-age cohorts tends to be higher than that of the 35–64 age group, largely explained by the fact that this middle-age cohort tends to live in larger households characterized by lower-energy intensity on a per person basis and that residential energy consumption and electricity consumption of the 65+ age group tends to be higher (Liddle and Lung, 2010). Similar results emerge for 14 'foundational' European Union countries between 1960 and 2000: an increasing share of the 65+ age group in the total population leads to increasing energy consumption although the aggregated data disguise micro-level processes:

ageing may well influence the structure of production, consumption, transport, social services, and their location (York, 2007). Several studies assessed above indicate that part of the increasing emissions with age is due to the differences in household size. A five-country multivariate analysis of household energy requirement confirms this (Lenzen et al., 2006). Immigration is not explicitly considered in these studies, probably because it does not make much difference.

It remains an open question by how much the household-level effects of increasing CO_2 emissions as a result of ageing population will counterbalance the declining emissions as a result of slower economic growth caused by lower labour force participation and productivity. The balance is varied and depends on many circumstances. The most important is changes in labour participation: increasing retirement age in response to higher life expectancy will keep former retirement-age cohorts (60+) economically active, which means that the implications of ageing for incomes, lifestyles, energy use, and emissions are 'postponed' and the ratio of active/retired population changes less. Other important aspects include the macroeconomic structure, key export and import commodity groups, the direction and magnitude of financial transfers on the macro side, and on the health status, financial profile, and lifestyle choices and possibilities of the elderly at the household level. This makes it difficult to draw firm conclusions about the ageing-emissions linkages.

Despite the widely varying magnitudes and patterns of household energy use due to differences in geographical and technological characteristics, lifestyles, and population density, most studies tend to indicate that past trends of increasing age, smaller household size, and increasing urbanization were positive drivers for increasing energy use, and associated GHG emissions.

5.3.3 Economic growth and development

5.3.3.1 Production trends

This section reviews the role of income per capita as a driver of emissions while reserving judgement on the appropriateness of GDP per capita as an indicator of development or welfare (see Kubiszewski et al., 2013). Global trends in per capita GDP and GHG emissions vary dramatically by region as shown in Figure 5.12. Economic growth was strongest in ASIA averaging 5.0 % per annum over the 1970–2010 period. Economic growth averaged 1.9 % p.a. in the OECD-1990, but was below the global average of 1.8 % in the remaining regions. The MAF and the reforming economies saw setbacks in growth related to the changing price of oil and the collapse of the centrally planned economies, respectively. However, all regions showed a decline in emissions intensity over time. Emissions per capita grew in ASIA and were fairly constant in LAM, OECD-1990, and EIT, as well as globally, and declined in MAF. The levels of GDP and emissions per capita also vary tremendously globally as shown in Figure 5.12.

Per capita emissions are positively correlated with per capita income. But per capita emissions have declined in all regions but ASIA over time, so that there has been convergence in the level of per capita

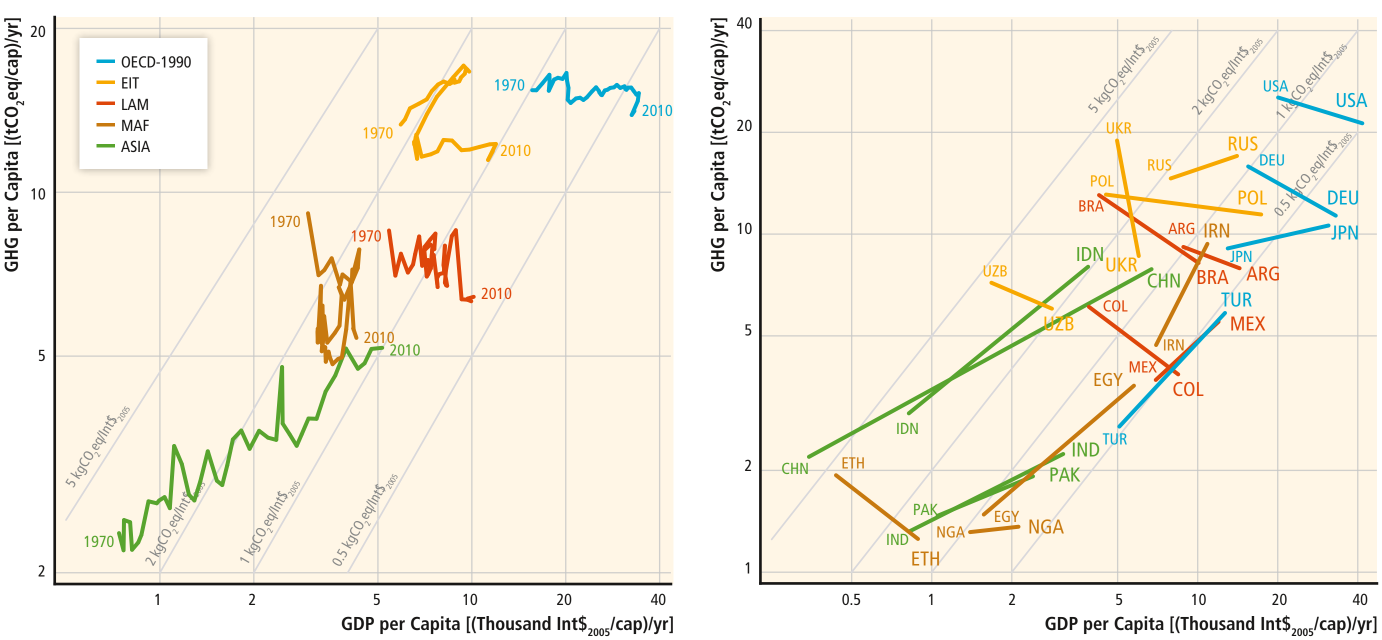


Figure 5.12 | Regional trends in per capita production and GHG emissions (left panel), and for each region the four most populous countries in 2010 (right panel). Regions are defined in Annex II.2. Grey diagonals connect points with constant emission intensity (emissions/GDP). A shift to the right presents income growth. A flat or downwards line presents a decrease in energy intensity, 1971 and 2010. Right panel: The small labels refer to 1970, the large labels to 2010. The figure shows a clear shift to the right for some countries: increasing income at similar per capita emission levels. The figures also show the high income growth for Asia associated with substantial emissions increase. Data from JRC/PBL (2013) and IEA (2012).

emissions over time. Despite this convergence, there is still a wide variation in per capita emissions levels among countries at a common level of income per capita due to structural and institutional differences (Pellegrini and Gerlagh, 2006; Matisoff, 2008; Stern, 2012).

The nature of the relationship between growth and the environment and identification of the causes of economic growth are both uncertain and controversial (Stern, 2011). The sources of growth are important because the degree to which economic growth is driven by technological change versus accumulation of capital and increased use of resources will strongly affect its impact on emissions. In particular, growth in developing countries might be expected to be more emissions-intensive than growth through innovation in technologically leading developed economies (Jakob et al., 2012). However, despite this, energy use per capita is strongly linearly correlated with income per capita across countries (Krausmann et al., 2008; see also Figure 5.15). The short-run effects of growth are slightly different; it seems that energy intensity rises or declines more slowly in the early stages of business cycles, such as in the recovery from the global financial crisis in 2009–2010, and then declines more rapidly in the later stages of business cycles (Jotzo et al., 2012).

Mainstream economic theory (Aghion and Howitt, 2009), and empirical evidence (e.g., Caselli, 2005) point to technological change and increases in human capital per worker as the key underlying drivers of per capita economic output growth in the long run. Technological change encompasses both quality improvements in products and efficiency improvements in production. Human capital is increased through improving workers' skills through education and training. While mainstream growth and development economics does not allocate much role for increasing energy and resource use as drivers of economic growth (Toman and Jemelkova, 2003), many researchers in energy and ecological economics do (Stern, 2011).

Productivity is lower in developing countries than developed countries (Caselli, 2005; Parente and Prescott, 2000). Developing countries can potentially grow faster than developed countries by adopting technologies developed elsewhere and 'catch up' to the productivity leaders (Parente and Prescott, 2000). Income per capita has risen in most countries of the world in the last several decades but there is much variation over time and regions, especially among low- and middle-income countries (Durlauf et al., 2005). The highest growth rates are found for countries that are today at middle-income levels such as China and India (and before them Singapore, South Korea, etc.), which are in the process of converging to high-income levels. But many developing countries have not participated in convergence to the developed world and some have experienced negative growth in income per capita. Therefore, there is both convergence among some countries and divergence among others and a bi-modal distribution of income globally (Durlauf et al., 2005). A large literature attempts to identify why some countries succeed in achieving economic growth and development and others not (Durlauf et al., 2005; Caselli, 2005; Eberhardt and Teal, 2011). But there seems to be little

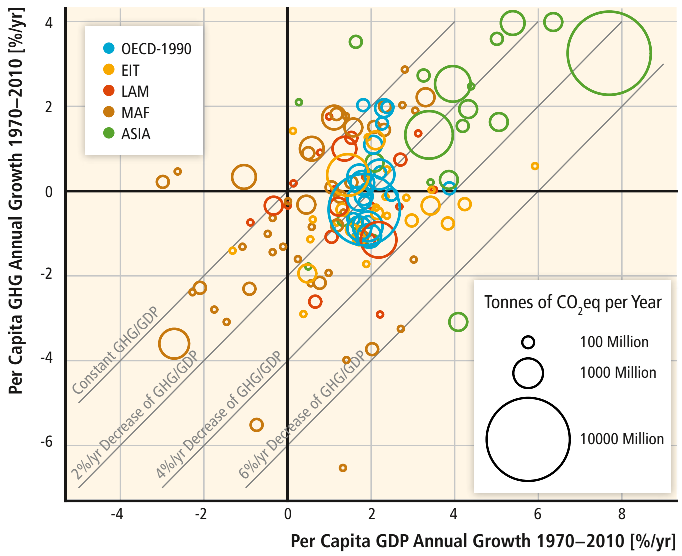


Figure 5.13 | Growth rates of per capita income and GHG emissions. The figure shows the correlation between the average annual growth rate of per capita income and per capita emissions from 1970–2010, for all countries with more than 1 million people by 2010 | Points along the grey lines have either constant emissions intensity or emissions intensity declining at 2 %, 4 % or 6 % per annum. The size of the circles is proportional to countries' emissions. The figure shows that fast growing economies also tend to have increasing emissions, while slower growing economies tend to have declining per capita emissions. This is despite quite rapidly declining emissions intensity in some fast growing economies (upper right corner). Regions are defined in Annex II.2 | Data from JRC/PBL (2013) and IEA (2012).

consensus as yet (Eberhardt and Teal, 2011). A very large number of variables could have an effect on growth performance and disentangling their effects is statistically challenging because many of these variables are at least partially endogenous (Eberhardt and Teal, 2011). This incomplete understanding of the drivers of economic growth makes the development of future scenarios on income levels a difficult task.

Ecological economists such as Ayres and Warr (2009) often ascribe to energy the central role in economic growth (Stern, 2011). Some economic historians, such as Wrigley (2010), Allen (2009), and to some degree Pomeranz (2000), argue that limited availability of energy resources can constrain economic growth and that the relaxation of the constraints imposed by dependence of pre-industrial economies on biomass energy and muscle power sources alone, with the adoption of fossil energy was critical for the emergence of the Industrial Revolution in the 18th and 19th centuries. Stern and Kander (2012) develop a simple growth model including an energy input and econometrically estimate it using 150 years of Swedish data. They find that since the beginning of the 19th century constraints imposed on economic growth by energy availability have declined as energy became more abundant, technological change improved energy efficiency, and the quality of fuels improved. A large literature has attempted using time series analysis to test whether energy use causes economic growth or vice versa, but results are significantly varied and no firm conclusions can be drawn yet (Stern, 2011).

The effect of economic growth on emissions is another area of uncertainty and controversy. The environmental Kuznets curve hypothesis proposes that environmental impacts tend to first increase and then eventually decrease in the course of economic development (Grossman and Krueger, 1994). This theory has been very popular among economists but the econometric evidence has not been found to be very robust (Wagner, 2008; Gallagher, 2009; Vollebergh et al., 2009; Stern, 2010) and in any case, even early studies found that carbon emissions continue to rise with increasing income (e.g., Shafik, 1994). More recent research (Brock and Taylor, 2010) has attempted to disentangle the effects of economic growth and technological change. Rapid catch-up growth in middle-income countries tends to overwhelm the effects of emissions-reducing technological change resulting in strongly rising emissions. But in developed countries economic growth is slower and hence the effects of technological change are more apparent and emissions grow slower or decline. This narrative is illustrated by Figure 5.13. Almost all countries had declining emissions intensity over time but in more rapidly growing economies, this was insufficient to overcome the effect of the expansion of the economy. As a result, though there is much variation in the rate of decline of emissions intensity across countries, there is, in general, a strong positive correlation between the rates of growth of emissions and income per capita. The rapidly growing countries tend to be middle- and lower-income countries and hence there is a tendency for per capita emissions to grow in poorer countries and decline in wealthier ones (Brock and Taylor, 2010).

In conclusion, while economic growth increases the scale of the economy in the Kaya decomposition and, therefore, should increase emissions, the technological change that is the main underlying driver of growth tends to reduce emissions. This has resulted in a tendency for slower growing or declining emissions per capita in wealthier, slower growing, economies, and global convergence in emissions per capita.

5.3.3.2 Consumption trends

Production and consumption are closely connected, but when we study their effect on GHG emissions, we find subtle but important differences. Box 5.2 presents two methods: one for allocating GHG emissions to production (territories), and the other to consumption. Between 1990 and 2010, emissions from Annex B countries decreased by 8 % when taking a territorial perspective (production) to carbon accounting, while over the same period, emissions related to consumption in Annex B increased by 5 % (Wiedmann et al., 2010; Peters et al., 2011, 2012; Caldeira and Davis, 2011; Andrew et al, 2013). In a similar vein, as Figure 5.14 shows, while territorial emissions from non-OECD Asian countries together surpassed those of the OECD-1990 countries in 2009, for consumption-based emissions, the OECD countries as a group contributed more than all non-OECD Asian countries together for every year between 1990 and 2010. The difference between the two methods also shows up in the trends for the per capita emissions. The OECD-1990 territorial per capita emissions declined over 1990–2010, while consumption-based emissions increased. By 2010, per capita territorial emissions for OCED countries are three times those for non-OECD Asian countries, but per capita consumption-related emissions differ by a factor of five. The overall picture shows a

Box 5.2 | Definitions of territorial and consumption-based emissions

The United Nations Framework Convention on Climate Change (UNFCCC) requires countries to submit, following the IPCC guidelines, annual National GHG Emissions Inventories to assess the progress made by individual countries on GHG emissions and removals taking place within national (including administered) territories and offshore areas over which the country has jurisdiction (IPCC, 1997; House of Commons, 2012). These inventories are called 'territorial-based emission inventories'.

Consumption-based emissions allocate emissions to the consumers in each country, usually based on final consumption as in the System of National Accounting but also as trade-adjusted emissions (Peters and Hertwich, 2008; DEFRA, 2012). Conceptually, consumption-based inventories can be thought of as consumption equals production minus emissions from the production of exports (see reviews by (Wiedmann et al., 2007; Wiedmann, 2009; Barrett et al., 2013). The methodology employed is predominately 'Multi-Regional Input-Output Analysis' (MRIO).

Note on Uncertainty—There is increased uncertainty in consumption-based emission estimates. MRIO datasets combine data from different data sets, often large and incoherent. As a result, uncertainties arise in relation to calibration, balancing, and harmonisation; use of different time periods; different currencies; different country classifications; levels of disaggregation, inflation, and raw data errors (Lenzen et al., 2004, 2010; Peters, 2007; Weber and Matthews, 2008; Peters et al., 2012). Production-based emissions data are a key input to the MRIO models that can vary for some countries significantly between databases (Peters et al., 2012). A process of harmonization can greatly reduce the necessary manipulations, and hence, uncertainties reflected in inconsistent reporting practices in different countries and regions (Peters and Solli, 2010; House of Commons, 2012; Barrett et al., 2013). For a detailed description in the variation of MRIO models, please read Peters et al.(2012). Peters et al (2012) concludes that estimates from different studies are robust and that the variation between estimates relates to different input data and approaches to assign emissions to trade and not uncertainty.

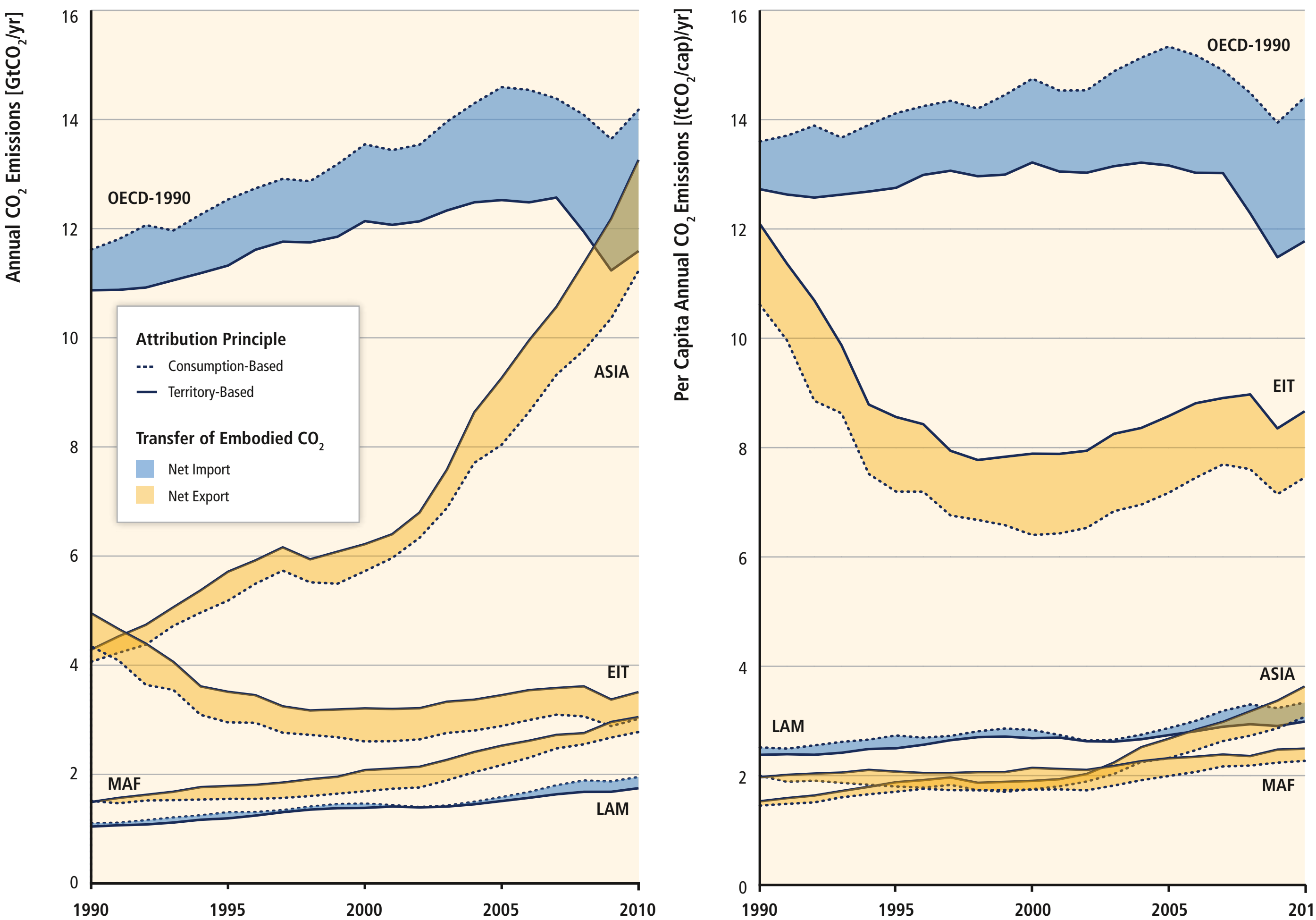


Figure 5.14 | Territory-based versus consumption-based CO_2 emissions in five world regions, from 1990 to 2010 | The left panel presents total emissions, while the right panel presents per capita emissions. The blue areas indicate that a region is a net importer of embodied CO_2 emissions. The yellow area indicates a region is a net exporter of embodied CO_2 | Data from Lenzen et al. (2010). Regions are defined in Annex II.2.

substantial gap between territorial and consumption-based emissions, due to emissions embedded in trade. For the OECD-1990 countries, the gap amounts to 2.6 $GtCO_2$ in 2010. The data shows that the reduction in territorial emissions that has been achieved in the OECD-1990 countries has been more than negated by an increase in emissions in other countries, but related with consumption in OECD-1990 countries. Furthermore, while countries with a Kyoto Protocol commitment did reduce emissions over the accounting period by 7 %, their share of imported over domestic emissions increased by 14 % (Peters et al., 2011; Aichele and Felbermayr, 2012).

Numerous studies have used a structural decomposition analysis to quantify the factors for changes in GHG emissions over time in both developed and developing countries (De Haan, 2001; Peters et al., 2007; Baiocchi and Minx, 2010; Wood, 2009; Weber, 2009). The analysis has been used to separate factors such as the intensity per output, shifts in production structure, as well as changes in the composition and the level of consumption. In all of these studies, increasing levels of consumption is the main contributor to increasing emissions. Specifically, all the studies show that reductions in emissions resulting from improvements in emissions intensity and changes in the structure of production and consumption have been offset by significant increases in emissions, resulting from the volume of consumption, resulting in an overall increase in emissions (De Haan, 2001; Peters et al., 2007; Baiocchi and Minx, 2010). For example, De Haan (2001) demonstrates for the Netherlands that final demand increased by 31 % over 11 years (1987–1998), Peters et al. (2007) demonstrate an increase of consumption by 129 % over 10 years for China, and Baiocchi and Minx (2010) show for the United Kingdom that final demand increased by 49 % between 1992 and 2004. In all these cases, the increase in final demand was greater than the emission reduction caused by structural change and efficiency improvements, leading to an overall increase in consumption-related emissions.

Calculating emissions based on a consumption-based approach sketches a more negative view on the decoupling of economic growth from greenhouse gas emissions. According to York (2007), territorial emissions showed a relative decoupling; emissions grew by 0.73 % for every 1 % increase in GDP per capita from 1960–2008. However, the elasticity of consumption-based emissions with respect to economic growth will have to be revised upwards for OECD-1990 countries, given that their consumption emissions grew at a faster rate than territorial ones (Peters et al., 2011). In this sense, there is less decoupling in industrialized nations.

5.3.3.3 Structural change

Changes in the structure of the economy—shares of each economic or industry sector in the output of the economy—might also affect emissions. Over the course of economic development, as income grows, the share of agriculture in the value of production and employment tends to decline and the share of services increases (Syrquin and Chenery, 1989). The share of manufacturing tends to follow an inverted U-shaped path (Hettige et al., 2000). The income levels at which these transitions occur differ across countries. For example, China's share of services in GDP and employment is small and its agriculture share large, given its income level (World Bank, 2011), while India has a relatively large service sector (Deb Pal et al., 2012). Between 1970 and 2010 the global share of agriculture in GDP has declined from 9 % to 3 % while the share of services increased from 53 % to 71 %. Industry declined from 38 % to 26 % of GDP (World Bank, 2011). Schäfer (2005) shows that there are similar changes in the sectoral composition of energy use. The share of total energy use used in services increases in the course of economic development while that of industry follows an inverted U-shaped curve. The share of residential energy use declines with rising per capita income.

The shift from the industrial sector to services reduces energy use and emissions less than commonly thought. Partly, this is due to strong gains in productivity in manufacturing. The productivity gain can be observed through the price of manufactured goods, which has historically fallen relative to the price of services. Because of the price decline, it appears that the share of manufacturing industry in the economy is falling when, in real output terms, it is constant or increasing (Kander, 2005). Part of the productivity gain in manufacturing is due to improvements in energy efficiency, which reduce energy intensity in the sector (Kander, 2005). Also, not all service sectors are low in energy intensity. Transport is clearly energy-intensive and retail and other service sectors depend on energy-intensive infrastructure.

In Austria and the United Kingdom, the transition of the industrial society into a service economy or post-industrial society did not lead to dematerialization (Krausmann et al., 2008), but instead it was systematically linked to an increase in per capita energy and material consumption as all parts of the economy shifted from traditional to modern methods of production. Further evidence (Henriques and Kander, 2010) for 10 developed countries (United States, Japan, and eight European countries), and three emerging economies (India, Brazil, and Mexico), indicates a minor role for structural change in reducing energy intensity, while the decline in energy intensity within industries is found to be the main driver of aggregate energy intensity. Yet the decomposition is sensitive to the level of disaggregation. A classic result in the growth-accounting literature (Jorgenson and Griliches, 1967) is that a finer disaggregation of inputs and outputs leads to lower estimates for technological change and a larger role for substitution between inputs and structural change. This is confirmed by Wing (2008), who found that structural change between industries explained most of the decline in energy intensity in the United States (1958–2000), especially before 1980 (Stern, 2011). An alternative perspective is provided by the literature on consumption-based emissions (see Section 5.3.3.2). Baiocchi and Minx (2010) show that the shift to a service economy in the United Kingdom was partly achieved by off-shoring emissions-intensive industrial activities and thus reducing industrial activity, and that the service sector uses imported emissions-intensive goods. Both of these offset the reduction in emissions from shifting toward the service sector in the United Kingdom. Likewise, Suh (2006) and Nansai et al. (2009b) show that if the entire supply chain is considered, the emissions intensity of services is much higher than if only the final production of services is considered.

The reform of centrally planned economies has been an important factor driving changes in GHG emissions. Emissions and energy intensity were high in China, the former Soviet Union, and many Eastern European countries prior to reform, and declined as their economies were reformed. China serves as a case in point. Its energy intensity was very high compared to similar but market-oriented countries before 1980, but China's energy intensity decreased sharply between 1980 and 2000, as it opened its economy through market-based reforms (Ma and Stern, 2008). Energy and emissions intensity rose and then fell again from 2000 to the present as at first easy options for energy efficiency improvements were exhausted and later new policies to improve energy and carbon intensity were put in place. On the other hand, China's carbon intensity of energy supply has increased steadily since at least 1970 (Stern and Jotzo, 2010). Sectoral shifts played only a small role in these large movements of the past three decades (Ma and Stern, 2008; Steckel et al., 2011), though they were important in the rise in emissions intensity from 2000 to 2005 (Minx et al., 2011).

In conclusion, the role of an increase in share of the service sector in output in reducing emissions is probably quite small, but finer-grained structural change could be important and economy-wide reforms contribute much to the adoption of more energy- and emissions-efficient production processes.

5.3.4 Energy demand and supply

5.3.4.1 Energy demand

Globally, per capita primary energy use, as estimated by the International Energy Agency (IEA) method (see Annex II.9), rose by 31 % from 1971–2010; however the five world regions exhibited two different pathways during this period, as seen in Figure 5.15 (left). In the OECD-1990 and EIT, energy use per capita rose by 13–14 %, while the other regions increased their per capita energy use at a much higher rate: LAM by 60 %, MAF by 90 %, and ASIA by 200 %. Nevertheless, the 2010 per capita energy use in these three regions still remains at less than half of the OECD-1990 and EIT countries 40 years ago.

The two pathways in per capita energy use are also reflected when looking at energy intensity over time (Figure 5.15 right). The measurement of energy intensity, i. e., ratio of energy use per unit of GDP and its limitations, are discussed in the following section. The differences in pathways between the OECD-1990 and EIT versus ASIA, LAM, and MAF illustrate the energy intensity gap between the industrialized and developing countries. In Figure 5.16, we show a similar chart for individual countries. Combining the left and right panels, we see that improvements in energy intensity have slowed the growth in energy use substantially, but have been insufficient to offset the growth in the scale of the economy (Stern, 2012).

The effects of the oil price shocks in 1973 and 1979 and perhaps 2008 (Hamilton, 2009) are particularly visible as dips in the OECD trend. These price shocks do not appear, however, to have reversed the upward trend in per capita primary energy use in the regions. In the long run, per capita energy consumption has increased with income and over time since the onset of the Industrial Revolution in Northern Europe (Gales et al., 2007) and the United States (Grübler, 2008; Tol et al., 2009) and since the Second World War in southern Europe (Gales et al., 2007).

Changes in total energy use can be decomposed to reflect the effects of growth in population and income per capita and changes in energy intensity, all of which are discussed in detail in other sections of this chapter as well as in Chapter 7.

The relationship between economic growth and energy use is complicated and variable over time. The provision of energy services is one of the necessary conditions for economic growth, yet in turn, economic growth increases the demand for energy services (Grübler et al., 2012). As income increases, so does energy use. This phenomenon, coupled with population growth, has resulted in global total primary energy use increasing by 130 % between 1971 and 2010, and almost 50 times since 1800 (Nakicenovic et al., 1998; Grübler, 2008).

5.3.4.2 Energy efficiency and Intensity

Energy efficiency can be defined as the ratio of the desired (usable) energy output for a specific task or service to the energy input for the given energy conversion process (Nakicenovic et al., 1996). For example, for an automobile engine, this is the mechanical energy at the crankshaft or the wheels divided by the energy input of gasoline. This definition of energy efficiency is called the first-law efficiency. Other approaches often define energy efficiency in relative terms, such as the ratio of minimum energy required by the current best practice technology to actual energy use, everything else being constant (Stern, 2012).

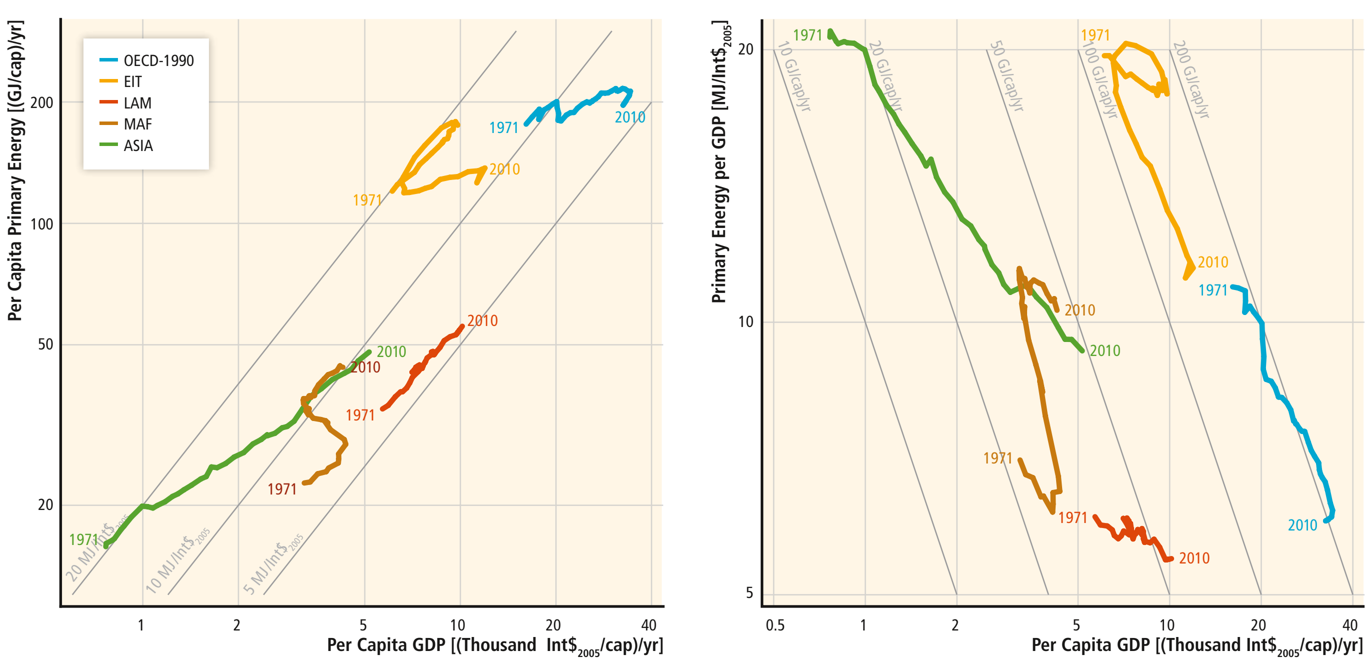


Figure 5.15 | Historical trend (1971–2010) by region in per capita primary energy (left panel), and primary energy intensity of GDP (right panel), against GDP per capita on the horizontal axis. Grey diagonals connect points with constant energy intensity (left panel) and constant per capita primary energy use (right panel). Note that both axes are logarithmic. Source: IEA (2012); UN WPP (2012); World Bank (2012). Regions are defined in Annex II.2.

In 2005, the global first-law efficiency of converting primary energy sources (such as coal or natural gas) to final energy forms (such as electricity or heat) was about 67 % (i. e., 330 EJ over 496 EJ). The efficiency of further converting final energy forms into useful energy is lower, with an estimated global average of 51 % (i. e., 169 EJ over 330 EJ). Thus, approximately one-third of global primary energy use is dissipated to the environment in the form of waste heat or what is colloquially termed energy 'losses' (Grübler et al., 2012).

The theoretical potential for efficiency improvements is thus very large (Grübler et al., 2012). However, efficiency improvements can lead to additional demand, a side-effect called the rebound effect, discussed later in Section 5.6.2, which needs to be taken into account (Pao and Tsai, 2010).

Economic studies, including those based on the Kaya identity (Nakicenovic and Swart, 2000), often use energy intensity—the ratio of energy use per dollar of GDP—as an indicator of how effectively energy is used to produce goods and services, also known as its inverse: the energy productivity. However, energy intensity depends on many factors other than technical efficiencies, as discussed in the remainder of this section, and is not an appropriate proxy of actual energy (conversion) efficiency (Ang, 2006; Filippini and Hunt, 2011; Stern, 2012; Grübler et al., 2012).

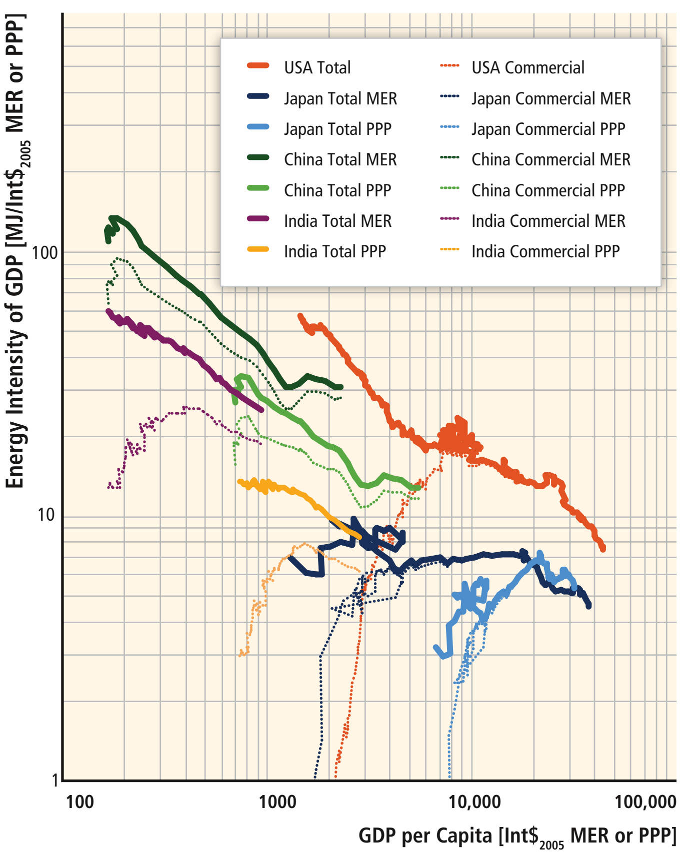


Figure 5.16 | Energy intensity improvements and per capita GDP—USA (1800–2008), Japan (1885–2008), India (1950–2008), and China (1970–2008). Source: Grübler et al., 2012. Note: Energy intensities (in MJ per USD) are always shown for total primary energy (bold lines), and commercial primary energy only (thin lines), and per unit of GDP expressed at market exchange rates (MER in USD_{2005}), and for China, India, and Japan also at purchasing power parities (PPP in $Int\$_{2005}$). For the United States, MER and PPP are identical.

Energy intensity metrics yield valuable insights into potentials for efficiency improvements related to various activities (Fisher and Nakicenovic, 2008; Grübler et al., 2012). Energy intensity measured at the economy-wide level is an attractive indicator because of its simplicity and ease of comparability across systems and time (e. g., national economies, regions, cities, etc.). However, the indicator is affected by a number of issues, including in relation to the way definitions are made and measurements are performed (Ang, 2006; Filippini and Hunt, 2011). Many factors besides technical efficiency drive energy intensity differences.

Energy intensities are strongly affected by energy and economic accounting conventions, which are not always disclosed prominently in the reporting reference. For energy, the largest influences on the metrics are whether primary or final energy are used in the calculations, and whether or not non-commercial energy[7] is included (Grübler et al., 2012; see Figure 5.16).

Figure 5.16 illustrates these differences in the evolution of historical primary energy intensity for four major world economies: China, India, Japan, and the United States. It shows the different ways energy intensity of GDP can be measured.

To see how the inclusion of non-commercial energy affects energy intensity, we take the United States as an example, as its PPP and MER GDP are the same by definition. The thin green curve shows United States commercial energy intensity. According to Grübler et al. (2012), commercial energy intensities increase during the early phases of industrialization, as traditional, less-efficient energy forms are replaced by commercial energy. Once this substitution is completed, commercial energy intensity peaks and starts to decline. This phenomenon is sometimes called the 'hill of energy intensity' (Grübler et al., 2012). These peaks are observed to be lower for countries reaching this transition stage now, promising lower energy intensity in developing countries that still have to reach the peak (Gales et al., 2007; Lescaroux, 2011; Reddy and Goldemberg, 1990; Nakicenovic et al., 1998). More important than this 'hill' in commercial energy intensities is, however, a pervasive trend toward overall lower total energy (including also non-commercial energy) intensities over time and across all countries (Grübler et al., 2012). It is interesting to note that despite the relatively wide upper and lower bounds of initial energy intensity among the investigated countries, they all exhibit very similar rates of energy

[7] Non-commercial energy is energy that is not commercially traded such as the traditional biomass or agricultural residues, which are of particular importance in developing countries.

intensity improvements independent of whether they are on a more or less energy-intensive development trajectory.

The most important accounting factor is the exchange rate used for converting income measured in local national currencies to internationally comparable currency units based on either MER or PPP exchange rates (both illustrated in Figure 5.16) (Grübler et al., 2012). In the cases of India and China, MER energy intensities are very high, similar to the energy intensities of the industrialized countries more than 100 years ago. This gives the appearance of very high energy intensity of GDP in developing countries. However, China and India's PPP-measured GDPs are much higher, meaning that with the same dollar amount, a Chinese or Indian consumer can purchase more goods and services in developing countries than in industrialized countries. The PPP-measured energy intensities are thus much lower for developing countries, indicating substantially higher energy effectiveness in these countries than would be calculated using MER (Grübler et al., 2012). A further limitation of GDP accounting, especially for developing countries, is the exclusion of 'grey economies' in official statistics, which would increase GDP.

Countries with long-term statistical records show improvements in total energy intensities by a factor of five or more since 1800, corresponding to an global annual average decline of total energy intensities of about 0.75–1 % (Gilli et al., 1990; Fouquet, 2008). Improvement rates can be much faster over periods of a few decades, as illustrated in the case of China, which exhibited a steep decline (2–3 %/year for PPP- and MER-based energy intensities, respectively) between 1979 and 2000 before the trend flattened (Stern and Jotzo, 2010). Faster economic growth leads to a faster turnover of the capital stock of an economy, thus offering more opportunities to switch to more energy-efficient technologies. The reverse also applies for the economies in transition (Eastern Europe and the former Soviet Union in the 1990s) or recession; that is, with declining GDP, energy intensities increase.

Energy intensity has declined globally in all developed and major developing countries including India and China (Steckel et al., 2011). When traditional (non-commercial) biomass fuels are included in the measure of energy input, energy intensity has declined over time in most investigated countries (Gales et al., 2007). However, historical improvements in energy intensities have not been sufficient to fully offset GDP growth, resulting in increased energy consumption over time (Bruckner et al., 2010). The literature indicates some albeit inconsistent convergence in energy intensities among developed economies, but not for both developed and developing countries (Le Pen and Sévi, 2010; Mulder and de Groot, 2012).

Changes in energy intensity over time can be decomposed into the effects of structural change (the shift to more or less energy-intensive industries), changes in the mix of energy sources, technological change, and the quantities of other inputs such as capital and labour used (Stern, 2012; Wang, 2011). Globally, structural changes play a smaller role in determining trends in energy use and CO_2 emissions, though they can be important in individual countries (Cian et al., 2013). More generally for countries and regions, energy intensity is also affected by the substitution of capital and other inputs for energy (Stern, 2012). The drivers of energy intensity trends are difficult to isolate. For example, in the United States, most researchers find that technological change has been the dominant factor in reducing energy intensity (Metcalf, 2008). Similar results have been found for Sweden (Kander, 2005) and China (Ma and Stern, 2008; Steckel et al., 2011). However, Wing (2008) finds that structural change explained most of the decline in energy intensity in the United States (1958–2000), especially before 1980, and Kaufmann (2004) attributes the greatest part of the decline to substitution towards higher-quality energy sources, in particular electricity that produces more output per Joule. Similarly, Liao et al. (2007) conclude that structural change, instead of technological change, is the most dominant factor in reducing energy intensity in China.

Some differences in energy intensity among countries are easily explained. Countries with cold winters and formerly centrally planned economies tend to be more energy-intensive economies, though the latter have improved energy intensities significantly in recent decades through reform of energy markets (Stern, 2012). The role of economic structure, resource endowments, and policies explain much of the differences in energy intensities (Ramachandra et al., 2006; Matisoff, 2008; Wei et al., 2009; Stern, 2012; Davidsdottir and Fisher, 2011). There is no clear one-to-one link between overall energy intensity and energy efficiency in production (Filippini and Hunt, 2011), though there is evidence for the role of energy prices. Higher energy prices are associated with lower levels of energy consumption and are significantly determined by policy. Countries that have high electricity prices tend to have lower demand for electricity, and vice-versa (Platchkov and Pollitt, 2011), with a price elasticity of demand for total energy use between −0.2 and −0.45 for the OECD countries between 1978 and 2006 (Filippini and Hunt, 2011).

5.3.4.3 Carbon-intensity, the energy mix, and resource availability

Carbon intensity is calculated as the ratio of emissions of CO_2 per unit of primary or final energy, whereas decarbonization refers to the rate at which the carbon intensity of energy decreases. Throughout the 20th century, the choice of fossil-fuels for energy has progressed towards less carbon intensive fuels and to conversion of energy to more usable forms (e.g., electricity) (Grübler et al., 2012). Hydrogen-rich fuels release, during combustion, more energy for every carbon atom that is oxidized to CO_2 (Grübler et al., 1999). The result is a shift from fuels such as coal with a high-carbon content to energy carriers with a lower-carbon content such as natural gas[8], as well as the introduction of near-zero carbon energy sources, such as renewables, including sus-

[8] For further detailed information on carbon emissions for various combustible fuels, see IPCC (1997) and IPCC (2006).

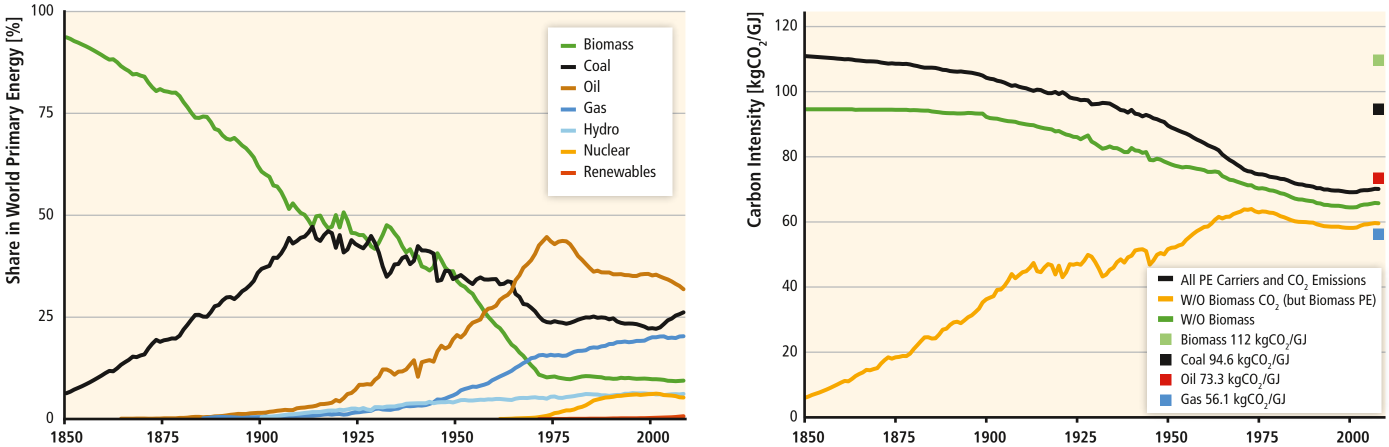


Figure 5.17 | Left Panel: Structural change in world primary energy (in percent) over 1850–2008 illustrating the substitution of traditional biomass (mostly non-commercial) by coal and later by oil and gas. The emergence of hydro, nuclear and new renewables is also shown. Source: Nakicenovic et al. (1998) and Grübler (2008). Right panel: Decarbonization of primary energy (PE) use worldwide over 1850–2008 (kg of CO_2 emitted per GJ). The black line shows carbon intensities of all primary energy sources, orange line of commercial energy sources without biomass CO_2 emissions, assuming they have all been taken up by the biosphere under a sustainable harvesting regime (biomass re-growth absorbing the CO_2 released from biomass burning) and the green line shows global decarbonization without biomass and its CO_2 emissions. Note: For comparison, the specific emission factors (OECD/IPCC default emission factors, lower-heating value (LHV) basis) for biomass (wood fuel), coal, crude oil, and natural gas are also shown (coloured squares). Source: updated from Grübler et al. (2012).

tainably managed biomass (biogenic carbon is reabsorbed through new growth), and nuclear, and consequently further decarbonization of energy systems (Grübler and Nakićenović, 1996; Grübler, 2008). Decarbonization can also affect the emissions of other GHGs and radiatively active substances such as aerosols. Figure 5.17 (left panel) shows the historical dynamics of primary energy. It indicates that the changes in primary energy are very slow, because it took more than half a century to replace coal as the dominant source of energy.

Figure 5.17 (right panel) illustrates the historical trend of global decarbonization of primary energy since 1850 in terms of the average carbon emissions per unit of primary energy (considering all primary energy sources, commercial energy sources with and without biomass). Historically, traditional biomass emissions related to LUCs, i.e., from deforestation to land for food and energy crops, have far exceeded carbon releases from energy-related biomass burning, which indicates that in the past, biomass, like fossil fuels, has also contributed significantly to increases in atmospheric concentrations of CO_2 (Grübler et al., 2012).

The global rate of decarbonization has been on average about 0.3 % annually, about six times too low to offset the increase in global energy use of approximately 2 % annually (Grübler et al., 2012). A significant slowing of decarbonization trends since the energy crises of the 1970s is noteworthy, particularly the rising carbon intensities as a result of increased use of coal starting in 2000 (IEA, 2009; Stern and Jotzo, 2010; Steckel et al., 2011). Recent increases in natural gas, in particular shale gas use, will tend to partially offset the carbonization trends.

Some future scenarios foresee continuing decarbonization over the next several decades as natural gas and non-fossil energy sources increase their share in total primary energy use. Other scenarios anticipate a reversal of decarbonization in the long term as more easily accessible sources of conventional oil and gas are replaced by more carbon-intensive alternatives such as coal and unconventional oil and gas (Fisher et al., 2007). Nonetheless, almost all scenarios anticipate an increase in future demand for energy services. The increase in energy demand means higher primary energy requirements and, depending on the rates of future energy-efficiency improvements, higher emissions. Therefore, energy-efficiency improvements alone will not be sufficient to significantly reduce GHG emissions, and it is thus essential to accelerate the worldwide rate of decarbonization. Current evidence indicates that further decarbonization will not be primarily driven by the exhaustion of fossil fuels, but rather by economics, technological and scientific advances, socio-political decisions, and other salient driving forces. Furthermore, new information and communication technologies (ICTs) can help reduce the energy needs and associated emissions to improve the efficiency measures as a result of better management of energy generation and end-use, e.g., emergence of smart grids and better control of end-use devices.

Fossil fuel reserves and resources make up the hydrocarbon endowments, which as a whole are not known with a high degree of certainty. Reserves are the part of global fossil occurrences that are known with high certainty and can be extracted using current technologies at prevailing prices. Thus, the quantification and classification of reserves relies on the dynamic balance between geological assurance, technological possibilities, and economic feasibility. There is little controversy that oil and gas occurrences are abundant, whereas the reserves are more limited, with some 50 years of production for oil and about 70 years for natural gas at the current rates of extraction (Rogner et al., 2012). Reserve additions have shifted to inherently more challenging and potentially costlier locations, with technological progress outbalancing potentially diminishing returns (Nakicenovic et al., 1998; Rogner et al., 2012).

In general, estimates of the resources of unconventional gas, oil, and coal are huge (GEA, 2012; Rogner et al., 2012) ranging for oil resources to be up to 20,000 EJ or almost 120 times larger than current global production; natural gas up to 120,000 EJ or 1300 times current production, whereas coal resources might be as large as 400,000 EJ or 3500 times larger than current production. However, global resources are unevenly distributed and are concentrated in some regions and not others (U.S. Energy Information Administration, 2010). These upper estimates of global hydrocarbon endowments indicate that their ultimate depletion cannot be the relied upon to limit global CO_2 emissions. For example, the carbon embedded in oil and gas reserves exceeds the current carbon content of the atmosphere. The emissions budget for stabilizing climate change at 2 °C above pre-industrial levels is about the same as the current carbon content of the atmosphere, meaning that under this constraint only a small fraction of reserves can be exploited (Meinshausen et al., 2009). Chapter 7 of this report discusses in detail the current and future availability of global energy resources (see also Table 7.2).

5.3.5 Other key sectors

This section briefly describes GHG emission trends for the other main economic sectors (transport, buildings, industry, AFOLU, and waste) and the correlation between emissions and income, showing marked differences between sectors and countries. The following sections provide short discussions of trends and drivers by sector, while the following chapters (7–11) provide detailed analyses. Note that in Chapter 5, we consider only direct emissions for the buildings sector, whereas Chapter 9 also includes indirect emissions.

GHG emissions grew in all sectors, except in AFOLU where positive and negative emission changes are reported across different databases and uncertainties in the data are high (see Section 11.2). As is clear from Figure 5.18, high-income countries contribute mostly to emissions associated with transport (Chapter 8) and buildings (Chapter 9). Low and lower middle-income countries contribute the largest share of emissions associated with AFOLU (Chapter 11). Between 2000 and 2010, emissions by upper middle-income countries from energy (+3.5 $GtCO_2e/yr$) and industry (+2.4 $GtCO_2e/yr$) more than doubled, and by 2010, emissions from industry in upper middle-income countries have passed those from high-income countries.

The large increase in energy and industry emissions in upper middle-income countries is consistent with the observed income growth and the correlation between emissions and income for these sectors (Figure 5.19). There is a robust positive relation between income and emissions, particularly for annual income levels between 1000 and 10,000 $Int\$_{2005}/cap$, while for transport, the correlation between income and emissions continues into higher-income levels. We find no positive correlation between income and emissions for AFOLU.

In 2010, the typical high-income country (median of the high-income group, population-weighted) had per capita emissions of 13 tCO_2eq/cap yr, while per capita emissions in the typical low-income country were only about one-tenth of that value, at 1.4 tCO_2eq/cap yr. But, there is a large variation among countries that have similar income levels. The per capita emissions in high-income countries range from 8.2 to 21 tCO_2eq/cap yr, for the (population weighted) 10 and 90 percentile, respectively. Many low-income countries (median income of 1,200 $Int\$_{2005}/cap$) have low per capita emissions (median of 1.4 tCO_2eq/yr), but for the low-income country group, average per capita emissions (4.3 tCO_2eq/yr) are pulled up by a few countries with very high emissions associated with land-use.

5.3.5.1 Transport

Global transport GHG emissions[9] grew from 2.8 $GtCO_2eq$ in 1970 to 7 $GtCO_2eq$ in 2010 (JRC/PBL, 2013). The OECD-1990 countries contributed the largest share of the emissions (i.e., 60 % in 1970, 56 % in 1990, and 46 % in 2010) but the highest growth rates in transport emissions were in the upper middle-income countries and international bunkers. The overall picture shows that transport emissions have steadily increased but show a marked decrease around 2008/2009.

Increasing demand for passenger and freight transport, urban development and sprawl, lack of rail and bus transit and cycle infrastructure in many regions, transport behaviour constrained by lack of modal choice in some regions, a high fuel-consuming stock of vehicles, relatively low oil prices, and the limited availability of low-carbon fuels have been the principal drivers of transport sector CO_2 emission growth over the past few decades (Jolley, 2004; Davies et al., 2007; IPCC, 2007; Timilsina and Shrestha, 2009; Ubaidillah, 2011; Wang et al., 2011 Chapter 8).

The marked growth rate of international transport emissions after 2002 coincides with growth in Chinese exporting industries sugges 3ting an influence of trade policies and world trade agreements on transport emissions (Olivier et al., 2011).

The high oil prices of 2008 and the global recession in 2009 both resulted in a decrease in fossil fuel consumption for the OECD countries, with CO_2 emissions declining by 2.0 % in 2008, and an estimated 6.3 % in 2009. GHG emissions in non-OECD countries were not affected (US EIA, 2011).

There is a strong correlation between per capita transport emissions and per capita incomes and alignment of the two variables is sharper in the high-income countries (Figure 5.19) as the demand for personal transportation increases as standards of living rise and economic activity increases (US EIA, 2011).

9 Consisting of direct CO_2, CH_4, N_2O, and F-gases (Freight Vision, 2009).

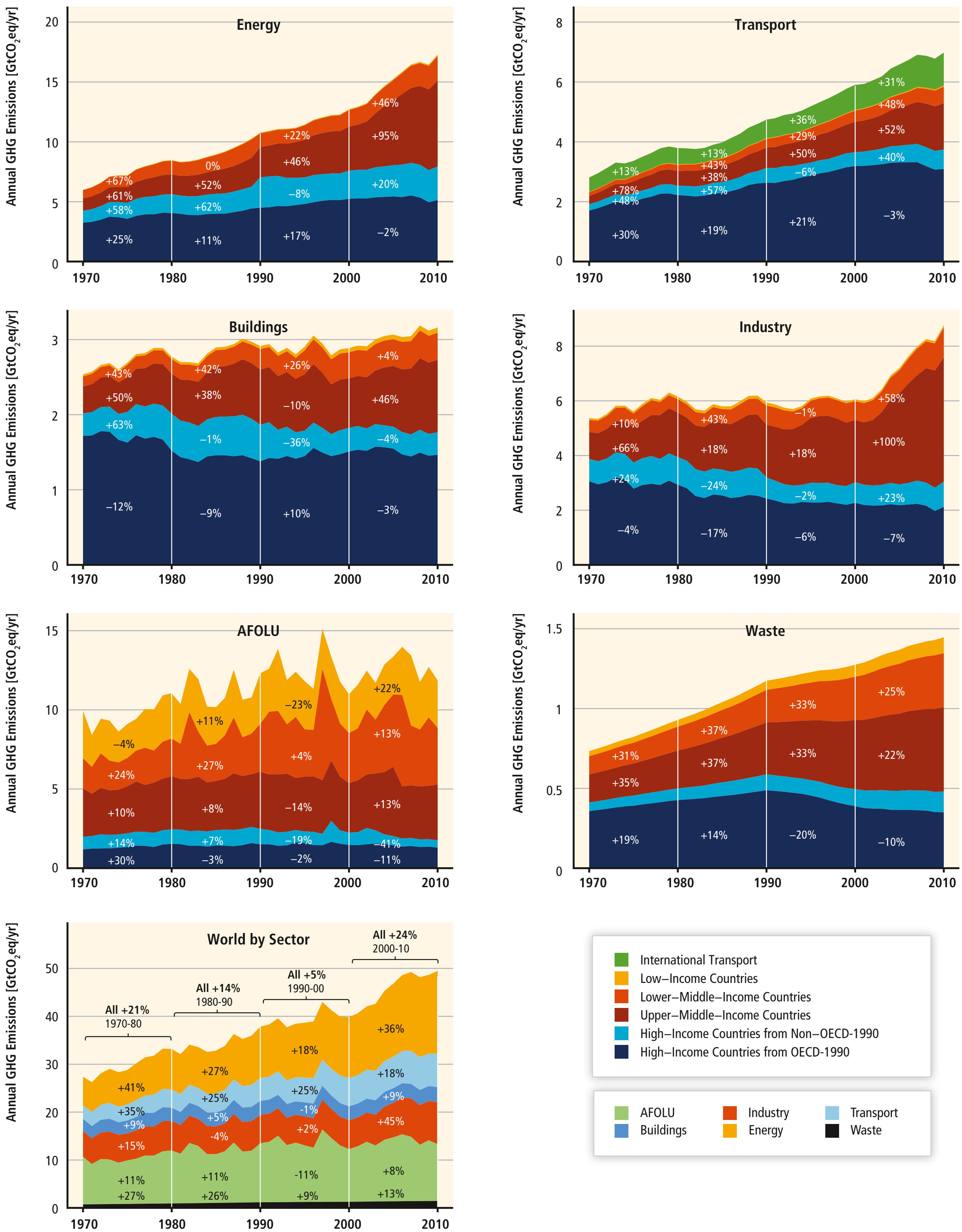
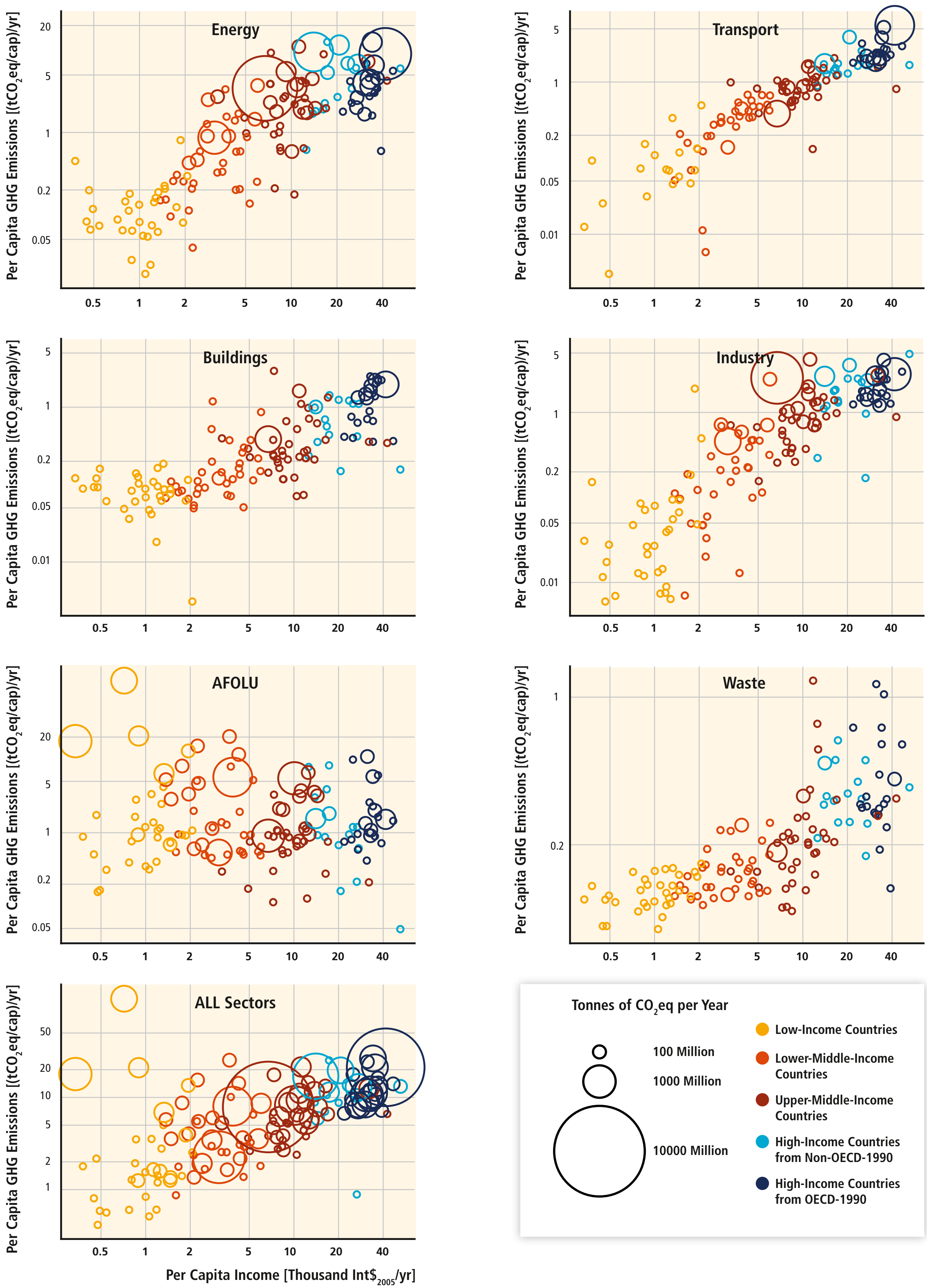


Figure 5.18 | Regional and sector distribution of GHG emission trends. Regions are defined in Annex II.2 | The figure shows annual GHG emissions for the six key sectors discussed in Sections 5.3.4 and 5.3.5 | The left-lower panel presents global sector emissions to assess the relative contribution. Decadal growth rates are projected on the charts for emissions exceeding 0.2 $GtCO_2eq/yr$. The direct emission data from JRC/PBL (2013) and IEA (2012) (see Annex II.9) represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthopogenic emission sources in the Forestry and Other Land Use (FOLU) sub-sector. For a more detailed representation of Agriculture and FOLU (AFOLU) GHG flux see Section 11.2 and Figures 11.2 and 11.6.


Energy
Transport
Buildings
Industry
AFOLU
Waste
ALL Sectors
Per Capita GHG Emissions [(tCO_2eq/cap)/yr]
Per Capita Income [Thousand Int$$_{2005}$/yr]
0.5
1
2
5
10
20
40
0.01
0.05
0.2
1
5
20
50
Tonnes of CO_2eq per Year
100 Million
1000 Million
10000 Million
Low-Income Countries
Lower-Middle-Income Countries
Upper-Middle-Income Countries
High-Income Countries from Non-OECD-1990
High-Income Countries from OECD-1990

⇒

Figure 5.19 | The relation between income and GHG emissions for the six key sectors discussed in Sections 5.3.4 and 5.3.5 | The left-lower panel presents the relation for emissions aggregated over all sectors. Each circle is one country, for the year 2010 | The area of a circle is proportional to the aggregate emissions for that country and sector, using the same scale consistently over all panels. The bubble size is bounded from below for visual ease. Note the logarithmic scales on both x and y axes. For most sectors apart from AFOLU, there is a clear positive relation between income and emissions. Data from JRC/PBL (2013) and IEA (2012). The direct emission data from JRC/PBL (2013) (see Annex II.9) represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthopogenic emission sources in the Forestry and Other Land Use (FOLU) sub-sector. For a more detailed representation of Agriculture and FOLU (AFOLU) GHG flux see Section 11.2 and Figures 11.2 and 11.6 | Regions are defined in Annex II.2.

5.3.5.2 Buildings

Building sector emissions grew from 2.5 $GtCO_2eq$ in 1970 to 3.2 $GtCO_2eq$ in 2010 with emissions growth rates in OECD-1990 countries being largely negative. Positive-emission growth rates were registered in the upper and lower middle-income countries, although the largest contribution to buildings emissions still came from OECD-1990 countries (Figure 5.18).

Per capita buildings emissions and per capita income are positively correlated. Considering a life-cycle assessment starting with manufacturing of building materials to demolition, over 80 % of GHG emissions take place during the building operation phase (UNEP, 2009) largely from consumption of electricity for heating, ventilation, and air conditioning (HVAC), water heating, lighting, and entertainment (US DOE, 2008). On average, most residential energy in developed countries is consumed for space heating, particularly in cold climates. 58 % of the demand for energy in buildings was contributed by space heating in 1990 and 53 % in 2005, while water heating contributed 17 % in 1990 and 16 % in 2005, appliances 16 % and 21 %, respectively, and cooking and lighting about 5 % (IEA, 2008; UNEP, 2009). In low-income countries, a large proportion of operational energy is derived from polluting fuels, mainly wood and other biomass, such as dung and crop residues, and a high number of people (2.4 billion) still use biomass for cooking and heating (International Energy Agency, 2002, 2006).

5.3.5.3 Industry

Direct emissions from industry (excluding waste / waste water and AFOLU contributions[10]) grew from 5.4 $GtCO_2eq/yr$ in 1970 to 8.8 $GtCO_2eq/yr$ in 2010. The contribution of OECD countries dominated these emissions at the start of the period with over 57 % of the total but declined to 24 % of the total in 2010. The middle-income countries have become the major emitters, particularly after 2000 (Figure 5.18) when the annual growth rate in emissions increased very significantly in the middle income countries. There is a positive correlation between per capita emissions from industry and per capita income up to an income level of 10,000 $Int\$_{2005}/cap$. Beyond that income level, the correlation decreases due to improvements in energy efficiency in the industrialized OECD countries (European Environment Agency, 2009).

[10] Industry emissions including emissions from waste and waste water are reported in Section 10.2 in Chapter 10.

Energy use in industry, which is the major source of emissions from the sector, has grown in both absolute and relative terms in the OECD-1990 region and in relative terms in EIT countries driven by changes in income, the level of industrial output, fuel switching, and structural changes (International Energy Agency, 2003). There has also been a complex restructuring and relocation of the production and consumption of goods and supply of services that has shaped the location of industrial emissions, resulting in the shift of emissions to some non-OECD Asian economies (De Backer and Yamano, 2012; Backer and Yamano, 2007).

The production of energy-intensive industrial goods including cement, steel, aluminium has grown dramatically. From 1970 to 2012, global annual production of cement increased 500 %; aluminium 400 %; steel 150 %, ammonia 250 %; and paper 200 % (USGS, 2013); with energy-intensive industries increasingly being located in developing nations (IPCC, 2007a). Rapid growth in export industries has also driven emissions growth, and since 2001, China dominates in production of goods for own consumption and export (Weber et al., 2008; see Chapter 10).

Non-energy industrial emissions such as perfluorocarbon (PFC) emissions have declined in many OECD countries, while trends in SF_6 emissions vary and HFC emissions have increased very rapidly, driven more by use in refrigeration equipment (International Energy Agency, 2003).

5.3.5.4 Agriculture, Forestry, Other Land Use

Emission of GHGs in the AFOLU sector increased by 20 % from 9.9 $GtCO_2eq$ in 1970 to 12 $GtCO_2eq$ in 2010 (Figure 5.18) contributing about 20–25 % of global emissions in 2010 (JRC/PBL, 2013). Both the agriculture sub-sector and the FOLU sub-sector showed an increase in emissions during the period 1970–2010, but there is substantial uncertainty and variation between databases (see Section 5.2.3); Chapter 11 provides an overview of other estimates. In the agriculture sub-sector, CH_4 from enteric fermentation and rice cultivation, and nitrous oxide (N_2O) mainly from soil, application of synthetic fertilizer and manure, and manure management made the largest contribution (≥ 80 %) to total emissions in 2010. Between 1970 and 2010, emissions of CH_4 increased by 20 %, whereas emissions of N_2O increased by 45–75 %. Though total global emissions increased, per capita emissions went down from 2.5 tonnes in 1970 to 1.7 tonnes in 2010 because of growth in population. Per capita emissions decreased in LAM, MAF, and EIT countries, whereas in ASIA and OECD-1990 countries, it remained almost unchanged. There was no clear relation between emissions in the AFOLU sector and per capita income (Figure 5.19).

Between 2000 and 2010, emission in the AFOLU sector marginally increased from 11.0 $GtCO_2eq$ to 11.9 $GtCO_2eq$ (Figure 5.18), but per capita emissions marginally decreased from 1.8 tCO_2eq/cap yr to 1.7 tCO_2eq/cap yr (JRC/PBL, 2013).

Drivers of emissions included increased livestock numbers linked to increased demand for animal products, area under agriculture, deforestation, use of fertilizer, area under irrigation, per capita food availability, consumption of animal products, and increased human and animal populations. Global agricultural land increased by 7 %, from 4560 Mha to 4900 Mha between 1970 and 2010 (FAOSTAT, 2013). Global population increased by about 90 % from 3.6 to 6.9 billion during the period. As a result, per capita cropland availability declined by about 50 %, from 0.4 ha to 0.2 ha. On the other hand, crop productivity increased considerably during the period. For example, cereal production has doubled from 1.2 Gt to 2.5 Gt and the average yield of cereals increased from 1600 kg ha^{-1} to 3000 kg ha^{-1}. To enable this increase, use of nitrogenous fertilizer increased by 230 % from 32 Mt in 1970 to 106 Mt in 2010 (FAOSTAT, 2013), which was a major driver for increased N_2O emission (Spark et al., 2012). During the past 40 years, there has been increase in irrigated cropped area (Foley et al., 2005). Population of cattle, sheep, and goats increased 1.4-fold and that of pigs and poultry 1.6 and 3.7-fold, respectively (FAOSTAT, 2014). This has increased GHG emissions directly and also through manure production (Davidson, 2009). Global per capita food availability and consumption of animal products increased, particularly in Asia (FAOSTAT, 2013).

Emissions in the AFOLU sector increased during the last four decades with marginal increase in the last decade (2000–2010). The continued growth in world population causing greater demand for food with reduced per capita land availability will have significant impact on emission. Further details of emissions, more on forestry and land use, and opportunities for mitigation in the AFOLU sector are discussed in Chapter 11.

Box 5.3 | Trends and drivers of GHG emissions in Least Developed Countries

Almost 90 % of 1970–2010 GHG emissions in the Least Developed Countries (LDCs) are generated by agriculture, forestry, and other land use activities (AFOLU) (Figure 5.20), and emissions have increased by 0.6 % per year in these countries during the last four decades. For the LDCs, the primary activities within AFOLU include subsistence farming and herding, and use of wood as fuel for cooking and heating (Golub et al., 2008; Dauvergne and Neville, 2010; Erb et al., 2012).

The effects of population growth on energy use and emissions are, in relative terms, greater in the LDCs and developing countries than in the developed countries (Poumanyvong and Kaneko, 2010). The dominance of AFOLU over buildings, industry, and transport as sources of emissions for LDC (Figure 5.20) suggests population growth as a major contributor to the growth in LDC emissions. Yet the low historic emissions growth of 0.6 % annually is substantially below population growth of 2.5 % annually. Changes in land use with regard to biofuels (Ewing and Msangi, 2009) and agricultural practices (Mann et al., 2009; Bryan et al., 2013) may also have affected the increase in emissions.

Changes in future trends of GHG emissions in LDCs will depend on the pace of urbanization and industrialization in the LDCs. Although currently most LDCs continue to have a large share of rural population, the rate of urbanization is progressing rapidly. This pattern is expected to lead to increasing access to and use of energy and emissions (Parikh and Shukla, 1995; Holtedahl and Joutz, 2004; Alam et al., 2008; Liu, 2009) particularly since early stages of urbanization and industrialization are associated with higher emissions than later stages (Martínez-Zarzoso and Maruotti, 2011).

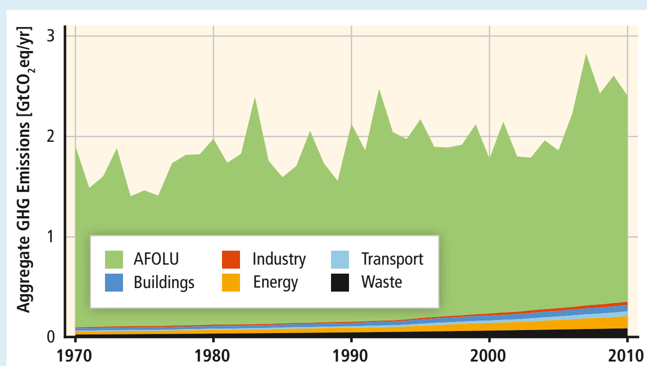


Figure 5.20 | Territorial GHG emissions per sector in LDCs over 1970 – 2010 aggregated using 100-year GWP values. The figure shows that for all sectors apart from AFOLU, emissions have increased sharply in relative terms. Yet AFOLU presents the largest share of emissions. Data from JRC/PBL (2013) and IEA (2012). The direct emission data from JRC/PBL (2013) (see Annex II.9) represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthopogenic emission sources in the Forestry and Other Land Use (FOLU) sub-sector. For a more detailed representation of Agriculture and FOLU (AFOLU) GHG flux see Section 11.2 and Figures 11.2 and 11.6.

5.3.5.5 Waste

Total global emissions from waste almost doubled from 1970–2010 (Figure 5.18), while in the period 2000–2010, the increment was 13 % (1278 $MtCO_2eq$ vs. 1446 $MtCO_2eq$) (JRC/PBL, 2013). In 2010 GHG emissions from waste represented 3.0 % of total GHG emissions from all sources (1446 $MtCO_2eq$), compared to 2.6 % in 1970 (734 $MtCO_2eq$) (JRC/PBL, 2013). The main sources of waste GHG emissions were solid waste disposal on land (46 % of total waste GHG emissions in 1970 and 43 % in 2010) and wastewater handling (51 % of total waste GHG emissions in 1970 and 54 % in 2010), waste incineration (mainly CO_2) and other sources are of minor importance (JRC/PBL, 2013).

Since 1998 waste GHG emissions from ASIA are greater than from OECD-1990 countries (mainly wastewater emissions). While in 1970 emissions from OECD-1990 countries represented 50 % of emissions (364 $MtCO_2eq$) and ASIA 27 % (199 $MtCO_2eq$), in 2010 ASIA represented 41 % of waste GHG emissions (596 $MtCO_2eq$) and OECD-1990 27 % (391 $MtCO_2eq$) (Figure 5.18) (JRC/PBL, 2013). The main GHG from waste is CH_4—mainly emitted from municipal solid waste disposal on land and from wastewater—representing 91 % of the total in 1970 (90 % in 2010), followed by N_2O (7 % in 1970, 8 % in 2010) (Monni et al., 2006; JRC/PBL, 2013).

Waste generation is closely related to population, urbanization, and affluence (see also Section 10.14). Waste generation rates are correlated with different indicators of affluence, including GDP per capita, energy consumption per capita, and private final consumption per capita (Monni et al., 2006; Bogner et al., 2008). Similarly Sjöström and Östblom (2009) remark that waste quantities have grown steadily along with GDP over recent decades. Moreover they report that the total quantity of municipal waste per capita increased by 29 % in North America, 35 % in OECD, and 54 % in the EU15 from 1980 to 2005 (Sjöström and Östblom, 2009).

There are many uncertainties concerning estimation of past, current, and future emissions, as well as the mitigation potential in the waste sector, the most important relating to the poor quality of the activity data needed for estimation of emissions (Monni et al., 2006; Bogner et al., 2008).

5.4 Production and trade patterns

5.4.1 Embedded carbon in trade

Between 1971 and 2010, world trade has grown by 6 % a year on average, meaning it doubled nearly every 12 years (World Trade Organisation, 2011), outpacing the growth of world GDP, which was 3.1 % per year on average. The ratio of world exports of goods and commercial services to GDP in real terms has increased substantially; steadily since 1985, and by nearly one-third between 2000 and 2008, before dropping in 2009 as world trade fell as a result of the Global Financial Crisis (World Trade Organisation, 2011). While information on the size of physical trade is more limited, Dittrich and Bringezu (2010) estimate that between 1970 and 2005, the physical tonnage of international trade grew from 5.4 to 10 Gt. Statistics on CO_2 emissions associated with international shipping support these findings (Heitmann and Khalilian, 2011); international shipping has grown at a rate of 3.1 % per annum for the past three decades (Eyring et al., 2010), and there is evidence of a recent acceleration in seaborne trade suggesting that trade, measured in ton-miles has increased by 5.2 % per annum (on average) between 2002 and 2007. This is further supported by van Renssen (2012), who observes a doubling of shipping and aviation emissions between 1990 and 2010.

Trade has increased the developing countries' participation in the global economy. According to the World Trade Organization, "From 1990 to 2008, the volume of exports from developing countries grew consistently faster than exports from developed countries, as did the share of developing countries' exports in the value of total world exports". Between 2000 and 2008, the volume of developing countries' exports almost doubled, while world exports increased by 50 %. Non-OECD Asia is by far the most important exporting region in the developing country group, with a 10 % share of world exports in 1990 (USD 335 million), which increased to 21 % (USD 2603 million) in 2009 (World Trade Organisation, 2011).

The consumption accounts presented in Section 5.3.3.2 showed that between 1990 and 2000, global CO_2 emissions increased by about 10 %, and by a further 29 % between 2000 and 2008 (Le Quere et al., 2009; Peters et al., 2011). Over the full period, all of the growth in CO_2 emissions occurred in non-Annex B countries while CO_2 emissions in Annex B countries stabilized. Partly, this was due to the collapse of the former Soviet Union in the early 1990s, which reduced emissions in these countries between 1990 and 2000. But the pattern also relates to the rapid increase in international trade between Annex B and non-Annex B countries. Twenty percent of the growth in CO_2 emissions in non-Annex B countries can, through trade, be attributed to the increased demand for products by Annex B countries (Peters et al., 2011).

In 1990, the global CO_2 emissions associated with exported products was 4.3 $GtCO_2$ (Peters et al., 2011). This figure includes the CO_2 emissions through the whole supply chain associated with the production of the final product, using the 'Environmentally Extended Multi-Region Input-Output Analysis' (Davis and Caldeira, 2010; Minx et al., 2009). In 2008, this figure had increased to 7.8 $GtCO_2$, (average annual increase of 4.3 %) (Peters et al., 2011). Between 1990 and 2000, the growth in the embedded CO_2 emissions of products being traded grew by 10 %. Between 2000 and 2008, CO_2 emissions embedded in trade grew by a further 26 %, demonstrating a more recent and rapid increase (Peters et al., 2011). In 2005, China accounted for 25 % of the total global CO_2

Box 5.4 | Definition of carbon leakage

Carbon leakage refers to phenomena whereby the reduction in emissions (relative to a benchmark) are offset by an increase outside the jurisdiction (Peters and Hertwich, 2008; Barrett et al., 2013). Leakage can occur at a number of levels, be it a project, state, province, nation, or world region. This can occur through:

- **Changes in the relative prices** whereby national climate regulation reduces demand for fossil fuels, thereby causing a fall in world prices resulting in an increase in demand outside the jurisdiction
- **Relocation of industry** where a firm relocates their operation to another nation due to less favourable financial benefits in the original jurisdiction brought about by the reduction measures
- **Nested regulation** where, for example, the European Union imposes an aggregate cap on emissions meaning that the efforts of individual countries exceed the cap freeing up allowances in other country under the scheme
- **Weak consumption leakage** describes the increase of emissions in one country as a consequence of actions or policies that are unrelated to climate policy (such as a changed quantity or composition of imports) in another country.

emissions embedded in exports, with China's exported emissions at 1.7 Gt (Weber et al., 2008) compared to the global total of 6.8 Gt (Peters et al., 2011). In terms of total CO_2 emissions due to the production of goods and services that were finally consumed in another country, a number of papers suggest that this represents between 20 % and 26 % of total global emissions in 2004 (Davis and Caldeira, 2010; Peters et al., 2011).

Trade explains the divergence between territorial and consumption-based emissions in OECD countries to the extent that it has resulted in an increase of emissions in the exporting countries. The associated increase in emissions in exporting countries (mostly non Annex B) is often defined in the literature as 'weak leakage' (see Box 5.4) (Davis and Caldeira, 2010; Rothman, 2000; Peters and Hertwich, 2008; Weber and Peters, 2009; Strømman et al., 2009; Peters, 2010; Yunfeng and Laike, 2010). Lenzen et al. (2010) confirm these findings along with numerous national-level studies (Wiedmann et al., 2010; Hong et al., 2007; Liu et al., 2011; Ackerman et al., 2007; Weber and Matthews, 2007; Mäenpää and Siikavirta, 2007; Muñoz and Steininger, 2010; Minx et al., 2011).

Trade has allowed countries with a higher than global average emission intensity to import lower emission intensity goods and vice versa. For example, exports from China have a carbon intensity four times higher than exports from the United States (Davis and Caldeira, 2010). Net exports of carbon could occur due to (i) a current account surplus, (ii) a relatively high energy intensity of production, (iii) a relatively high carbon intensity of energy production, and (iv) specialization in the export of carbon-intensive products (Jakob et al., 2013). Jakob and Marchinski (2013) argue that further analysis is required to better understand the gap in consumption and territorial emissions, and to assess the validity of possible but different causes.

Calculating emissions embodied in trade tells us the amount of emissions generated to produce goods and services that are consumed elsewhere, but it doesn't allow us to establish a causal interpretation. In particular, it doesn't allow identifying which fraction of observed changes in regional emissions can be attributed to regulatory changes undertaken elsewhere, such as adoption of climate measures in one region (often called 'strong carbon leakage' in the literature). Due to the sparse data available, only a few empirical studies exist. (Aichele and Felbermayr, 2012, 2013) provide evidence for a strong carbon leakage effect resulting from the Kyoto protocol. Most estimates of how GHG emissions could react to regional regulatory changes have so far relied on numerical modelling. These studies find a wide variety of rates of leakage (i. e., the fraction of unilateral emission reductions that are offset by increases in other regions), with one study demonstrating that under some specific assumptions, leakages rates could even exceed 100 % (Babiker, 2005). However, it has also been pointed out that energy represents a small fraction of the total cost for most industries and therefore leakage should not be expected to render unilateral climate policies grossly ineffective (Hourcade et al., 2008; Jakob, 2011). This is confirmed by recent model comparison of 12 computable general equilibrium models. Boehringer et al. (2012) finds leakage rates between 5 % and 19 %, with a mean value of 12 %. However, taking into account (non-energy related) industrial process emissions, which are not included in the latter model comparison, may result in higher leakage rates, as some of the most energy—as well as trade-intensive sectors are also important sources of industrial process emissions (Bednar-Friedl et al., 2012) find that accounting for industrial process emissions raises the leakage rate by one-third.

5.4.2 Trade and productivity

Trade does not only affect emissions through its effect on consumption patterns, the relocation of production, and emissions for international transport, it also affects emissions through its effect on innovation and the exchange of technologies between trading partners. Section 5.6

assesses the literature on innovation while this section assesses the theoretical and empirical literature on channels through which trade (broadly defined as trade in goods and foreign direct investment) affects productivity (Havrylyshyn, 1990).

At the aggregate level, trade can improve productivity through increased allocative efficiency. Furthermore, trade increases the international flow of intermediate goods (Hummels et al., 2001; Koopman et al., 2008), allowing for the production of higher-quality final products with the same amount of emissions and other inputs (Rutherford and Tarr, 2002). Though, trade may impede productivity growth in developing countries if it causes them to specialize in low-tech labour and energy intensive sectors with little scope for productivity improvements. Trade can also increase income inequality in developing countries. For example, because the least skill-intensive industries in developed countries often become the most skill-intensive sectors in developing countries (Zhu and Trefler, 2005; Meschi and Vivarelli, 2009), developing countries can experience a negative impact on productivity growth (Persson and Tabellini, 1994).

At the sector level, trade liberalization increases competition in import-competing sectors, and causes the least-productive firms in these sectors to collapse or exit (Pavcnik, 2002). Therefore, through this mechanism, trade liberalization can cause job losses, especially for those working in the previously protected sectors. At the same time, trade can also increase productivity, energy-efficiency, and research and development (R&D) incentives in import-competing sectors: trade intensifies import-competition and increases the remaining firms' domestic market shares, both of which are associated with higher R&D efforts—possibly because firms with large market shares use innovation to deter entry (Blundell et al., 1999).

Aside allocation and competition effects, trade can increase productivity growth through knowledge spillovers. Multinationals do more R&D than purely domestic firms, thus Foreign Direct Investment (FDI) can increase the knowledge stock of the recipient country. Moreover, the entry of foreign multinationals facilitates the diffusion of energy-saving technologies if domestic firms reverse-engineer their products or hire away their employees (Keller and Yeaple, 2009). In addition to these horizontal spillovers, foreign entrants have an incentive to share their knowledge with domestic suppliers and customers to improve the quality of domestically sourced inputs and to enable domestic customers to make better use of their products (Javorcik, 2004).

Turning to empirical analyses, there are many studies that estimate the effect of trade on sector overall productivity or the international diffusion of specific technologies, but little that quantify the effect of trade, through productivity, on emissions. Empirical work, mostly focusing on labour and total factor productivity, suggests that trade openness indeed enhances productivity. Coe and Helpman (1995) and Edwards (2001) find that foreign R&D has a larger positive effect for countries with a higher import volume, and that for small countries, foreign R&D matters more for domestic productivity than domestic R&D. Keller (2000) finds that imports from high-productivity countries lead to more productivity growth than imports from low-productivity countries. According to Kim (2000), trade liberalization increased total factor productivity growth by 2 percentage points in Korea between 1985–1988. For United States firms, FDI spillovers accounted for 14 % of productivity growth between 1987–1996 (Keller and Yeaple, 2009).

With regards to specifically environmental applications, Verdolini and Galeotti (2011a) and Bosetti and Verdolini (2012) constructed and tested a model to show that the factors that impede international trade in physical goods, such as geographic distance, also hinder the diffusion of environmentally benign technologies. Reppelin-Hill (1998) finds that the Electric Arc Furnace, a technology for cleaner steel production, diffused faster in countries that are more open to trade. Trade reduces global energy efficiency if it relocates production to countries that have a comparative advantage in unskilled labour but low-energy efficiency (Li and Hewitt, 2008). Lastly, Mulder and De Groot (2007) document a convergence of energy-productivity across OECD countries over time. The results may be attributable to knowledge diffusion through trade, but the authors do not estimate a link between convergence and trade.

5.5 Consumption and behavioural change

Behaviour is an underlying driver affecting the factors in the decomposition of anthropogenic GHG emissions. Although it is difficult to delineate and attribute the effects of behaviour unambiguously, there is empirical evidence of variation in behaviour and consumption patterns across regions, social groups, and over time, and its connection to, e.g., energy and emission intensity of consumption.

This section reviews the evidence of how behaviour affects energy use and emissions through technological choices, lifestyles, and consumption preferences. It focuses on behaviour of consumers and producers, delineates the factors influencing behaviour change, and reviews policies and measures that have historically been effective in changing behaviour for the benefit of climate change mitigation.

5.5.1 Impact of behaviour on consumption and emissions

Consumer choices with regard to food, mobility, and housing, and more generally consumption patterns affect the environmental impact and GHG emissions associated with the services (Faber et al., 2012). Consumption patterns are shaped not only by economic forces, but also by technological, political, cultural, psychological, and environmental factors. For example, domestic energy use and travel choices are intrinsically related to social identity, status, and norms (Layton et al., 1993; Black et al., 2001; Steg et al., 2001; Exley and Christie, 2002). Senses of security, clean environment, family ties, and friendships are also viewed as important factors in determining consumption patterns (Chitnis and Hunt, 2012). The cultural context in which an individual lives and the inherent values of a society also shape the intrinsic motivation underlying consumer choices (Fuhrer et al., 1995; Chawla, 1998, 1999). As an example, the high proportion of people following a vegetarian diet in India can be attributed to its cultures and religions, resulting in lower GHG emissions per caloric intake (Ghosh, 2006). Similar explanations are given for India's relatively low levels of waste generation coupled with higher levels of waste recycling and re-use (Ghosh, 2006). Cross-cultural differences are also revealed at higher-income levels. In some high-income countries people appreciate high-density neighbourhoods and public transport more as compared to other countries (Roy and Pal, 2009).

Studies indicate that approximately one-third of food produced for human consumption (about 1.3 billion tonnes per year) is wasted globally, adding to GHG emissions for food production (Gustavsson et al., 2011). It is estimated that substantially more food is wasted in the developed countries than in developing countries. In Europe and North America, per capita food waste by consumers is estimated at 95–115 kg/year, while in sub-Saharan Africa and South/Southeast Asia is about 6–11 kg/year (Gustavsson et al., 2011). There is significant inter-regional variation with regard to the stage of the food chain at which wastage occurs. About 40 % of food wastage in medium- and high-income countries is generated at the consumer and retail stages, while in low-income countries food waste at the consumer level is much smaller and food waste in the early and middle stages of the food supply chain reaches about 40 %. Food losses and waste in low-income countries are attributed to financial, managerial, and technical limitations, while consumer behaviour and lack of coordination between different actors in the supply chain influence food wastage in the high-income countries (Gustavsson et al., 2011).

Empirical evidence indicates that per capita energy consumption varies widely across regions (see Sections 5.3 and 5.4), resulting in significantly different CO_2 emissions in per capita terms and per unit economic activity, but that GDP per capita does not explain all variation (see Figures 5.16 and 5.19). While part of this variability can be attributed, inter alia, to population density, infrastructure and resource endowments, social and cultural predispositions, such as lifestyle, also influence the choice and consumption levels of energy and materials (Marechal, 2009; Tukker et al., 2010; Sovacool and Brown, 2010). Historic data show a clear increase at the global level of key consumption activities of households that contribute to emissions, such as personal travel by car, intake of meat and fossil fuel consumption (Mont and Plepys, 2008). Energy intensity, which depends on behaviour at the individual and economy-wide level, is therefore one of the key determinants of emissions in the decomposition analysis. Behaviour is not only an implicit and relevant driver of emissions, but also equally important a potential agent for change in emissions.

Apart from individuals and households, companies and organizations also contribute to emissions, through both direct and indirect use of energy. Businesses, policy makers, as well as non-governmental consumer organizations also play a role in inducing behaviour change and therefore indirectly changing emissions. Studies show that environmental values are important determinants of willingness to accept climate change policy measures, and that values and norms are required for climate policy support within public and private organizations (Biel and Lundqvist, 2012).

Technological solutions directed at improving resource productivity may not be sufficient for curbing the environmental impact of consumption (Hunt and Sendhil, 2010). Complementary to eco-efficiency in production, sustainable development strategies may need to support sufficiency in consumption, shifting from a culture of consumerism without limits to a society with less materialistic aspirations (Mont and Plepys, 2008). This implies an addition to the focus on more environmentally sound products and services; finding happiness with lower levels of material consumption, especially in higher-income countries (Hunt and Sendhil, 2010).

5.5.2 Factors driving change in behaviour

The literature differentiates between efficiency behaviours, (1) the purchase of more or less energy-efficient equipment (e.g., insulation), and (2) curtailment behaviours that involve repetitive efforts to reduce energy use, such as lowering thermostat settings (Gardner and Stern, 1996). It is suggested that the energy saving potential through efficiency behaviour is greater than that through curtailment behaviour. However, energy-efficient appliances can lead to an increase in demand for the service due to the lower cost of these services, discussed in Section 5.6.2.

Behavioural economics studies anomalies in consumer's energy choices but it is also used to design approaches aimed at influencing and modifying those behaviours (see Sections 2.4 and 3.10.1). There is evidence that consumers consistently fail to choose appliances that offer energy savings, which, according to engineering estimates, more than compensate for their higher capital cost. In analyses of appliance choices, Hausman (1979) and subsequent studies found implicit consumer discount rates ranging from 25 % to over 100 % (Train, 1985; Sanstad et al., 2006). A variety of explanations have been offered, including consumer uncertainty regarding savings, lack of liquidity and financing constraints, other hidden costs, and the possibility that the engineering estimates may overstate energy savings in practice. Recent ideas draw on bounded rationality, the notion that consumers 'satisfice' rather than 'optimize' (Simon, 1957), the importance of non-price product attributes and consumers' perceptions thereof (Lancaster, 1965; Van den Bergh, 2008), and asymmetric information and the principal-agent problem (Akerlof, 1970; Stiglitz, 1988). From psychology and behavioural economics come notions such as loss aversion (consumers place more weight on avoiding a loss than on securing a gain of the same magnitude (Kahneman et al., 1982); see Greene (2011) for an application to energy efficiency), attention[11] and the role of salience[12] (Fiske and Morling, 1996), priming (Richardson-Klavehn and Bjork, 1988), affect (Slovic et al., 2002), norms[13] (Axelrod, 2006), a present-bias in inter-temporal decision making (O'Donoghue and Rabin, 2008; DellaVigna, 2009), and mental accounts (separate decision making for subsets of commodities; Thaler, 1999). The literature is not unanimous, though, regarding the magnitude of the 'energy efficiency gap' (Allcott and Greenstone, 2012).

Ayres et al. (2009) estimate that non-price, peer-comparison interventions can induce a consumption response equivalent to a 17–29 % price increase.[14] Newell et al. (1999) provides evidence that the United States room air conditioners energy efficiency gain since 1973 is only about one quarter induced by higher energy prices, while another quarter is due to raised government standards and labelling.

Behavioural interventions can be aimed at voluntary behavioural change by targeting an individual's perceptions, preferences, and abilities, or at changing the context in which decisions are made. Such non-price context interventions have been used across countries with varying degrees of success to bring about behaviour change in consumption choices and patterns of energy use. These include antecedent strategies (involving commitment, goal setting, information or modelling) and consequence strategies (feedback or rewards) (Abrahamse et al., 2005; Fischer, 2008). As an example, the Property Assessed Clean Energy (PACE) program tackles the high-discount rate that residential energy users ascribe to investments associated with energy-efficiency retrofits of buildings through providing local governments financing for retrofits of buildings repayable through a supplement to property taxes (Ameli and Kammen, 2012). Various United States and United Kingdom government agencies and the private sector, including some electric and water utilities, have developed strategies collected under the rubrics Nudge (Thaler and Sunstein, 2009) and Mindspace (Dolan et al., 2012). These programs involve elements such as increasing the salience of financial incentives, invoking norms, providing information on social comparisons, and modifying the choice architecture (the structure of the choice) including the default alternative.[15] Laboratory studies and small-scale pilots have demonstrated a potential role for behavioural interventions, but there is uncertainty on the scalability of these interventions and the level of impacts they can achieve (Hunt and Sendhil, 2010).

The state of awareness and concern about climate change and the willingness to act is an important underlying driver for voluntary reduction in energy consumption by individuals. Some studies indicate that the provision of information, or awareness creation by itself, is unlikely to bring about significant change in consumption behaviour and reduction in emissions (Van Houwelingen and Van Raaij, 1989; Kollmuss and Agyeman, 2002; Jackson, 2005). Other studies indicate that awareness creation and provision of information facilitates the deployment of energy-efficient technologies. The establishing of benchmarks for the energy consumption of homes and commercial buildings may contribute to reduce information asymmetries in the marketplace and to lower the discount rates used by consumers to evaluate future efficiency gains (Cox et al., 2013). Coller and Williams (1999) suggest that information about energy consumption will result in a 5 % decline in discount rates for energy decisions made by the median population, an estimate that is adopted by Cox et al. (2013).

Rewards are seen to have effectively encouraged energy conservation, though with possibly short-lived effects (Dwyer and Leeming, 1993; Geller, 2002). Feedback has also proven to be useful, particularly when given frequently (Becker et al., 1981), while a combination of strategies is generally found to be more effective than applying any one strategy (Abrahamse et al., 2005).

Ability to change, or opportunities, is also essential, and can be constrained by institutional and physical structures. Old habits are also seen as a strong barrier to changing energy behaviours (Pligt, 1985; Kollmuss and Agyeman, 2002; Mont and Plepys, 2008; Whitmarsh, 2009).

5.6 Technological change

5.6.1 Contribution of technological change to mitigation

The AR4 acknowledged the importance of technological change as a driver for climate change mitigation (IPCC, 2007a). It also gave an extensive review of technological change and concluded, among other things, that there is a relationship between environmental regulation and innovative activity on environmental technologies, but that policy is not the only determinant for technological change. It also discussed the debate around technology push and market pull for technological change, the role of different actors and market failures around technological innovation. Since 2007, more studies have documented improvements of energy efficiency and the impact of different drivers, including technological change, on energy intensity (e.g., Fan and Xia; Sheinbaum et al., 2011; Wu et al., 2012).

[11] For example, Allcott (2011) indicates that 40 % of US consumers do not consider a vehicle's gasoline consumption when purchasing a car.

[12] Chetty et al. (2009) show that consumers' reaction to taxes depends on the visibility and salience of the tax.

[13] Responsiveness to norm-based messages has been demonstrated in a number of domains (e.g., Frey and Meier, 2004; Cialdini et al., 2006; Salganik et al., 2006; Goldstein et al., 2008; Cai et al., 2009).

[14] Similarly, with household water use, Ferraro and Price (2011) find that the social-comparison effect is equivalent to what would be expected if average prices were to increase by 12 % to 15 %.

[15] UK Cabinet Office (2012).

5.6.1.1 Technological change: a drive towards higher or lower emissions?

Previous assessment reports have focused on the contribution of technological change in reducing GHG emissions. The rising emissions in emerging economies and accompanied rapid technological change, however, point at a question of whether technological change might also lead to rising emissions—in developed and developing countries. Due to a combination of rebound effects (see Section 5.6.2) and an observed tendency towards cost-saving innovations, the rebound effect could be enhanced so much that energy-saving technological change could indirectly lead to an increase in emissions (Fisher-Vanden and Ho, 2010). Probably more importantly, technological change may favour non-mitigation issues over reduction of GHG emissions. For example, compact cars in the 1930s have a similar fuel consumption rate to compact cars in the 1990s, but have far advanced in terms of speed, comfort, safety, and air pollution (Azar and Dowlatabadi, 1999).

The energy sector is of great importance to technological change and climate change mitigation. Changes in the energy intensity that are not related to changes in the relative price of energy are often called changes in the autonomous energy-efficiency index (Kaufmann, 2004; Stern, 2011). How do macro-economic factors affect differences in energy efficiency between countries and changes over time? Using country-based case study approach, the general trend at the macro-level over the 20th century in the United States, the United Kingdom, Japan, and Austria has been to greater energy efficiency (Warr et al., 2010).

Recent research investigates the factors that affect the adoption of energy-efficiency policies or energy-efficiency technology (Matisoff, 2008; Fredriksson et al., 2004; Gillingham et al., 2009; Linares and Labandeira, 2010; Wei et al., 2009; Popp, 2011; Stern, 2011). Differences in endowments, preferences, or the state of technology create differences in the adoption of energy-efficiency technologies across countries and among individuals over time. The rate of adoption may also be influenced by market failures such as environmental externalities, information access, and liquidity constraints in capital markets, and behavioural factors. Behavioural factors are discussed in Section 5.5.2. The variation of implementation of energy-efficiency measures varies greatly, both between countries and between sectors and industries, especially if developing countries are taken into account (Sanstad et al., 2006).

5.6.1.2 Historical patterns of technological change

There is ample evidence from historical studies, for instance in the United States, Germany, and Japan, that technological change can affect energy use (Carley, 2011b; Welsch and Ochsen, 2005; Unruh, 2000). In Japan, it has also shown to be a driver for reduction of CO_2 emissions (Okushima and Tamura, 2010). Technological change is also a dominant factor in China's fast-declining energy intensity until 2003 (Ma and Stern, 2008); but between 2003 and 2010, energy intensity declined only slightly (IEA, 2012).

Technological change in the energy sector is best studied. Several studies find that technological change in energy was particularly pronounced in periods with a great political sense of urgency and/or energy price hikes, such as during oil crises (Okushima and Tamura, 2010; Karanfil and Yeddir-Tamsamani, 2010). Wilbanks (2011) analyzes the discovery of innovations and argues that only with a national sense of threat and the entailing political will it is worthwhile and possible to set up an "exceptional R&D" effort in the field of climate change mitigation. Aghion et al. (2012) conclude an increase in clean technology patenting in the auto industry as a consequence of policy-induced increases in energy prices. In a study on 38 countries, Verdolini and Galeotti (2011b) find that technological opportunity and policy, proxied by energy prices, affect the flow of knowledge and technological spillovers.

There is more evidence supporting the conclusion that policy matters as a part of systemic developments. Dechezleprêtre (2008) find that the Kyoto Protocol has a positive impact on patenting and cross-border technology transfer, although they did not evaluate the impact of those on emissions. In a study on photovoltaic (PV) technology in China, a policy-driven effort to catch up in critical technological areas related to manufacturing proved successful, although it also mattered that capabilities could be built through the returning of a Chinese diaspora (de la Tour et al., 2011). Calel and Dechezleprêtre (2012) show that the European Union Emissions Trading System led to an increase in climate technology-related patents in the European Union.

5.6.2 The rebound effect

Section 3.9.5 distinguishes between 'direct' and 'indirect' rebound effects. Direct rebounds appear when, for example, an energy-efficient car has lower-operating costs encouraging the owner to drive further (Sorrell, 2007). In addition, this could apply to a company where new, more energy efficient technology reduces costs and leads to an increase in production. Indirect rebounds (Lovins, 1988; Sorrell, 2007) appear when increased real income is made available by saving energy costs that are then used to invest or purchase other goods and services that emit GHG emissions (Berkhout et al., 2000; Thomas and Azevedo, 2013). For example, savings in fuel due to a more-efficient car provides more disposable income that could be spent on an additional holiday. These could include substitution or income effects or changes in consumption patterns (Thomas and Azevedo, 2013). Economy-wide changes include market price effects, economic growth effects, and adjustments in capital stocks that result in further increases in long-run demand response for energy (Howarth, 1997).

Rebound effects are context-specific, making it difficult to generalize on their relative size and importance. Being context-specific means that there is evidence of both negative rebound effects where further energy saving is induced beyond the initial savings and 'backfire' where the rebound effects exceed the initial saving (Gillingham et al., 2013; Chakravarty et al., 2013; Saunders, 2013). There is much debate on the size of the rebound effect with considerably more evidence on direct rebounds than on indirect rebounds. There are numerous studies relying predominately on econometric techniques to evaluate rebounds. A comprehensive review of 500 studies suggests that direct rebounds are likely to be over 10 % and could be considerably higher (i.e., 10 % less savings than the projected saving from engineering principles). Other reviews have shown larger ranges with Thomas and Azevedo (2013) suggesting between 0 and 60 %. For household-efficiency measures, the majority of studies show rebounds in developed countries in the region of 20–45 % (the sum of direct and indirect rebound effects), meaning that efficiency measures achieve 65–80 % of their original purposes (Greening et al., 2000; Bentzen, 2004; Sorrell, 2007; Sorrell et al., 2009; Haas and Biermayr, 2000; Berkhout et al., 2000; Schipper and Grubb, 2000; Freire González, 2010). For private transport, there are some studies that support higher rebounds, with Frondel et al. (2012) findings rebounds of between 57 and 62 %.

There is evidence to support the claim that rebound effects can be higher in developing countries (Wang et al., 2012b; Fouquet, 2012; Chakravarty et al., 2013). Roy (2000) argues that rebound effects in the residential sector in India and other developing countries can be expected to be larger than in developed economies because high-quality energy use is still small in households in India and demand is very elastic (van den Bergh, 2010; Stern, 2011; Thomas and Azevedo, 2013). However, there is considerable uncertainty of the precise scale of rebound effects in developing countries with more research required (Thomas and Azevedo, 2013; Chakravarty et al., 2013). In terms of developed countries, Fouquet (2012) provides evidence on diminishing rebound effects in developed countries due to less inelastic demand for energy.

While generalization is difficult, a circumstance where rebounds are high is when energy costs form a large proportion of total costs (Sorrell, 2007). Rebounds effects are often diminished where energy-efficiency improvements are coupled with an increase in energy prices. For industry, targeted carbon-intensity improvements can reduce costs and therefore prices and subsequently increase output (Barker et al., 2007). Therefore, the relative scale of the saving is a good indicator of the potential size of the rebound effect. In conclusion, rebound effects cannot be ignored, but at the same time do not make energy-efficiency measures completely redundant. By considering the size of the rebound effect, a more-realistic calculation of energy-efficiency measures can be achieved providing a clearer understanding of their contribution to climate policy. Particular attention is required where efficiency saving are made with no change in the unit cost of energy.

5.6.3 Infrastructure choices and lock in

Infrastructure in a broad sense covers physical, technological, and institutional categories but is often narrowed down to long-lasting and capital-intensive physical assets to which public access is allowed, such as transport infrastructure (Ballesteros et al., 2010; Cloete and Venter, 2012). The assessment in this part focuses on the narrower physical part. Among physical infrastructure are buildings, roads and bridges, ports, airports, railways, power, telecom, water supply and waste water treatment, irrigation systems, and the like. Energy consumption and CO_2 emissions vary greatly between different types of infrastructure. Infrastructure choices reflect the practice at the time of investment but they have long-lasting consequences. The infrastructure and technology choices made by industrialized countries in the post-World War II period, at low energy prices, still have an effect on current worldwide GHG emissions. Davis et al. (2010) estimate the commitment to future emissions and warming by existing CO_2-emitting devices, totalling to 500 (280–700) $GtCO_2$ between 2010 and 2060, and an associated warming of 1.3 °C (1.1 °C to 1.4 °C).

Transport is a case in point. Air, rail, and road transport systems all rely on a supporting infrastructure, and compete for distances in the range of 1500 km. Of these options, railways typically have the lowest emissions, but they require substantial infrastructure investments. Similarly, for urban transport, public transport requires substantial infrastructure investments to provide mobility with relatively low-emission intensities. At the same time, existing roads are designed for use for decades and consequently automobiles remain a major means for mobility. In United States cities, 20–30 % of the land-area is used for roads, the corresponding share for major cities in Asia is 10–12 % (Banister and Thurstain-Goodwin, 2011; Banister, 2011a; b). But the emerging megacities around the world are associated with population expansion and large-scale increase in infrastructure supply. Investment in urban physical investment in these emerging megacities will have a significant long-lasting impact on GHG emissions. Investment in waste disposal facilities (incinerators) is an example of a path dependency and lock-in of an industry barrier that will prevent material efficiency strategies for a long period of time. A recent study proves how this lock-in effect in places such as Denmark, Sweden, Germany, or the Netherlands is threatening recycling and encouraging the shipment of waste that otherwise could be treated locally with less environmental cost (Sora and Ventosa, 2013).

Carley (2011a) provides historical evidence from the United States electricity sector indicating that crucial drivers—market, firm, government, and consumer—can work together to improve efficiency, but that they can also lead to "persistent market and policy failures that can inhibit the diffusion of carbon-saving technologies despite their apparent environmental and economic advantages" (Unruh, 2000, 2002).

Avoiding the lock-in in emission-intensive physical infrastructure is highly important to reduce emissions not only in the short run but also far into the future. At the planning stage, when choice of materials and construction are made, a forward-looking life-cycle assessment can help to reduce undesired lock-in effects with respect to the construction and operation of large physical infrastructure.

5

5.7 Co-benefits and adverse side-effects of mitigation actions

The implementation of mitigation policies and measures can have positive or negative effects on broader economic, social, and/or environmental objectives—and vice versa. As both co-benefits and adverse side-effects occur, the net effect is sometimes difficult to establish (Holland, 2010).[16] The extent to which co-benefits and adverse side-effects will materialize in practice as well as their net effect on social welfare differ greatly across regions, and is strongly dependent on local circumstances, implementation practices, as well as the scale and pace of the deployment of the different mitigation measures (see Section 6.6). Section 4.8 relates co-benefits to sustainable development, Section 5.2 covers the historic emission trends of many substances related to air quality co-benefits and adverse side-effects, Section 6.6 covers the forward-looking perspective, and the sectoral dimensions are discussed in Sections 7.9, 8.7, 9.7, 10.8, and 11.7. While Section 12.8 focuses on co-effects in cities, Chapter 15 considers the policy implications. This section looks at co-benefits and adverse effects from a macro-perspective to understand their role in decision making for climate change mitigation and sustainable development. We focus on cross-sectoral air pollution literature and the role of pollutant emission trends and briefly discuss the difficulty for assessing the role of co-benefits and adverse effects as an underlying driver when it plays a role for GHG-mitigation decisions. Figure 5.21 offers a picture of the connection between climate change and other social and environmental objectives through policies affecting the emissions of various substances. The following chapters will assess many of these interactions between air pollutants associated with the combustion of fossil fuels and their direct and indirect impacts.

The quantitative key findings of the AR4 were three-fold: First, the reduction of fossil fuel combustion will lead to the reduction of a number of air pollutants that interact with a number of policy objectives (see Figure 7.8). Second, the policy costs of achieving air pollution objectives through direct control measures decrease as a result of mitigation policies. Third, monetized health benefits counterbalance a substantial fraction of mitigation costs, even exceeding them in certain cases, particularly in developing countries (Barker et al., 2008). The next section will assess new literature that relates to the third finding while the post-AR4 literature on the first two findings is presented in the sector chapters and summarized in Section 6.6.

[16] Co-benefits and adverse side-effects describe co-effects without yet evaluating the net effect on overall social welfare. Please refer to Sections 3.6.3 and 4.8.2 as well as to the glossary in Annex I.

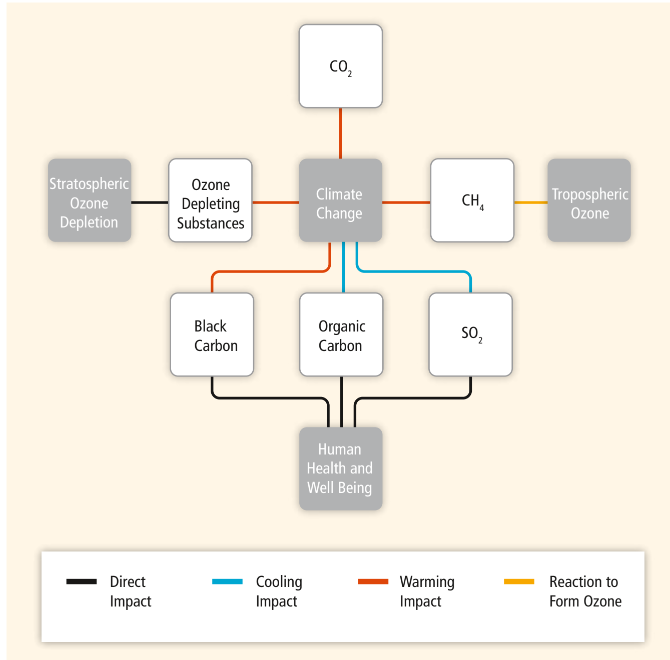


Figure 5.21 | Impacts of and links between selected substances emitted to the atmosphere. Adopted from (UNEP, 2012).

5.7.1 Co-benefits

A substantial share of estimated co-benefits is related to improving health through limiting air pollution while reducing GHG emissions. Estimates in the literature for the monetized air quality co-benefits from climate change mitigation range from 2 to 930 USD_{2010}/tCO_2, and co-benefits in developing countries around twice those in industrialized countries (see Nemet et al., 2010a) for a review and (West et al., 2013) for the high estimate. The gap between developing and industrialized countries results from lower levels of air pollution control and higher pollution levels in the former countries, and thus the greater potential for improving health, particularly in the transport and household energy demand sectors (Markandya et al., 2009; Nemet et al., 2010b; West et al., 2013; Shukla and Dhar, 2011). In industrialized countries, substantial reductions in air pollutant emissions have already occurred in the absence of climate policy and further tightening of air regulations is underway (Rao et al., 2013). If climate policy provides only small incremental reductions, then the co-benefit is small (see Section 3.6.3), while large emission reductions are expected to yield substantial air quality co-benefits and associated cost savings (see Section 6.6.2).

Much of the literature assessed in AR4 did not explicitly analyze policies targeted at reducing air pollution—thereby neglecting the associated opportunity costs of mitigation polices (Bollen et al., 2009; Edenhofer et al., 2013). But for countries and regions that do not have or do not enforce current air quality regulations, it is important to consider expected future air pollution policies. Rapidly industrializing developing countries may follow the pattern of developed countries and adopt regulations to improve local air quality (and provide immediate local

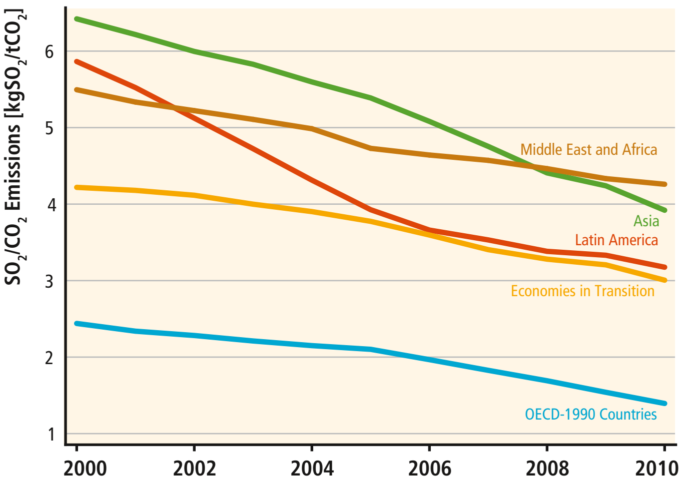


Figure 5.22 | Trends for SO_2 per CO_2 emissions per region over 2000–2010 | For CO_2: territorial, excluding AFOLU and Waste. Data Source: JRC/PBL, 2013. For SO_2, data source: Klimont et al., 2013. Regions are defined in Annex II.2.

health and environmental benefits) before focusing on climate policy (Nemet et al., 2010b; Klimont et al., 2013). If this is indeed the case, the co-benefits of climate policy will be much smaller. Figure 5.22 shows the declining trend in SO_2-emission intensity per CO_2 emissions (see Section 5.2 for trends in global SO_2 emissions). It shows that assumptions about the extrapolation of the historic trends into the future will be a major determinant of future co-benefits estimates (Burtraw and Evans, 2003; Bell et al., 2008), see Section 6.6.2.7 for an example from the scenario literature).

Due to a lack of a counterfactual historic baseline for other policies, it is not possible to determine a clean ex-post measure for the co-benefits of climate policies such as the Kyoto Protocol. But it is clear that drivers for fossil fuel combustion affect both CO_2 emissions and SO_2 emissions (see van Vuuren et al., 2006).

5.7.2 Adverse side-effects

There are also adverse side-effects associated with mitigation. A comprehensive discussion is given in the following chapters (6–12), while this section presents some examples in the context of air pollution. While many low-carbon energy supply technologies perform better than pulverized coal technologies for most air pollutants, some solar energy technologies, for example, have comparable or even higher life-cycle emissions of SO_2 (see Figure 7.8 in Section 7.9.2). Desulphurization of existing coal power plants, however, requires additional consumption of coal in the thermal power sector implying higher CO_2 emissions for a given electricity output (Pan, 2013). While CO_2 capture processes reduce SO_2 emissions at the same time, some carbon dioxide capture and storage (CCS) technologies would imply an increase in NO_x and/or ammonia (NH_3) emissions (Koornneef et al., 2012).

For the displacement of fossil-based transport fuels with biofuels, many studies indicate lower carbon monoxide and hydrocarbon emissions, but NO_x emissions are often higher. Next-generation biofuels are expected to improve performance, such as the low particulate matter emissions from lignocellulosic ethanol (see Hill et al., 2009; Sathaye et al., 2011; and Sections 8.7 and 11. A.6). In the buildings sector, the most important health risks derive from insufficient ventilation practices in air-tight buildings (Section 9.7).

5.7.3 Complex issues in using co-benefits and adverse side-effects to inform policy

Mitigation options that improve productivity of energy, water, or land use yield, in general, positive benefits. The impact of other mitigation actions depend on a wider socio-economic context within which the action is implemented (Sathaye et al., 2007). A complete incorporation of co-benefits and adverse side-effects into climate policy is compli-

Box 5.5 | The Chinese experience with co-benefits from a cross-sectoral perspective[1]

Pan et al. (Pan et al., 2011) estimate the amount of green jobs in three sectors (energy, transportation, and forestry) and the result suggests a number at least 4.5 million in 2020 in China. The wind power industry in China, including power generation and turbine manufacturing, has created 40,000 direct jobs annually between 2006 and 2010 (Pan et al., 2011). Beijing’s ambitious metro-system plan, which includes 660 km by 2015 and another 340 km during 2016–2020,could bring more than 437,000 jobs each year (Pan et al., 2011). China’s forestation activities could create as many as 1.1 million direct and indirect jobs annually during 2011–2020 to achieve its 2020 goals (Pan et al., 2011).

In 2007, China called for a more environmentally friendly and resource-saving models of production and consumption (Pan, 2012). Twelve out of 17 mandatory targets in the 12th five-year (2011–2015) plan are related to the protection of natural resources and the environment; the rest are related to the improvement of social welfare (Pan, 2012). The actions taken under the five-year plan include progressive pricing for electricity consumption; implementation of energy consumption quota, disaggregated emission targets; emissions-trading schemes; initiatives for eco-cities and low-carbon cities; and upgraded building codes with improved enforcement (Pan, 2012).

[1] See Sections 7.9, 8.7, 9.7, 10.9, and 11.8 for sectoral effects.

cated, but it is part of a shift of the development paradigm towards sustainability (Pan, 2012).

Co-benefits are pervasive and inseparable (Grubb et al., 2013). It is not possible to 'separate' each benefit with different decisions: both technically and politically, most decisions involve multiple dimensions. In addition, most suggested policy changes involve large changes in the policy environment as opposed to the concept of marginal changes (see also Section 3.6.3). Finally, many effects are measured in very different metrics or are not quantified at all. As an example, whereas local air quality co-benefits are measured in health terms, energy security is typically measured with indicators of the sufficiency of domestic resources (e.g., dependence on fossil fuel imports) and resilience of energy supply (see Sections 6.6 and 7.9 for details). All these characteristics make a comprehensive analysis of co-benefits and adverse side-effects of a particular policy or measure challenging. This is why a synthesis of results from different research communities is crucial for robust decision making (see Section 6.6).

Despite the difficulties, side-effects from climate policy are important for policy design (see Section 15.2.4). Costs of mitigation policies are over- or under-estimated when co-benefits and adverse side-effects are not included (see Sections 3.6.3 and 6.3.6). Co-benefits estimates are particularly important for policymakers because most of the climate benefits are realized decades into the future while most co-benefits, such as improvement in air quality, are realized immediately (Barker et al., 2008; Nemet et al., 2010b; Shindell et al., 2012; Jack and Kinney, 2010; Henriksen et al., 2011).

5.8 The system perspective: linking sectors, technologies and consumption patterns

Between 1970 and 2010 global greenhouse gas emissions have increased by approximately 80 %. The use of fossil fuels for energy purposes has been the major contributor to GHG emissions. Emissions growth can be decomposed in population growth and per capita emissions growth. Population growth is a major immediate driver for global GHG-emissions trends. Global population grew from 3.7 to 6.9 billion. The largest growth rates are found in MAF.

GHG emissions can be attributed to regions according to the territorial location of emissions, or alternatively emissions can be attributed to the consumption of goods and services, and located to regions where consumption takes place. There is an emerging gap between territorial and consumption-based emissions, signalling a trend where a considerable share of CO_2 emissions from fossil fuel combustion in developing countries is released in the production of goods and services exported to developed countries. At a regional level, OECD-1990 is the largest net importer of CO_2 embedded in trade, while ASIA is the largest net exporter. This emerging gap opens questions about the apparent decoupling between economic growth and GHG emissions in several Annex I countries; when consumption-related emissions are taking into account both GDP and GHG emissions have grown. Yet, a robust result is that, between 2000 and 2010, the developing country group has overtaken the developed country group in terms of annual CO_2 emissions from fossil fuel combustion and industrial processes, from both territorial and consumption perspectives.

When considering per capita emissions, rather than aggregate GHG emissions, other trends become visible. Global average per capita GHG emissions have shown a rather stable trend over the last 40 years. This global average, however, masks differences between regions and sectors. A strong correlation appears between per capita income and per capita GHG emissions both from a cross-country comparison on income and emission levels, and when considering income and emissions growth. The relation is most clearly for the sectors' energy, industry, and transport (Section 5.3.5), and holds despite the reduction in the average emission intensity of production, from 1.5 to 0.73 $kgCO_2eq/Int\$_{2005}$ over the same 40-year period.

ASIA had low per capita emission levels in 1970, but these increased steadily, by more than 150 %. The EIT region showed a rapid increase in per capita emissions between 1970 and 1990, and a sharp drop immediately after 1990. In 2010, per capita emissions are comparable in ASIA, LAM, and MAF (5.2, 6.4, and 5.4 tCO_2eq/yr, respectively) but per capita GHG emissions in OECD-1990 and EIT are still higher by a factor of 2 to 3 (14.1 and 11.9 tCO_2eq/yr, respectively). Also, between 1970 and 2010, per capita land-use related emissions decreased, but fossil fuel-related emissions increased. Regions vary greatly with respect to the income trends. The OECD-1990 and LAM countries showed a stable growth in per capita income, which was in the same order of magnitude as the GHG-intensity improvements, so that per capita emissions remained almost constant and total emissions increased by the rate of population growth. The EIT showed a decrease in income around 1990, which together with decreasing emissions per output and a very low population growth led to a robust decrease in overall emissions. The MAF sector also shows a decrease in GDP per capita but a high population growth led to a robust increase in overall emissions. Emerging economies in Asia showed very high economic growth rates; rapidly expanding industries resulted in sharply increasing emissions. In 2010, ASIA emitted more than half of worldwide industry-related emissions. ASIA showed both the highest economy-wide efficiency improvements measured as output per emissions, and the largest growth in per capita emissions.

The underlying drivers for economic growth are diverse and vary among regions and countries. Technological change and human capital are key underlying drivers, but some authors also underscore the availability of energy resources to play a central role in economic growth. Economic growth is strongly correlated to growth in energy use, and the direction of causality is not clearly established. At the global level, per capita primary energy consumption rose by 29 % from 1970 to 2010, but due to population growth total energy use has increased much more–140 % over the same period.

Energy-related GHG emissions can be further decomposed in two additional immediate drivers: energy intensity and carbon intensity. Energy intensity has declined globally in all developed and major developing countries including India and China. This decline can be explained through technological changes, the effects of structural changes, and the substitution of other inputs such as capital and labour used. These historical improvements in energy intensities, however, have not been enough to compensate the effect of GDP growth, thus, increasing energy consumption over time as a result.

In addition, energy resources have historically become less carbon-intensive, though increased use of coal, relative to other resources, since 2000 has changed the trends exacerbating the burden of energy-related GHG emissions. Estimates of the resources of coal and conventional plus unconventional gas and oil are very large; indicating that resource scarcity has not been and will not be an underlying driver for decarbonization.

The immediate drivers that directly affect GHG emissions, namely population, GDP per capita, energy intensity and carbon intensity, are affected, in turn, by underlying drivers as described in Figure 5.1. These underlying drivers include resource availability, development status and goals, level of industrialization and infrastructure, international trade, urbanization, technological changes, and behavioural choices. Among these, infrastructure, technological changes and behavioural choices appear to be critical but, even though their influences on other drivers is well established, the magnitude of this impact remains difficult to quantify.

Co-benefits have large potential to contribute to emission reductions, but its historic contribution is not established. Infrastructural choices have long-lasting effects directing the development path to higher or lower energy and carbon intensities. Infrastructure also guides the choices in technological innovation. Technological change affects both income and emission intensity of income; it can lead to both increasing and decreasing GHG emissions. Historically, innovation increased income but also resource use, as past technological change has favoured labour productivity increase over resource efficiency. There is clear empirical evidence that prices and regulation affect the direction of innovations. Innovations that increase energy efficiency of appliances often also lead to increased use of these appliances, diminishing the potential gains from increased efficiency, a process called 'rebound effect'.

Behaviour and life-styles are important underlying drivers affecting the emission intensity of expenditures through consumption choices and patterns for transportation modes, housing, and food. Behaviour and lifestyles are very diverse, rooted in individuals' psychological traits, cultural, and social context, and values that influence priorities and actions concerning climate change mitigation. Environmental values are found to be important for the support of climate change policies and measures. Chapter 4 discusses formal and civil institutions and governance in the context of incentivizing behavioural change. There are many empirical studies based on experiments showing behavioural interventions to be effective as an instrument in emission reductions, but not much is known about the feasibility of scaling up experiments to the macro economy level.

As described across the different sections of the chapter, factors and drivers are interconnected and influence each other and, many times, the effects of an individual driver on past GHG emissions are difficult to quantify. Yet historic trends reveal some clear correlations. Historically, population growth and per capita income growth have been associated with increasing energy use and emissions. Technological change is capable to substantially reduce emissions, but historically, labour productivity has increased more compared to resource productivity leading to increased emissions. Regulations and prices are established as directing technological change towards lower emission intensities. Behavioural change is also established as a potentially powerful underlying driver, but not tested at the macro level. Policies and measures can be designed and implemented to affect drivers but at the same time these drivers influence the type of policies and measures finally adopted. Historic policies and measures have proved insufficient to curb the upward GHG emissions trends in most countries. Future policies need to provide more support for emission reductions compared to policies over the period 1970–2010, if the aim is to change the future GHG emissions trends.

5.9 Gaps in knowledge and data

- **There is a need for a more timely and transparent update of emission estimates.** The collection and processing of statistics of territorial emissions for almost all countries since 1970, as used in Section 5.2, is far from straightforward. There are multiple data sources, which rarely have well-characterized uncertainties. Uncertainty is particularly large for sources without a simple relationship to activity factors, such as emissions from LUC, fugitive emissions, and gas flaring. Formally estimating uncertainty for LUC emissions is difficult because a number of relevant processes are not well-enough characterized to be included in estimates. Additionally, the dependence of the attribution of emissions to sectors and regions on the relative weight given to various GHGs is often not specified.

- **The calculation of consumption-based emissions (in addition to territorial emissions) is dependent on strong assumptions.** The calculations require an additional layer of processing on top of the territorial emissions, increasing uncertainties without a clear characterization of the uncertainties. The outcomes presented in Sections 5.3.1 and 5.3.3.2 are only available for years since 1990.

- **Empirical studies that connect GHG emissions to specific policies and measures or underlying drivers often cannot be interpreted in terms of causality, have attribution problems, and provide competing assessments.** Statistical association is not the same as a chain of causality, and there are competing explanations for correlations. Studies can attribute changes in emissions to changes of activities when all other things are kept equal, but historically, all other things rarely are equal. Section 5.3 identifies population, income, the economic structure, the choice of energy sources related to energy resource availability and energy price policies as proximate and underlying drivers for greenhouse gas emissions. But for most demography variables other than the population level, the literature provides competing assessments; different studies find different significant associations, and at different levels. Underlying drivers work in concert and cannot be assessed independently. From a cause-effect perspective, there is, for instance, no conclusive answer whether ageing, urbanization, and increasing population density as such lead to increasing or decreasing emissions; this depends on other underlying drivers as well. The results from the literature are often limited to a specific context and method. Our understanding could benefit from a rigorous methodological comparison of different findings (Sections 5.3.2, 5.6, 5.7).

- **It is debated whether greenhouse gas emissions have an 'autonomous' tendency to stabilize at higher income levels** (Section 5.3.3.1). It is agreed that economic growth increases emissions at low- and middle-income levels. With respect to energy, there are competing views whether energy availability is a driver for economic growth, or inversely that economic growth jointly with energy prices drives energy use, or that the causality depends on the stage of development (Sections 5.3.3.1 and 5.3.4).

- **The net effect of trade, behaviour, and technological change as a determinant of a global increase or decrease of emissions is not established** (Sections 5.4.2, 5.6.1, 5.7). There is evidence that the social, cultural, and behavioural context is an important underlying driver, and there are case studies that identify emission reductions for specific policies and technologies. For technology, empirical studies that ask whether innovations have been emission-saving or emission-increasing are limited in scope (Section 5.6.1). There is a rich theory literature on the potential of innovations to make production energy—or emission efficient—but evidence on the macro-effects and the rebound effect is still context-dependent (Section 5.6.2). How much carbon is exactly locked in existing physical infrastructure is uncertain and gaps of knowledge exist in how long physical infrastructure like housing, plants, and transport infrastructure typically remains in place in which geographical context (Section 5.6.3). Finally, most if not all of the literature on co-benefits and risk tradeoffs focuses on future potential gains. There is a total absence of empirical assessment about the role that co-benefits and adverse sideeffects have played, historically, in policy formation and GHG emissions (Section 5.7).

5.10 Frequently Asked Questions

FAQ 5.1 Based on trends in the recent past, are GHG emissions expected to continue to increase in the future, and if so, at what rate and why?

Past trends suggest that GHG emissions are likely to continue to increase. The exact rate of increase cannot be known but between 1970 and 2010, emissions increased 79 %, from 27 Gt of GHG to over 49 Gt (Figure 5.2). Business-as-usual would result in that rate continuing. The UN DESA World Population Division expects human population to increase at approximately the rate of recent decades (Section 5.3.2.1) of this report. The global economy is expected to continue to grow (Sections 5.3.3 and 5.4.1), as well as energy consumption per person (Sections 5.3.4.1 and 5.5.1). The latter two factors already vary greatly among countries (Figure 5.16), and national policies can affect future trajectories of GHG emissions directly as well as indirectly through policies affecting economic growth and (energy) consumption (Section 5.5). The existing variation and sensitivity to future policy choices make it impossible to predict the rate of increase in GHG emissions accurately, but past societal choices indicate that with projected economic and population growth, emissions will continue to grow (Section 5.8).

FAQ 5.2 Why is it so hard to attribute causation to the factors and underlying drivers influencing GHG emissions?

Factors influencing GHG emissions interact with each other directly and indirectly, and each factor has several aspects. Most things people produce, consume, or do for recreation result in GHG emissions (Sections 5.3 and 5.5). For example, the food chain involves land use, infrastructure, transportation, and energy production systems (Section 5.3). At each stage, emissions can be influenced by available agricultural and fishing technologies (Section 5.6), by intermediaries along the supply chain (Section 5.4), by consumers and by technology choices (Section 5.5). Technology and choice are not independent: available technologies affect prices, prices affect consumer preferences, and consumer preferences can influence the development and distribution of technologies (Sections 5.5). Policies, culture, traditions, and economic factors intervene at every stage. The interaction of these factors makes it difficult to isolate their individual contributions to carbon emissions growth or mitigation (Section 5.8). This interaction is both a cause for optimism, because it means there are many pathways to lower emissions, and a challenge because there will be many potential points of failure in even well-designed plans for mitigation.

FAQ 5.3 What options, policies, and measures change the trajectory of GHG emissions?

The basic options are to have individuals consume less, consume things that require less energy, use energy sources that have lower-carbon content, or have fewer people. Although inhabitants of the most developed countries have the option to consume less, most of the human population is located in less-developed countries and economies in transition where population growth is also higher (Section 5.3.2). In these countries, achieving a 'middle-class lifestyle' will involve consuming more rather than less (Section 5.3.3.2). Accepting that population will continue to grow, choices will involve changes in technology and human behaviour, so that the production and use of products and services is associated with lower rates of GHG emissions (technology Section 5.6), and consumers choose products, services, and activities with lower-unit GHG emissions (behaviour Section 5.5).

FAQ 5.4 What considerations constrain the range of choices available to society and their willingness or ability to make choices that would contribute to lower GHG emissions?

Choices are constrained by what is available, what is affordable, and what is preferred (Section 5.3.3). For a given product or service, less carbon-intensive means of provision need to be available, priced accessibly, and appeal to consumers (Section 5.3.4.2). Availability is constrained by infrastructure and technology, with a need for options that are energy-efficient and less-dependent on fossil fuels (Section 5.3.5). The choice of what to consume given the availability of accessible and affordable options is constrained by preferences due to culture, awareness, and understanding of the consequences in terms of emissions reduction (Sections 5.5.1, 5.5.2). All of these constraints can be eased by the development of alternative energy generation technologies and distribution systems (Section 5.6), and societies that are well-informed about the consequences of their choices and motivated to choose products, services, and activities that will reduce GHG emissions (Sections 5.5.3, 5.7).

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6 Assessing Transformation Pathways

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Executive Summary

Stabilizing greenhouse gas (GHG) concentrations will require large-scale transformations in human societies, from the way that we produce and consume energy to how we use the land surface. A natural question in this context is what will be the 'transformation pathway' towards stabilization; that is, how do we get from here to there? The topic of this chapter is transformation pathways. The chapter is primarily motivated by three questions. First, what are the near-term and future choices that define transformation pathways, including the goal itself, the emissions pathway to the goal, technologies used for and sectors contributing to mitigation, the nature of international coordination, and mitigation policies? Second, what are the key characteristics of different transformation pathways, including the rates of emissions reductions and deployment of low-carbon energy, the magnitude and timing of aggregate economic costs, and the implications for other policy objectives such as those generally associated with sustainable development? Third, how will actions taken today influence the options that might be available in the future? As part of the assessment in this chapter, data from over 1000 new scenarios published since the IPCC Fourth Assessment Report (AR4) were collected from integrated modelling research groups, many from large-scale model intercomparison studies. In comparison to AR4, new scenarios, both in this AR5 dataset and more broadly in the literature assessed in this chapter, consider more ambitious concentration goals, a wider range of assumptions about technology, and more possibilities for delays in additional global mitigation beyond that of today and fragmented international action.

Atmospheric concentrations in baseline scenarios collected for this assessment (scenarios without additional efforts to constrain emissions beyond those of today) all exceed 450 parts per million (ppm) carbon dioxide-equivalent (CO_2eq) by 2030 and lie above the RCP 6.0 representative concentration pathway in 2100 (770 ppm CO_2eq in 2100); the majority lie below the RCP 8.5 concentration pathway in 2100 (1330 ppm CO_2eq in 2100) (*high confidence*). The scenario literature does not systematically explore the full range of uncertainty surrounding development pathways and the possible evolution of key drivers such as population, technology, and resources. However, the baseline scenarios do nonetheless strongly suggest that absent explicit efforts at mitigation, cumulative CO_2 emissions since 2010 will exceed 700 GtCO_2 by 2030, exceed 1500 GtCO_2 by 2050, and potentially be well over 4000 GtCO_2 by 2100. [Section 6.3.1]

Scenarios can be distinguished by the long-term concentration level they reach by 2100; however, the degree to which concentrations exceed (overshoot) this level before 2100 is also important (*high confidence*). The large majority of scenarios produced in the literature that reach about 450 ppm CO_2eq by 2100 are characterized by concentration overshoot facilitated by the deployment of carbon dioxide removal (CDR) technologies. Many scenarios have been constructed to reach about 550 ppm CO_2eq by 2100 without overshoot. Scenarios with more overshoot exhibit less mitigation today, but they often rest on the assumption that future decision makers deploy CDR technologies at large scale. An assessment in this chapter of geophysical climate uncertainties consistent with the dynamics of Earth System Models assessed in Working Group I (WG I) provides estimates of the temperature implications of different emissions pathways. This assessment found that the likelihood of exceeding temperature goals this century increases with peak concentration levels, which are higher in overshoot scenarios. [6.3.2]

All major-emitting regions make substantial reductions from their baseline CO_2eq emissions over the century in scenarios that bring atmospheric concentrations to about 550 ppm CO_2eq or below by 2100 (*high confidence*). In most scenarios collected for this assessment that reach concentrations of about 550 ppm CO_2eq by 2100, global CO_2eq emissions are reduced by more than 50 %, and in some cases by more than 100 %, by the end of the century relative to 2010 levels. The CO_2eq emissions are brought to near or below zero by 2100 in the majority of the scenarios reaching concentrations of about 450 ppm CO_2eq by 2100. In large part because baseline emissions from the countries not part of the Organisation for Economic Co-operation and Development (OECD) in 1990 are projected to outstrip those from the OECD-1990 countries, the total CO_2eq reductions from baseline occurring in the non-OECD-1990 countries are larger than in the OECD-1990 countries, particularly in scenarios that cost-effectively allocate emissions reductions across countries. Emissions peak earlier in the OECD-1990 countries than in the non-OECD-1990 countries in these cost-effective scenarios. [6.3.2]

Bringing concentrations to about 550 ppm CO_2eq or below by 2100 will require large-scale changes to global and national energy systems, and potentially to the use of land; these changes are inconsistent with both long- and short-term trends (*high confidence*). Accelerated electrification of energy end use, coupled with decarbonization of the majority of electricity generation by 2050 and an associated phaseout of freely emitting coal generation, is a common feature of scenarios reaching about 550 ppm CO_2eq or less by 2100. Scenarios suggest that sectors currently using liquid fuel are more costly to decarbonize than electricity and may be among the last sectors to be decarbonized for deep CO_2 emissions reductions. Scenarios articulate very different changes in the land surface, reflecting different assumptions about the potential for bioenergy production, afforestation, and reduced deforestation. Studies indicate a large potential for energy use reductions, but also demonstrate that these reductions will not be sufficient by themselves to constrain GHG emissions. [6.3.4, 6.3.5, 6.8]

Estimates of the aggregate economic costs of mitigation vary widely, but increase with stringency of mitigation (*high confidence*). Most scenario studies collected for this assessment that are based on the idealized assumptions that all countries of the world begin mitigation immediately, there is a single global carbon price applied to well-functioning markets, and key technologies are available, estimate that reaching about 450 ppm CO_2eq by 2100 would entail global consumption losses of 1–4 % in 2030 (median of 1.7 %), 2–6 % in 2050 (median of 3.4 %), and 3–11 % in 2100 (median of 4.8 %) relative to what would happen without mitigation. These consumption losses correspond to an annual average reduction of consumption growth of 0.06 to 0.20 percentage points from 2010 to 2030 (median of 0.09), 0.06 to 0.17 percentage points through 2050 (median of 0.09), and 0.04 to 0.14 percentage points over the century (median of 0.06). To put these losses in context, studies assume annual average consumption growth rates without mitigation between 1.9 % and 3.8 % per year until 2050 and between 1.6 % and 3.0 % per year over the century. These growth rates correspond to increases in total consumption from roughly four-fold to over ten-fold over the century. Costs for maintaining concentrations at around 550 ppm CO_2eq are estimated to be roughly one-third to two-thirds lower. Substantially higher and lower cost estimates have been obtained based on assumptions about less idealized policy implementations, interactions with pre-existing distortions, non-climate market failures, or complementary policies. (Limits on technology and delayed mitigation are discussed below.) [6.3.6]

Effort-sharing frameworks could help address distributional issues and decouple regional mitigation investments from financial burdens, but could be associated with significant international financial flows (*medium confidence*). In the absence of effort-sharing frameworks, cost-effectively allocating emissions across countries would yield an uneven distribution of mitigation costs. Scenarios indicate that this would lead to higher relative costs in developing economies as well as for many fossil fuel exporters. Studies exploring effort-sharing frameworks in the context of a global carbon market estimate that the financial flows to ameliorate this asymmetry could be on the order of hundreds of billions of USD per year before mid-century to bring concentrations to about 450 ppm CO_2eq in 2100. [6.3.6]

Emissions through 2030 will have strong implications for the challenges of, and options for, bringing concentrations to about 450 to about 500 ppm CO_2eq by the end of the twenty-first century (*high confidence*). The vast majority of cost-effective scenarios leading to 2100 concentrations of about 450 to about 500 ppm CO_2eq are characterized by 2030 emissions roughly between 30 $GtCO_2$eq and 50 $GtCO_2$eq. Scenarios with emissions above 55 $GtCO_2$eq in 2030 are predominantly driven by delays in additional mitigation relative to what would be most cost-effective. These scenarios are characterized by substantially higher rates of emissions reductions from 2030 to 2050, a larger reliance on CDR technologies in the long term, and higher transitional and long-term economic impacts. Due to these challenges, many models with 2030 emissions in this range could not produce scenarios reaching about 450 ppm CO_2eq in 2100. Studies confirm that delaying additional mitigation through 2030 has substantially larger influence on the subsequent challenges of mitigation than delaying only through 2020. [6.3.2, 6.4]

The availability of key technologies and improvements in the cost and performance of these technologies will have important implications for the challenge of achieving concentration goals (*high confidence*). Many models in recent multi-model comparisons could not produce scenarios reaching approximately 450 ppm CO_2eq by 2100 with broadly pessimistic assumptions about key mitigation technologies. Large-scale deployment of CDR technologies in particular is relied upon in many of these scenarios in the second-half of the century. For those models that could produce such scenarios, pessimistic assumptions about important technologies for decarbonizing non-electric energy supply significantly increased the discounted global mitigation costs of reaching about 450 ppm and about 550 ppm CO_2eq by the end of the century, with the effect being larger for more stringent goals. These studies also showed that reducing energy demand can potentially decrease mitigation costs significantly. [6.3.2, 6.3.4, 6.3.6, 6.4]

Mitigation efforts will influence the costs of meeting other policy objectives. Recent studies indicate that climate policies significantly reduce the costs of reaching energy security and air quality objectives (*medium evidence, high agreement*). The associated economic implications for these objectives are not taken into account in most scenario studies. Sectoral studies suggest that the potential for co-benefits of energy end-use mitigation measures outweighs the potential for adverse side-effects, whereas the evidence suggests this may not be the case for all supply-side and AFOLU measures. The overall welfare implications associated with these additional objectives have not been assessed thoroughly in the literature. [6.6]

There is uncertainty about the potential of geoengineering by CDR or solar radiation management (SRM) to counteract climate change, and all techniques carry risks and uncertainties (*high confidence*). A range of different SRM and CDR techniques has been proposed, but no currently existing technique could fully replace mitigation or adaptation efforts. Nevertheless, many low-GHG concentration scenarios rely on two CDR techniques, afforestation and biomass energy with carbon dioxide capture and storage (BECCS), which some studies consider to be comparable with conventional mitigation methods. Solar radiation management could reduce global mean temperatures, but with uneven regional effects, for example on temperature and precipitation, and it would not address all of the impacts of increased CO_2 concentrations, such as ocean acidification. Techniques requiring large-scale interventions in the earth system, such as ocean fertilization or stratospheric aerosol injections, carry significant risks. Although proposed geoengineering techniques differ substantially from each other, all raise complex questions about costs, risks, governance, and ethical implications of research and potential implementation. [6.9]

Despite the advances in our understanding of transformation pathways since AR4, many avenues of inquiry remain unanswered. Important future research directions include the following: development of a broader set of socioeconomic and technological storylines to support development of scenarios; scenarios explicitly pursuing a wider set of climate goals, including those related to temperature change; more mitigation scenarios that include impacts from, and adaptations to, a changing climate, including energy and land use systems critical for mitigation; expanded treatment of the benefits and risks of CDR and SRM options; expanded treatment of co-benefits and adverse side-effects of mitigation pathways; improvements in the treatment and understanding of mitigation options and responses in end-use sectors in transformation pathways; and more sophisticated treatments of land use and land use-based mitigation options in mitigation scenarios. [6.10]

6.1 Introduction

6.1.1 Framing and evaluating transformation pathways

Stabilizing greenhouse gas (GHG) concentrations at any level will require deep reductions in GHG emissions. Net global CO_2 emissions, in particular, must eventually be brought to or below zero. Emissions reductions of this magnitude will require large-scale transformations in human societies, from the way that we produce and consume energy to how we use the land surface. The more ambitious the stabilization goal, the more rapid this transformation must occur. A natural question in this context is what will be the transformation pathway toward stabilization; that is, how do we get from here to there?

The topic of this chapter is transformation pathways. The chapter is motivated primarily by three questions. First, what are the near-term and future choices that define transformation pathways including, for example, the goal itself, the emissions pathway to the goal, the technologies used for and sectors contributing to mitigation, the nature of international coordination, and mitigation policies? Second, what are the key decision making outcomes of different transformation pathways, including the magnitude and international distribution of economic costs and the implications for other policy objectives such as those associated with sustainable development? Third, how will actions taken today influence the options that might be available in the future?

Two concepts are particularly important for framing any answers to these questions. The first is that there is no single pathway to stabilization of GHG concentrations at any level. Instead, the literature elucidates a wide range of transformation pathways. Choices will govern which pathway is followed. These choices include, among other things, the long-term stabilization goal, the emissions pathway to meet that goal, the degree to which concentrations might temporarily overshoot the goal, the technologies that will be deployed to reduce emissions, the degree to which mitigation is coordinated across countries, the policy approaches used to achieve these goals within and across countries, the treatment of land use, and the manner in which mitigation is meshed with other policy objectives such as sustainable development.

The second concept is that transformation pathways can be distinguished from one another in important ways. Weighing the characteristics of different pathways is the way in which deliberative decisions about transformation pathways would be made. Although measures of aggregate economic implications have often been put forward as key deliberative decision making factors, these are far from the only characteristics that matter for making good decisions. Transformation pathways inherently involve a range of tradeoffs that link to other national and policy objectives such as energy and food security, the distribution of economic costs, local air pollution, other environmental factors associated with different technology solutions (e.g., nuclear power, coal-fired carbon dioxide capture and storage (CCS)), and economic competitiveness. Many of these fall under the umbrella of sustainable development.

A question that is often raised about particular stabilization goals and transformation pathways to those goals is whether the goals or pathways are 'feasible'. In many circumstances, there are clear physical constraints that can render particular long-term goals physically impossible. For example, if additinional mitigation beyond that of today is delayed to a large enough degree and carbon dioxide removal (CDR) options are not available (see Section 6.9), a goal of reaching 450 ppm CO_2eq by the end of the 21st century can be physically impossible. However, in many cases, statements about feasibility are bound up in subjective assessments of the degree to which other characteristics of particular transformation pathways might influence the ability or desire of human societies to follow them. Important characteristics include economic implications, social acceptance of new technologies that underpin particular transformation pathways, the rapidity at which social and technological systems would need to change to follow particular pathways, political feasibility, and linkages to other national objectives. A primary goal of this chapter is to illuminate these characteristics of transformation pathways.

6.1.2 New mitigation scenarios since AR4

Since the IPCC Fourth Assessment Report (AR4), the integrated modelling community has produced a range of new transformation pathway scenarios. Major advances include an increase in the number of scenarios exploring the following: low-concentration goals such as 450 ppm CO_2eq; overshoot emissions trajectories with and without CDR technologies; a variety of international mitigation policy configurations, including fragmented action and delays in additional mitigation beyond that of today; and the implications of variations in technology cost, performance, and availability. The literature also includes a small but growing set of scenarios and research exploring the linkage between mitigation and other policy objectives, an increasingly sophisticated treatment of the role of land use in mitigation, and scenarios exploring non-market approaches to mitigation. Two particularly important categories for the discussion in this chapter are non-idealized international implementation scenarios and scenarios with limits on technology cost, performance, or availability. These categories of scenarios are discussed in more detail below.

6.1.2.1 Non-idealized international implementation scenarios

At the time of AR4, the majority of mitigation scenarios were based on the idealized assumption that mitigation is undertaken where and when it is least expensive. Such 'idealized implementation' scenarios assume the imposition of a global price on carbon that reaches across countries, permeates all economic sectors within countries, and rises over time in a way that will minimize discounted economic costs over a long period of time, typically through 2100. These are often referred to as 'cost-effective' scenarios, because they lead to the lowest aggregate global mitigation costs under idealized assumptions about the functioning of markets and economies (see Section 6.3.6). However, the reality of international strategies for mitigation is one of different countries taking on mitigation at different times and using different and independent implementation approaches. Responding to this reality, the research community has produced a large set of 'non-idealized' international implementation scenarios for reaching long-term concentration goals. Often, but not always, non-idealized implementation is focused on the coming decades, with a transition toward idealized implementation in the long run. In addition to individual papers (for example, Richels et al., 2007; Edmonds et al., 2008; Luderer et al., 2014b; Rogelj et al., 2013a), there have been a number of multi-model projects exploring non-idealized implementation scenarios (Table 6.1). This chapter relies heavily on those multi-model studies.

There are a number of ways that scenarios may deviate from the idealized implementation, but two are most prominent in the new literature. One set of scenarios includes those in which near-term mitigation is inconsistent with—typically less than—what would be called for to minimize the discounted, century-long costs of meeting a long-term goal such as 450 ppm CO_2eq by 2100. These scenarios are intended to capture the implications of 'delayed action' or 'delayed mitigation' or 'constrained near-term ambition'. Mitigation is not undertaken 'when' it would be least expensive. The other set of scenarios includes those in which the price on carbon is not consistent across countries. Some countries reduce emissions more aggressively than others, particularly in the near-term, so that mitigation is not undertaken 'where' it is least expensive. These scenarios are intended to capture the implications of 'fragmented action' or 'delayed participation'. Non-idealized international implementation scenarios may include one or both of these deviations.

6.1.2.2 Limited technology scenarios

Scenario research prior to AR4 emphasized the importance of technology in constraining the costs of mitigation. A range of individual papers had made initial explorations of this space for more than a decade before AR4. Since AR4, however, a range of new studies have emerged including large model intercomparison studies, that have focused on the implications of limitations on technology cost, performance, availability on the cost and other characteristics of meeting concentration goals such as 450 ppm CO_2eq by 2100. The large model intercomparison studies include Energy Modeling Forum (EMF) 27 (Krey et al., 2014; Kriegler et al., 2014a), ADAM (Adaptation and Mitigation Strategies: Supporting European Climate Policy) (Edenhofer et al., 2010), RECIPE (Report on Energy and Climate Policy in Europe) (Luderer et al., 2012a; Tavoni et al., 2012), and AMPERE (Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates) (Riahi et al., 2014). In addition to the large model intercomparison studies, a number of individual

Table 6.1 | Multi-model studies exploring non-idealized international implementation

Multi-Model Study	Description
EMF 22 (Clarke et al., 2009)	Delayed participation (fragmented action) scenarios in which Organisation for Economic Co-operation and Development (OECD) countries begin mitigation immediately; Brazil, Russia, India, and China begin after 2030; remaining countries begin after 2050. Scenarios meet various 2100 concentration goals, with and without overshooting the concentration goal.
EMF 27 (Blanford et al., 2014; Kriegler et al., 2014a)	Delayed and limited participation scenario with Annex I adopting 80 % emissions reductions until 2050, non-Annex I adopting a global 50 % emissions reduction by 2050 after 2020, and resource exporting countries not undertaking emissions reductions.
AMPERE (Kriegler et al., 2014c; Riahi et al., 2014)	Two studies: AMPERE WP2 focused on delayed mitigation scenarios with the world following moderate mitigation until 2030, and adopting long-term concentration goals thereafter. AMPERE WP3 focused on delayed participation scenarios with EU27 or EU27 and China acting immediately and the remaining countries transitioning from moderate policies to a global carbon pricing regime (without mitigation goal) between 2030 and 2050.
LIMITS (Kriegler et al., 2013b; Tavoni et al., 2013)	Delayed mitgation scenarios with the world following two levels of moderate fragmented action through 2020 or 2030, and adopting two long-term concentration goals thereafter. Three different effort-sharing schemes are considered.
RoSE (Luderer et al., 2014a)	Delayed mitgation scenarios with the world following moderate fragmented action in the near term and adopting a long-term concentration goal after 2020 or 2030.

Note: The Energy Modeling Forum (EMF) 27, AMPERE (Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates), LIMITS (Low Climate Impact Scenarios and the Implications of Required Tight Emission Control Strategies), and RoSE (Roadmaps Towards Sustainable Energy Futures) studies also included scenarios of moderate fragmented action throughout the 21st century without the goal of meeting any specific long-term concentration.

research papers and reports have explored this space since AR4, typically constrained to a single model (Richels et al., 2007; Calvin et al., 2009a; Krey and Riahi, 2009; van Vliet et al., 2009; Riahi et al., 2012; Luderer et al., 2013; Rogelj et al., 2013b). In many cases, these studies have simply assumed that particular technologies, such as CCS or nuclear power, may not be available. In others, studies have put constraints on resource supplies, for example, the supply of bioenergy. In others, they have called for variations in cost and performance of different technologies. Many have also explored the implications of energy end-use improvements.

6.2 Tools of analysis

6.2.1 Overview of integrated modelling tools

The long-term scenarios assessed in this chapter were generated primarily by large-scale, integrated models that can project key characteristics of transformation pathways to mid-century and beyond. These models represent many of the most relevant interactions among important human systems (e.g., energy, agriculture, the economic system), and often represent important physical processes associated with climate change (e.g., the carbon cycle). Other approaches to explore transformation pathways include qualitative scenario methods and highly aggregated modelling tools, such as those used for cost-benefit analysis (see Box 6.1 on cost-benefit analysis, p. 394). These other approaches provide a different level of quantitative information about transformation pathways than scenarios from large-scale integrated models.

All integrated models share some common traits. Most fundamentally, integrated models are simplified, stylized, numerical approaches to represent enormously complex physical and social systems. They take in a set of input assumptions and produce outputs such as energy system transitions, land-use transitions, economic effects of mitigation, and emissions trajectories. Important input assumptions include population growth, baseline economic growth, resources, technological change, and the mitigation policy environment. The models do not structurally represent many social and political forces that can influence the way the world evolves (e.g., shocks such as the oil crisis of the 1970s). Instead, the implications of these forces enter the model through assumptions about, for example, economic growth and resource supplies. The models use economics as the basis for decision making. This may be implemented in a variety of ways, but it fundamentally implies that the models tend toward the goal of minimizing the aggregate economic costs of achieving mitigation outcomes, unless they are specifically constrained to behave otherwise. In this sense, the scenarios tend towards normative, economics-focused descriptions of the future. The models typically assume fully functioning markets and competitive market behavior, meaning that factors such as non-market transactions, information asymmetries, and market power influencing decisions are not effectively represented. Maintaining a long-term, integrated, and often global perspective involves tradeoffs in terms of the detail at which key processes can be represented in integrated models. Hence, the models do not generally represent the behaviour of certain important system dynamics, such as economic cycles or the operation of electric power systems important for the integration of solar and wind power, at the level of detail that would be afforded by analyses that the focus exclusively on those dynamics.

Beyond these and other similarities, integrated modelling approaches can be very different, and these differences can have important implications for the variation among scenarios that emerge from different models. The following paragraphs highlight a number of key differences in model structure. To provide insight into the implications of these tradeoffs, potential implications for aggregate economic costs are provided as examples, when appropriate.

Economic coverage and interactions. Models differ in terms of the degree of detail with which they represent the economic system and the degree of interaction they represent across economic sectors. *Full-economy* models (e.g., general equilibrium models) represent interactions across all sectors of the economy, allowing them to explore and understand ripple effects from, for example, the imposition of a mitigation policy, including impacts on overall economic growth. *Partial-economy* models, on the other hand, take economic activity as an input that is unresponsive to policies or other changes such as those associated with improvements in technology. These models tend to focus more on detailed representations of key systems such as the energy system. All else equal, aggregate economic costs would tend to be higher in full-economy models than in partial-economy models because full-economy models include feedbacks to the entire economy. On the other hand, full-economy models may include more possibilities for substitution in sectors outside of those represented in partial-economy models, and this would tend to reduce aggregate economic costs.

Foresight. *Perfect-foresight* models (e.g., intertemporal optimization models) optimize over time, so that all future decisions are taken into account in today's decisions. In contrast, *recursive-dynamic* models make decisions at each point in time based only on the information in that time period. In general, perfect-foresight models would be likely to allocate emissions reductions more efficiently over time than recursive-dynamic models, which should lead to lower aggregate costs.

Representation of trade. Models differ in terms of how easy it is for goods to flow across regions. On one end of the spectrum are models assuming goods are homogeneous and traded easily at one world price (Heckscher-Ohlin) or that there is one global producer (quasi-trade). On the other end of the spectrum are models assuming a preference for domestic goods over imported goods (Armington) or models without explicit trade across regions (e.g., models with import supply functions). In general, greater flexibility to trade will result in lower-aggregate mitigation costs because the global economy is more flexible to undertake mitigation where it is least expensive. More generally, many partial-equilibrium models include trade only in carbon permits and basic energy commodities. These models are not capable of exploring the full nature of carbon leakage that might emerge from mitigation policies, and particularly those associated with fragmented international action.

Model flexibility. The *flexibility* of models describes the degree to which they can change course. Model flexibility is not a single, explicit choice for model structure. Instead, it is the result of a range of choices that influence, for example, how easily capital can be reallocated across sectors including the allowance for premature retirement of capital stock, how easily the economy is able to substitute across energy technologies, whether fossil fuel and renewable resource constraints exist, and how easily the economy can extract resources. The complexity of the different factors influencing model flexibility makes clear delineations of which models are more or less flexible difficult. Evaluation and characterization of model flexibility is an area of current research (see Kriegler et al., 2014b). Greater flexibility will tend to lower mitigation costs.

Sectoral, regional, technology, and GHG detail. Models differ dramatically in terms of the detail at which they represent key sectors and systems. These differences influence not only the way that the models operate, but also the information they can provide about transformation pathways. Key choices include the number of regions, the degree of technological detail in each sector, which GHGs are represented and how, whether land use is explicitly represented, and the sophistication of the model of earth system process such as the carbon cycle. Some models include only CO_2 emissions, many do not treat land-use change (LUC) and associated emissions, and many do not have submodels of the carbon cycle necessary to calculate CO_2 concentrations. In addition, although the scenarios in this chapter were generated from global models that allow for the implications of mitigation for international markets to be measured, regional models can provide finer detail on the implications for a specific region's economy and distributional effects. The effects of detail on aggregate mitigation costs are ambiguous

Representation of technological change. Models can be categorized into two groups with respect to technological change. On one end of the spectrum, models with *exogenous technological change* take technology as an input that evolves independently of policy measures or investment decisions. These models provide no insight on how policies may induce advancements in technology. On the other end of the spectrum, models with *endogenous technological change* (also known as *induced technological change*) allow for some portion of technological change to be influenced by deployment rates or investments in research and development (R&D). Models featuring endogenous technological change are valuable for understanding how the pace of technological change might be influenced by mitigation policies.

6.2.2 Overview of the scenario ensemble for this assessment

The synthesis in this chapter is based on a large set of new scenarios produced since AR4. The number of models has increased and model functionality has significantly improved since AR4, allowing for a broader set of scenarios in the AR5 ensemble. The majority of these scenarios were produced as part of multi-model comparisons. Most model intercomparison studies produce publicly available databases that include many of the key outputs from the studies. Although crucial for our understanding of transformation pathways, these intercomparison exercises are not the only source of information on transformation pathways. A range of individual studies has been produced since AR4, largely assessing transformation pathways in ways not addressed in the model intercomparison exercises. For the purposes of this assessment, an open call was put forward for modellers to submit scenarios not included in the large model intercomparison databases. These scenarios, along with those from many of the model intercomparison studies, have been collected in a database that is used extensively in this chapter. A summary of the models and model intercomparison exercises that generated the scenarios referenced in this chapter can be found in Annex II.10.

6.2.3 Uncertainty and the interpretation of large scenario ensembles

The interpretation of large ensembles of scenarios from different models, different studies, and different versions of individual models is a core component of the assessment of transformation pathways in this chapter. Indeed, many of the tables and figures represent ranges of results across all these dimensions.

There is an unavoidable ambiguity in interpreting ensemble results in the context of uncertainty. On the one hand, the scenarios assessed in this chapter do not represent a random sample that can be used for formal uncertainty analysis. Each scenario was developed for a specific purpose. Hence, the collection of scenarios included in this chapter does not necessarily comprise a set of 'best guesses.' In addition, many of these scenarios represent sensitivities, particularly along the dimensions of future technology availability and the timing of international action on climate change, and are therefore highly correlated. Indeed, most of the scenarios assessed in this chapter were generated as part of model intercomparison exercises that impose specific assumptions, often regarding long-term policy approaches to mitigation, but also in some cases regarding fundamental drivers like technology, population growth, and economic growth. In addition, some modelling groups have generated substantially more scenarios than others, introducing a weighting of scenarios that can be difficult to interpret. At the same time, however, with the exception of pure sensitivity studies, the scenarios were generated by experts making informed judgements about how key forces might evolve in the future and how important systems interact. Hence, although they are not explicitly representative of uncertainty, they do provide real and often clear insights about our lack of knowledge about key forces that might shape the future (Fischedick et al., 2011; Krey and Clarke, 2011). The synthesis in this chapter does not attempt to resolve the ambiguity associated with ranges of scenarios, and instead focuses simply on articulating the most robust and valuable insights that can be extracted given this ambiguity. However, wherever possible, scenario samples are chosen in such a way as to reduce bias, and these choices are made clear in the discussion and figure legends.

6.2.4 Interpretation of model inability to produce particular scenarios

A question that is often raised about particular stabilization goals and transformation pathways is whether the goals or pathways are 'feasible' (see Section 6.1). Integrated models can be helpful in informing this question by providing information about key elements of transformation pathways that might go into assessments of feasibility, such as rates of deployment of energy technologies, rates of reductions in global and regional emissions, aggregate economic costs, financial flows among regions, and links to other policy objectives such as energy security or energy prices. However, beyond cases where physical laws might be violated to achieve a particular scenario (for example, a 2100 carbon budget is exceeded prior to 2100 with no option for negative emissions), these integrated models cannot determine feasibility in an absolute sense.

This is an important consideration when encountering situations in which models are incapable of producing scenarios. Many models have been unable to achieve particularly aggressive concentration goals such as reaching 450 ppm CO_2eq by 2100, particularly under challenging technological or policy constraints. In some cases, this may be due to the violation of real physical laws, the most common of which is when the cumulative carbon budget associated with meeting a long-term goal is exceeded without options to remove carbon from the atmosphere. Frequently, however, instances of model infeasibility arise from pushing models beyond the boundaries of what they were built to explore, for example, rates of change in the energy system that exceed what the model can represent, or carbon prices sufficiently high that they conflict with the underlying computational structure. Indeed, in many cases, one model may be able to produce scenarios while another will not, and model improvements over time may result in feasible scenarios that previously were infeasible. Hence, although these model infeasibilities cannot generally be taken as an indicator of feasibility in an absolute sense, they are nonetheless valuable indicators of the challenge associated with achieving particular scenarios. For this reason, whenever possible, this chapter highlights those situations where models were unable to produce scenarios.

Unfortunately, this type of result can be difficult to fully represent in an assessment because, outside of model intercomparison studies intended explicitly to identify these circumstances, only scenarios that could actually be produced (as opposed that could not be produced) are generally published. Whether certain circumstances are underrepresented because they have been under-examined or because they have been examined and the scenarios failed is a crucial distinction, yet one that it is currently not possible to fully report. Model infeasibilities can bias results in important ways, for example, the costs of mitigation, because only those models producing scenarios can provide estimated costs (Tavoni and Tol, 2010).

6.3 Climate stabilization: Concepts, costs and implications for the macro economy, sectors and technology portfolios, taking into account differences across regions

6.3.1 Baseline scenarios

6.3.1.1 Introduction to baseline scenarios

Baseline scenarios are projections of GHG emissions and their key drivers as they might evolve in a future in which no explicit actions are taken to reduce GHG emissions. Baseline scenarios play the important role of establishing the projected scale and composition of the future energy, economic, and land-use systems as a reference point for measuring the extent and nature of required mitigation for a given climate goal. Accordingly, the resulting estimates of mitigation effort and costs in a particular mitigation scenario are always conditional upon the associated baseline.

Although the range of emissions pathways across baseline scenarios in the literature is broad, it may not represent the full potential range of possibilities. There has been comparatively little research formally constructing or eliciting subjective probabilities for comprehensive ranges of the key drivers of baseline emissions in a country-specific context, and this remains an important research need for scenario development. As discussed in Section 6.2, although the range of assumptions used in the literature conveys some information regarding modellers' expectations about how key drivers might evolve and the associated implications, several important factors limit its interpretation as a true uncertainty range. An important distinction between scenarios in this regard is between those that are based on modellers' 'default' assumptions and those that are harmonized across models within specific studies. The former can be considered a better, although still imperfect, representation of modellers' expectations about the future, while, as is discussed below, the latter consider specific alternative views that in some cases span a larger range of possible outcomes.

6.3.1.2 The drivers of baseline energy-related emissions

As discussed in Chapter 5, the drivers of the future evolution of energy-related emissions in the baseline can be summarized by the terms of the Kaya identity: population, per capita income, energy intensity of economic output, and carbon intensity of energy. At the global level, baseline projections from integrated models are typically characterized by modest population growth stabilizing by the end of the century, fast but decelerating growth in income, decline in energy intensity, and modest changes in carbon intensity with ambiguous sign (Figure 6.1).

There is comparatively little variation across model scenarios in projected population growth, with virtually all modelling studies relying on central estimates (UN, 2012). One exception is the RoSE project (Bauer et al., 2014b; Calvin et al., 2014b; De Cian et al., 2014), which explicitly considers high population scenarios, as well as the storyline beneath the representative concentration pathways (RCP) 8.5 scenario. Among the majority of default population projections, there are some minor differences across models, for example, the extent to which declining rates for certain regions in coming decades are incorporated. On the other hand, there is substantially more variation in model projections of per capita income, with a few scenarios harmonized at both the low and high ends of the range, and energy intensity, for which two studies (AMPERE and EMF27) specified alternative 'fast' decline baselines. Still, the interquartile range of default assumptions for both indicators is narrow, suggesting that many scenarios are based on a

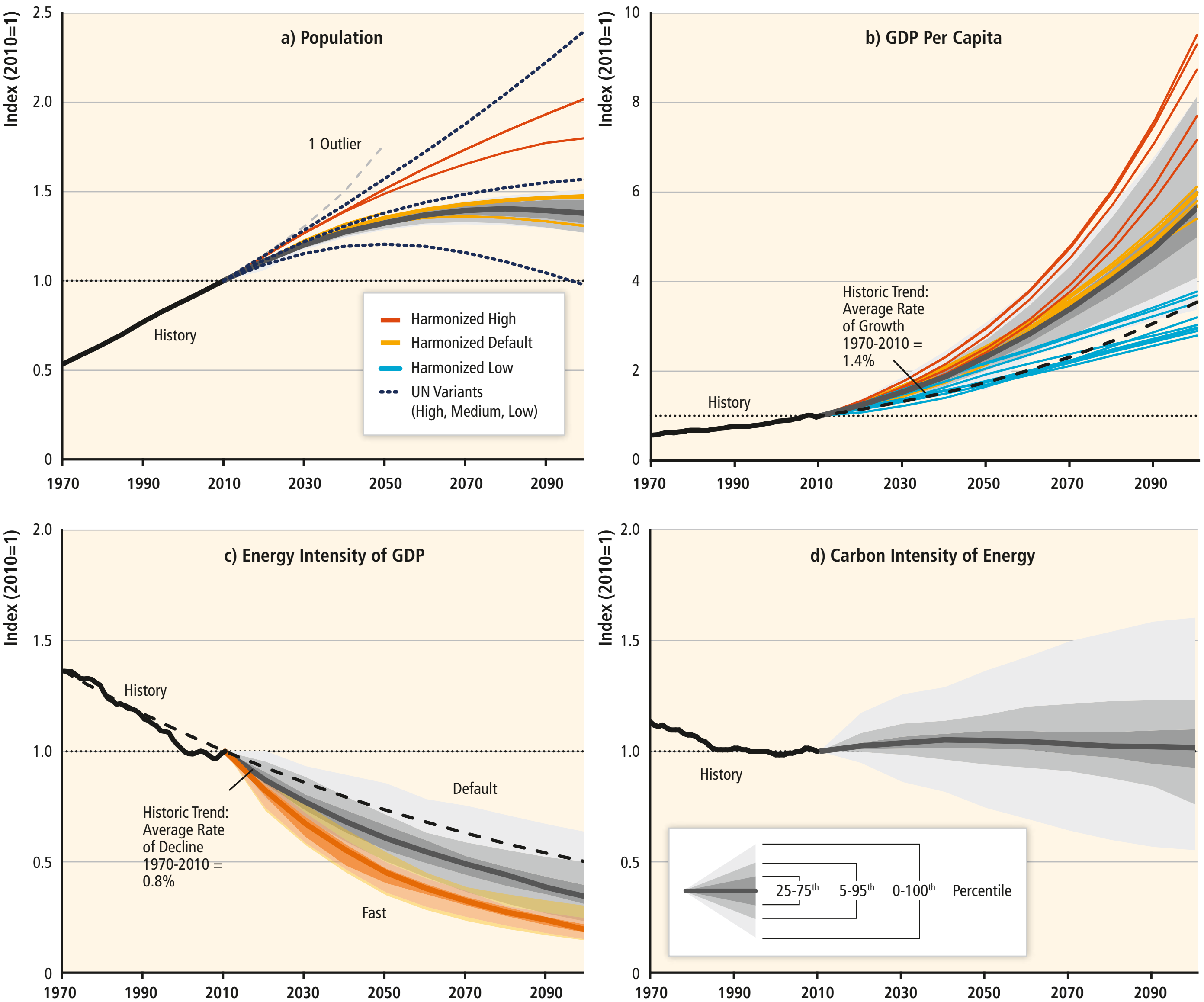


Figure 6.1 | Global baseline projection ranges for Kaya factors. Scenarios harmonized with respect to a particular factor are depicted with individual lines. Other scenarios are depicted as a range with median emboldened; shading reflects interquartile range (darkest), 5th—95th percentile range (lighter), and full range (lightest), excluding one indicated outlier in panel a) Scenarios are filtered by model and study for each indicator to include only unique projections. Model projections and historic data are normalized to 1 in 2010. Gross domestic product (GDP) is aggregated using base-year market exchange rates. Energy and carbon intensity are measured with respect to total primary energy. Sources: UN (2012), WG III AR5 Scenario Database (Annex II.10). Historic data: JRC/PBL (2013), IEA (2012a), see Annex II.9; Heston et al. (2012), World Bank (2013), BP (2013).

similar underlying narrative. Models project a faster global average growth rate in the future as dynamic emerging economies constitute an increasing share of global output. Energy intensity declines more rapidly than in the past, with an especially marked departure from the historical trend for 'fast' energy intensity decline scenarios. Carbon intensity, typically viewed as a model outcome driven by resource and technology cost assumptions, is projected in most baseline scenarios to change relatively little over time, but there are exceptions in both directions. Declining carbon intensity could result from rapid improvements in renewable technologies combined with rising fossil fuel prices. Conversely, the fossil share in energy could rise with favourable resource discoveries, or the fossil mix could become more carbon intensive, for example, due to replacement of conventional petroleum with heavier oil sands or coal-to-liquids.

While all models assume increasing per capita income and declining energy intensity, broad ranges are projected and high uncertainty remains as to what rates might prevail. Most models describe income growth as the result of exogenous improvement over time in labour productivity. The processes of technological advance by which such improvement occurs are only partially understood. Changes in aggregate energy intensity over time are the net result of several trends, including both improvements in the efficiency of energy end-use technology and structural changes in the composition of energy demand. Structural changes can work in both directions: there may be increased demand for energy-intensive services such as air-conditioning as incomes rise, while on the production side of the economy, there may be shifts to less energy-intensive industries as countries become wealthier. Although increasing energy intensity has been observed for some countries during the industrialization stage, the net effect is usually negative, and in general energy intensity has declined consistently over time. Both efficiency improvements and structural change can be driven by changes in energy prices, but to a significant extent both are driven by other factors such as technological progress and changing preferences with rising incomes. Most integrated models are able to project structural and technological change only at an aggregate level, although some include explicit assumptions for certain sectors (Sugiyama et al., 2014).

Because of limited variation in population and carbon-intensity projections, the relative strength of the opposing effects of income growth and energy intensity decline (summarized by changes in per capita energy), plays the most important role in determining the growth of emissions in the baseline scenario literature (see Blanford et al., 2012). Assumptions about the evolution of these factors vary strongly across regions. In general, rates of change in population, income, energy intensity, and per capita energy are all expected to be greater in developing countries than in currently developed countries in coming decades, although this pattern has not necessarily prevailed in the past 40 years, as non-OECD-1990 countries had slower energy intensity decline than OECD-1990 countries (Figure 6.2). Among default energy-intensity scenarios, assumed rates of change appear to be positively correlated between income and energy intensity, so that equivalent per capita energy outcomes are realized through varying combinations of these two indicators. The harmonized shift in the energy intensity decline rate leads to very low per capita energy rates, with global per capita energy use declining in a few cases (Figure 6.2). Projected emissions are essentially the product of per capita energy and carbon intensity projections, with most variation in future emissions scenarios explained by variation in per capita energy; the highest emissions projections arise from instances with high levels in both indicators (Figure 6.3).

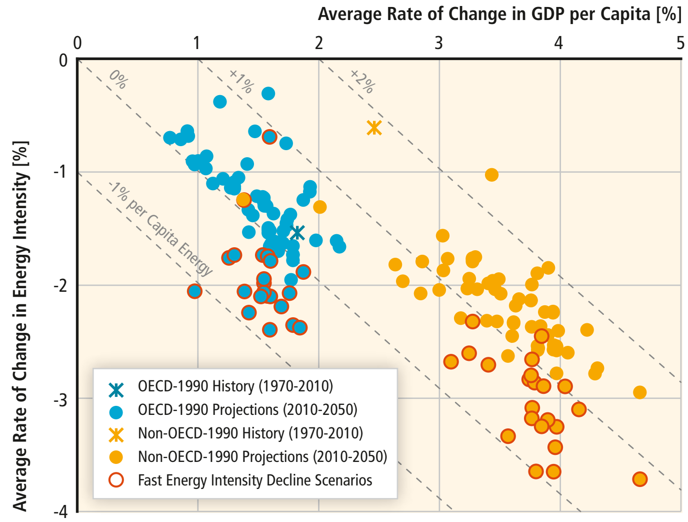


Figure 6.2 | Average rates of change between 2010 and 2050 in baseline scenarios for GDP per capita and energy intensity of GDP in OECD-1990 and Non-OECD-1990. There are 62 of 77 unique default intensity scenarios and 22 of 24 unique fast intensity scenarios plotted. Omitted are scenarios without OECD-1990 break-out. Sources: UN (2012), WG III AR5 Scenario Database (Annex II.10). Historic data: JRC/PBL (2013), IEA (2012a), see Annex II.9; Heston et al. (2012), World Bank (2013), BP (2013).

6.3.1.3 Baseline emissions projections from fossil fuels and industry

Based on the combination of growing population, growing per capita energy demand, and a lack of significant reductions in carbon intensity of energy summarized in the previous section, global baseline emissions of CO_2 from fossil fuel and industrial (FF&I) sources are projected to continue to increase throughout the 21st century (Figure 6.4, left panel). Although most baseline scenarios project a deceleration in emissions growth, especially compared to the rapid rate observed in the past decade, none is consistent in the long run with the pathways in the two most stringent RCP scenarios (Sections 2.6 and 4.5), with the majority falling between the 6.0 and 8.5 pathways (see IPCC (2013), Chapter 12 for a discussion of the RCP study). The RCP 8.5 pathway has higher emissions than all but a few published baseline scenarios. Projections for baseline FF&I CO_2 emissions in 2050 range from only slightly higher than current levels (in scenarios with explicit assumptions about fast energy intensity decline) to nearly triple current levels.

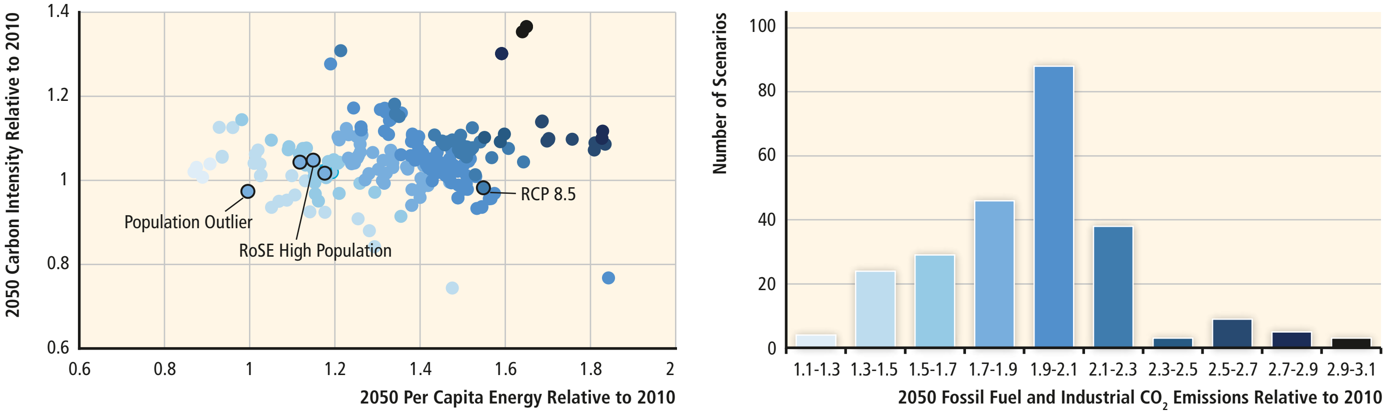


Figure 6.3 | Indexed change through 2050 in carbon intensity of energy and per capita energy use in baseline scenarios. Color reflects indexed 2050 global fossil fuel and industrial (FF&I) CO_2 emissions according to key in right panel showing histogram of plotted scenarios. For default population projections, emissions are correlated with chart position; exceptions with high population are noted. Source: UN (2012), WG III AR5 Scenario Database (Annex II.10). Historic data: JRC/PBL (2013), IEA (2012a), see Annex II.9; BP (2013).

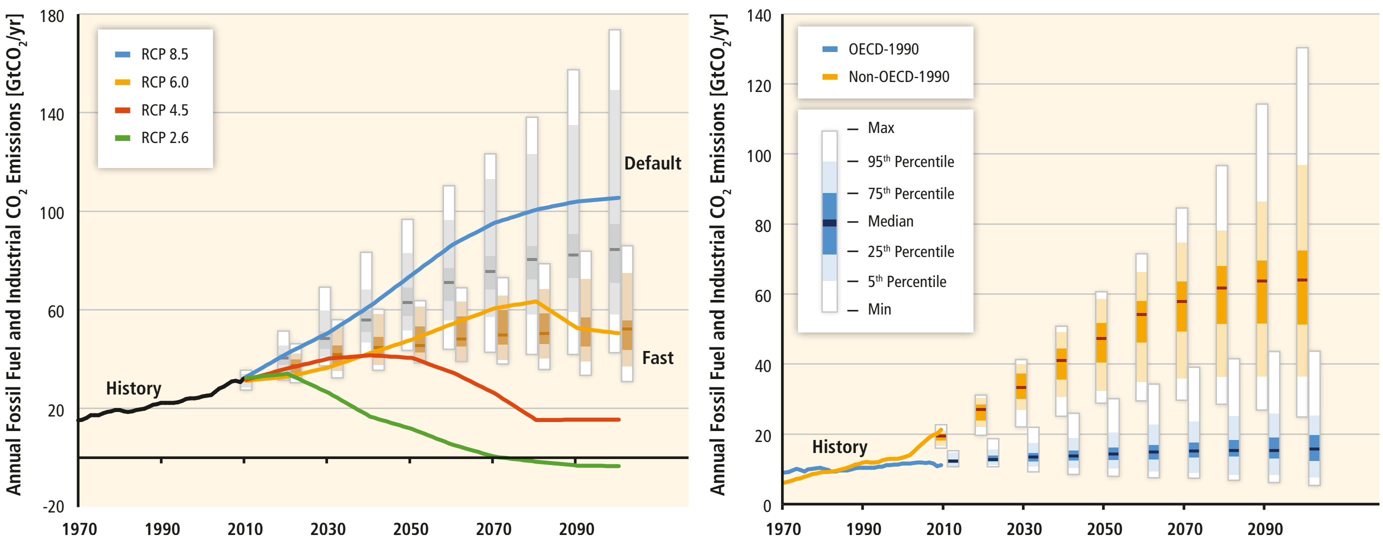


Figure 6.4 | Global FF&I CO_2 emissions in baseline scenarios with default growth assumptions (grey range) and fast energy intensity decline (gold range) (left panel), and for OECD-1990 vs. non-OECD-1990 (right panel) from 1970 to 2100. RCP scenarios are shown for comparison with the global baseline ranges. Scenarios are depicted as ranges with median emboldened; shading reflects interquartile range (darkest), 5th–95th percentile range (lighter), and full extremes (lightest). Absolute projections are subject to variation in reported base-year emissions arising from different data sources and calibration approaches (Chaturvedi et al., 2012). Some of the range of variation in reported 2010 emissions reflects differences in regional definitions. Sources: WG III AR5 Scenario Database (Annex II.10), van Vuuren et al. (2011a). Historic data: JRC/PBL (2013), IEA (2012a), see Annex II.9.

A common characteristic of all baseline scenarios is that the majority of emissions over the next century occur among non-OECD-1990 countries (Figure 6.4, right panel). Because of its large and growing population and projected rates of economic growth relatively faster than the industrialized OECD-1990 countries, this region is projected to have the dominant share of world energy demand over the course of the next century. While the range of emissions projected in the OECD-1990 region remains roughly constant (a few models have higher growth projections), nearly all growth in future baseline emissions is projected to occur in the non-OECD-1990 countries. It is important to note that while a baseline by construction excludes explicit climate policies, management of non-climate challenges, particularly in the context of sustainable development, will likely impact baseline GHG pathways. Many of these policy objectives (but likely not all) are taken into account in baseline scenarios, such as reductions in local air pollution and traditional biomass use and fuel switching more generally away from solids towards refined liquids and electricity. Section 6.6 provides more details on this issue.

6.3.1.4 Baseline CO_2 emissions from land use and emissions of non-CO_2 gases

Baseline projections for global land-use related carbon emissions and sequestration (also referred to as net Agriculture, Forestry and Other Land Use (AFOLU) CO_2 emissions) are made by a smaller subset of models. Net AFOLU CO_2 emissions have greater historical uncertainty than FF&I emissions as discussed in Section 11.2 (Pan et al., 2011;

Houghton et al., 2012). Baseline projections for land-use related CO_2 emissions reflect base-year uncertainty and suggest declining annual net CO_2 emissions in the long run (Figure 6.5, left panel). In part, projections are driven by technological change, as well as projected declining rates of agriculture area expansion, a byproduct of decelerating population growth. Though uncertain, the estimated contribution of land-use related carbon over the coming century is small relative to emissions from fossil fuels and industry, with some models projecting a net sink late in the century. For non-CO_2 GHGs, the contribution in CO_2eq terms is larger than land-use CO_2 with projected emissions increasing over time (Figure 6.5, left panel). Along with fugitive methane and a few industrial sources, land-use related activities are projected to be a major driver of non-CO_2 emissions, accounting for roughly 50 % of total methane (CH_4) emissions and 90 % of nitrous oxide (N_2O) emissions. Total CO_2eq emissions are projected as the sum of FF&I CO_2, land-use related CO_2, and non-CO_2 (Figure 6.5, right panel), with FF&I CO_2 constituting around 80 %.

6.3.1.5 Baseline radiative forcing and cumulative carbon emissions

The emissions pathways for all of the emissions from the scenarios collected for this assessment were run through a common version of the MAGICC model to obtain estimates of CO_2eq concentrations (Section 6.3.2). As a result of projected increasing emissions in the scenarios, radiative forcing from all sources continues to grow throughout the century in all baseline scenarios, exceeding 550 CO_2eq (3.7 W/m^2) between 2040 and 2050, while 450 CO_2eq (2.6 W/m^2) is surpassed between 2020 and 2030 (Figure 6.6, left panel). Again, the majority of baseline forcing scenarios fall below the RCP 8.5 path but above RCP 6.0. Total forcing projections include the highly uncertain contribution of aerosols and other non-gas agents, which are based on the MAGICC model's median estimates of forcing as a function of aerosol emissions (for scenarios that do not project emissions of these substances, emissions were prescribed from other sources; see Annex II.10). Due to variation in driver assumptions, which may not reflect true uncertainty, baseline scenarios could lead to a range of long-term climate outcomes, with cumulative carbon emissions from 1751 to 2100 reaching between 1.5 and 3 TtC (Figure 6.6, right panel). Noting that all of the baseline scenarios reviewed here include improvements to technology throughout the economy, there is strong evidence that, conditional on rates of growth assumed in the literature, technological change in the absence of explicit mitigation policies is not sufficient to bring about stabilization of GHG concentrations.

6.3.2 Emissions trajectories, concentrations, and temperature in transformation pathways

6.3.2.1 Linking between different types of scenarios

There are important differences among long-term scenarios that complicate comparison between them. One difference is the nature of the goal itself. The majority of long-term scenarios focus on reaching long-term radiative forcing or GHG concentration goals. However, scenarios based on other long-term goals have also been explored in the literature. This includes scenarios focused on specific policy formulations (e.g., goal of 50 % emission reduction in 2050 (G8, 2009) or the pledges made in the context of United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC, 2011a; b)), those based on cumulative emissions goals over a given period, those based on prescribed carbon prices, and those resulting from cost-benefit analysis (see Box 6.1 for a discussion of cost-benefit analysis scenarios). A second important difference is that some scenarios include all relevant forcing agents, while others only cover a subset of gases or focus only on CO_2. Finally, some scenarios

Box 6.1 | Cost benefit analysis scenarios

Cost-benefit studies (e.g. Tol, 1997; Nordhaus and Boyer, 2000; Hope, 2008) monetize the impacts of climate change and then balance the economic implications of mitigation and climate damages to identify the optimal trajectory of emissions reductions that will maximize total welfare. There are other frameworks of analysis for considering impacts as well (Bradford, 1999; Barrett, 2008; Keller et al., 2008b). For example, risk assessment is also often used to determine overall goals. A theoretical discussion of cost-benefit analysis, including models that have conducted these analyses, can be found in both Chapters 2 and 3. One important characteristic of cost-benefit analyses is that the bulk of research in this domain has been conducted using highly-aggregate models that do not have the structural detail necessary to explore the nature of energy system or agricultural and land-use transitions that are the focus of this chapter. For this reason, they are not assessed in this chapter. In contrast, the scenarios explored here rely on more detailed integrated models and have been implemented in a cost-effectiveness framework, meaning that they are designed to find a least-cost approach to meeting a particular goal, such as a concentration goal in 2100. Additionally, the scenarios and models described in this chapter typically examine mitigation independent from potential feedbacks from climate impacts and adaptation responses. A discussion of studies that do incorporate impacts into their assessment of transformation pathways, and a characterization of how these feedbacks might affect mitigation strategies, is provided in Section 6.3.3.

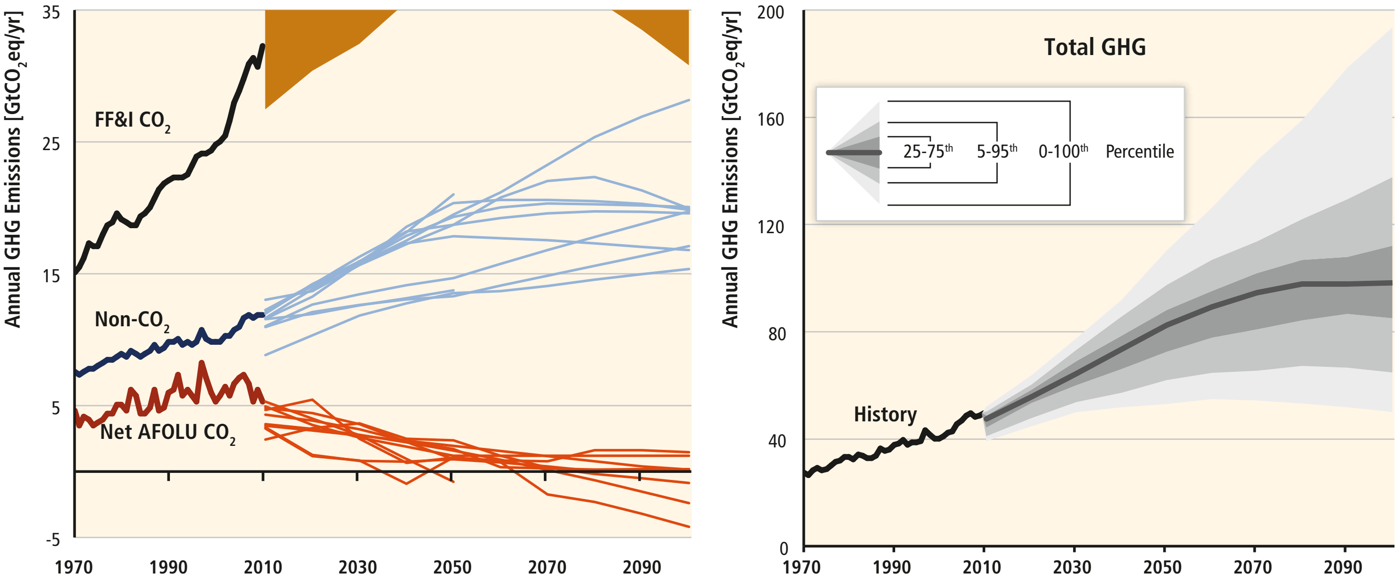


Figure 6.5 | Global CO_2-equivalent emissions in baseline scenarios by component (left panel) and total (right panel) for baseline scenarios. Net AFOLU CO_2 and total non-CO_2 (CH_4, N_2O, and F-gases) projections are shown for individual models from EMF27. The FF&I CO_2 projections are depicted in detail above (see Fig.6.4); the range is truncated here. FF&I CO_2 includes CO_2 from AFOLU fossil fuel use. Total CO_2eq emissions* are shown for all baseline scenarios with full coverage, depicted as a range with median emboldened; shading reflects interquartile range (darkest), 5th–95th percentile range (lighter), and full range (lightest). Sources: WG III AR5 Scenario Database (Annex II.10); historic data: JRC/PBL (2013), IEA (2012a), see Annex II.9.

Note: In this chapter, CO_2eq emissions are constructed using Global Warming Potentials (GWPs) over a 100-year time horizon derived from the IPCC Second Assessment Report (see Annex II.9.1 for the GWP values of the different GHGs). A discussion about different GHG metrics can be found in Sections 1.2.5 and 3.9.6.

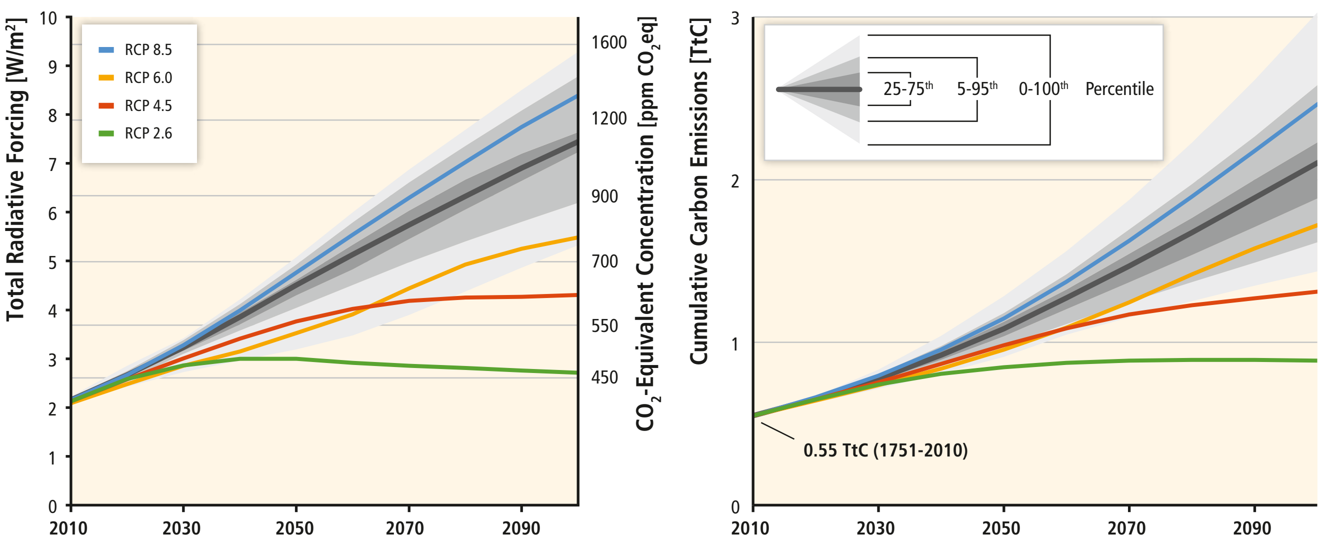


Figure 6.6 | Total radiative forcing (left panel) and cumulative carbon emissions since 1751 (right panel) in baseline scenario literature compared to RCP scenarios. Forcing was estimated ex-post from models with full coverage the median output from the MAGICC results. Secondary axis in the left panel expresses forcing in CO_2eq concentrations. Scenarios are depicted as ranges with median emboldened; shading reflects interquartile range (darkest), 5th–95th percentile range (lighter), and full range (lightest). Sources: WG III AR5 Scenario Database (Annex II.10); Boden et al. (2013); Houghton (2008); van Vuuren et al. (2011a).

allow concentrations to temporarily exceed long-term goals (overshoot scenarios), while others are formulated so that concentrations never exceed the long-term goal ('not-to-exceed scenarios').

Despite these differences, it is necessary for the purposes of assessment to establish comparability across scenarios. To this end, scenarios assessed here have been grouped according to several key parameters (Table 6.2) (for more detail on this process, see Annex II.10). The main criterion for grouping is the full radiative forcing level in 2100, expressed in CO_2eq concentrations. (Full radiative forcing here includes GHGs, halogenated gases, tropospheric ozone, aerosols, and land-use related albedo change). Radiative-forcing levels are often used as goal in scenarios, and the RCPs have been formulated in terms of this indicator (Moss et al., 2010; van Vuuren et al., 2011a). The scenario categories were chosen to relate explicitly to the four RCPs. A similar table in AR4 (Table 3.5) presented equilibrium values rather than 2100 values. Equilibrium values (as presented in AR4) and 2100 concentration and temperature values (as presented in this report) cannot easily be compared given the wide range of possible post-2100 trajectories and the lags in the physical processes that govern both. In particular, equilibrium values assume that concentrations stay constant after 2100, while many scenarios in the literature since AR5 show increasing or decreasing concentrations in 2100. Thus, it is more appropriate to focus on 21st century values to avoid relying on additional assumptions about post-2100 dynamics.

Another issue that complicates comparison across scenarios reported in the literature is that the Earth-System components (e.g., the carbon cycle and climate system) of integrated models can vary substantially (van Vuuren et al., 2009b). Hence, similar emissions pathways may arrive at different 2100 CO_2eq concentration levels and climate outcomes in different models. To provide consistency in this regard across the scenarios assessed in the scenario database for AR5 (Annex II.10), and to facilitate the comparison with the assessment in Working Group I (WG I), the variation originating from the use of different models was removed by running all the scenarios in the database with at least information on Kyoto gas emissions through a standard reduced-form climate model called MAGICC (see Meinshausen et al., 2011a; b; c; Rogelj et al., 2012). For each scenario, MAGICC was run multiple times using a distribution of Earth-System parameters, creating an ensemble of MAGICC runs. The resulting median concentration from this distribution was used to classify each scenario (see Section 6.3.2.6 for more on this process and a discussion of temperature outcomes). This means that the median concentration information reported here does not reflect uncertainty by Earth-System components, unless mentioned otherwise, and it also means that the concentrations may differ from those that were originally reported in the literature for the individual models and scenarios.

The consistency of the MAGICC model version used here and the more comprehensive general circulation models used in the WGI report (IPCC, 2013) is discussed in Section 6.3.2.6, where MAGICC is also used to produce probabilistic temperature estimates. The CO_2eq concentration in 2010 based on the parameters used in this version of MAGICC is roughly consistent with the 2011 radiative forcing estimate from WGI.

Table 6.2 | Definition of CO_2eq concentration categories used in this assessment, the mapping used to allocate scenarios based on different metrics to those categories, and the number of scenarios that extend through 2100 in each category. [Note: This table shows the mapping of scenarios to the categories; Table 6.3. shows the resulting characteristics of the categories using this mapping. The table only covers the scenarios with information for the full 21st century. The mapping of scenarios based on 2011–2050 cumulative total CO_2eq emissions is described in the Methods and Metrics Annex.

CO_2-equivalent concentration in 2100 (ppm CO_2eq) (based on full radiative forcing)[1]		Secondary categorization criteria[2]		Corresponding RCP[3]	No of scenarios extending through 2100	
CO_2eq concentration (ppm)	Radiative forcing (W/m^2)	Kyoto gas only CO_2eq concentration in 2100 (ppm)	Cumulative total CO_2 emissions 2011–2100 ($GtCO_2$)		Total[4]	With Overshoot Greater than 0.4 W/m^2
430–480	2.3–2.9	450–500	< 950	RCP 2.6	114 (114)	72 (72)
480–530	2.9–3.45	500–550	950–1500		251 (257)	77 (77)
530–580	3.45–3.9	550–600	1500–1950		198 (222)	22 (22)
580–650	3.9–4.5	600–670	1950–2600	RCP 4.5	102 (109)	8 (8)
650–720	4.5–5.1	670–750	2600–3250		27 (27)	0 (0)
720–1000	5.1–6.8	750–1030	3250–5250	RCP .6	111 (120)	0 (0)
> 1000	> 6.8	> 1030	> 5250	RCP 8.5	160 (166)	0 (0)

1 Scenarios with information for the full 21st century were categorized in different categories based on their 2100 full radiative forcing/CO_2eq concentration level (including GHGs and other radiatively active substances).

2 If insufficient information was available to calculate full forcing, scenarios were categorized, in order of preference, by 2100 Kyoto gas forcing or cumulative CO_2 emissions in the 2011–2100 period. Scenarios extending only through 2050 were categorized based on cumulative CO_2 emissions in the 2011–2050 period. Those scenarios are not included in this table. (See the Methods and Metrics Annex for more information.)

3 The column indicates the corresponding RCP falling within the scenario category based on 2100 CO_2 equivalent concentration.

4 Number of scenarios in the respective category, which report at least total CO_2 emissions (and potentially other GHGs and other radiatively active substances) to 2100. Numbers in parentheses denote all scenarios in the respective category, including those scenarios that report only CO_2 emissions from fossil fuels and industry (but not land-use CO_2).

Table 6.3 | Key characteristics of the scenarios categories introduced in Table 6.2. For all parameters, the 10th to 90th percentile of the scenarios are shown.[1] Source: WG III AR5 Scenario Database (Annex II.10).

CO_2-equivalent concentration in 2100 (ppm CO_2eq)[2]	Subcategories	Cumulative CO_2 emissions[3] ($GtCO_2$)		CO_2eq. emissions in 2050 relative to 2010 (%)[4]	CO_2eq emissions in 2100 relative to 2010 (%)	Concentration (ppm)[5]		Temperature (relative to 1850–1900)[6, 7]				
		2011–2050	2011–2100			CO_2 in 2100	Peak CO_2eq.	2100 Temperature (°C)	Probability of Exceeding 1.5 °C (%)	Probability of Exceeding 2 °C (%)	Probability of Exceeding 3 °C (%)	Probability of Exceeding 4 °C (%)
430–480	Total range	550–1300	630–1180	−72 to −41	−118 to −78	390–435	465–530	1.5–1.7 (1.0–2.8)	49–86	12–37	1–3	0–1
	Overshoot < 0.4 W/m²	*550–1030*	*630–1180*	*−72 to −49*	*−94 to −78*	*390–435*	*465–500*	*1.5–1.7 (1.0–2.6)*	*49–72*	*12–22*	*1–2*	*0–0*
	Overshoot > 0.4 W/m²	*920–1300*	*670–1180*	*−66 to −41*	*−118 to −103*	*400–435*	*505–530*	*1.6–1.7 (1.1–2.8)*	*76–86*	*22–37*	*1–3*	*0–1*
480–530	Total range	860–1600	960–1550	−57 to 4[8]	−179 to −127	425–460	505–575	1.7–2.1 (1.2–3.3)	80–96	32–61	3–10	0–2
	Overshoot < 0.4 W/m²	*870–1240*	*960–1490*	*−57 to −42*	*−103 to −76*	*425–460*	*505–560*	*1.8–2.0 (1.2–3.2)*	*81–94*	*32–56*	*3–10*	*0–2*
	Overshoot > 0.4 W/m²	*1060–1600*	*1020–1500*	*−54 to 4*[8]	*−179 to −98*	*425–460*	*530–575*	*1.8–2.1 (1.2–3.3)*	*86–96*	*38–61*	*3–10*	*1–2*
	No exceedance of 530 ppm CO_2eq	*860–1180*	*960–1430*	*−57 to −42*	*−107 to −73*	*425–455*	*505–530*	*1.7–1.9 (1.2–2.9)*	*80–87*	*32–40*	*3–4*	*0–1*
	Exceedance of 530 ppm CO_2eq	*1130–1530*	*990–1550*	*−55 to −25*	*−114 to −90*	*425–460*	*535–575*	*1.8–2.0 (1.2–3.3)*	*88–96*	*39–61*	*4–10*	*1–2*
530–580	Total range	1070–1780	1170–2240	−47 to 7	−184 to −59	425–520	540–640	2.0–2.3 (1.4–3.6)	93–99	54–84	8–19	1–3
	Overshoot < 0.4 W/m²	*1090–1490*	*1400–2190*	*−47 to −12*	*−86 to −60*	*465–520*	*545–585*	*2.0–2.2 (1.4–3.6)*	*93–96*	*55–71*	*8–14*	*1–2*
	Overshoot > 0.4 W/m²	*1540–1780*	*1170–2080*	*−7 to 7*	*−184 to −98*	*425–505*	*590–640*	*2.1–2.2 (1.4–3.6)*	*95–99*	*63–84*	*8–19*	*1–3*
	No exceedance of 580 ppm CO_2eq	*1070–1460*	*1240–2240*	*−47 to −19*	*−81 to −59*	*450–520*	*540–575*	*2.0–2.2 (1.4–3.6)*	*93–95*	*54–70*	*8–13*	*1–2*
	Exceedance of 580 ppm CO_2eq	*1420–1750*	*1170–2100*	*−16 to 7*	*−183 to −86*	*425–510*	*585–640*	*2.1–2.3 (1.4–3.6)*	*95–99*	*66–84*	*8–19*	*1–3*
580–650	Total range	1260–1640	1870–2440	−38 to 24	−134 to −50	500–545	585–690	2.3–2.6 (1.5–4.2)	96–100	74–93	14–35	2–8
650–720	Total range	1310–1750	2570–3340	−11 to 17	−54 to −21	565–615	645–710	2.6–2.9 (1.8–4.5)	99–100	88–95	26–43	4–10
720–1000	Total range	1570–1940	3620–4990	18 to 54	−7 to 72	645–780	765–935	3.1–3.7 (2.1–5.8)	100–100	97–100	55–83	14–39
> 1000	Total range	1840–2310	5350–7010	52 to 95	74 to 178	810–975	1075–1285	4.1–4.8 (2.8–7.8)	100–100	100–100	92–98	53–78

1 Italicized text in blue shows results of the subset of the scenarios from column one. One subcategory distinguishes scenarios that have a large overshoot (i.e., a maximum forcing during the 21st century that is > 0.4 W/m² higher than its 2100 forcing) from those that do not have a large overshoot. The second set of subcategories shows whether a scenario exceeds the maximum equivalent concentration level of its category somewhere before 2100. For categories above 580 ppm CO_2eq, the information in the row 'total range' refers to the 10th to 90th percentiles for the total set of scenarios in the category. For the categories below 580 ppm CO_2eq, the total range is based on the 10th to 90th percentiles of the subcategories (the lowest and highest values from the subcategories).

2 The CO_2eq concentration includes the forcing of all GHGs including halogenated gases and tropospheric ozone, as well as aerosols and albedo change (calculated on the basis of the total forcing from a simple carbon cycle/climate model MAGICC).

3 For comparison of the cumulative CO_2 emissions estimates assessed here with those presented in WGI AR5, an amount of 515 [445 to 585] GtC (1890 [1630 to 2150] $GtCO_2$), was already emitted by 2011 since 1870 (WGI Section 12.5). Note that cumulative CO_2 emissions are presented here for different periods of time (2011–2050 and 2011–2100) while cumulative CO_2 emissions in WGI AR5 are presented as total compatible emissions for the RCPs (2012–2100) or for total compatible emissions for remaining below a given temperature target with a given likelihood. (WGI Table SPM.3, WGI SPM.E.8)

4 The global 2010 emissions are 31 % above the 1990 emissions (consistent with the historic GHG emission estimates presented in this report). CO_2eq emissions include the basket of Kyoto gases (CO_2, CH4, N2O as well as F-gases).

5 The assessment in WGIII AR5 involves a large number of scenarios published in the scientific literature and is thus not limited to the RCPs. To evaluate the CO_2eq concentration and climate implications of these scenarios, the MAGICC model was used in a probabilistic mode (see Annex II). For a comparison between MAGICC model results and the outcomes of the models used in WGI AR5, see WGI Sections 12.4.1.2, 12.4.8 and Section 6.3.2.6 of this report. Reasons for differences with WGI AR5 SPM Table.2 include the difference in reference year (1986–2005 vs. 1850–1900 here), difference in reporting year (2081–2100 vs 2100 here), set-up of simulation (CMIP5 concentration-driven versus MAGICC emission-driven here), and the wider set of scenarios (RCPs versus the full set of scenarios in the WGIII AR5 scenario database here).

6 Temperature change in 2100 is provided for a median estimate of the MAGICC calculations, which illustrates differences between the emissions pathways of the scenarios in each category. The range of temperature change in the parentheses includes in addition also the carbon cycle and climate system uncertainties as represented by the MAGICC model (see 6.3.2.6 for further details). The temperature data compared to the 1850–1900 reference year was calculated by taking all projected warming relative to 1986–2005, and adding 0.61 °C for 1986–2005 compared to 1850–1900, based on HadCRUT4, as also applied in WGI Table SPM.2.

7 Temperature change is reported for the year 2100, which is not directly comparable to the equilibrium warming reported in WGIII AR4 (see Table 3.5; see also Section 6.3.2). For the 2100 temperature estimates, the transient climate response (TCR) is the most relevant system property. The assumed 90 % range of the TCR for MAGICC is 1.2–2.6 °C (median 1.8 °C). This compares to the 90 % range of TCR between 1.2–2.4 °C for CMIP5 (WGI Section 9.7) and an assessed ***likely*** range of 1–2.5 °C from multiple lines of evidence reported in the WGI AR5 (Box 12.2 in Section 12.5).

8 The high estimate is influenced by multiple scenarios from the same model in this category with very large net negative CO_2eq emissions of about 40 $GtCO_2$eq/yr in the long term. The higher bound CO_2eq emissions estimate, excluding extreme net negative emissions scenarios and thus comparable to the estimates from the other rows in the table, is about −19 % in 2050 relative to 2010.

To compare scenarios with different coverage of relevant substances or goals, a set of relationships was developed to map scenarios with only sufficient information to assess Kyoto gas forcing or with information only on cumulative CO_2 budgets to the full-forcing CO_2eq concentration categories (Table 6.2 and Method and Metrics Annex). Scenarios without full forcing information and that extend to the end of the century were mapped, in order of preference, by Kyoto gas forcing in 2100 or by cumulative CO_2 budgets from 2011 to 2100. In addition, scenarios that only extend to mid-century were mapped according to cumulative CO_2 budgets from 2011 to 2050. These mappings allow for a practical, though still imperfect, means to compare between scenarios with different constructions.

The categories leading to CO_2eq concentration above 720 ppm contain mostly baseline scenarios and some scenarios with very modest mitigation policies (Figure 6.7). The categories from 580–720 ppm CO_2eq contain a small number of baseline scenarios at the upper end of the range, some scenarios based on meeting long-term concentration goals such as 650 ppm CO_2eq by 2100, and a number of scenarios without long-term concentration goals but based instead on emissions goals. There has been a substantial increase in the number of scenarios in the two lowest categories since AR4 (Fisher et al., 2007). The RCP 2.6 falls in the 430–480 ppm CO_2eq category based on its forcing level by 2100. A limited number of studies (Rogelj et al 2013a,b; Luderer et al, 2013) have explored emissions scenarios leading to concentrations below 430 ppm CO_2eq by 2100. These scenarios were not submitted to the AR5 database.

This mapping between different types of scenarios allows for roughly comparable assessments of characteristics of scenarios, grouped by 2100 full-forcing CO_2eq concentration, across the full database of scenarios collected for AR5 (Table 6.3.). The cumulative CO_2 budgets from 2011 to 2100 in each category in Table 6.3 span a considerable range. This variation in CO_2 budgets results from the range of concentration levels assigned to each category, the timing of emission reductions, and variation in non-CO_2 emissions, including aerosols. Although this leads

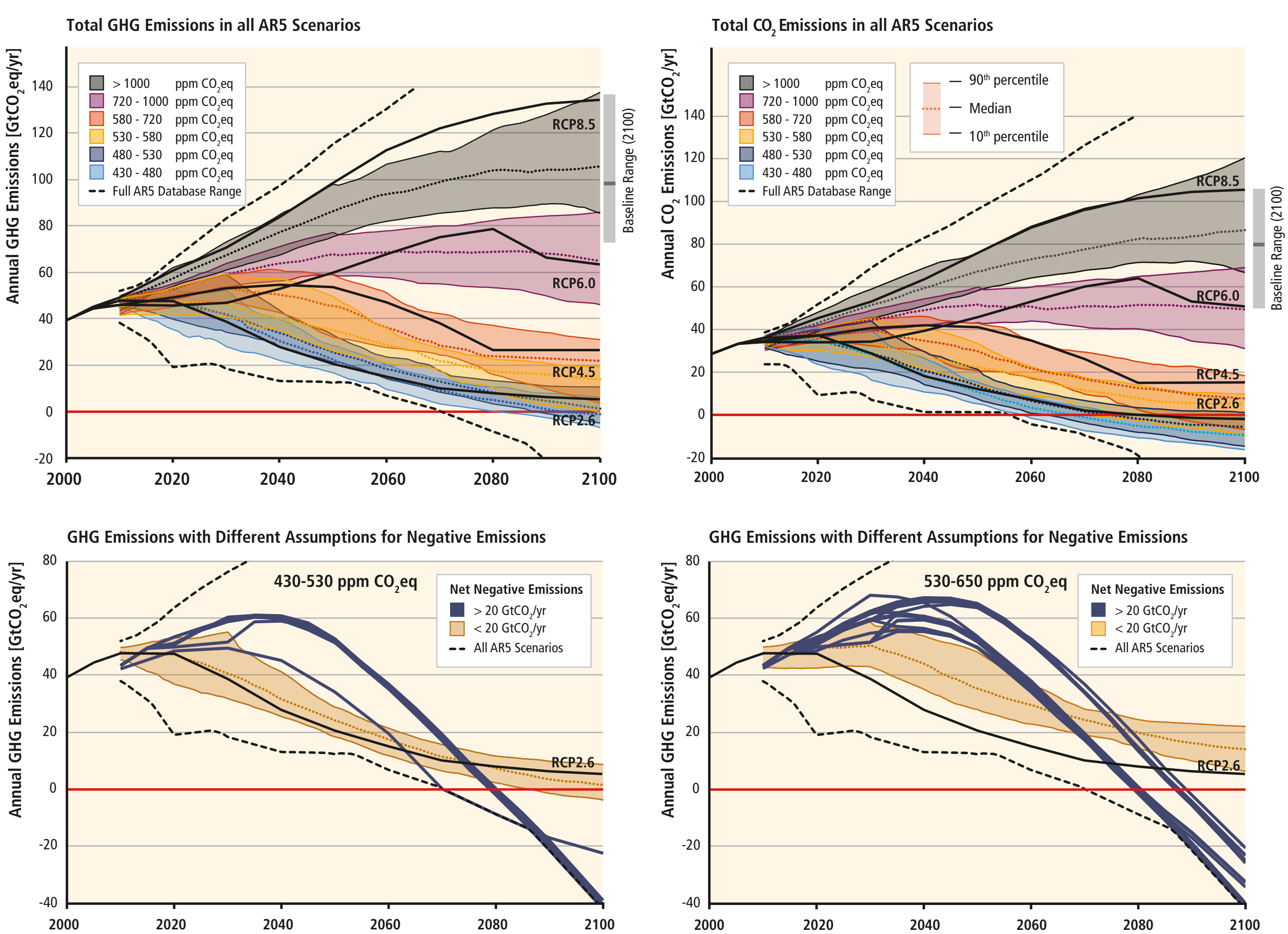


Figure 6.7 | Emissions pathways for total CO_2 and Kyoto gases for the various categories defined in Table 6.2. The bands indicate the 10th to 90th percentile of the scenarios included in the database. The grey bars to the right of the top panels indicate the 10th to 90th percentile for baseline scenarios (see Section 6.3.1). The bottom panels show for the combined categories 430–530 ppm and 530–650 ppm CO_2eq the scenarios with and without net negative emissions larger than 20 $GtCO_2$eq/yr. Source: WG III AR5 Scenario Database (Annex II.10).

to a wider range of CO_2 budgets than for the scenarios used in WG I (SPM Figure 10), the central estimates for the period 2011–2100 are very consistent. (Temperature results are discussed in Section 6.3.2.6).

An important distinction between scenarios is the degree to which concentrations exceed the 2100 goal before decreasing to reach it. Table 6.3 includes subcategories for scenarios in which concentrations exceed their 2100 level by more than 0.4 W/m^2 and scenarios that sometime during the century overshoot the upper-bound concentration level of the category. Both subcategories result in different emission profiles and temperature outcomes compared to those that do not meet these criteria (see Section 6.3.2.6 regarding temperature outcomes).

6.3.2.2 The timing of emissions reductions: The influence of technology, policy, and overshoot

There are many different emissions pathways associated with meeting 2100 CO_2eq concentrations (Figure 6.7). For all categories below a 2100 CO_2eq concentration of 720 ppm CO_2eq, emissions are reduced in the long-run relative to current levels. The decision on timing of emission reductions is a complex one. Model scenarios are typically designed to find the least-cost pathway to meet a long-term goal, in some cases under specific constraints, such as the availability of certain technologies or the timing and extent of international participation. Because models differ in, among other things, technology representations and baseline assumptions, there are clear differences among scenarios with regards to the timing of emissions reductions and the allocation of reductions across gases.

Three interrelated factors are particularly important determinants of emissions profiles in the modelling literature: (1) the degree of overshoot, (2) technology options and associated deployment decisions, and (3) policy assumptions. Overshoot scenarios scenarios entail less mitigation today in exchange for greater reductions later (Wigley, 2005; Meinshausen et al., 2006; den Elzen and van Vuuren, 2007; Nusbaumer and Matsumoto, 2008). Overshooting a long-term concentration goal, however, may lead to higher transient temperature change than if the goal is never exceeded (Section 6.3.2.6). Overshoot is particularly important for concentration goals that are close to today's levels. The majority of scenarios reaching 480 ppm CO_2eq or below by 2100, for instance, rely on overshoot pathways. Those that do not include overshoot, need faster emissions reductions (and associated energy system changes) during the next 1–2 decades (Calvin et al., 2009b).

The second consideration is technology. The most critical set of technologies in the context of the timing of emission reductions is CDR technologies, which can be used to generate negative emissions (van Vuuren et al., 2007; Edenhofer et al., 2010; Azar et al., 2010, 2013; van Vuuren and Riahi, 2011; Tavoni and Socolow, 2013). In most model studies in the literature, negative emissions are generated via the use of biomass energy with carbon dioxide capture and storage (BECCS), and to a lesser extent, afforestation, though in principle other options could potentially result in negative emissions as well (see Section 6.9). CDR technologies have not been applied yet at large scale. The potential of afforestation is limited, and the use of BECCS is ultimately constrained by the potential for CCS and biomass supply (van Vuuren et al., 2013). CDR technologies have two key implications for transformation pathways. One is that by removing emissions from the atmosphere, CDR technologies can compensate for residual emissions from technologies and sectors with more expensive abatement. The second is that CDR technologies can create net negative emissions flows, which allow faster declines in concentrations in the second half of the century and thus facilitate higher near-term emissions, effectively expanding the potential scope for overshoot. In model comparison studies, many of the models that could not produce scenarios leading to concentrations of about 450 ppm CO_2eq by 2100, particularly in combination with delayed or fragmented policy approaches, did not include CDR techniques (Clarke et al., 2009). The vast majority of scenarios with overshoot of greater than 0.4 W/m^2 (greater than 20 ppm CO_2eq) deploy CDR technologies to an extent that net global CO_2 emissions become negative. Evidence is still mixed whether CDR technologies are essential for achieving very low GHG concentration goals (Rose et al., 2013). A limited number of studies have explored scenarios with net negative emissions as large as 20 $GtCO_2$ per year or more (lower panels Figure 6.7), which allow for very substantial delays in emission reductions. However, the majority of studies have explored futures with smaller, but often still quite substantial, contributions of CDR technologies. Technology portfolio assumptions other than CDR technologies (e.g., regarding renewables, CCS, efficiency, and nuclear power) can also have implications for emissions trajectories, although these are often less pronounced and may in fact shift mitigation earlier or later (Rogelj et al., 2012; Eom et al., 2014; Krey et al., 2014; Kriegler et al., 2014a; Riahi et al., 2014).

The third consideration is policy structure. Since AR4, scenario studies have increasingly focused on the outcomes of fragmented international action and global delays in emission reduction (Clarke et al., 2009; van Vliet et al., 2012; Kriegler et al., 2013b; Tavoni et al., 2013; Rogelj et al., 2013a; see Riahi et al., 2014). Considering both idealized implementation and non-idealized implementation scenarios, a considerable range of 2020 and 2030 emissions can be consistent with specific long-term goals. Although studies show that low long-term concentration goals could still be met with near-term emissions above those in idealized scenarios, initial periods of delay are typically followed by periods rapid reductions in subsequent decades (Kriegler et al., 2014c; Riahi et al., 2014). This has important implications for costs and technology transitions, among other things (see Section 6.3.5). In general, delays in mitigation decrease the options for meeting long-term goals and increase the risk of foreclosing on certain long-term goals (Riahi et al., 2014).

The intersection of these three factors—overshoot, CDR technologies, and delayed mitigation—can be viewed in the context of emissions pathways over the next several decades, for example, the emissions level in 2030 (Figure 6.8). For a given range of forcing at the end of the century, pathways with the lowest levels in 2030 have higher emissions in the long run and slower rates of decline in the middle of the century. On the other hand, high emissions in 2030 leads to more rapid declines in the medium term and lower or eventually net negative emissions in the long-run, with the pattern exaggerated in a few extreme scenarios exploring deployment of CDR of 20 $GtCO_2$/yr or more. (See Section 6.4 for a more thorough discussion of the relationship between near-term actions and long-term goals.) Deeper long-term goals also interact with these factors. For example, scenarios leading to concentrations below 430 ppm CO_2eq by 2100 (Rogelj et al., 2013a,b; Luderer et al., 2013) feature large-scale application of CDR technologies in the long-term, and most of them have deep emission reductions in the near term.

A final observation is that the characteristics of emissions profiles discussed here are, in many cases, driven by the cost-effectiveness framing of the scenarios. A more comprehensive consideration of timing would also include, among other things, considerations of the tradeoff between the risks related to both transient and long-term climate change, the risks associated with deployment of specific technologies and expectation of the future developments of these technologies, short-term costs and transitional challenges, flexibility in achieving climate goals, and the linkages between emissions reductions and a wide range of other policy objectives (van Vuuren and Riahi, 2011; Krey et al., 2014; Riahi et al., 2014).

6.3.2.3 Regional roles in emissions reductions

The contribution of different regions to mitigation is directly related to the formulation of international climate policies. In idealized implementation scenarios, which assume a uniform global carbon price, the extent of mitigation in each region depends most heavily on relative baseline emissions, regional mitigation potentials, and terms of trade effects. All of these can vary significantly across regions (van Vuuren et al., 2009a; Clarke et al., 2012; Tavoni et al., 2013; Chen et al., 2014; van Sluisveld et al., 2013). In this idealized implementation environment, the carbon budgets associated with bringing concentrations to between 430 and 530 ppm CO_2eq in 2100 are generally highest in Asia, smaller in the OECD-1990, and lowest for other regions (Figure 6.9, left panel). However, the ranges for each of these vary substantially across scenarios. Mitigation in terms of relative reductions from baseline emissions is distributed more similarly between OECD-1990, ASIA, and Economies in Transition (EIT) across scenarios (Figure 6.9, right panel). The Middle East and Africa (MAF) region and especially Latin America (LAM) have the largest mitigation potential. In absolute terms, the remaining emissions in the mitigation scenarios are largest in Asia (Figure 6.9, left panel) as are the absolute emissions reductions (Figure 6.9, right panel), due to the size of this region. It is important to note that the mitigation costs borne by different regions and countries do not need to translate directly from the degree of emissions reductions, because the use of effort-sharing schemes can reallocate economic costs (see Section 6.3.6.6).

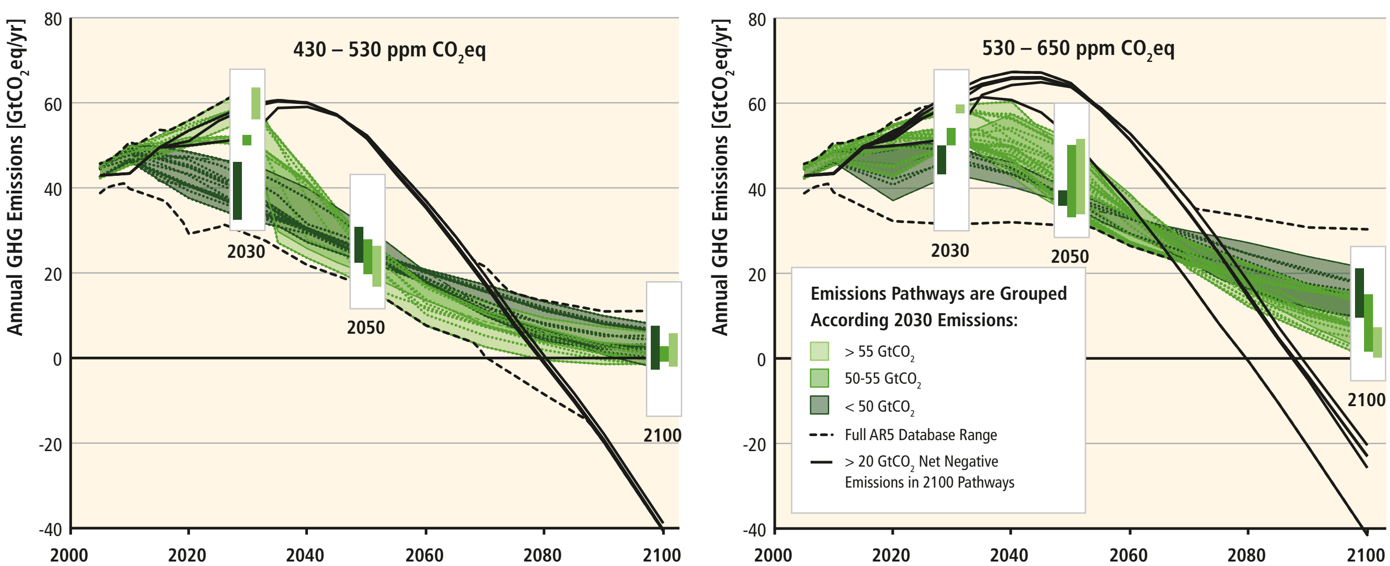


Figure 6.8 | Emissions pathways from three model comparison exercises with explicit 2030 emissions goals. Mitigation scenarios are shown for scenarios reaching 430–530 ppm CO_2eq in 2100 (left panel) and 530–650 ppm CO_2eq in 2100 (right panel). Scenarios are distinguished by their 2030 emissions: < 50 $GtCO_2$eq, 50–55 $GtCO_2$eq, and > 55 $GtCO_2$eq. Individual emissions pathways with net negative emissions of > 20 $GtCO_2$/yr in the second-half of the century are shown as solid black lines. The full range of the scenarios in the AR5 database is given as dashed black lines. (Source: Scenarios from intermodelling comparisons with explicit interim goals (AMPERE: Riahi et al. (2014); LIMITS: Kriegler et al. (2013b), ROSE: Luderer et al. (2014a), and WG III AR5 Scenario Database (Annex II.10)).

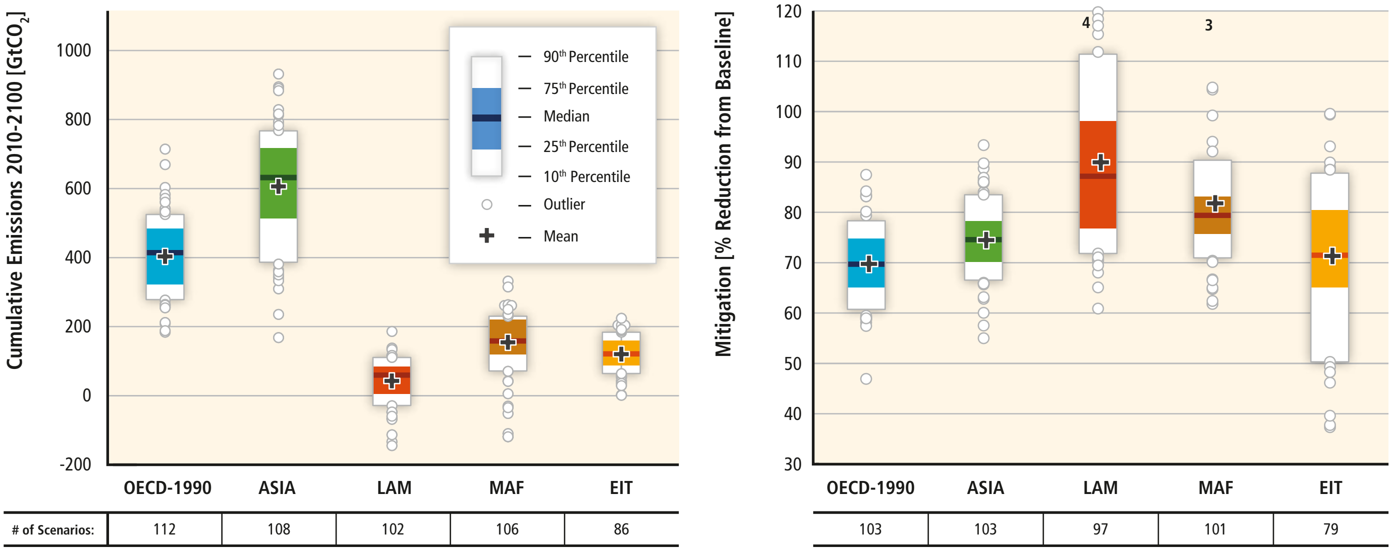


Figure 6.9 | Regional carbon budget (left panel) and relative mitigation effort (right panel) for mitigation scenarios reaching 430–530 ppm CO_2eq in 2100, based on cumulative CO_2 emissions from 2010 to 2100. Carbon budgets below 0 and relative mitigation above 100 % can be achieved via negative emissions. The number of scenarios is reported below the regional acronyms. The number of scenarios outside the figure range is noted at the top. Source: WG III AR5 Scenario Database (Annex II.10), idealized implementation and default technology cases.

The transient emission reductions implications also vary across regions in idealized implementation scenarios (Table 6.4). In general, emissions peak in the OECD-1990 sooner than in other countries with higher baseline growth. Similarly, emissions are reduced in the OECD-1990 countries by 2030 relative to today, but they may increase in other regions, particularly the fast-growing Asian and MAF regions.

Deviations from the idealized implementation, either through global delays in mitigation or delays by particular countries or regions, will lead to different regional contributions to emissions reductions. When mitigation is undertaken by a subset of regions, it will have implications on other non-participating countries through energy markets, terms of trade, technology spillovers, and other leakage channels. Multi model ensembles have shown leakage rates of energy-related emissions to be relatively contained, often below 20 % (Arroyo-Curras et al., 2014; Babiker, 2005; Bauer et al., 2014a; Blanford et al., 2014; Böhringer et al., 2012; Bosetti and De Cian, 2013; Kriegler et al., 2014c). Policy instruments such as border carbon adjustment can effectively reduce these effects further (Böhringer et al., 2012). Leakage in land use, on the other hand, could be substantial, though fewer studies have quantified it (Calvin et al., 2009).

6.3.2.4 Projected CO_2 emissions from land use

Net AFOLU CO_2 emissions (see Figure 6.5) result from an interplay between the use of land to produce food and other non-energy products, to produce bioenergy, and to store carbon in land. Land-management practices can also influence CO_2 emissions (see Section 6.3.5). Currently about 10–20 % of global CO_2 emissions originate from land use and LUC. In general, most scenarios show declining CO_2 emissions from land use as a result of declining deforestation rates, both with and without mitigation (see also Section 6.3.1.4). In fact, many scenarios project a net uptake of CO_2 as a result of reforestation after 2050 (Figure 6.10).

Scenarios provide a wide range of outcomes for the contribution of CO_2 emissions from land use (see Section 11.9 for a sample from a model intercomparison study). However, one difficulty in interpreting this range is that many scenarios were developed from models that do not explicitly look at strategies to reduce net AFOLU CO_2 emissions. Nonetheless, the spread in net AFOLU emissions still reflects the implications of land-use related mitigation activities—bioenergy, avoided deforestation, and afforestation—in both models that explicitly represent land use and those that do not (see Section 6.3.5 for a detailed discussion). Some studies emphasize a potential increase in net AFOLU emissions due to bioenergy production displacing forests (van Vuuren et al., 2007; Searchinger et al., 2008; Wise et al., 2009; Melillo et al., 2009; Reilly et al., 2012). Others show a decrease in net AFOLU emissions as a result of decreased deforestation, forest protection, and/or net afforestation enacted as a mitigation measure (e.g. Wise et al., 2009; Popp et al., 2011b; Riahi et al., 2011; Reilly et al., 2012). Wise et al. (2009) show a range of results from a single model, first focusing mitigation policy on the energy sector, thereby emphasizing the bioenergy production effect, and then focusing policy more broadly to also encourage afforestation and slow deforestation. Reilly et al. (2012) conduct a similar analysis, but with more policy design alternatives. However, policies to induce large-scale land-related mitigation will be challenging and actual implementation will affect costs and net benefits (Lubowski and Rose, 2013) (see Section 6.3.5, Section 6.8 and Chapter 11).

Table 6.4 | Regional peak year of CO_2 emission and emissions reductions in 2030 over 2010, for 430–530 and 530–650 ppm CO_2eq scenarios. Negative values for emissions reductions indicate that 2030 emissions are higher than in 2010. Figures are averages across models. The numbers in parenthesis show the interquartile range across scenarios. The number of underlying scenarios is the same as in Figure 6.9. Source: WG III AR5 Scenario Database (Annex II.10), idealized implementation and default technology scenarios.

		OECD-1990	ASIA	LAM	MAF	EIT
Peak year of emissions	430–530 ppm CO_2eq	2010 (2010/2010)	2020 (2015/2030)	2015 (2010/2020)	2020 (2010/2030)	2014 (2010/2015)
Peak year of emissions	530–650 ppm CO_2eq	2014 (2010/2015)	2030 (2030/2030)	2020 (2010/2030)	2034 (2020/2040)	2016 (2010/2020)
2030 Emission reductions w.r.t. 2010	430–530 ppm CO_2eq	32 % (23/40 %)	–1 % (–15/14 %)	35 % (16–59 %)	8 % (–7/18 %)	32 % (18/40 %)
2030 Emission reductions w.r.t. 2010	530–650 ppm CO_2eq	14 % (6/21 %)	–34 % (–43/–26 %)	9 % (–17/41 %)	–22 % (–41/–12 %)	8 % (–5/16 %)

6.3.2.5 Projected emissions of other radiatively important substances

Beyond CO_2, the scenario literature has focused most heavily on the mitigation opportunities for the gases covered by the Kyoto protocol, including the two most important non-CO_2 gases, CH_4 and N_2O. Attention is also increasingly being paid to the climate consequences of other emissions such as aerosols and ozone precursors (e.g. Shindell et al., 2012; Rose et al., 2014b). Although several models have produced projections of aerosol forcing and have incorporated these emissions into the constraint on total forcing, most of them do not have specific mitigation measures for these emissions.

For non-CO_2 Kyoto gases, the relative depth and timing of emissions reductions are influenced by two primary factors: (1) the abatement potential and costs for reducing emissions of different greenhouse forcers, and (2) the strategies for making tradeoffs between them. With respect to abatement potential and costs, studies indicate that in the short run, there are many low-cost options to reduce non-CO_2 gases relative to opportunities to reduce CO_2 emissions. Partially as a result, studies indicate that short-term reduction strategies may rely more heavily in the near term on non-CO_2 gases than in the long run (Weyant et al., 2006; Lucas et al., 2007). In the longer run, emission reductions, particularly for CH_4 and N_2O, are expected to be constrained by several hard-to-mitigate sources such as livestock and the application of fertilizers. This ultimately results in lower reduction rates than for CO_2 for the lower concentration categories despite slower growth in baseline projections (see Figure 6.11, and also discussed by Lucas et al., 2007). For scenarios resulting in 430–480 CO_2eq concentration in 2100, CH_4 reductions in 2100 are about 50 % compared to 2005. For

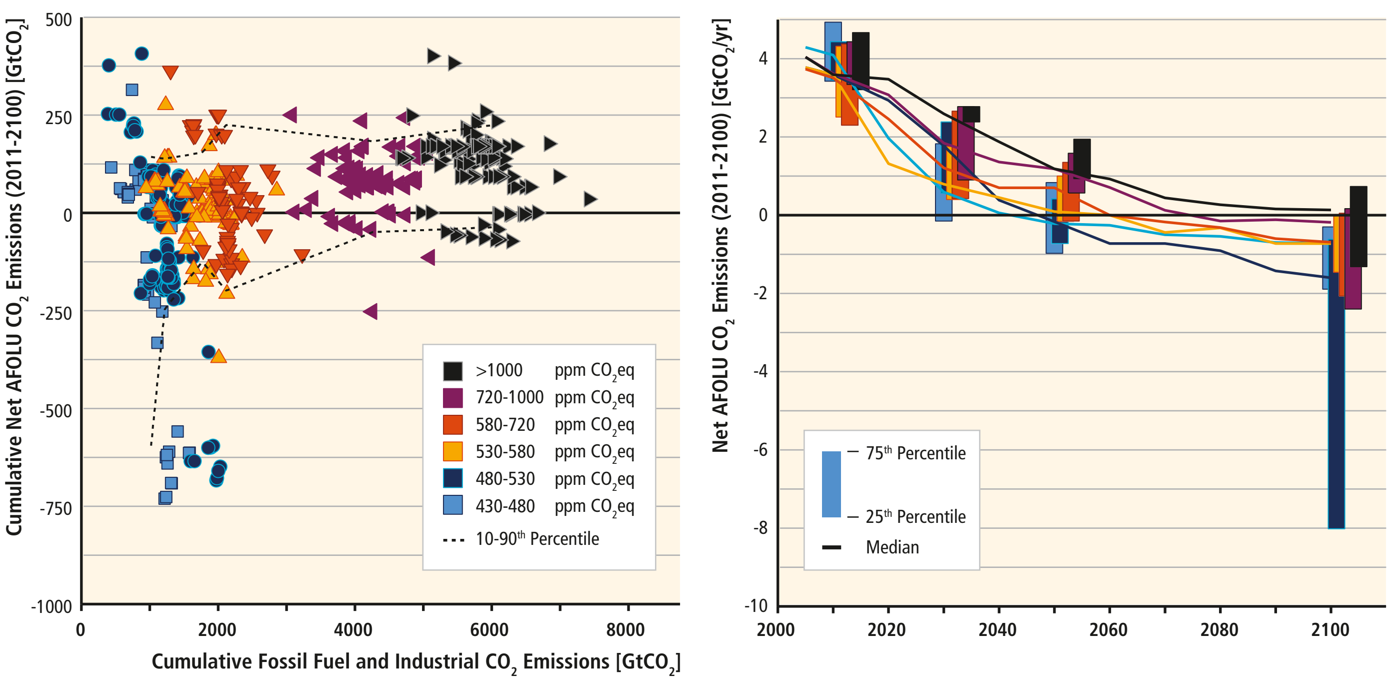


Figure 6.10 | Net AFOLU CO_2 emissions in mitigation scenarios. The left panel shows cumulative net CO_2 emission (2011–2100) from energy/industry (horizontal axis) and AFOLU (land use) (vertical axis). The right panel shows net CO_2 emission from land use as function of time. FF&I CO_2 includes CO_2 from AFOLU fossil fuel use. Source: WG III AR5 Scenario Database (Annex II.10).

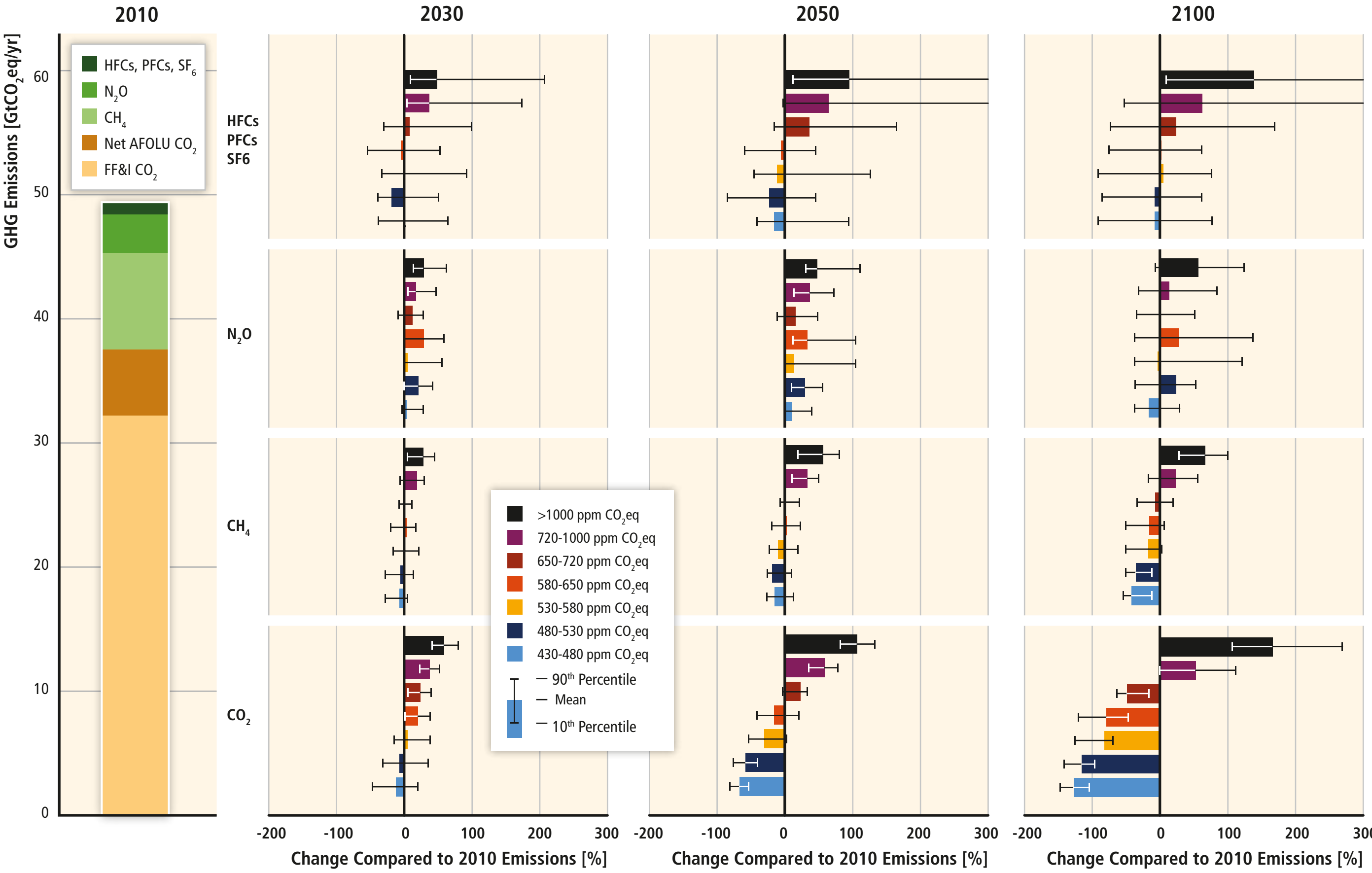


Figure 6.11 | Emissions reductions for different GHGs in 2030, 2050, and 2100. The left panel shows 2010 historic emissions and the bars in the right panel indicate changes compared to 2010 (AR5 Scenario Database). FF&I CO_2 includes CO_2 from AFOLU fossil fuel use. Source: WG III AR5 Scenario Database (Annex II.10). Historic data: JRC/PBL (2013), IEA (2012a), see Annex II.9.

N_2O, the most stringent scenarios result in emission levels just below today's level. For halogenated gases, emission growth is significantly reduced for the lower concentration categories, but variation among models is large, ranging from a 90 % reduction to a 100 % increase compared to 2005.

Strategies for making tradeoffs across greenhouse forcers must account for differences in both radiative effectiveness and atmospheric lifetime and the associated impacts on near-term and long-term climate change. They must also consider relationships between gases in terms of common sources and non-climate impacts such as air pollution control. Models handle these tradeoffs differently, but there are essentially two classes of approaches. Most models rely on exogenous metrics such as Global Warming Potentials (GWPs) (discussed further below) and trade off abatement among gases based on metric-weighted prices. Other models make the tradeoff on the basis of economic optimization over time and the physical characterization of the gases within the model with respect to a specified goal such as total forcing (e.g. Manne and Richels, 2001). Differences both within these classes of approaches and among them lead to very different results, especially with respect to the timing of mitigation for short-lived substances. Several studies have looked into the role of these substances in mitigation (Shine et al., 2007; Berntsen et al., 2010; UNEP and WMO, 2011; Myhre et al., 2011; McCollum et al., 2013a; Rose et al., 2014a). Studies can be found that provide argument for early emission reduction as well as a more delayed response of short-lived forcers. Arguments for early reductions emphasize the near-term benefits for climate and air pollution associated with ozone and particulate matter. An argument for a delayed response is that, in the context of long-term climate goals, reducing short-lived forcers now has only a very limited long-term effect (Smith and Mizrahi, 2013).

Model analysis has also looked into the impact of using different substitution metrics (see Section 3.9.6 for a theoretical discussion the implication of various substitution metrics and Section 8.7 of the WGI report for the physical aspects of substitution metrics). In most current climate policies, emission reductions are allocated on the basis of GWPs for a time of horizon of 100 years. Several papers have explored the use of metrics other than 100-year GWPs, including updated GWP values and Global Temperature Change Potential (GTP) values (Smith et al., 2012; Reisinger et al., 2012; Azar and Johansson, 2014). Quantitative studies show that the choice of metrics is critical for the timing of CH_4 emission reductions among the Kyoto gases, but that it rarely has a strong impact on overall global costs. The use of dynamic GTP values (as alternative to GWPs) has been shown to postpone emissions reductions of short-lived gases. Using different estimates for 100-year GWP from the various previous IPCC Assessment Reports has no major impact on transition pathways.

6.3.2.6 The link between concentrations, radiative forcing, and temperature

The assessment in this chapter focuses on scenarios that result in alternative CO_2eq concentrations by the end of the century. However, temperature goals are also an important consideration in policy discussions. This raises the question of how the scenarios assessed in this chapter relate to possible temperature outcomes. One complication for assessing this relationship is that scenarios can follow different concentration pathways to the same end-of-century goal (see Section 6.3.2.2), and this will lead to different temperature responses. A second complication is that several uncertainties confound the relationship between emissions and temperature responses, including uncertainties about the carbon cycle, climate sensitivity, and the transient climate response (see WG I, Box 12.2). This means that the temperature outcomes of different concentration pathways assessed here (see Section 6.3.2.1) are best expressed in terms of a range of probable temperature outcomes (see Chapter

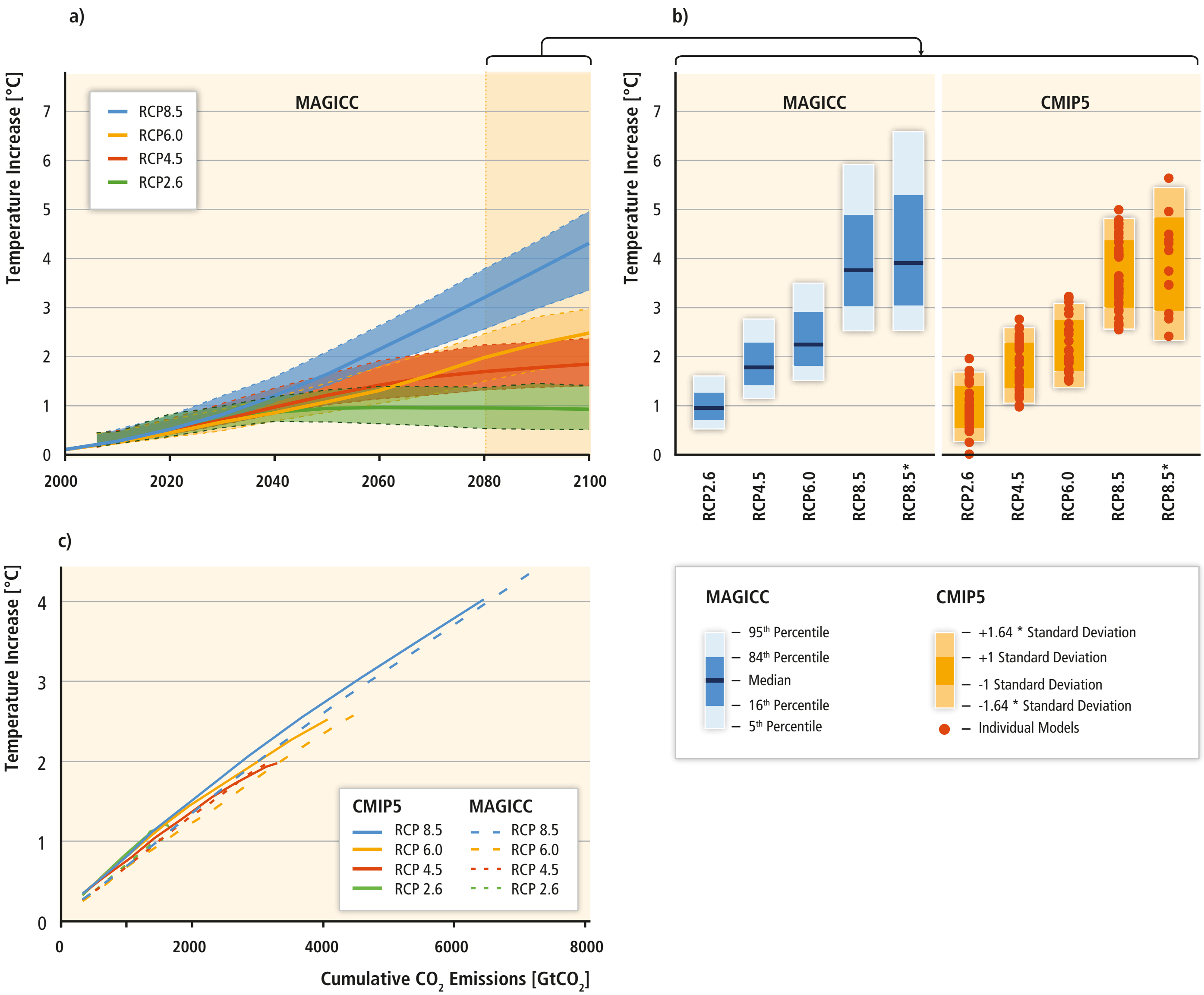


Figure 6.12 | Comparison of CMIP5 results (as presented in Working Group I) and MAGICC output for global temperature increase. Note that temperature increase is presented relative to the 1986–2005 average in this figure (see also Figure 6.13). Panel a) shows concentration-driven runs for the RCP scenarios from MAGICC (lines) and one-standard deviation ranges from CMIP5 models. Panel b) compares 2081–2100 period projections from MAGICC with CMIP5 for scenarios driven by prescribed RCP concentrations (four left-hand bars of both model categories) and the RCP 8.5 run with prescribed emissions (fifth bar; indicated by a star). Panel c) shows temperature increases for the concentration-driven runs of a subset of CMIP5 models against cumulative CO_2 emissions back-calculated by these models from the prescribed CO_2 concentration pathways (full lines) and temperature increase projected by the MAGICC model against cumulative CO_2 emissions (dotted lines) (based on WG I Figure SPM.10). Cumulative emissions are calculated from 2000 onwards. Source: WG I AR5 (Section 12.5.4.2, Figure 12.46, TFE.8 Figure 1) and MAGICC calculations (RCP data (van Vuuren et al., 2011a), method as in Meinshausen et al., 2011c).

2 and Section 6.2.3 for a discussion of evaluating scenarios under uncertainty). The definition of the temperature goals themselves forms a third complication. Temperature goals might be defined in terms of the long-term equilibrium associated with a given concentration, in terms of the temperature in a specific year (e.g., 2100), or based on never exceeding a particular level. Finally, the reference year, often referred to as 'pre-industrial', is ambiguous given both the lack of real measurements and the use of different reference periods. Given all of these complications, a range of emissions pathways can be seen as consistent with a particular temperature goal (see also Figure 6.12, 6.13, and 6.14).

Because of the uncertain character of temperature outcomes, probabilistic temperature information has been created for the scenarios in the AR5 database that have reported information on at least CO_2, CH_4, N_2O and sulphur aerosol emissions. Several papers have introduced methods for probabilistic statements on temperature increase for emission scenarios (Meinshausen, 2006; Knutti et al., 2008; Schaeffer et al., 2008; Zickfeld et al., 2009; Allen et al., 2009; Meinshausen et al., 2009; Ramanathan and Xu, 2010; Rogelj et al., 2011). For this assessment, the method described by Rogelj et al. (2012) and Schaeffer et al. (2014) is used, which employs the MAGICC model based on the probability distribution of input parameters from Meinshausen (2009) (see also Meinshausen et al., 2011c).

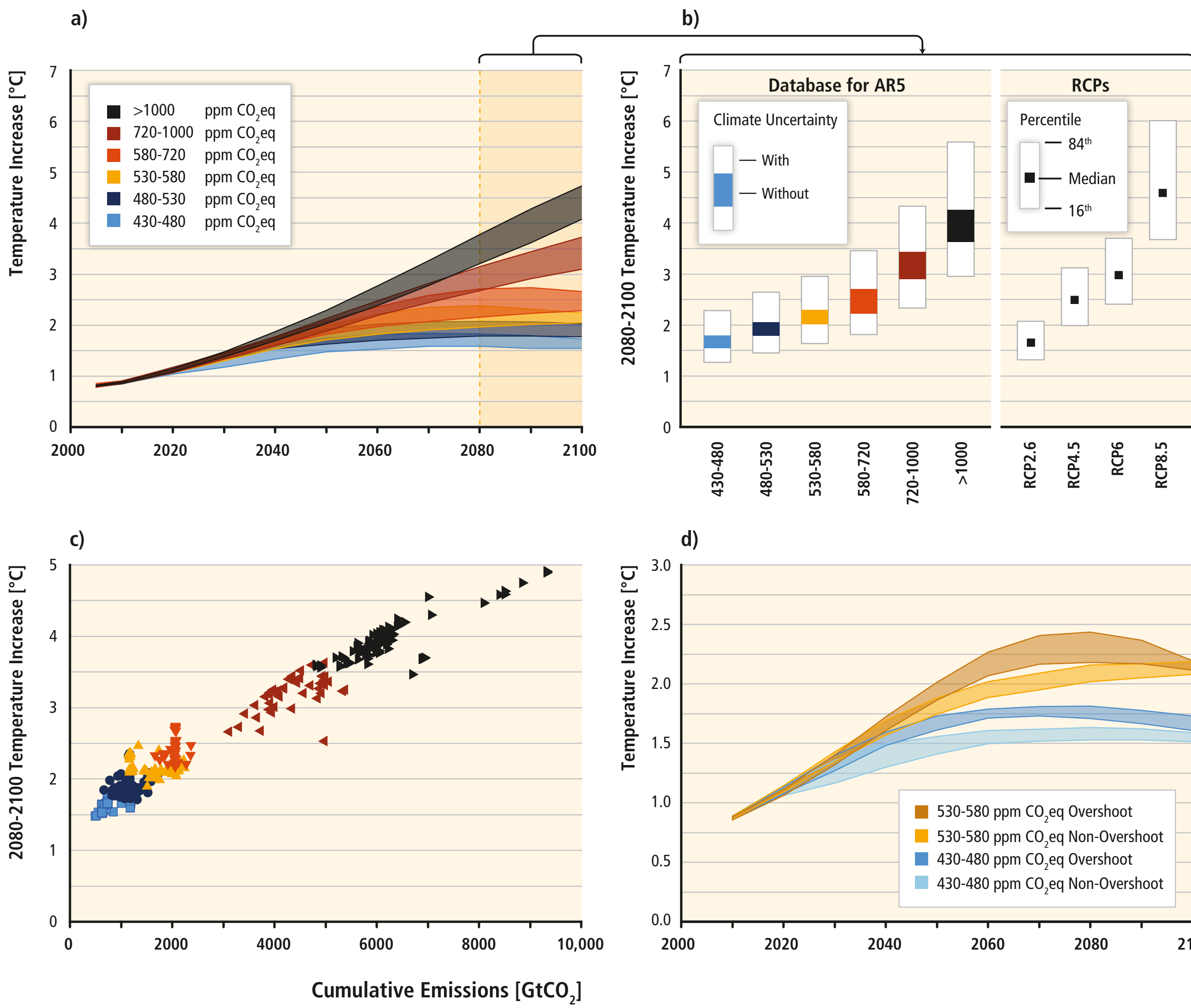


Figure 6.13 | Changes in global temperature for the scenario categories above 1850–1900 reference level as calculated by MAGICC. (Observed temperatures in the 1985–2006 period were about 0.61 deg C above the reference level—see e.g. WG1 Table SPM.2). Panel a) shows temperature increase relative reference as calculated by MAGICC (10th to 90th percentile for median MAGICC outcomes). Panel b) shows 2081–2100 temperature levels for the scenario categories and RCPs for the MAGICC outcomes. The bars for the scenarios used in this assessment include both the 10th to 90th percentile range for median MAGICC outcomes (colored portion of the bars) and the 16th to 84th percentile range of the full distribution of MAGICC outcomes from these scenarios, which also captures the Earth-System uncertainty. The bars for the RCPs are based on the 16th to 84th of MAGICC outcomes based on the RCP emissions scenarios, capturing only the Earth-System uncertainty. Panel c) shows relationship between cumulative CO_2 emissions in the 2011–2100 period and median 2081–2100 temperature levels calculated by MAGICC. Panel d indicates the median temperature development of overshoot (> 0.4 W/m²) and non-overshoot scenarios for the first two scenario categories (25th to 75th percentile of scenario outcomes). Source: WG III AR5 Scenario Database (Annex II.10).

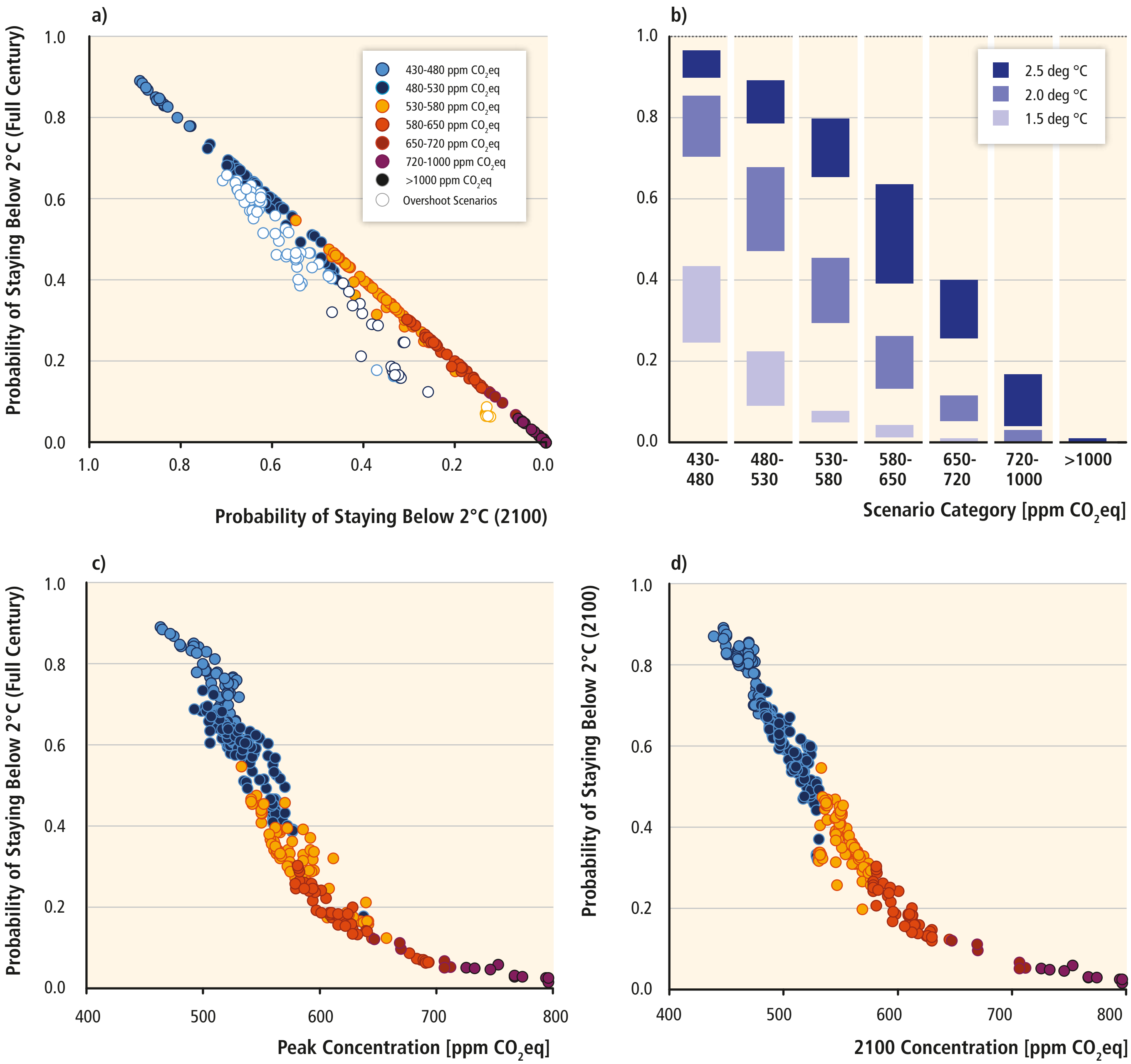


Figure 6.14 | The probability of staying below temperature levels for the different scenario categories as assessed by the MAGICC model (representing the statistics of 600 different climate realizations for each emission scenario). Panel a) probability in 2100 of being below 2 °C versus probability of staying below 2 °C throughout the 21st century. Open dots indicate overshoot scenarios (> 0.4 W/m²). Panel b) probability of staying below 1.5, 2.0, and 2.5 °C (10th to 90th percentile) during 21st century. Panel c) relationship between peak concentration and the probability of exceeding 2 °C during the 21st century. Panel d) relationship between 2100 concentration and the probability of exceeding 2 °C in 2100. Source: WG III AR5 Scenario Database (Annex II.10).

MAGICC was run 600 times for each scenario. Probabilistic temperature statements are based on the resulting distributions (see also the Methods and Metrics Annex; and the underlying papers cited). Because the temperature distribution of these runs is based on a single probability distribution in a single modelling framework, resulting probabilistic temperature statements should be regarded as indicative.

An important consideration in the evaluation of this method is the consistency between the distributions of key parameters used here and the outcome of the WG I research regarding these same parameters. Carbon-cycle parameters in the MAGICC model used in this chapter are based on Earth-System Coupled Model Intercomparison Project (CMIP) 4 model results from AR4, and a probability density function (PDF) for climate sensitivity is assumed that corresponds to the assessment of IPCC AR4 (Meehl et al., 2007; Rogelj et al., 2012, Box 10.2). The MAGICC output based on this approach has been shown to be consistent with the output of the CMIP5 Earth-System models (see also WG I Sections 12.4.1.2 and 12.4.8). The MAGICC model captures the temperature outcomes of the CMIP5 models reasonably well, with median estimates close to the middle of the CMIP5 uncertainty ranges (see panels a and b in Figure 6.12).

For lower-emission scenarios, the MAGICC uncertainty range is more narrow, mainly due to the larger range methodologies representing non-CO_2 forcings in the CMIP5 models, as well as the fact that MAGICC does not reflect all of the structural uncertainty represented by the range of CMIP5 models (see panels a and b in Figure 6.12, and WG I Figure 12.8 and Section 12.4.1.2). Uncertainty ranges are largest for emissions-driven runs (only available for RCP 8.5 from CMIP5 models), since uncertainties in carbon-cycle feedbacks play a larger role (see also WG I Section 12.4.8.1). The relationship between the cumulative CO_2 emissions and the transient temperature increase from MAGICC is well aligned with the CMIP5 model results for the RCP pathways (Figure 6.12 panel c, and WG I Section 12.5.4.2, Figure 12.46, TFE.8 Figure 1). WG I has estimated that a cumulative CO_2 emissions budget of around 1000 $GtCO_2$ from 2011 onward is associated with a likely (> 66 %) chance of maintaining temperature change to less than 2 °C. For the database of scenarios assessed here, the majority of scenarios with a greater than 66 % chance of limiting temperature change to less than 2 °C, based on the MAGICC analysis, are those that reach between 430 and 480 ppm CO_2eq, and these are associated with cumulative emissions over the century of 630–1180 $GtCO_2$ (Table 6.3). The two budgets are not fully comparable, however, since the WG I budget relates to the cumulative emissions at the time of peak warming which are higher than the cumulative emissions until 2100 in overshoot scenarios with net negative emissions by the end of the century. In addition, the WGI AR5 estimate is based on a single scenario for non-CO_2 substances, whereas the database assessed here considers a much wider range of non-CO_2 emissions.

Based on the results of the MAGICC analysis, temperature outcomes are similar across all scenarios in the next few decades, in part due to physical inertia in the climate system (Figure 6.13, panel a). In the second half of the century, however, temperatures diverge. Scenarios leading to 2100 concentrations over 1000 ppm CO_2eq lead to a temperature increase of about 3 to 6 °C (66th percentile of the distribution of temperature outcomes), while scenarios with 2100 concentrations between 430–480 ppm CO_2eq lead to a temperature increase of about 1.3 to 2.2 °C (66th percentile of the distribution of temperature outcomes) (Figure 6.13, panels a and b). Cumulative CO_2 emissions for all scenarios in the database correlate well to the temperature level—see also WG I Section 12.5.4 (Figure 6.13, panel c). However, there is some variation due to differences in emissions of other forcing agents, in particular CH_4 and sulphur, along with the timing of emissions reduction and the associated extent of overshoot. In general, both the 2100 temperatures and the relationship between the cumulative emissions and 2100 temperature change are roughly consistent with the correlation for the RCPs in WG I (Figure 6.13, panel c). Scenarios that overshoot the 2100 concentration goal by more than 0.4 W/m^2 result in higher levels of temperature increase mid-century and prolonged periods of relatively rapid rates of change in comparison to those without overshoot or with less overshoot (Figure 6.13, panel d). By 2100, however, the different scenarios converge.

Defining temperature goals in terms of the chance of exceeding a particular temperature this century accounts for both the 2100 concentration and the pathway to get to this concentration (Figure 6.14). Overshoot scenarios of greater than 0.4 W/m^2 have a higher probability of exceeding 2 °C prior to 2100 than in 2100 (Figure 6.14, panel a). In general, the results suggest that the peak concentration during the 21st century is a fundamental determinant of the probability of remaining below a particular temperature goal (Figure 6.14, panel c). The CO_2eq concentration in 2100, on the other hand, is a proxy for the probability of exceeding end-of-the-century temperature goals (panel d). Based on the MAGICC results, only scenarios leading to 2100 concentrations of 430–480 ppm and a small number of scenarios leading to 2100 concentrations of 480–530 ppm have a probability of greater than 66 % probability of maintaining temperature change below 2 °C throughout the century. Scenarios that reach 2100 concentrations between 530 and 580 ppm CO_2eq while exceeding this range (that is, exceeding 580 ppm CO_2eq) during the course of the century have less than a 33 % probability of limiting transient temperature change to below 2 °C over the course of the century, based on the MAGICC results.

Other temperature levels in addition to 2 °C are relevant for mitigation strategy. Based on the MAGICC results, scenarios leading to concentrations between 430 and 480 ppm CO_2eq have less than a 50 % probability of maintaining temperature change below 1.5 °C throughout the 21st century, and many have less than a 33 % probability of achieving this goal. As noted in Section 6.3.2.1, there are scenarios in the literature that reach levels below 430 ppm CO_2eq by 2100, but these were not submitted to the database used for this assessment. Using the same methods for assessing temperature implications of scenarios as used in this assessment, the associated studies found that these scenarios have a probability (also based on MAGICC) of more than 66 % of remaining below 1.5 °C, after peaking earlier in the century (e.g., Luderer et al., 2013, Rogelj et al., 2013a,b).[1] In contrast, the scenarios submitted to this assessment that lead to CO_2eq concentration below 580 ppm to CO_2eq by 2100 have more than a 50 % probability of limiting temperature change to below 2.5 °C during the 21st century, based on the MAGICC results, and many have more than a 66 % probability. (Section 6.9 discusses how the use of geoengineering techniques can change the relationships between GHG emissions and radiative forcing.)

6.3.3 Treatment of impacts and adaptation in transformation pathways

The importance of considering impacts and adaptation responses when assessing the optimal level of mitigation in a cost-benefit framework has been well studied in highly-aggregated models (see Box 6.1. on cost-benefit analysis). However the role impacts and adaptation in scenarios from large-scale integrated models has seen far less treatment. Mitigation, impacts, and adaptation are interlinked in several important

[1] In these scenarios, the cumulative CO_2 emissions range between 680–800 $GtCO_2$ from 2011 to 2050 and between 90–310 $GtCO_2$ from 2011 to 2100. Global CO_2eq emissions in 2050 are between 70 % and 95 % below 2010 emissions, and they are between 110 % and 120 % below 2010 emissions in 2100.

ways and should, ideally, be considered jointly in the context of achieving concentration goals such as those explored in this chapter. A few studies from large-scale integrated models consider mitigation, impacts, and adaptation simultaneously in their construction of scenarios (see Reilly et al., 2007; Isaac and van Vuuren, 2009; Chum et al., 2011; Nelson et al., 2014; Calvin et al., 2013; Zhou et al., 2013; Dowling, 2013). In the vast majority of cases, however, the scenarios discussed in this chapter do not consider these linkages, and this is considered a major gap in the transformation pathways literature. (For a summary of integrated models that capture impacts and adaptation, see, e.g., Füssel (2010) and Fisher-Vanden et al. (2013). For a comprehensive discussion of climate impacts, adaptation, and vulnerability, see IPCC WG II AR5). Major efforts are now underway to incorporate impacts and adaptation into large-scale integrated models, but these efforts must overcome a range of challenges, including incorporating the sectoral and regional character of impact and adaptation into integrated models, which have higher spatial aggregation, and a lack of data and empirical evidence on impacts and adaptation required for model inputs.

Omitting climate impacts and adaptation responses from scenarios is likely to lead to biased results for three main reasons. First, climate impacts could influence the effectiveness of mitigation options. For instance, electricity production could be affected by changes in cooling water availability (Schaeffer et al., 2012) or air temperature, changes in precipitation will alter hydroelectric power, and climate change could impact biofuel crop productivities (Chum et al., 2011). Unfortunately, the set of modelling studies that explore these issues is limited (Fisher-Vanden et al., 2011), so there is insufficient evidence today to draw broad conclusions about how the omission of impacts and adaptation responses would alter mitigation options and the resulting scenarios reviewed in this chapter. Second, adaptation responses to climate change could themselves alter emissions from human activities, either increasing or decreasing the emissions reductions required to reach GHG-concentration goals. For example, a warmer climate is likely to lead to higher demand for air conditioning (Mansur et al., 2008), which will lead to higher emissions if this increased electricity demand is met by electric power generated with fossil fuels. On the other hand, a warmer climate will lead to reductions in heating demand, which would lower emissions from fuels used in heating. Also, impacts could potentially lead to lower economic growth and thus lower emissions. Further, because electricity is relatively easier to decarbonize than solid, liquid, or gaseous fuels, changing in heating and cooling demands could reduce the economic costs of mitigation (Isaac and van Vuuren, 2009; Zhou et al., 2013). Climate change will also change the ability of the terrestrial biosphere to store carbon. Again, there is a limited number of studies that account for this adaptive response to climate change (Bosello et al., 2010b; Eboli et al., 2010; Anthoff et al., 2011) or optimal mitigation levels when adaptation responses are included (Patt et al., 2009). Finally, mitigation strategies will need to compete with adaptation strategies for scarce investment and R&D resources, assuming these occur contemporaneously. A number of studies account for competition for investment and R&D resources. In a cost benefit framework, several modelling studies

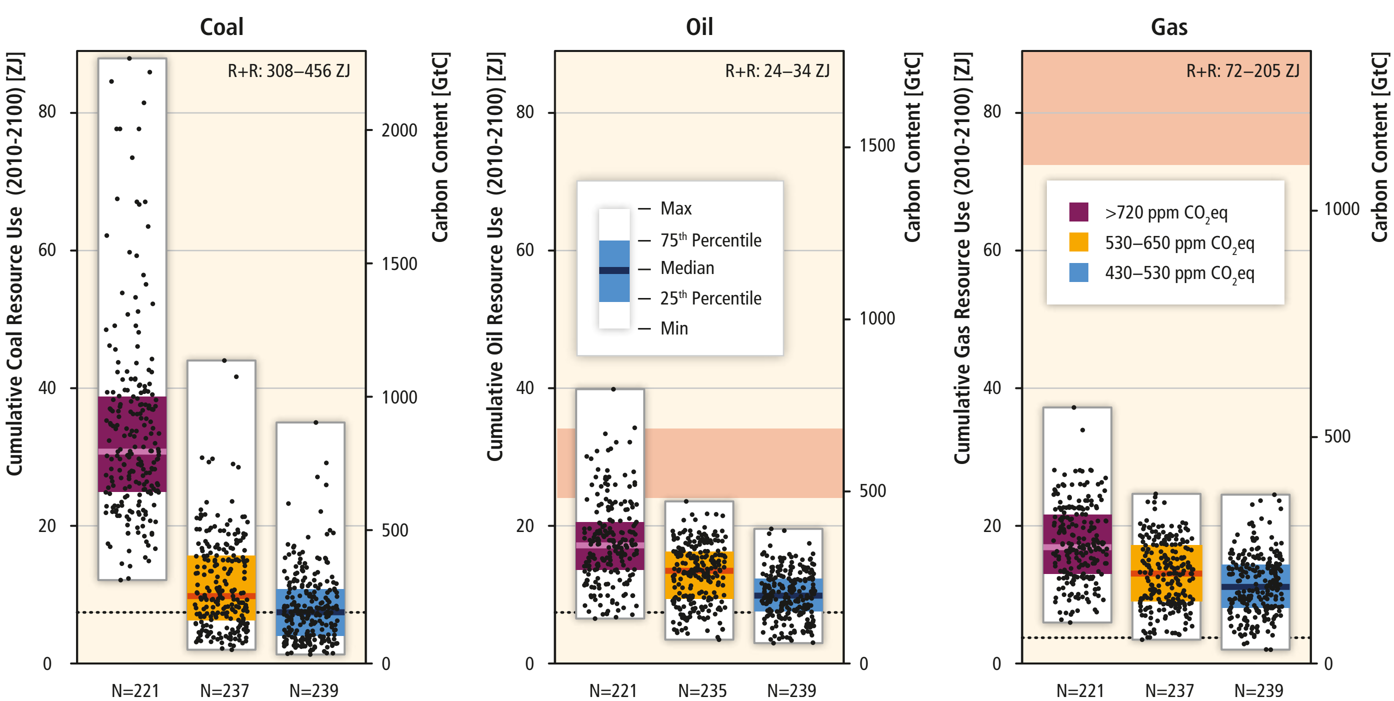


Figure 6.15 | Cumulative global coal, oil, and gas use between 2010 and 2100 in baseline and mitigation scenarios compared to reserves and resources. Estimates of reserves and resources ('R+R') are shown as shaded areas and historical cumulative use until 2010 is shown as dashed black line. Dots correspond to individual scenarios, of which the number in each sample is indicated at the bottom of each panel. Note that the horizontal distribution of dots does not have a meaning, but avoids overlapping dots. Source: WG III AR5 Scenario Database (Annex II.10). Includes only scenarios based on idealized policy implementation. Reserve, resource, and historical cumulative use from Table 7.1 in Section 7.4.1.

(Bosello et al., 2010a, 2010b; de Bruin et al., 2009) adaptation, and mitigation are both decision variables and compete for investment resources. Competition for investment resources is also captured in studies measuring the economic impacts of climate impacts, but rather than competing with mitigation investments, competition is between investment in adaptation and consumption (Bosello et al., 2007) and other capital investments (Darwin and Tol, 2001). Some simulation studies that estimate the economic cost of climate damages add adaptation cost to the cost of climate impacts and do not capture crowding out of other expenditures, such as investment and R&D (Hope, 2006). No existing study, however, examines how this crowding out will affect an economy's ability to invest in mitigation options to reach concentration goals.

6.3.4 Energy sector in transformation pathways

The fundamental transformation required in the energy system to meet long-term concentration goals is a phase-out in the use of freely emitting fossil fuels, the timing of which depends on the concentration goal (Fischedick et al., 2011). Baseline scenarios indicate that scarcity of fossil fuels alone will not be sufficient to limit CO_2eq concentrations to levels such as 450, 550, or 650 ppm by 2100 (Verbruggen and Al Marchohi, 2010; Riahi et al., 2012; Bauer et al., 2014b; Calvin et al., 2014b; McCollum et al., 2014a, see also Section 7.4.1). Mitigation scenarios indicate that meeting long-term goals will most significantly reduce coal use, followed by unconventional oil and gas use, with conventional oil and gas affected the least (Bauer et al., 2014a, 2014b; McCollum et al., 2014a) (Figure 6.15). This will lead to strong re-allocation effects on international energy markets (Section 6.3.6.6).

The reduction in freely emitting fossil fuels necessary for mitigation is not necessarily equal to the reduction in fossil fuels more generally, however, because fossil resources can be used in combination with CCS to serve as a low-carbon energy source (McFarland et al., 2009; Bauer et al., 2014b; McCollum et al., 2014a, see also Sections 7.5.5 and 7.11.2). This means that the total use of fossil fuels can exceed the use of freely emitting fossil fuels.

To accommodate this reduction in freely emitting fossil fuels, transformations of the energy system rely on a combination of three high-level strategies: (1) decarbonization of energy supply, (2) an associated switch to low-carbon energy carriers such as decarbonized electricity, hydrogen, or biofuels in the end-use sectors, and (3) reductions in energy demand. The first two of these can be illustrated in terms of changes in the carbon intensity of energy. The last can be illustrated in terms of energy intensity of GDP, energy per capita, or other indexed measures of energy demand.

The integrated modelling literature suggests that the first of these two (carbon intensity of energy) will make the largest break from past trends in the long run on pathways toward concentration goals (Figure 6.16). The fundamental reason for this is that the ultimate potential for end-use demand reduction is limited; some energy will always be required to provide energy services. Bringing energy system CO_2 emissions down toward zero, as is ultimately required for meeting any concentration goal, requires a switch from carbon-intensive (e.g., direct use of coal, oil, and natural gas) to low-carbon energy carriers (most prominently electricity, but also heat and hydrogen) in the end-use sectors in the long run.

At the same time, integrated modelling studies also sketch out a dynamic in which energy intensity reductions equal or outweigh decar-

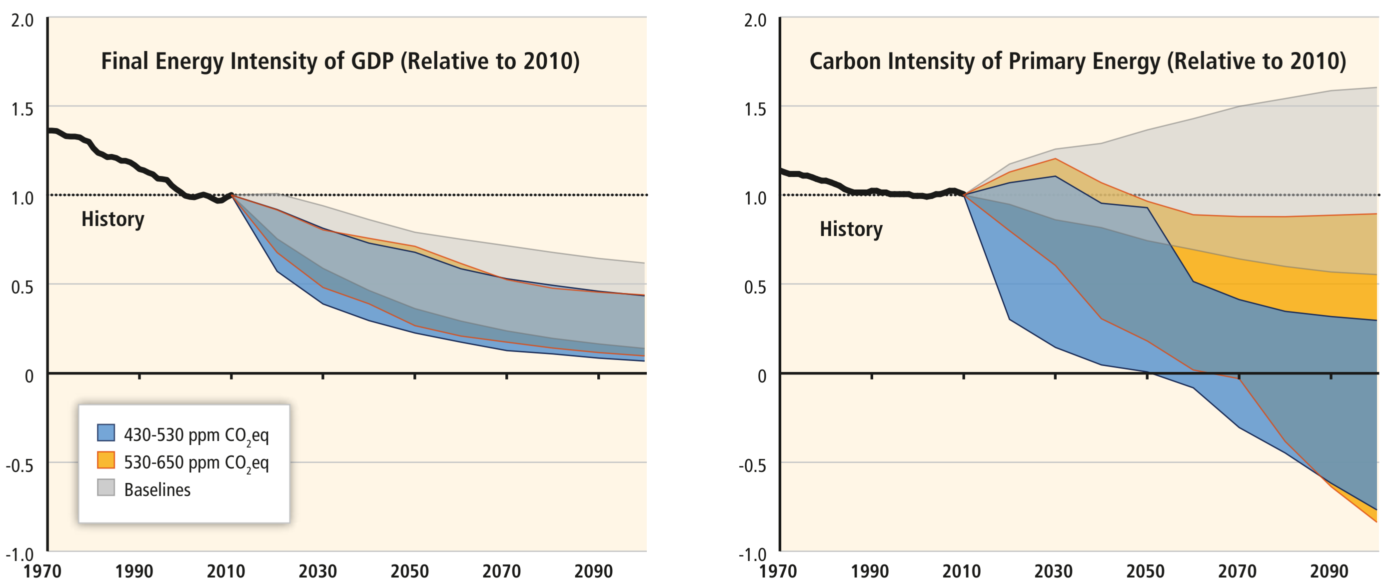


Figure 6.16 | Final energy intensity of GDP (left panel) and carbon intensity of primary energy (right panel) in mitigation and baseline scenarios, normalized to 1 in 2010 showing the full scenario range. GDP is aggregated using base-year market exchange rates. Sources: WGIII AR5 Scenario Database (Annex II.10). Historic data: JRC/PBL (2013), IEA (2012a), see Annex II.9; Heston et al. (2012); World Bank (2013); BP (2013).

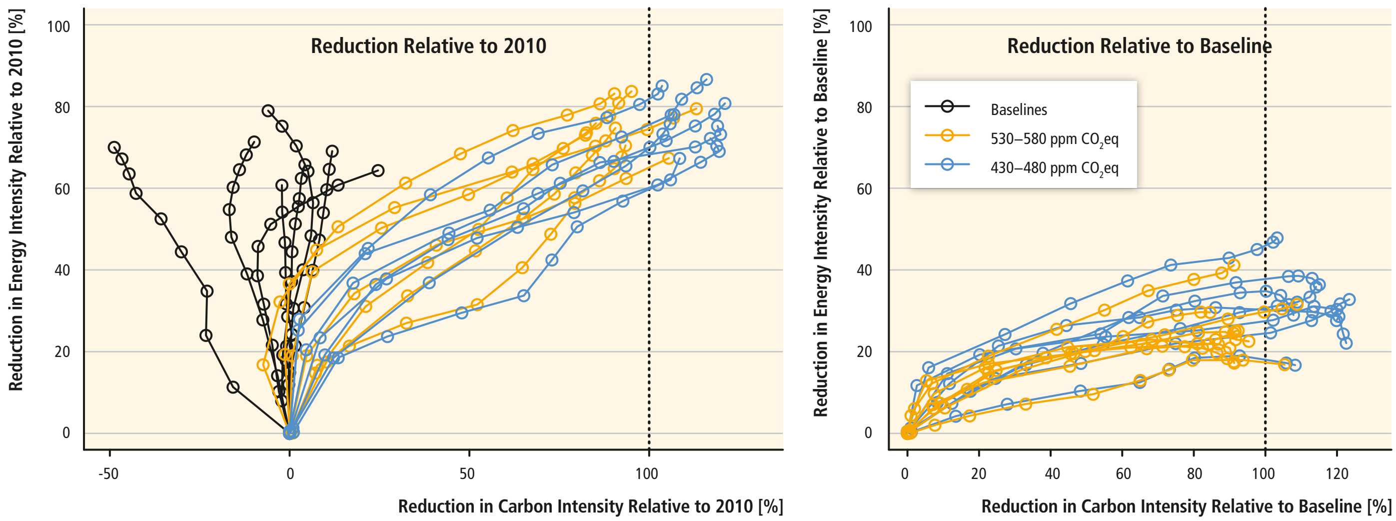


Figure 6.17 | Development of carbon-intensity vs. final energy-intensity reduction relative to 2010 in selected baseline and mitigation scenarios reaching 530–580 ppm and 430–480 ppm CO_2eq concentrations in 2100 (left panel) and relative to baseline in the same scenarios (right panel). Consecutive dots represent 10-year time steps starting in 2010 at the origin and going out to 2100. Source: WG III AR5 Scenario Database (Annex II.10). Sample includes only 2100 scenarios with idealized policy implementation for which a baseline, a 530–580 ppm and a 430–480 ppm CO_2eq scenario are available from the same set.

bonization of energy supply in the near term when the supply system is still heavily reliant on largely carbon-intensive fossil fuels, and then the trend is reversed over time (Figure 6.17, see Fisher et al. (2007, Figure 3.21)). At the most general level, this results directly from assumptions about the flexibility to achieve end-use demand reductions relative to decarbonization of supply in integrated models (Kriegler et al., 2014b), about which there is a great deal of uncertainty (see Section 6.8). More specifically, one reason for this dynamic is that fuel-switching takes time to take root as a strategy because there is little incentive to switch, say, to electricity early on when electricity may still be very carbon-intensive. As electricity generation decreases in carbon intensity through the use of low-carbon energy sources (see Section 7.11.3), there is an increasing incentive to increase its use relative to sources associated with higher emissions, such as natural gas. A second factor is that there may be low-cost demand reduction options available in the near term, although there is limited consensus on the costs of reducing energy demand. Indeed, much of the energy reduction takes place in baseline scenarios. Of importance, these trends can be very

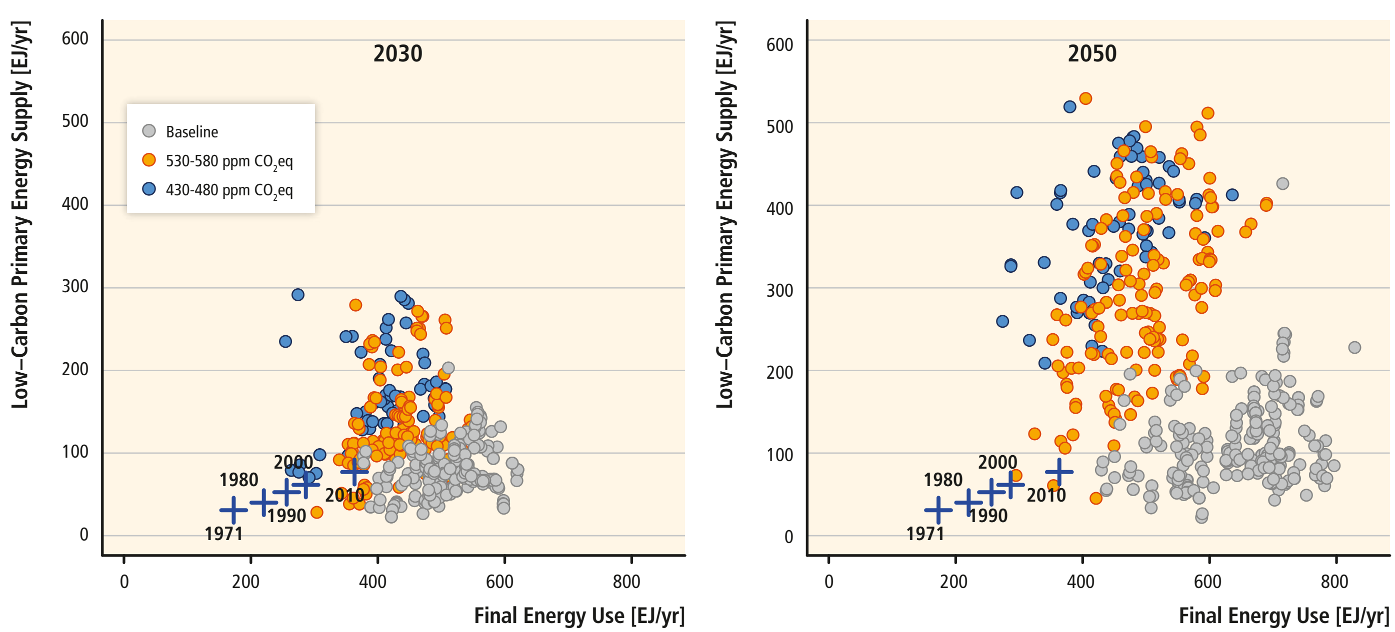


Figure 6.18 | Global low-carbon primary energy supply (direct equivalent, see Annex II.4) vs. total final energy use by 2030 and 2050 for idealized implementation scenarios. Low-carbon primary energy includes fossil energy with CCS, nuclear energy, bioenergy, and non-biomass renewable energy. Source: WG III AR5 Scenario Database (Annex II.10). Sample includes baseline and idealized policy implementation scenarios. Historical data from IEA (2012a).

regional in character. For example, the value of fuel-switching will be higher in countries that already have low-carbon electricity portfolios.

The decarbonization of the energy supply will require a significant scaleup of low-carbon energy supplies, which may impose significant challenges (see Section 7.11.2). The deployment levels of low-carbon energy technologies are substantially higher than today in the vast majority of scenarios, even under baseline conditions, and particularly for the most stringent concentration categories. Scenarios based on an idealized implementation approach in which mitigation begins immediately across the world and with a full portfolio of supply options indicate a scaleup of anywhere from a modest increase to upwards of three times today's low-carbon energy by 2030 to bring concentrations to about 450 ppm CO_2eq by 2100. A scaleup of anywhere from roughly a tripling to over seven times today's levels in 2050 is consistent with this same goal Figure 6.18, Section 7.11.4). The degree of scaleup depends critically on the degree of overshoot, which allows emissions reductions to be pushed into the future.

The degree of low-carbon energy scaleup also depends crucially on the degree that final energy use is altered along a transformation pathway. All other things being equal, higher low-carbon energy technology deployment tends to go along with higher final energy use and vice versa (Figure 6.18, Figure 7.11). Final energy demand reductions will occur both in response to higher energy prices brought about by mitigation as well as by approaches to mitigation focused explicitly on reducing energy demand. Hence, the relative importance of energy supply-and-demand technologies varies across scenarios (Riahi et al., 2012).

A major advance in the literature since AR4 is the assessment of scenarios with limits on available technologies or variations in the cost and performance of key technologies. These scenarios are intended as a rough proxy for economic and various non-economic obstacles faced by technologies. Many low-carbon supply technologies, such as nuclear power, CO_2 storage, hydro, or wind power, face public acceptance issues and other barriers that may limit or slow down their deployment (see Section 7.9.4). In general, scenarios with limits on available technologies or variations in their cost and performance demonstrate the simple fact that reductions in the availability and/or performance or an increase in costs of one technology will necessarily result in increases in the use of other options. The more telling result of these scenarios is that limits on the technology portfolio available for mitigation can substantially increase the costs of meeting long-term goals. Indeed, many models cannot produce scenarios leading to 450 ppm CO_2eq when particularly important technologies are removed from the portfolio. This topic is discussed in more detail in Section 6.3.6.3.

Delays in climate change mitigation both globally and at regional levels simply alter the timing of the deployment of low-carbon energy sources and demand reductions. As noted in Sections 6.3.2 and 6.4, less mitigation over the coming decades will require greater emissions reductions in the decades that follow to meet a particular long-term climate goal. The nature of technology transitions follows the emissions dynamic directly. Delays in mitigation in the near term will lower the rate of energy system transformation over the coming decades but will call for a more rapid transformation in the decades that follow. Delays lead to higher utilization of fossil fuels, and coal in particular, in the short run, which can be prolonged after the adoption of stringent mitigation action due to carbon lock-ins. To compensate for the prolonged use of fossil fuels over the next decades, fossil fuel use—particularly oil and gas—would need to be reduced much more strongly in the long run. One study found that this leads to a reduction in overall fossil energy use over the century compared to a scenario of immediate mitigation (Bauer et al., 2014a). Another study (Riahi et al., 2014) found that if 2030 emissions are kept to below 50 GtCO_2eq, then low-carbon energy deployment is tripled between 2030 and 2050 in most scenarios reaching concentrations of about 450 ppm CO_2eq by 2100. In contrast, if emissions in 2030 are greater than 55 GtCO_2eq in 2030, then low-carbon energy deployment increases by five-fold in most scenarios meeting this same long-term concentration goal (see Section 7.11.4, specifically Figure 7.15).

Beyond these high-level characteristics of the energy system transformation lie a range of more detailed characteristics and tradeoffs. Important issues include the options for producing low-carbon energy and the changes in fuels used in end uses, and the increase in electricity use in particular, both with and without mitigation. These issues are covered in detail in Section 6.8 and Chapter 7 through 12.

6.3.5 Land and bioenergy in transformation pathways

Scenarios suggest a substantial cost-effective, and possibly essential, role for land in transformation pathways (Section 6.3.2.4 and Section 11.9), with baseline land-use emissions and sequestration an important uncertainty (Section 6.3.1.4). Changes in land use and management will result from a confluence of factors, only some of which are due to mitigation. The key forces associated with mitigation are (1) the demand for bioenergy, (2) the demand to store carbon in land by reducing deforestation, encouraging afforestation, and altering soil management practices, and (3) reductions in non-CO_2 GHG emissions by changing management practices. Other forces include demand for food and other products, such as forest products, land for growing urban environments, and protecting lands for environmental, aesthetic, and economic purposes. Currently, only a subset of models explicitly model LUC in scenarios. The development of fully integrated land use models is an important area of model development.

Scenarios from integrated models suggest the possibility of very different landscapes relative to today, even in the absence of mitigation. Projected global baseline changes in land cover by 2050 typically exhibit increases in non-energy cropland and decreases in 'other' land, such as abandoned land, other arable land, and non-arable land (Figure 6.19). On the other hand, projected baseline pasture and forest land exhibit both increases and decreases. The projected increases in non-energy cropland and decreases in forest area through 2050 are typically projected to outpace historical changes from the previous 40 years (+165 and −105 million hectares of crop and forest area changes, respectively, from 1961–2005 (Food and Agriculture Organization of the United Nations (FAO), 2012). Energy cropland is typically projected to increase as well, but there is less agreement across scenarios. Overall, baseline projections portray large differences across models in the amount and composition of the land converted by agricultural land expansion. These baseline differences are important because they represent differences in the opportunity costs of land use and management changes for mitigation. (See Chapter 11.9 for regional baseline, and mitigation, land cover projections for a few models and scenarios.)

Mitigation generally induces greater land cover conversion than in baseline scenarios, but for a given level of mitigation, there is large variation in the projections (Figure 6.19). Projections also suggest additional land conversion with tighter concentration goals, but declining additional conversion with increased mitigation stringency. This is consistent with the declining relative role of land-related mitigation with the stringency of the mitigation goal (Rose et al., 2012). However, additional land conversion with more stringent goals could be substantial if there are only bioenergy incentives (see below).

A common, but not universal, characteristic of mitigation scenarios is an expansion of energy cropland to support the production of modern bioenergy. There is also a clear tradeoff in the scenarios between energy cropland cover and other cover types. Most scenarios project reduced non-energy cropland expansion, relative to baseline expansion, with some projections losing cropland relative to today. On the other hand, there are projected pasture changes of every kind. Forest changes depend on the incentives and constraints considered in each scenario. Some of the variations in projected land cover change are attributable to specific assumptions, such as fixed pasture acreage, prioritized food provision, land availability constraints for energy crops, and the inclusion or exclusion of afforestation options (e.g. Popp et al., 2014). Others are more subtle outcomes of combinations of modelling assumption and structure, such as demands for food and energy, land productivity and heterogeneity, yield potential, land-production options, and land-conversion costs.

Which mitigation activities are available or incentivized has important implications for land conversion (Figure 6.19). Bioenergy incentives alone can produce energy cropland expansion, with increased forest and other land conversion (Wise et al., 2009; Reilly et al., 2012). In general, forest land contraction results when increased demand for energy crops is not balanced by policies that incentivize or protect the storage

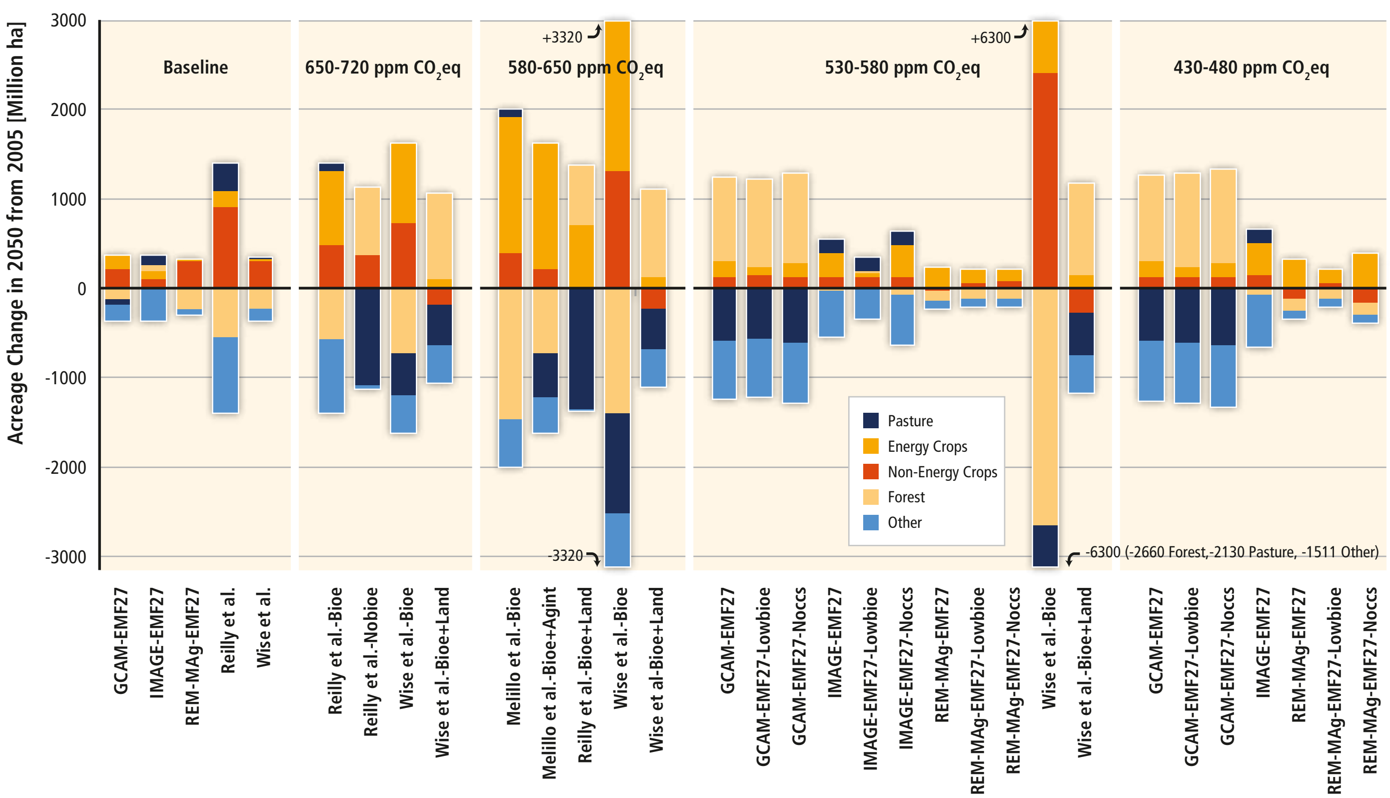


Figure 6.19 | Global land cover change by 2050 from 2005 for a sample of baseline and mitigation scenarios with different technology assumptions. 'REM-MAg' = REMIND-MAgPIE. Sources: EMF27 Study (Kriegler et al., 2014a), Reilly et al. (2012), Melillo et al. (2009), Wise et al. (2009). Notes: default (see Section 6.3.1) fossil fuel, industry, and land mitigation technology incentives assumed except as indicated by the following—'bioe' = only land-based mitigation incentive is for modern bioenergy, 'nobioe' = land incentives but not for modern bioenergy, 'bioe+land' = modern bioenergy and land carbon stocks incentives, 'bioe+agint' = modern bioenergy incentive and agricultural intensification response allowed, 'lowbio' = global modern bioenergy constrained to 100 EJ/year, 'noccs' = CCS unavailable for fossil or bioenergy use. Other land cover includes abandoned land, other arable land, and non-arable land.

of carbon in terrestrial systems. However, the degree of this forest conversion will depend on a range of factors, including the potential for agricultural intensification and underlying modelling approaches. For example, Melillo et al. (2009) find twice as much forest land conversion by 2050 when they ignore agricultural intensification responses. Forest land expansion is projected when forests are protected, there are constraints on bioenergy deployment levels, or there are combined incentives for bioenergy and terrestrial carbon stocks (e.g., Wise et al., 2009; Reilly et al., 2012, and GCAM-EMF27 in Figure 6.19). Differences in forest land expansion result largely from differences in approaches to incorporating land carbon in the mitigation regime. For example, in Figure 6.19, GCAM-EMF27 (all variants), Wise et al. (2009) (low bioe+land) and Reilly et al. (2012)(low bioe and bioe+land) include an explicit price incentive to store carbon in land, which serves to encourage afforestation and reduce deforestation of existing forests, and discourage energy cropland expansion. In contrast, other scenarios consider only avoided deforestation (REMIND-MAgPIE-EMF27), or land conversion constraints (IMAGE-EMF27). Both protect existing forests, but neither encourages afforestation. In other studies, Melillo et al. (2009) protect existing natural forests based on profitability and Popp et al. (2011a) (not shown) impose conservation policies that protect forest regardless of cost. The explicit pricing of land carbon incentives can lead to large land use carbon sinks in scenarios, and an afforestation incentive or constraint on bioenergy use can result in less land conversion from bioenergy, but not necessarily less land conversion as afforestation may increase.

An important issue with respect to bioenergy, and therefore to land transformation, is the availability and use of BECCS. As discussed in Section 6.3.2, BECCS could be valuable for reaching lower-concentration levels, in part by facilitating concentration overshoot. The availability of CCS could therefore also have land-use implications. Constraints on the use of CCS would prohibit BECCS deployment. However, CCS (for BECCS as well as fossil energy with CCS) may not increase land conversion through 2050 relative to scenarios without BECCS. Instead, the presence of BECCS could decrease near-term energy crop expansion as some models project delayed mitigation with BECCS (Rose et al., 2014a, 6.3.2.2). In addition to biomass feedstock requirements, BECCS land considerations include bioenergy CCS facility land, as well as optimal siting relative to feedstock, geologic storage, and infrastructure.

As noted above, land transformation is tightly linked to the role of bioenergy in mitigation. To understand bioenergy's role in transformation pathways, it is important to understand bioenergy's role within the energy system. The review by Chum et al. (2011) estimated technical potential for bioenergy of 300 and 500 EJ/year in 2020 and 2050, respectively, and deployment of 100 to 300 EJ of biomass for energy globally in 2050, while Rose et al. (2012) found bioenergy contributing up to 15 % of cumulative primary energy over the century under climate policies. Rose et al. (2014a) analyze more recent results from 15 models (Figure 6.20). They find that modelled bioenergy structures vary substantially across models, with differences in feedstock assumptions, sustainability constraints, and conversion technologies. Nonetheless, the scenarios project increasing deployment of, and dependence on, bioenergy with tighter climate change goals, both in a given year as well as earlier in time. Shares of total primary energy increase under climate policies due to both increased deployment of bioenergy and

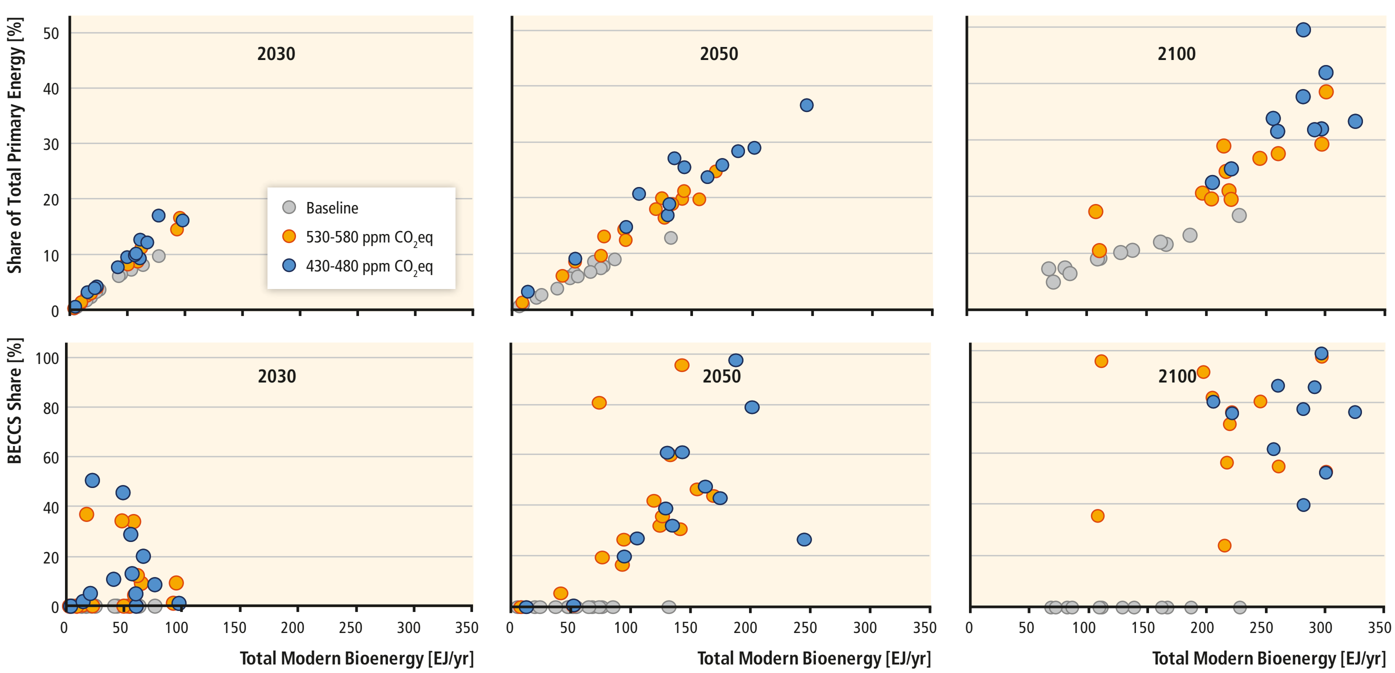


Figure 6.20 | Annual global modern biomass primary energy supply and bioenergy share of total primary energy supply (top panels) and BECCS share of modern bioenergy (bottom panels) in baseline, 550 ppm and 450 ppm CO_2eq scenarios in 2030, 2050, and 2100. Source: Rose et al. (2014a). Notes: All scenarios shown assume idealized implementation. Results for 15 models shown (3 models project to only 2050). Also, some models do not include BECCS technologies and some no more than biopower options.

shrinking energy systems. Bioenergy's share of total regional electricity and liquid fuels is projected to be up to 35 % and 75 %, respectively, by 2050. However, there is no single vision about where biomass is cost-effectively deployed within the energy system (electricity, liquid fuels, hydrogen, and/or heat), due in large part to uncertainties about relative technology options and costs over time. (See Chapter 7 for more detail on bioenergy's role in energy supply.) As noted above, the availability of CCS, and therefore BECCS, has important implications for bioenergy deployment. In scenarios that do include BECCS technologies, BECCS is deployed in greater quantities and earlier in time the more stringent the goal, potentially representing 100 % of bioenergy in 2050 (Figure 6.20).

Models universally project that the majority of biomass supply for bioenergy and bioenergy consumption will occur in developing and transitional economies. For instance, one study (Rose et al., 2014a) found that 50–90 % of global bioenergy primary energy is projected to come from non-OECD countries in 2050, with the share increasing beyond 2050. Developing and transitional regions are also projected to be the home of the majority of agricultural and forestry mitigation.

Finally, a number of integrated models have explicitly modelled land use with full emissions accounting, including indirect land cover change and agricultural intensification. These models have suggested that it could be cost-effective to tradeoff lower land carbon stocks from land cover change and increase N_2O emissions from agricultural intensification for the long-run climate change management benefits of bioenergy (Popp et al., 2014; Rose et al., 2014a).

Overall, the integrated modelling literature suggests opportunities for large-scale global deployment of bioenergy and terrestrial carbon gains. However, the transformations associated with mitigation will be challenging due to the regional scale of deployments and implementation issues, including institution and program design, land use and regional policy coordination, emissions leakage, biophysical and economic uncertainties, and potential non-climate social implications. Among other things, bioenergy deployment is complicated by a variety of social concerns, such as land conversion and food security (See Section 6.6 and the Chapter 11 Bioenergy Annex). Coordination between land-mitigation policies, regions, and activities over time will affect forestry-, agricultural-, and bioenergy-mitigation costs and net GHG mitigation effectiveness. When land options and bioenergy are included in mitigation scenarios, it is typically under the assumption of a highly idealized implementation, with immediate, global, and comprehensive availability of land-related mitigation options. In these cases, models are assuming a global terrestrial carbon-stock incentive or global forest-protection policy, global incentives for bioenergy feedstocks, and global agriculture-mitigation policies. They also assume no uncertainty, risk, or transactions costs. For a discussion of these issues, see Lubowski and Rose (2013). The literature has begun exploring more realistic policy contexts and found that there is likely less available mitigation potential in the near term than previously estimated, and possibly unavoidable emissions leakage associated with getting programs in place, as well as with voluntary mitigation supply mechanisms (Section 11.9, Section 6.8). Additional exploration into the need for and viability of large-scale land-based mitigation is an important area for future research.

6.3.6 The aggregate economic implications of transformation pathways

6.3.6.1 Overview of the aggregate economic implications of mitigation

Mitigation will require a range of changes, including behavioural changes and the use of alternative technologies. These changes will affect economic output and the consumption of goods and services. The primary source of information on these costs over multi-decade or century-long time horizons are integrated models such as those reviewed in this chapter.

Mitigation will affect economic conditions through several avenues, only some of which are included in estimates from integrated models. To a first-order, mitigation involves reductions in the consumption of energy services, and perhaps agricultural products, and the use of more expensive technologies. This first-order effect is the predominant feature and focus of the integrated modelling estimates discussed in this chapter and will lead to aggregate economic losses. However, mitigation policies may interact with pre-existing distortions in labour, capital, energy, and land markets, and failures in markets for technology adoption and innovation, among other things. These interactions might increase or decrease economic impacts (Sections 3.6.3 and 6.3.6.5).

Estimates of the potential aggregate economic effects from mitigation are generally expressed as deviations from a counter-factual baseline scenario without mitigation policies; that is, the difference in economic conditions relative to what would have happened without mitigation. They can be expressed in terms of changes in these economic conditions at a particular point in time (for example, reductions in total consumption or GDP at a given point in time) or in terms of reductions in the growth rates leading to these economic conditions (for example, reductions in the rate of consumption or GDP growth). The estimates, and those discussed in this section, generally do not include the benefits from reducing climate change, nor do they consider the interactions between mitigation, adaptation, and climate impacts (Section 6.3.3). In addition, the estimates do not take into account important co-benefits and adverse side-effects from mitigation, such as impacts on land use and health benefits from reduced air pollution (Sections 11.13.6 and 6.6).

A wide range of methodological issues attends the estimation of aggregate economic costs in integrated models, one of which is the metric itself. (For more discussion on these issues in estimating aggregate economic costs, see Annex II.3.2 on mitigation costs metrics and Chapter 3.) A change in welfare due to changes in household consumption is commonly measured in terms of equivalent and compensating variation, but other, more indirect cost measures such as GDP losses, consumption losses, and area under the marginal abatement cost function are more widely used (Paltsev and Capros, 2013). For consistency, results in this section are presented preferentially in terms of cost measures commonly reported by the models: consumption losses and GDP losses for general-equilibrium models, and area under the marginal abatement cost function or reduction of consumer and producer surplus (in the following summarized with the term abatement cost) for partial-equilibrium models. These cost metrics differ in terms of whether or not general equilibrium effects in the full economy have been taken into account and whether or not the direct impact on households or the intermediate impact on economic output is measured. They are therefore treated separately in this chapter.

Emissions prices (carbon prices) are also assessed in this chapter. However, they are not a proxy for aggregate economic costs for two primary reasons. First, emissions prices measure marginal cost, that is, the cost of an additional unit of emissions reduction. In contrast, total economic costs represent the costs of all mitigation that has taken place. Second, emissions prices can interact with other policies and measures, such as regulatory policies or subsidies directed at low-carbon technologies, and will therefore indicate a lower marginal cost than is actually warranted if mitigation is achieved partly by these other measures.

Different methods can be used to sum costs over time. For this purpose, in the absence of specific information from individual models about the discount rate used in studies, the estimates of net present value (NPV) costs in this chapter are aggregated ex-post using a discount rate of 5 %. This is roughly representative of the average interest rate that underlies the discounting approach in most models (Kriegler et al., 2014a). Other rates could have been used to conduct this ex-post aggregation. Since mitigation costs tend to rise over time, lower (higher) rates would lead to higher (lower) aggregate costs than what are provided here. However, it is important to note that constructing NPV metrics based on other rates is not the same as actually evaluating scenarios under alternative discounting assumptions and will not accurately reflect aggregate costs under such assumptions.

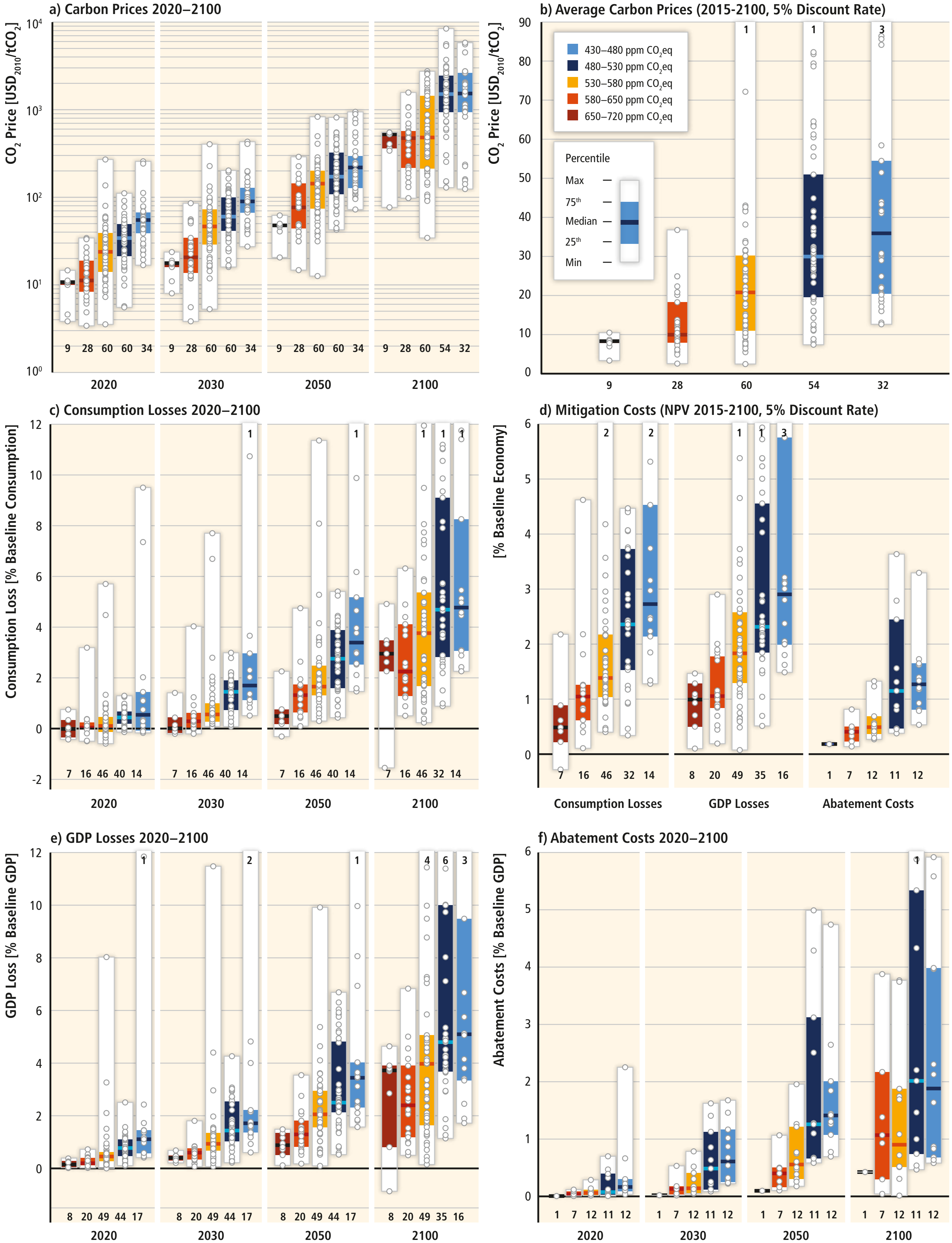
Estimates of aggregate economic effects from integrated models vary substantially. This arises because of differences in assumptions about driving forces such as population and economic growth and the policy environment in the baseline, as well as differences in the structures and scopes of the models (Section 6.2). In addition, aggregate economic costs are influenced by the future cost, performance, and availability of mitigation technologies (Section 6.3.6.3), the nature of international participation in mitigation (Section 6.3.6.4), and the policy instruments used to reduce emissions and the interaction between these instruments and pre-existing distortions and market failures (Section 6.3.6.5).

6.3.6.2 Global aggregate costs of mitigation in idealized implementation scenarios

A valuable benchmark for exploring aggregate economic mitigation costs is estimates based on the assumption of a stylized implementation approach in which a ubiquitous price on carbon and other GHGs is applied across the globe in every sector of every country and rises over time in a way that minimizes the discounted sum of costs over time. These 'idealized implementation' scenarios are included in most studies as a benchmark against which to compare results based on less-idealized circumstances. One reason that these idealized scenarios have been used as a benchmark is that the implementation approach provides the lowest costs under idealized implementation conditions of efficient global markets in which there are no pre-existing distortions or interactions with other, non-climate market failures. For this reason, they are often referred to as 'cost-effective' scenarios. However, the presence of pre-existing market distortions, non-climate market failures, or complementary policies means that the cost of the idealized approach could be lower or higher than in an idealized implementation environment, and that the idealized approach may not be the least-cost strategy (see Section 6.3.6.5). Most of the idealized implementation scenarios assessed here consider these additional factors only to a limited degree or not at all, and the extent to which a non-idealized implementation environment is accounted for varies between them.

A robust result across studies is that aggregate global costs of mitigation tend to increase over time and with stringency of the concentration goal (Figure 6.21). According to the idealized implementation scenarios collected in the WG III AR5 Scenario Database (Annex II.10), the central 70 % (10 out of 14) of global consumption loss estimates for reaching levels of 430–480 ppm CO_2eq by 2100 range between 1 % to 4 % in 2030, 2 % to 6 % in 2050, and 3 % to 11 % in 2100 relative to consumption in the baseline (Figure 6.21, panel c). These consumption losses correspond to an annual average reduction of consumption growth by 0.06 to 0.20 percentage points from 2010 to 2030 (median of 0.09), 0.06 to 0.17 percentage points through 2050 (median of 0.09), and 0.04 to 0.14 percentage points over the century (median of 0.06). To put these losses in context, studies assume annual average consumption growth rates without mitigation between 1.9 % and 3.8 % per year until 2050 and between 1.6 % and 3.0 % per year over the century. These growth rates correspond to increases in total consumption by roughly a factor of 2 to 4.5 by 2050, and from roughly four-fold to over ten-fold over the century (values are based on global projections in market exchange rates).

An important caveat to these results is that they do not account for a potential model bias due to the fact that higher-cost models may have not been able to produce low-concentration scenarios and have therefore not reported results for these scenarios (see discussion of model failures in Section 6.2, and Tavoni and Tol, 2010). They also do not capture uncertainty in model parameter assumptions (Webster et al., 2012). Since scenario samples for different concentration levels do not come from precisely the same models, it is informative to look at the cost changes between different concentration levels as projected by


a) Carbon Prices 2020–2100
CO_2 Price [USD_{2010}/tCO_2]
10^0
10^1
10^2
10^3
10^4
9 28 60 60 34
9 28 60 60 34
9 28 60 60 34
9 28 60 54 32
2020
2030
2050
2100
b) Average Carbon Prices (2015-2100, 5% Discount Rate)
CO_2 Price [USD_{2010}/tCO_2]
430–480 ppm CO_2eq
480–530 ppm CO_2eq
530–580 ppm CO_2eq
580–650 ppm CO_2eq
650–720 ppm CO_2eq
Percentile
Max
75th
Median
25th
Min
9 28 60 54 32
c) Consumption Losses 2020–2100
Consumption Loss [% Baseline Consumption]
7 16 46 40 14
7 16 46 40 14
7 16 46 40 14
7 16 46 32 14
2020
2030
2050
2100
d) Mitigation Costs (NPV 2015-2100, 5% Discount Rate)
[% Baseline Economy]
7 16 46 32 14
8 20 49 35 16
1 7 12 11 12
Consumption Losses
GDP Losses
Abatement Costs
e) GDP Losses 2020–2100
GDP Loss [% Baseline GDP]
8 20 49 44 17
8 20 49 44 17
8 20 49 44 17
8 20 49 35 16
2020
2030
2050
2100
f) Abatement Costs 2020–2100
Abatement Costs [% Baseline GDP]
1 7 12 11 12
1 7 12 11 12
1 7 12 11 12
1 7 12 11 12
2020
2030
2050
2100

⇒

Figure 6.21 | Global mitigation costs of idealized implementation scenarios. Panels show the development of (a) carbon prices, (c) consumption losses, (e) GDP losses and (f) abatement costs over time, and (b) the average carbon price (2015–2100), and (d) the NPV mitigation costs (2015–2100) discounted at a 5 % discount rate. Costs are expressed as a fraction of economic output—or in the case of consumption losses—consumption in the baseline. The number of scenarios included in the boxplots is indicated at the bottom of the panels, 2030 numbers also apply for 2020 and 2050. The number of scenarios outside the figure range is noted at the top. One model shows NPV consumption losses of 13 %/9.5 %, and GDP losses of 15 %/11 % for 430–480/530–580 ppm CO_2eq (see text). Source: WG III AR5 Scenario Database (Annex II.10).The scenario selection includes all idealized implementation scenarios that reported costs or carbon prices to 2050 or 2100 (only the latter are included in aggregate cost and price plots) after removal of similar scenarios (in terms of reaching similar goals with similar overshoots and assumptions about baseline emissions) from the same model.

individual models within a given study (Figure 6.22). This can partly remove model bias, although the bias from a lack of models that could not produce low-concentration scenarios remains. The large majority of studies in the scenario database for AR5 report a factor 1.5 to 3 higher global consumption and GDP losses, and 2 to 4 times higher abatement costs, for scenarios reaching 430–530 ppm CO_2eq by 2100 compared to the 530–650 ppm CO_2eq range.

Aggregate economic costs vary substantially, even in idealized scenarios. The variation of cost estimates for individual CO_2eq concentration ranges can be attributed, among other things, to differences in assumptions about driving forces such as population and GDP and differences in model structure and scope (see Section 6.2 for a discussion of model differences). Diagnostic studies have indicated that the assumed availability and flexibility of low-carbon technologies to substitute fossil energy is a key factor influencing the level of carbon prices for a given level of emissions reductions (Kriegler et al., 2014a). The extent to which carbon prices translate into mitigation costs through higher energy prices is another factor that differs between models. Both the variation of carbon prices and the variation of the economic impact of higher prices are major determinants of the observed range of aggregate economic costs for a given amount of emissions reductions. Assumptions about the implementation environment can be another important driver of costs. For example, the highest consumption and GDP losses in the scenario sample are from a model with an emphasis on market imperfections, infrastructure lock-ins, and myopia (Waisman et al., 2012).

It is possible to control for several key sources of variation by relating mitigation costs to cumulative emissions reductions from baseline emissions (Figure 6.23). As expected, carbon prices and mitigation costs increase with the amount of mitigation. Since different models have different capabilities for deep emissions reductions, the inter-model spread in carbon price and cost estimates increases as well. In other words, scenarios indicate greater consensus regarding the nature of mitigation costs at higher-concentration levels than those at lower levels. This increase in variation reflects the challenge associated with modelling energy and other human systems that are dramatically different than those of today.

6.3.6.3 The implications of technology portfolios for aggregate global economic costs

Because technology will underpin the transition to a low-carbon economy, the availability, cost, and performance of technologies will exert an influence on economic costs. Several multi-model studies and a wide range of individual model studies have explored this space (see Section 6.1.2.2). A precise understanding of the implications of technology availability on costs is confounded by several factors. One issue is that the sensitivities among technologies are not necessarily comparable across models or scenarios. Some models do not represent certain technologies such as BECCS and therefore do not exhibit a strong cost increase if these options are restricted. These models may instead have difficulties in achieving tighter concentration goals regardless of the restriction (Krey et al., 2014). In addition, assumptions about cost and performance can vary across models, even within a single, multi-model study. Moreover, many limited technology scenarios are characterized by frequent model infeasibilities, as shown by the fraction of models in the EMF27 study (Kriegler et al., 2014a) able to meet a particular goal with different technology combinations at the bottom of Figure 6.24. (See Section 6.2.4 regarding interpretation of model infeasibility).

Despite these limitations, the literature broadly confirms that mitigation costs are heavily influenced by the availability, cost, and performance of mitigation technologies. In addition, these studies indicate that the influence of technology on costs generally increases with increasing stringency of the concentration goal (Figure 6.24). The effect on mitigation costs varies by technology, however, the ranges reported by the different models tend to strongly overlap (Figure 6.24, Krey et al., 2014), reflecting the general variation of mitigation costs across models (Section 6.3.6.2, Fisher et al., 2007). In general, models have been able to produce scenarios leading to about 550 ppm CO_2eq by 2100, even under limited technology assumptions. However, many models could not produce scenarios leading to about 450 ppm CO_2eq by 2100 with limited technology portfolios, particularly when assumptions preclude or limit the use of BECCS (Azar et al., 2006; van Vliet et al., 2009; Krey et al., 2014; Kriegler et al., 2014a).

As noted above, the lack of availability of CCS is most frequently associated with the most significant cost increase (Edenhofer et al., 2010; Tavoni et al., 2012; Krey et al., 2014; Kriegler et al., 2014a; Riahi et al., 2014), particularly for concentration goals approaching 450 ppm CO_2eq, which are characterized by often substantial overshoot. One fundamental reason for this is that the combination of biomass with CCS can serve as a CDR technology in the form of BECCS (Azar et al., 2006; Krey and Riahi, 2009; van Vliet et al., 2009; Edmonds et al., 2013; Kriegler et al., 2013a; van Vuuren et al., 2013) (see Sections 6.3.2 and 6.9). In addition to the ability to produce negative emissions when coupled with bioenergy, CCS is a versatile technology that

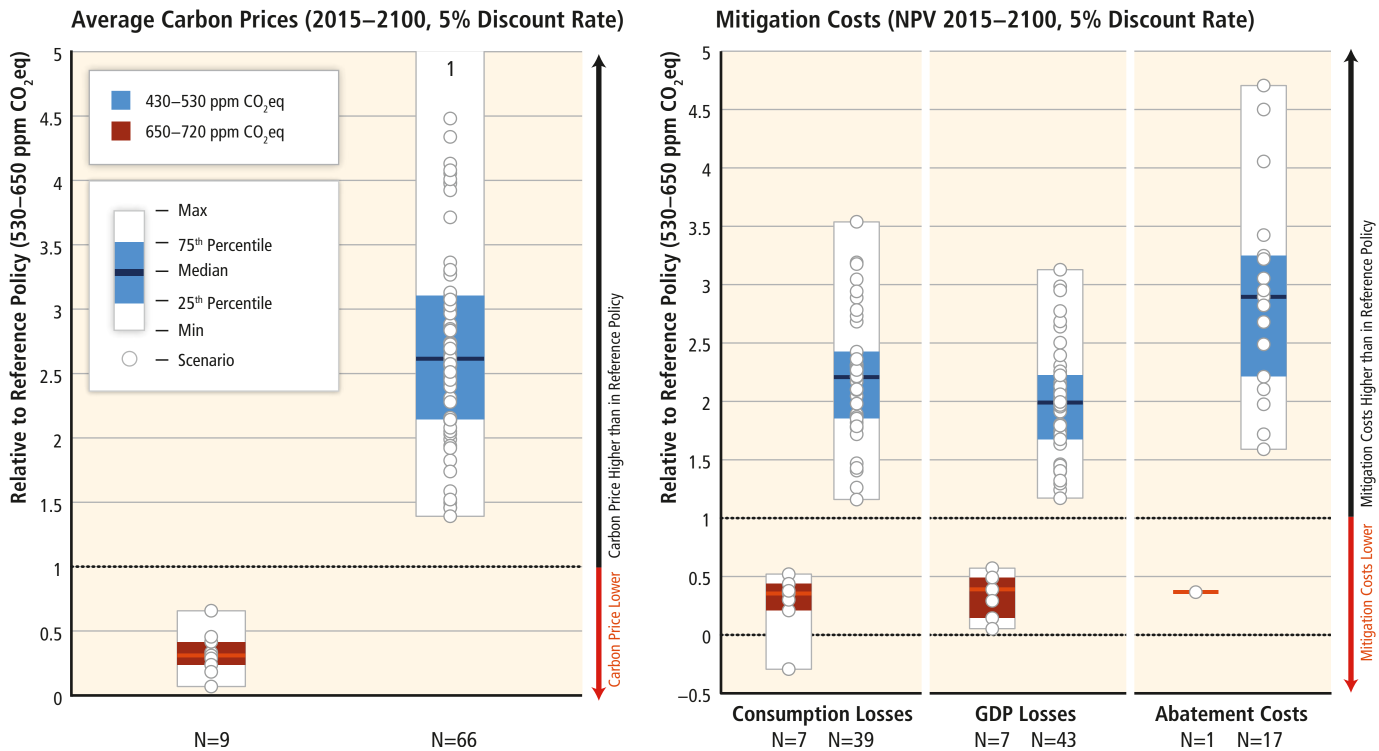


Figure 6.22 | Carbon price (left panel) and global mitigation cost changes (right panel) for idealized implementation scenarios relative to a reference concentration category (530–650 ppm CO_2eq in 2100). Results for NPV costs are shown by consumption losses, GDP losses, and abatement costs. Results are based on pairs of idealized implementation scenarios, one in the 530–650 ppm CO_2eq range and one in a neighbouring concentration range, from a single model and study. Cost changes were calculated on the basis of NPV economic costs (discounted at 5 % per year) and carbon price changes on the basis of average discounted values for the period 2015–2100. See Figure 6.21 caption for further explanation on the presentation of results. Source: WG III AR5 Scenario Database (Annex II.10).

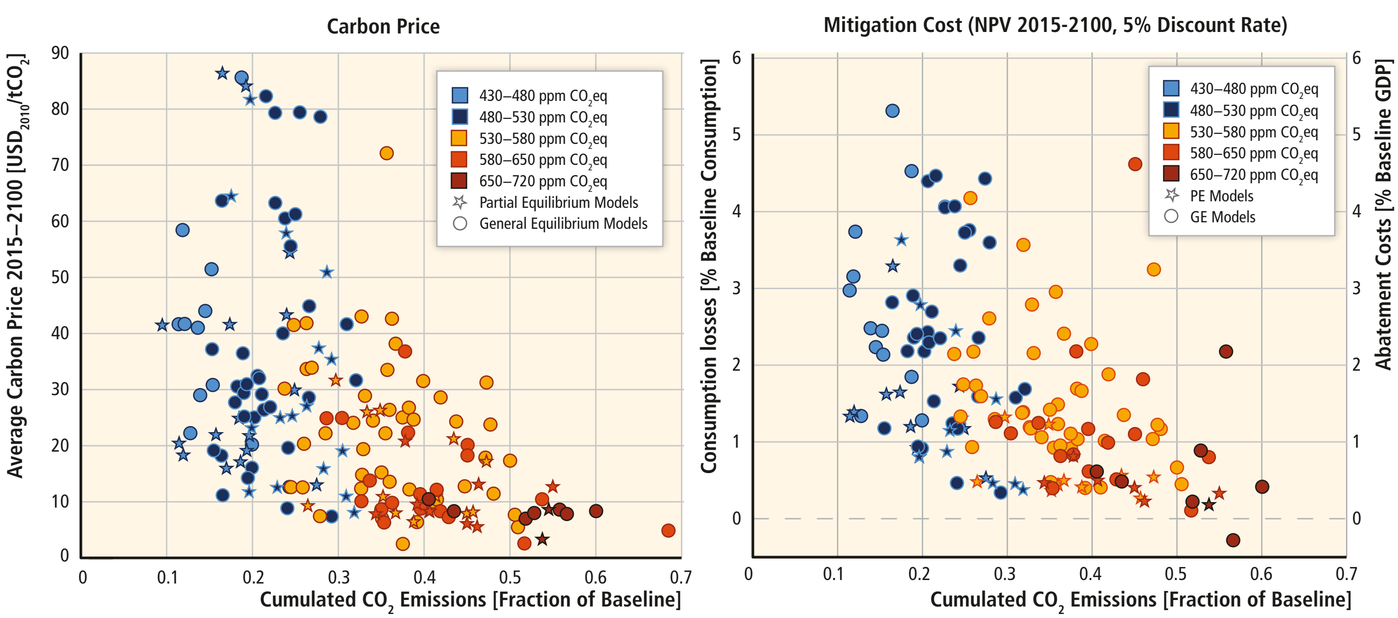


Figure 6.23 | Average carbon prices (left panel) and global mitigation costs (right panel) as a function of residual cumulative CO_2 emissions expressed as fraction of cumulative baseline emissions over the period 2011–2100. Emissions reductions relative to baseline can be deduced by subtracting the fraction of residual cumulative emissions from unity. Mitigation costs are reported in NPV consumption losses in percent baseline consumption for general equilibrium (GE) models and abatement costs in percent baseline GDP for partial equilibrium (PE) models. A discount rate of 5 % per year was used for calculating average carbon prices and net present value mitigation costs. See description of Figure 6.21 for the selection of scenarios. Source: WG III AR5 Scenario Database (Annex II.10).

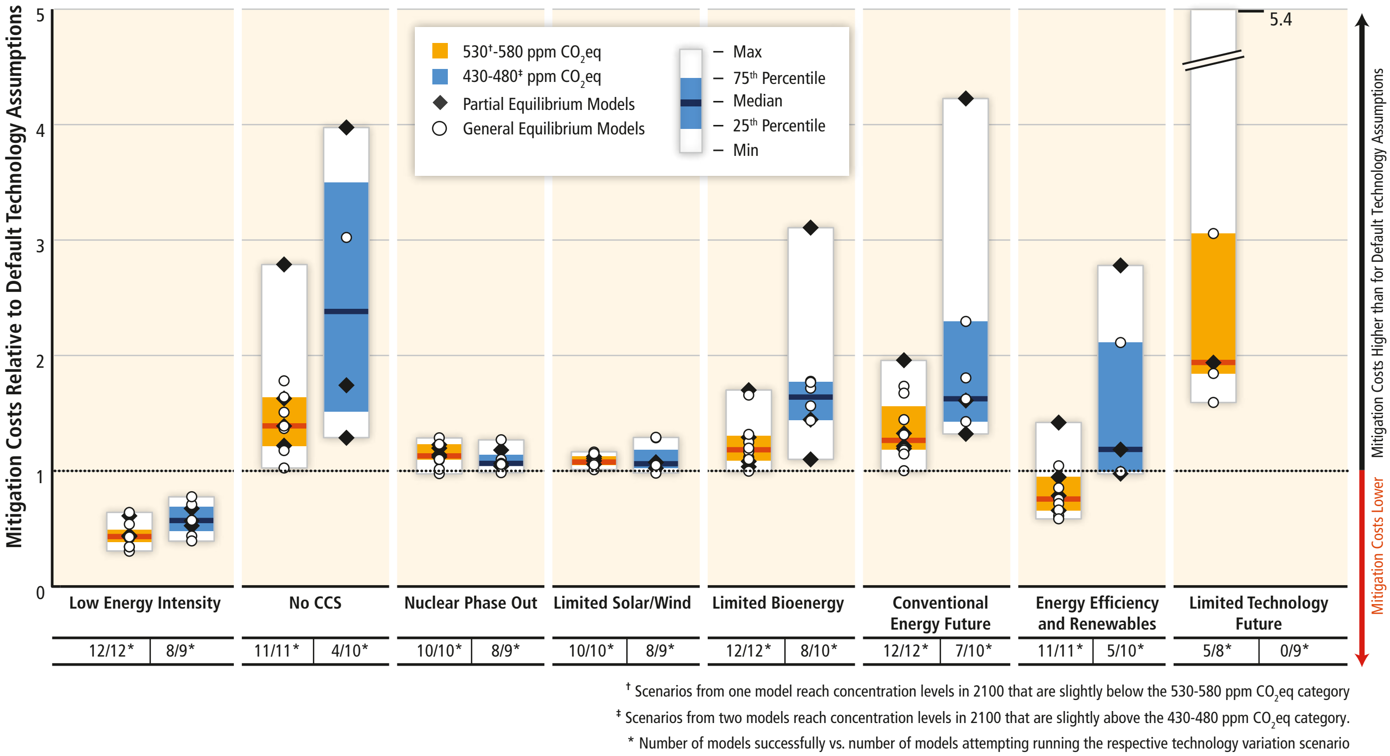


Figure 6.24 | Relative increase of NPV mitigation costs (period 2015–2100, 5 % discount rate) from technology portfolio variations compared to a scenario with default technology availability. Scenario names on the horizontal axis indicate the technology variation relative to the default assumptions: Low Energy Intensity = higher energy intensity improvements leading to energy demand reductions of 20–30 % by 2050 and 35–45 % by 2100 relative to the default baseline; No CCS = unavailability of CCS; Nuclear Phase Out = No addition of nuclear power plants beyond those under construction; existing plants operated until the end of their lifetime; Limited Solar/Wind = a maximum of 20 % global electricity generation from solar and wind power in any year of these scenarios; Limited Bioenergy = maximum of 100 EJ/yr of modern bioenergy supply globally; Conventional Energy Future = combining pessimistic assumptions for renewable energy (Limited Solar/Wind + Limited Bioenergy); Energy efficiency and Renewables = combining low energy intensity with non-availability of CCS and nuclear phase-out; Limited Technology Future = all supply-side options constrained and energy intensity developing in line with historical records in the baseline. Source: EMF27 study, adapted from (Kriegler et al., 2014a). Only those scenarios from the EMF27 study are included that reached the 430–480 and 530–580 ppm CO_2eq concentration ranges or were close to it (see footnotes in the figure).

can be combined with electricity, synthetic fuel, and hydrogen production from several feedstocks and in energy-intensive industries such as cement and steel. The CCS can also act as bridge technology that is compatible with existing fossil-fuel dominated supply structures (see Sections 7.5.5, 7.9, and 6.9 for a discussion of challenges and risks of CCS and CDR). Bioenergy shares some of these characteristics with CCS. It is also an essential ingredient for BECCS, and it can be applied in various sectors of the energy system, including for the provision of liquid low-carbon fuels for transportation (see Chapter 11, Bioenergy Annex for a discussion of related challenges and risks). In contrast, those options that are largely confined to the electricity sector (e.g., wind, solar, and nuclear energy) and heat generation tend to show a lower value, both because they cannot be used to generate negative emissions and because there are a number of low-carbon electricity supply options available that can generally substitute each other (Krey et al., 2014).

Scenarios also suggest that energy end-use technologies and measures have an important influence on mitigation costs. For example, in the EMF27 and AMPERE multi-model studies, reductions in the final energy demand of 20–30 % by 2050 and 35–45 % by 2100 led to reductions in the cumulative discounted aggregate mitigation costs on the order of 50 % (Krey et al., 2014; Kriegler et al., 2014a; Riahi et al., 2014). An important caveat to these results is that the costs of achieving these reductions were not considered nor were the policy or technology drivers that led to them. Energy end-use measures are important not just for reducing energy consumption, but also for facilitating the use of low-carbon fuels. For example, a number of studies (Kyle and Kim, 2011; Riahi et al., 2012; Pietzcker et al., 2014; McCollum et al., 2014b) show that allowing electricity or hydrogen in transportation lowers mitigation costs by opening up additional supply routes to the transportation sector (see Section 6.8 for more on this topic). An increasing ability to electrify the end-use sectors and transport in particular, in turn, tends to reduce the importance of CCS and bioenergy technologies for achieving lower-concentration goals such as 450 ppm CO_2eq.

6.3.6.4 Economic implications of non-idealized international mitigation policy implementation

Research has consistently demonstrated that delaying near-term global mitigation as well as reducing the extent of international participation in mitigation can significantly affect aggregate economic costs of mitigation. One way in which aggregate mitigation costs are increased is by delaying near-term global mitigation relative to what would be warranted in the hypothetical idealized case that a long-term goal was adopted and a least-cost approach to reach the global mitigation goal was implemented immediately. This represents one manifestation of not undertaking mitigation 'when' it is least expensive (Keppo and Rao, 2007; Bosetti et al., 2009b; Krey and Riahi, 2009; Jakob et al., 2012; Kriegler et al., 2013b; Luderer et al., 2013; Rogelj et al., 2013b; Riahi et al., 2014). In scenarios in which near-term global mitigation is limited, the increase in mitigation costs is significantly and positively related to the gap in short-term mitigation with respect to the idealized scenarios (Figure 6.25). Costs are lower in the near-term, but increase more rapidly in the transition period following the delayed mitigation, and are also higher in the longer term. Future mitigation costs are higher because delays in near-term mitgation not only require deeper reductions in the long run to compensate for higher emissions in the short term, but also produce a larger lock-in in carbon infrastructure, increasing the challenge of these accelerated emissions reduction rates. The effects of delay on mitigation costs increase with the stringency of the mitigation goal. Studies suggest that important transitional economic metrics other than aggregate costs—for example, reduced growth rates in economic output and consumption, escalating energy prices, and increasing carbon rents—may be more affected by delayed mitigation than aggregate costs (Kriegler et al., 2013b; Luderer et al., 2014a).

Studies have consistently found that delays through 2030 have substantially more profound aggregate economic implications than delays through 2020, both in terms of higher transitional impacts due to more rapidly increasing mitigation costs at the time of adopting the long-term strategy and higher long-term costs (Kriegler et al., 2013b; Rogelj et al., 2013a; Luderer et al., 2014a). This is directly related to prolonged delays in mitigation leading to both larger carbon lock-ins and higher short term emissions that need to be compensated by deeper emissions cuts in the long run (Sections 6.3.2 and 6.4). Moreover, delayed mitigation further increases the dependence on the full availability of mitigation options, especially on CDR technologies such as BECCS (Luderer et al., 2013; Rogelj et al., 2013b; Riahi et al., 2014). (See Section 6.3.6.3, Section 6.4).

Fragmented action or delayed participation by particular countries—that is, not undertaking mitigation 'where' it is least expen-

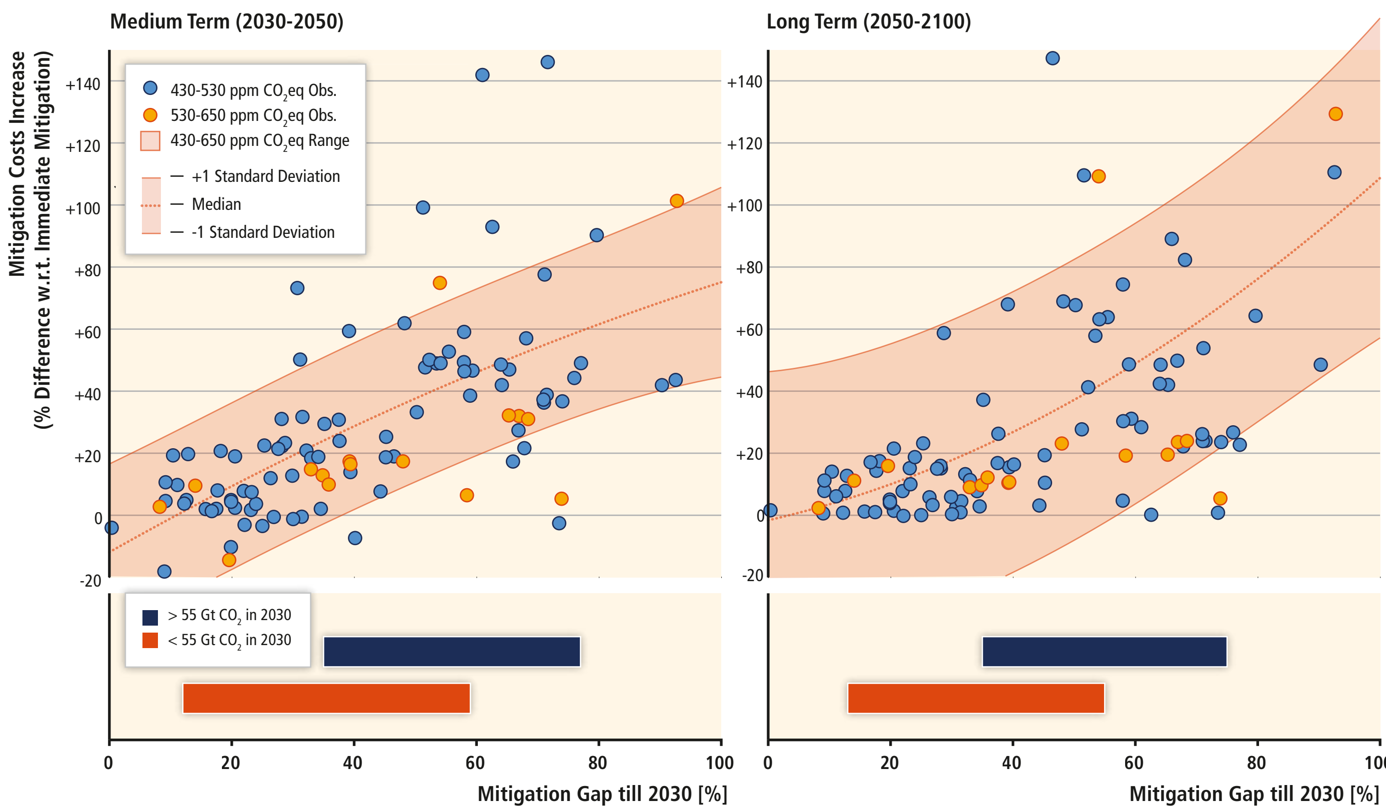


Figure 6.25 | Mitigation costs increase as a function of reduced near-term mitigation effort, expressed as relative change to immediate mitigation (idealized implementation) scenarios (referred to as the 'mitigation gap'). Cost increase is shown both in the medium term (2030–2050, left panel) and in the long term (2050–2100, right panel), calculated on undiscounted costs. The mitigation gap is calculated from cumulative CO_2 mitigation to 2030. Blue and yellow dots show scenarios reaching concentration goals of 430–530 ppm and 530–650 ppm CO_2eq, respectively. The shaded area indicates the range for the whole scenario set (two standard deviations). The bars in the lower panel indicate the mitigation gap range where 75 % of scenarios with 2030 emissions, respectively, above and below 55 $GtCO_2$ are found. Not all model simulations of delayed additional mitigation until 2030 could reach the lower concentration goal of 430–530 ppm CO_2eq (for 2030 emissions above 55 $GtCO_2eq$, 29 of 48 attempted simulations could reach the goal; for 2030 emissions below 55 $GtCO_2eq$, 34 of 51 attempted simulations could reach the goal). Source: WG III AR5 Scenario Database (Annex II.10), differences between delayed mitigation to 2020 and 2030 and immediate mitigation categories.

sive—has also been broadly shown to increase global mitigation costs (Edmonds et al., 2008; Calvin et al., 2009b; Clarke et al., 2009; Tol, 2009; Richels et al., 2009; Bosetti et al., 2009d; van Vliet et al., 2009; Kriegler et al., 2014c). Fragmented action will influence aggregate global economic costs not only because of misallocation of mitigation across countries, but also through emissions leakage and trade-related spillover effects (Arroyo-Curras et al., 2014; Babiker, 2005; Bauer et al., 2014a; Blanford et al., 2014; Böhringer et al., 2012; Bosetti and De Cian, 2013; Kriegler et al., 2014c). The range and strength of these adverse effects and risks depends on the type of policy intervention and the stringency of the mitigation effort. Border carbon adjustments have been found to reduce economic impacts of exposed industries, but not to yield significant global cost savings (Böhringer et al., 2012). Some studies have indicated that the increased costs from fragmented action could be counterbalanced by increased incentives to carry out innovation, though only to a limited extent (Di Maria and Werf, 2007; Golombek and Hoel, 2008; Gerlagh et al., 2009; De Cian and Tavoni, 2012; De Cian et al., 2014).

Multi model studies have indeed found that the smaller the proportion of total global emissions included in a climate regime due to fragmented action, the higher the costs and the more challenging it becomes to meet any long-term goal. For example, only 2 (5) of 10 participating models could produce 450 ppm CO_2eq overshoot (550 ppm CO_2eq not to exceed) scenarios under the regional fragmentation assumptions in the EMF22 scenarios (Clarke et al., 2009). In these scenarios, the Annex I countries began mitigation immediately, followed by major emerging economies in 2030, and the rest of the world in 2050 (see Table 6.1, (Clarke et al., 2009) (see Section 6.2 for a discussion of model infeasibility). Discounted global aggregate mitigation costs over the century increased by 50 % to more than double for those models that could produce these scenarios (FIgure 6.26).

In general, when some countries act earlier than others, the increased costs of fragmented action fall on early actors. However, aggregate economic costs can also increase for late entrants, even taking into account their lower near-term mitigation (Clarke et al., 2009; Jakob et al., 2012). Late entrants benefit in early periods from lower mitigation; however, to meet long-term goals, they must then reduce emissions more quickly once they begin mitigation, in just the same way that global emissions must undergo a more rapid transition if they are delayed in total. The increased costs of this rapid and deep mitigation can be larger than the reduced costs from delaying near-term mitigation (Figure 6.26). The degree to which the late entrants' mitigation costs increase with fragmented action depends on the extent of carbon-intensive technologies and infrastructure put in place during the period during which they delay reductions and the speed at which emissions must be reduced after they begin emissions reductions. Indeed, in the face of a future mitigation commitment it is optimal to anticipate emissions reductions, reducing the adjustment costs of confronting mitigation policy with a more carbon-intensive capital stock (Bosetti et al., 2009a; Richels et al., 2009). In addition, countries may incur costs from international mitigation policy even if they do not participate, for example, from a loss of fossil fuel revenues (Blanford et al., 2014).

6.3.6.5 The interactions between policy tools and their implementation, pre-existing taxes, market failures, and other distortions

The aggregate economic costs reported in Section 6.3.6.2 have assumed an idealized policy implementation and in many cases an idealized implementation environment with perfectly functioning economic markets devoid of market failures, institutional constraints, and pre-existing tax distortions. Many models represent some of these distortions, but most models represent only a small portion of possible distortions and market failures. The reality that assumptions of idealized implementation and idealized implementation environment will not be met in practice means that real-world aggregate mitigation costs could be very different from those reported here.

Under the assumption of a perfect implementation environment, economic analysis has long demonstrated that the way to minimize the aggregate economic costs of mitigation is to undertake mitigation where and when it is least expensive (Montgomery, 1972). This implies that policies be flexible and comprehensive with a ubiquitous price on GHG emissions, as might be achieved by a cap-and-trade policy or carbon tax (Goulder and Parry, 2008). The literature presented thus far in this section has assumed such an approach. Even

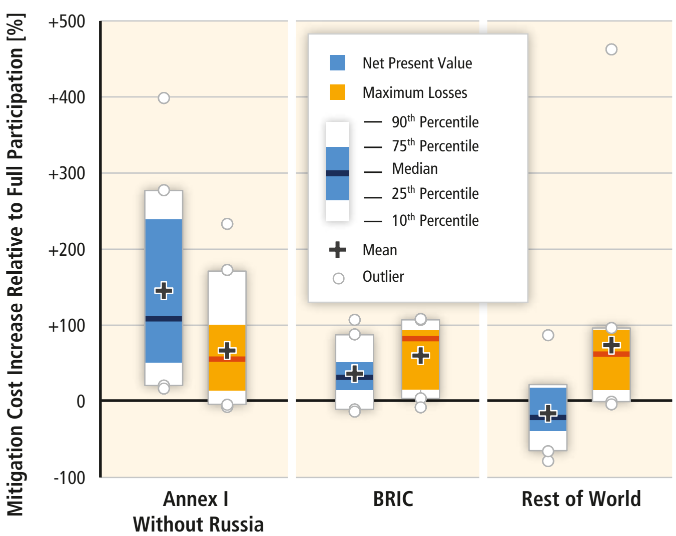


Figure 6.26 | Impact of fragmented action on the relative mitigation costs of three representative regions: Annex I without Russia; Brasil, Russia, India, and China (BRIC); and Rest of the World (ROW) from the EMF22 Study. In this study, Annex I (without Russia) joins immediately, BRIC in 2030, and ROW in 2050 (see Table 6.1). The vertical axis shows the increase in mitigation costs between full participation and fragmented action scenarios. Thus, values above 0 indicate that fragmented action increases costs. Mitigation costs are calculated relative to baseline over 2015–2100 both in NPV at 5 % discount rate (left bars) and as maximum losses over the century (right bars). Source: EMF22 data base.

scenarios with fragmented or limited near-term emissions reductions have typically assumed efficient, full-economy carbon prices for all countries undertaking mitigation. However, real-world approaches may very well deviate from this approach. For example, some policies may only address particular sectors, such as power generation; other policies may regulate the behaviour of particular sectors through command and control measures, for example, through renewable portfolio standards for power generation or fuel economy standards for transport.

In an idealized implementation environment, the literature shows that approaches that exclude sectors or regulate reductions by sector will lead to higher aggregate mitigation costs, particularly for goals requiring large emissions reductions where coverage and flexibility are most important (Paltsev et al., 2008). A wide range of recent studies have corroborated this general result, including the large scale multi-model comparison studies such as EMF22 (Böhringer et al., 2009), EMF24 (Fawcett et al., 2014), and EMF28 (Knopf et al., 2013) along with a wide range of individual papers. As an example, a survey of results (OECD, 2009) indicates that exempting energy-intensive industries increases mitigation costs for achieving concentrations of 550 ppm by 50 % in 2050, and that excluding non-CO_2 GHG emissions increases the mitigation costs by 75 % in 2050. The EMF22 study (Böhringer et al., 2009) find that differential prices for the European Union (EU) Emission Trading Scheme (ETS) and non-ETS emissions in the EU and the inclusion of a renewable portfolio standard could double the mitigation costs for the EU goals for 2020. Wise et al. (2009) found that the failure to include changes in land use emissions in mitigation policy could double global carbon prices in a 450 ppm CO_2 scenario. At the same time, it is important to recognize that mitigation may not be the only objective of these sectoral approaches and regulatory policies. They may also be designed to address other policy priorities such as energy security and local environmental concerns.

Climate policies will interact with pre-existing policy structures as well as with other market failures beyond the market failure posed by climate change—that is, a non-idealized implementation environment—and these interactions can either increase or decrease policy costs. A number of authors have argued that costs could be much lower or even negative compared to those produced by studies assuming idealized policy and implementation environments (Bosquet, 2000; Bye et al., 2002; Waisman et al., 2012). The results of these studies rest on one or several assumptions—that mitigation policy be used not only to address the climate externality, but also to achieve other policy priorities such as sustainable development; the use of mitigation policy instruments for the correction of the implementation environment including removal of market failures and pre-existing distortions; and/or on optimistic views of climate-related innovation and technology development, adoption, and penetration.

Because technology is so critical to the economic costs of mitigation, the economic costs and efficacy of climate policies more generally will necessarily be influenced by market failures in markets for technology adoption and those for development and R&D (Jaffe, 2012). There are numerous market failures, such as research and adoption spillovers, limited foresight, limited information, and imperfect capital markets, which can cause underinvestment in mitigation technologies, discussed in more detail in Section 15.6 (Thollander et al., 2010; Allcott, 2011, 2013; Kalkuhl et al., 2012, among many others). Studies indicate aggregate mitigation costs could be lower if these market failures could be removed through complementary policies (Jaffe et al., 2005; Thollander et al., 2010). Additionally, literature that focuses in particular on failures in markets for investments in technology and R&D has found large reductions in aggregate mitigation costs as a result of correcting these failures, for example, through the recycling of revenue from climate policies or otherwise using public funds (Bosquet, 2000; Edenhofer et al., 2010; Waisman et al., 2012). The literature has also shown the value of related complementary policies to enhance labor flexibility (Guivarch et al., 2011) or impact the mobility of demand, such as transportation infrastructures or urban and fiscal policies lowering real estate prices and urban sprawl (Waisman et al., 2012).

Interactions with pre-existing policies and associated distortions will also influence economic costs. The EU ETS offers an example where an efficient policy tool (cap-and-trade system) that is applied on partial sectors (partial coverage) and interacts with pre-existing distortions (high energy taxes) and other energy policies (renewable energy requirements) is affected by over-allocation of permits and slower than expected economic growth (Ellerman and Buchner, 2008; Ellerman, 2010; Batlle et al., 2012). Paltsev et al (2007) show that pre-existing distortions (e.g., energy taxes) can greatly increase the cost of a policy that targets emission reduction. In contrast, literature has also looked into the use of carbon revenues to reduce pre-existing taxes (generally known as the 'double dividends' literature). This literature indicates that total mitigation costs can be reduced through such recycling of revenues (Goulder, 1995; Bovenberg and Goulder, 1996). Nonetheless, a number of authors have also cautioned against the straight generalization of such results indicating that the interplay between carbon policies and pre-existing taxes can differ markedly across countries showing empirical cases where a 'double dividend' does not exist as discussed in Section 3.6.3.3 (Fullerton and Metcalf, 1997; Babiker et al., 2003; Metcalf et al., 2004).

6.3.6.6 Regional mitigation costs and effort-sharing regimes

The costs of climate change mitigation will not be identical across countries (Clarke et al., 2009; Hof et al., 2009; Edenhofer et al., 2010; Lüken et al., 2011; Luderer et al., 2012b; Tavoni et al., 2013; Aboumahboub et al., 2014; Blanford et al., 2014). The regional variation in costs will be influenced by the nature of international participation in mitigation, regional mitigation potentials, and transfer payments across regions. In the idealized setting of a universal carbon price leading to reductions where they would be least expensive, and in the absence of transfer payments, the total aggregate economic costs of mitigation would vary substantially across countries and regions. In results collected from modelling studies under these circumstances, relative aggregate costs in the OECD-1990, measured as a percentage change from, or relative to, baseline conditions, are typically lower than the global average, those in Latin America are typically around the global average, and those in other regions are higher than the global average (Figure 6.27) (Clarke et al., 2009; Tavoni et al., 2013).

The variation in these relative regional costs can be attributed to several factors (Stern et al., 2012; Tavoni et al., 2013). First, costs are driven by relative abatement with respect to emissions in a baseline, or no-policy, scenario, which are expected to be higher in developing countries (see Section 6.3.2 for more discussion). Second, developing countries are generally characterized by higher energy and carbon intensities due to the structure of economies in economic transition. This induces a higher economic feedback for the same level of mitigation (Luderer et al., 2012b). Third, domestic abatement is only one determinant of policy costs, since international markets would interact with climate policies (Leimbach et al., 2010). For some regions, notably the fossil energy exporting countries, higher costs would originate from unfavourable terms of trade effects of the mitigation policy (OECD, 2008; Luderer et al., 2012a; Massetti and Tavoni, 2011; Aboumahboub et al., 2014; Blanford et al., 2014), while some regions could experience increased bio-energy exports (Persson et al., 2006; Wise et al., 2009; Leimbach et al., 2010). A final consideration is that the total costs (as opposed to costs measured as a percentage change from baseline conditions) and associated mitigation investments are also heavily influenced by baseline emissions, which are projected to be larger in the developing regions than the developed regions (see Section 6.3.1).

A crucial consideration in the analysis of the aggregate economic costs of mitigation is that the mitigation costs borne in a region can be separated from who pays those costs. Under the assumption of efficient markets, effort-sharing schemes have the potential to yield a more equitable cost distribution between countries (Ekholm et al., 2010b; Tavoni et al., 2013). Effort-sharing approaches will not meaningfully change the globally efficient level of regional abatement, but can substantially influence the degree to which mitigation costs or investments might be borne within a given country or financed by other countries (e.g. Edenhofer et al., 2010). A useful benchmark for consideration of effort-sharing principles is the analysis of a framework based on the creation of endowments of emission allowances and the ability to freely exchange them in an international carbon market. Within this framework, many studies have analyzed different effort-sharing allocations according to equity principles and other indicators (see Section 3.3, Section 4.6.2) (den Elzen and Höhne, 2008, 2010; Höhne et al., 2014).

Comparing emission allocation schemes from these proposals is complex because studies explore different regional definitions, timescales, starting points for calculations, and measurements to assess emission allowances such as CO_2 only or as CO_2eq (see Höhne et al., 2014). The range of results for a selected year and concentration goal is relatively large due to the fact that the range includes fundamentally different effort-sharing approaches and other variations among the assumptions of the studies.

Nonetheless, it is possible to provide a general comparison and characterization of these studies. To allow comparison of substantially different proposals, Höhne et al. (2014) developed a categorization into seven cat-

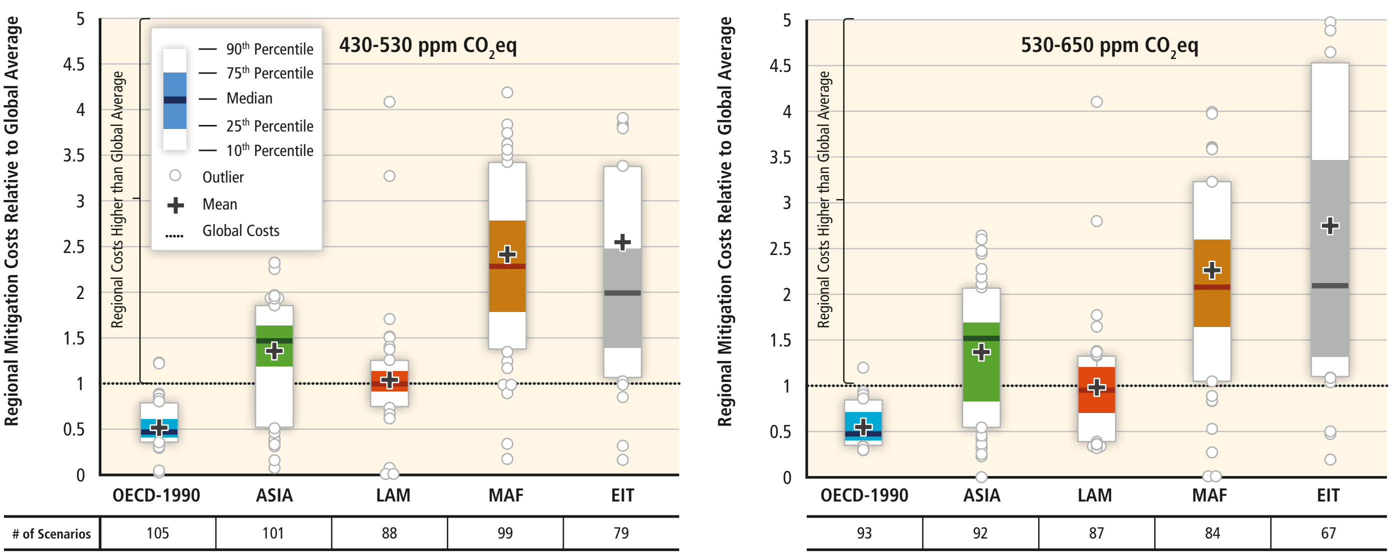


Figure 6.27 | Regional mitigation costs relative to global average for scenarios reaching 430–530 ppm CO_2eq in 2100 (left panel) and 530–650 ppm CO_2eq in 2100 (right panel). Values above (below) 1 indicate that the region has relative mitigation costs higher (lower) than global average. Relative costs are computed as the cumulative costs of mitigation over the period 2020–2100, discounted at a 5 % discount rate, divided by cumulative discounted economic output over that period. Scenarios assume no carbon trading across regions. The numbers below the regions names indicate the number of scenarios in each box plot. Source: WGIII AR5 Scenario Database (Annex II.10), idealized implementation and default (see Section 6.3.1) technology scenarios.

Table 6.5 | Categories of effort-sharing proposals. Source: Höhne et al. (2014)

Categories	Responsibility	Capability	Equality	Description	References
Responsibility	X			The concept to use historical emissions to derive emission goals was first directly proposed by Brazil in the run-up of the Kyoto negotiations (UNFCCC, 1997), without allocations. Allowances based only on this principle were quantified by only a few studies.	Berk and den Elzen (2001)*, Den Elzen et al. (2005); Den Elzen and Lucas (2005)
Capability		X		Frequently used for allocation relating reduction goals or reduction costs to GDP or human development index (HDI). This includes also approaches that are focused exclusively on basic needs.	Den Elzen and Lucas (2005); Knopf et al. (2011); Jacoby et al. (2009); Miketa and Schrattenholzer (2006); Kriegler et al. (2013b) and Tavoni et al. (2013) **
Equality			X	A multitude of studies provide allocations based on immediate or converging per capita emissions (e.g. Agarwal and Narain, 1991; Meyer, 2000). Later studies refine the approach using also per capita distributions within countries (e.g. Chakravarty et al., 2009).	Berk and den Elzen (2001)*, Kriegler et al. (2013b) and Tavoni et al. (2013)**, Böhringer and Welsch (2006); Bows and Anderson (2008); Chakravarty et al. (2009); Criqui et al.(2003); Den Elzen and Lucas (2005); Den Elzen and Meinshausen (2006); Den Elzen et al.(2005, 2008); Edenhofer et al. (2010); Hof et al. (2010b); Höhne and Moltmann (2008, 2009); Knopf et al.(2009, 2011); Kuntsi-Reunanen and Luukkanen (2006); Nabel et al. (2011); Miketa and Schrattenholzer (2006); Peterson and Klepper (2007); Onigkeit et al. (2009); Van Vuuren et al. (2009a, 2010)
Responsibility, capability, and need	X	X		Recent studies used responsibility and capability explicitly as a basis, e.g., Greenhouse Development Rights (Baer et al., 2008); or 'Responsibility, Capability, and Sustainable Development'(Winkler et al., 2011)	Baer et al. (2008); Baer (2013); Höhne and Moltmann (2008, 2009); Winkler et al. (2011)
Equal cumulative per capita emissions	X		X	Several studies allocate equal cumulative per capita emission rights based on a global carbon budget (Pan, 2005, 2008). Studies diverge on how they assign the resulting budget for a country to individual years.	Bode (2004); Nabel et al. (2011); Jayaraman et al. (2011); Schellnhuber et al. (2009);
Staged approaches	X	X	X	A suite of studies propose or analyze approaches, where countries take differentiated commitments in various stages. Also approaches based on allocation for sectors such as the Triptych approach (Phylipsen et al., 1998) or sectoral approaches are included here. Categorization to a stage and the respective commitments are determined by indicators using all four equity principles. Finally, studies using equal percentage reduction goals, also called grandfathering, are also placed in this category.	Bosetti and Frankel (2012); Criqui et al. (2003); Den Elzen and Lucas (2005); Den Elzen and Meinshausen (2006); Den Elzen et al. (2007, 2008, 2012); Hof et al.(2010a); Höhne and Moltmann (2008, 2009); Höhne et al.(2005, 2006); Knopf et al. (2011); Vaillancourt and Waaub (2004); Peterson and Klepper (2007); Böhringer and Welsch (2006); Knopf et al.(2011) Berk and den Elzen (2001)
Equal Marginal Abatement Costs (for reference)				Modelling studies often use the allocations that would emerge from a global carbon price as a reference case for comparing other allocations.	Peterson and Klepper (2007), Van Vuuren et al. (2009a), Kriegler et al. (2013b) and Tavoni et al. (2013) **

* Not included in the quantitative results, because either too old or pending clarifications of the data.

** This is a model comparison study of seven integrated models as part of the LIMITS research project: PBL, IIASA, FEEM, ECN*, PIK, PNNL, NIES*. Each of these models represents one data point. Some of these model studies are more extensively described in a particular model study (Kober et al., 2014).

egories based on three equity principles (see Chapter 4): responsibility, capability, and equality (Table 6.5). The first three categories represent these equity principles alone. The following three categories represent combinations of these principles. 'Equal cumulative per capita emissions' combines equality (per capita) with responsibility (cumulative accounting for historical emissions); 'responsibility, capability, and need' includes approaches that put high emphasis on historical responsibility and at the same time on capability plus the need for sustainable development; 'staged approaches' includes those that already constitute a compromise over several principles. Finally, the last category, 'equal marginal abatement costs' (implemented in the models as uniform carbon tax with no compensatory transfers), represents the initial allocation to that which would emerge from a global price on carbon. This is used as a reference against which to compare the implications of other regimes.

The range of allowances can be substantial even within specific categories of effort sharing, depending on the way the principle is implemented (Figure 6.28). For some effort-sharing categories, the ranges are smaller because only a few studies were found. Despite the ranges within a category, distributional impacts differ significantly with underlying criteria for effort sharing.

The concentration goal is significant for the resulting emissions allowances (Figure 6.29). Indeed, for many regions, the concentration goal is of equal or larger importance for emission allowances than the effort-sharing approach. For concentration levels between 430 and 480 in 2100, the allowances in 2030 under all effort-sharing approaches in OECD-1990 are approximately half of 2010 emissions with a large range, roughly two-thirds in the EITs, roughly at the 2010 emissions level or slightly below in ASIA, slightly above the 2010 level in the Middle East and Africa, and well below the 2010 level in Latin America. For these same concentration levels, allowances in OECD-1990 and EITs are a fraction of today's emissions in 2050, and allowances for Asia and Latin America are approximately half of 2010 emission levels in 2050. For higher concentration levels, most studies show a significant decline in allowances below current levels for OECD-1990 and EITs by 2050. Most studies show a decline in allowances below current levels for the Latin America region, mostly increasing above current levels for the Africa and Middle East region, and an inconsistent picture for ASIA.

The creation of endowments of emissions allowances would generate payment transfers across regions in a global carbon market. These transfer payments would depend on the regional abatement opportunities, the distribution of allowances, and the concentration goal. To the extent that regional mitigation levels represent the cost-effective mitigation strategy across regions, the size of these allocations relative to domestic emissions provide an indication of the degree to which allowances would be transferred to or from any region. If allocations are higher than the 'equal marginal abatement cost' allocation in a particular country, then the country could possibly improve its financial position by reducing emissions and selling the remaining allowances. If allocations are lower than the 'equal marginal abatement cost' allocation, the country could possibly purchase allowances and therefore provide transfers.

Box 6.2 | Least-developed countries in integrated models

There are significant data and information deficits pertaining to least-developed countries(LDCs) and limits to the modelling of the specific features and characteristics of LDCs. For this reason, the integrated modelling literature provides relatively little information on the specific implications of transformation pathways for LDCs. Based on the limited available literature, LDCs contribute little to future GHG emissions until 2050 even though they are projected to grow faster than global emissions. Post-2050 emissions trends for LDCs depend on highly uncertain projections of their long-term economic growth prospects. One study in the available integrated modelling literature suggests that LDC's contribution to global emissions increases by about 50 % between 2000 and 2100 (Calvin et al., 2009b).The mitigation challenges for LDCs are particularly significant given their ambitions for economic growth, poverty alleviation, and sustainable development on the one hand, and their limited means for mitigation in terms of technology and finance on the other hand. Tradeoffs can include, among other things, a prolonged use of traditional bioenergy and a reduction in final energy use. Potential synergies include accelerated electrification (Calvin et al., 2014a).

The literature on the transformation pathways has also indicated the need for large deployment of low-carbon technologies. These projections pose critical challenges and uncertainties for LDCs when taking into account issues related to deployment, institutions and program design, and non-climate socioeconomic implications. In particular, many scenarios rely on technologies with potentially large land footprints, such as bioenergy and afforestation or reforestation, to achieve mitigation goals. The scenarios surveyed in the chapter universally project the majority of bioenergy primary energy will occur in developing economies (50–90 % in non-OECD in 2050, see Section 6.3.5). These abatement patterns imply significant challenges for developing countries in general, and LDCs in particular, where large land-use abatement potentials lie.

The literature related to effort-sharing and distributional implications of mitigation in LDCs is relatively scarce. The literature suggests that there are tradeoffs between food security and mitigation (e.g. Reilly et al., 2012) with negative impacts for poor, developing countries due to the high share of their incomes spent on food. Mitigation might increase the rural-urban gap and deteriorate the living standards of large sections of the population in developing countries (e.g. Liang and Wei, 2012). In contrast, policy and measures aligned to development and climate objectives can deliver substantial co-benefits and help avoid climate risks in developing countries (Shukla et al., 2009). Modelling studies that use the 'low carbon society' framework arrive at a similar conclusion about co-benefits in developing countries and LDCs (Kainuma et al., 2012; Shrestha and Shakya, 2012). Spillover effects from trade-related mitigation policies may pose certain risks for LDCs such as induced factor mobility, unemployment, and international transport-related impacts on food and tourism sectors (Nurse, 2009; ICTSD, 2010; Pentelow and Scott, 2011). Downscaling of integrated modelling to the level of LDCs is a key area for future research.

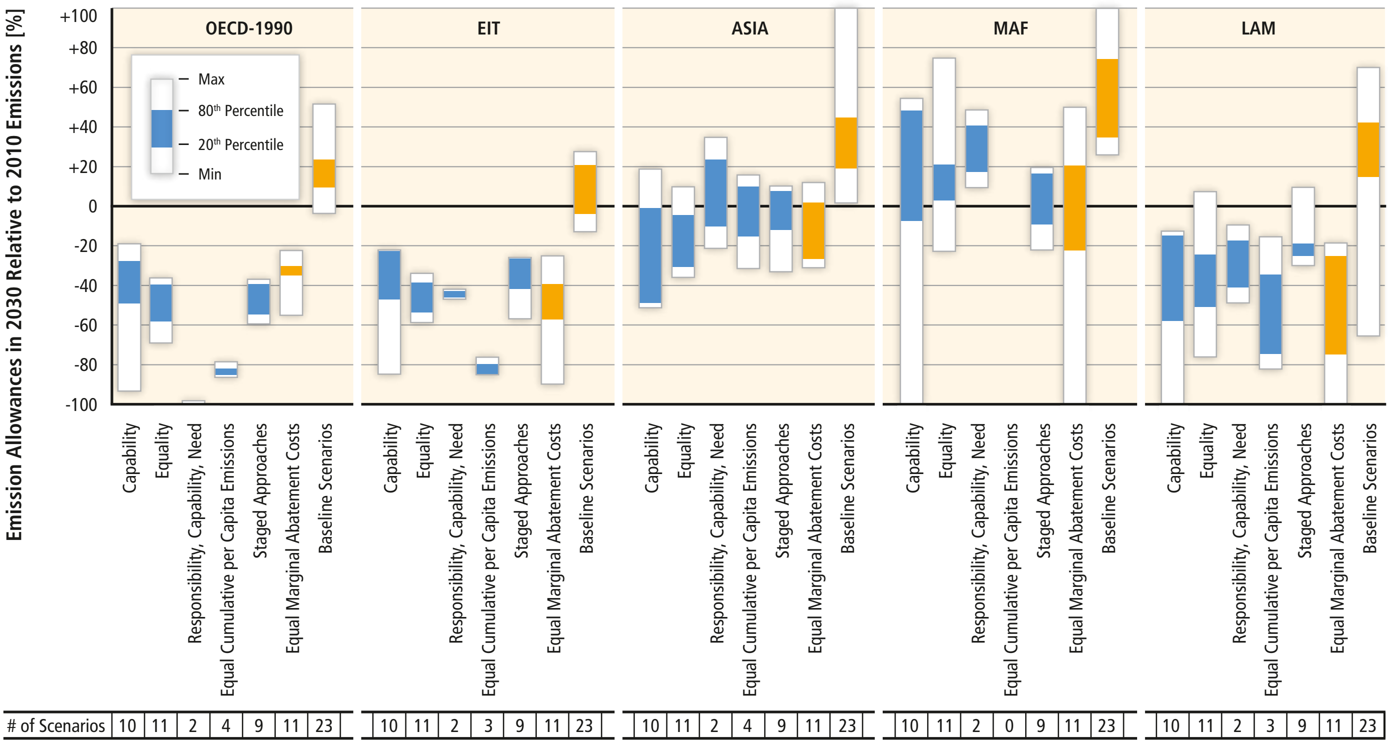


Figure 6.28 | Emission allowances in 2030 relative to 2010 emissions by effort-sharing category for mitigation scenarios reaching 430–480 ppm CO_2eq in 2100. GHG emissions (all gases and sectors) in $GtCO_2eq$ in 1990 and 2010 were 13.4 and 14.2 for OECD-1990, 8.4 and 5.6 for EIT, 10.7 and 19.9 for ASIA, 3.0 and 6.2 for MAF, 3.3 and 3.8 for LAM. Emissions allowances are shown compared to 2010 levels, but this does not imply a preference for a specific base-year. For the OECD-1990 in the category 'responsibility, capability, need' the emission allowances in 2030 is – 106 % to – 128 % (20th to 80th percentile) below 2010 level (therefore not shown here). The studies with the 'Equal cumulative per capita emissions' approaches do not have the regional representation MAF. For comparison in orange: 'Equal marginal abatement cost' (allocation based on the imposition of a global carbon price) and baseline scenarios. Source: Adapted from Höhne et al.(2014). Studies were placed in this CO_2eq concentration range based on the level that the studies themselves indicate. The pathways of the studies were compared with the characteristics of the range, but concentration levels were not recalculated.

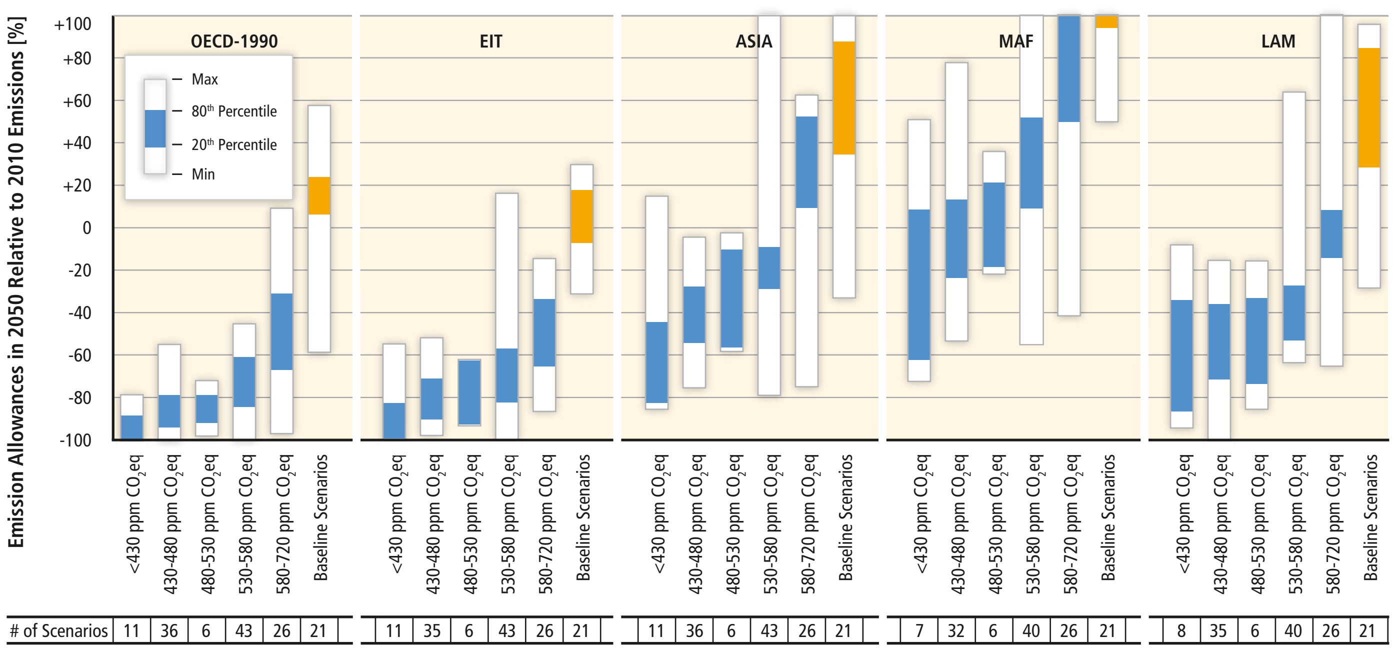


Figure 6.29 | Emission allowances in 2050 relative to 2010 emissions for different 2100 CO_2eq concentration ranges by all effort-sharing categories except 'equal marginal abatement costs'. For comparison in orange: baseline scenarios. Source: Adapted from Höhne et al. (2014). Studies were placed in the CO_2eq concentration ranges based on the level that the studies themselves indicate. The pathways of the studies were compared with the characteristics of the ranges, but concentration levels were not recalculated.

Multi-model studies indicate that the size of the carbon market transfers would be significant in relation to the total global aggregate economic costs of mitigation, of the order of hundreds of billions of United States dollars per year before mid-century (Clarke et al., 2009; Luderer et al., 2012b; Tavoni et al., 2013). Transfers through emissions allowances are also particularly high if the carbon price is high, because the transfers are based on the quantity of the allowances traded and the price of those allowances. Higher prices are associated with more ambitious mitigation. For some regions, financial flows could be on the same order of magnitude as the investment requirements for emissions reductions (McCollum et al., 2013b). Transfers are particularly high for some regions for the categories 'equal per capita cumulative emissions' and 'responsibility, capability, and need' in general and for 'staged approaches' in some of studies.

The transfers associated with different effort-sharing schemes have a direct impact on the regional distribution of mitigation policy costs (Luderer et al., 2012b). These costs are sensitive both to local abatement costs and to size and direction of transfers, both of which are related to the effort-sharing scheme as well as the carbon price and the associated climate goal (Russ and Criqui, 2007; den Elzen et al., 2008; Edenhofer et al., 2010; Ekholm et al., 2010b; Luderer et al., 2012b). Given the large uncertainty about future transfers and carbon prices, the regional distribution of costs under different sharing schemes varies widely (Luderer et al., 2012b; Tavoni et al., 2013). For example, emerging economies like China could incur relatively high expenditures (den Elzen et al., 2012; Johansson et al., 2014), but this would change when cumulative past emissions are also accounted for (Jiahua, 2008; Ding et al., 2009; He et al., 2009). Moreover, the uneven regional distribution of relative mitigation costs observed in Figure 6.27 in the case without transfers is not significantly alleviated when emissions rights are equalized per capita by 2050 and the concentration goal is stringent, as shown in Figure 6.30.

Optimal transfers can also be devised as a way to provide economic incentives to regions to participate in international climate agreements. When accounting for the strategic behaviour of the various regions and countries, the literature suggests that climate coalitions, which are self-enforcing and stable, can indeed be effective only in the presence of significant compensatory payments across regions (Finus et al., 2003; Nagashima et al., 2009; Bréchet et al., 2011). Transfers would also occur in the case that different regional social costs of carbon were equalized to maximize efficiency (Landis and Bernauer, 2012).

The impacts of mitigation policies on global fossil fuel trade depend on the type of fuel, time horizon, and stringency of mitigation efforts. Recent model intercomparison studies focusing on low-concentration goals (430–530 CO_2eq in 2100) have found an unambiguous decrease in coal trade over the first half of the century (Cherp et al., 2014; Jewell et al., 2013). In contrast, studies indicate that natural gas trade could potentially increase over the coming decades as gas serves as a transition fuel and substitutes for coal (Cherp et al., 2014). Studies present a less clear picture regarding the future of oil trade for concentration goals in this range. In general, however, studies find oil trade to be less sensitive to mitigation policy than coal and gas trade through 2030, and perhaps even to 2050 (Bauer et al., 2014a, 2014b; Cherp et al., 2014; Jewell et al., 2013; McCollum et al., 2014a).

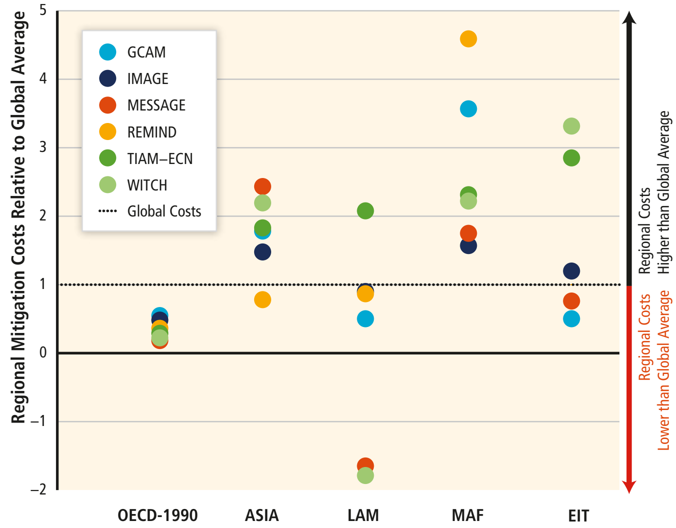


Figure 6.30 | Regional mitigation costs relative to global average for a 450 ppm CO_2eq concentration goal for a per capita effort-sharing scheme from the LIMITS multi-model study. Values above (below) 1 indicate that the region has relative mitigation costs higher (lower) than global average ones. Values below 0 are possible for regions who are large net sellers of carbon allowances. Mitigation costs are computed relative to the baseline, over 2020–2100 in NPV at a 5 % discount rate. Emission allocations are based on linear convergence from 2020 levels to equal per capita by 2050, with per capita equalization thereafter. Regions are allowed to trade emission rights after 2020 without any constraint. Source: WG III AR5 Scenario Database (Annex II.10), LIMITS per capita scenarios.

These changes in trade patterns will have important implications for the future trade revenues of fossil-exporting countries. There is high agreement among integrated models that revenues from coal trade are likely to fall for major exporters (Lüken et al., 2011; Bauer et al., 2014a, 2014b). For oil and gas, on the other hand, the effect of stringent climate policies on export revenues is less clear, with results varying across models. Notwithstanding these differences, the general conclusion of recent intercomparison exercises is that there is likely to be a decrease in oil and gas revenues for exporting countries over the first half of the century (IEA, 2009; Haurie and Vielle, 2010; Bauer et al., 2014a, 2014b; Tavoni et al., 2013; McCollum et al., 2014a). There are several studies that diverge from the bulk of the literature and argue that conventional oil exporters could in the short-term benefit from climate policies under certain conditions related to the cost of oil alternatives (biofuels and unconventional oil), the price elasticity of oil and the cost of backstop technologies (Persson et al., 2007; Johansson et al., 2009; Nemet and Brandt, 2012). Because exporters of these resources can benefit from the cheaper extraction costs and less carbon-intensive nature of conventional oil (relative to unconventional oil deposits and coal- or gas-derived liquids), mitigation efforts could potentially have a positive impact on export revenues for conventional oil. These dynamics depend critically on future commodity prices. No global studies have, as yet, systematically explored the impact of stringent climate policies on unconventional gas trade and export revenues, particularly those where methane leakage from extraction activities could be an issue. The deployment of fossil fuels is generally higher in scenarios with CCS. The availability of CCS would thus reduce the adverse effect of mitigation on the value of fossil fuel assets.

6.4 Integrating long- and short-term perspectives

6.4.1 Near-term actions in a long-term perspective

Stabilizing atmospheric concentrations of GHGs and radiative forcing is a long-term endeavour. Whether a particular long-term mitigation goal will be met, and what the costs and other implications will be of meeting it, will depend on decisions to be made and uncertainties to be resolved over many decades in the future. For this reason, transformation pathways to long-term climate goals are best understood as a process of sequential decision making and learning. The most relevant decisions are those that must be made in the near term with the understanding that new information and opportunities for strategic adjustments will arrive often in the future, but largely beyond the reach of those making decisions today. An important question for decision makers today is therefore how near-term decisions will influence choices available to future decision makers. Some decisions may maintain a range of future options, while others may constrain the future set of options for meeting long-term climate goals.

6.4.2 Near-term emissions and long-term transformation pathways

A key outcome of current decision making will be the level of near-term global emissions. Scenarios can provide important insights into the implications of the near-term (i.e., 2020–2030) emissions level for long-term climate outcomes. As discussed in Section 6.1.2, a number of multi-model studies have been designed specifically for this purpose, exploring delays in global mitigation, in which near-term emissions are held fixed to particular levels, and fragmented action, in which only a subset of regions initially respond to a long-term goal (see Table 6.1). These scenarios are typically designed as counterpoint to idealized implementation scenarios in which mitigation begins immediately, timing of reductions is unconstrained, and full participation is assumed from the outset. This distinction is essential for characterizing the relationship between the path emissions follow through 2030 and the possible climate outcomes through the end of the century. Among idealized implementation scenarios with 2100 concentrations in the range of 430–530 ppm CO_2eq, emissions in 2020 fall almost exclusively below the range of global GHG emissions implied by the Cancún Pledges (see Section 13.13.1.3 for more details), as in Rogelj et al. (2013a) (Figure 6.31, top panel). However, several scenarios with delayed mitigation imposed either through global delays or delayed participation have 2020 emissions in the possible range of the Cancún Agreements and in some cases 2030 emissions even higher than this range while still remaining consistent with the long-term goal (the cost implications of delay are discussed in Section 6.3.6.4).

A second distinction that can play a critical role is the extent to which CDR options are available and deployed. In scenarios designed with a forcing goal applied only at the end of the century, particularly concentrations in the range of 430–530 ppm CO_2eq, idealized implementation scenarios often choose to temporarily overshoot the 2100 concentration (Section 6.3.2). As noted in Section 6.3.2, CDR options, typically represented in integrated models by BECCS but also afforestation in some cases, facilitate more rapid declines in emissions, amplifying this overshoot pattern (Krey et al., 2014). A large number of scenarios reaching CO_2eq concentrations below 530 ppm CO_2eq by 2100 deploy CDR technologies at large enough scales that net global emissions become negative in the second half of the century. The availability of CDR options, as well as the representation of intertemporal flexibility, varies significantly across models and studies. The spread in reliance on CDR options across scenarios reveals a strong impact on the timing of emissions pathways. In scenarios reaching the the 2100 concentration range of 430–530 ppm CO_2eq in which global net CO_2 emissions remain positive through the century, near-term emissions are generally lower than if the scenario deploys CDR technologies to a large enough scale to lead to net negative total global CO_2 emissions later in the century (Figure 6.31, top panel). More generally, the scenarios indicate that a reliance on large-scale CDR, whether or not emissions become net negative, leads to higher near-term emissions (van Vuuren and Riahi, 2011).

The interaction between delayed mitigation and CDR options is also important. Very few scenarios are available to demonstrate emissions pathways consistent with 2100 concentrations of 430–530 ppm CO_2eq in which mitigation effort is delayed in some form and global carbon emissions do not become net negative. Whether these circumstances are not represented because they have been under-examined or because they have been examined and the scenarios failed is a crucial distinction, yet one that it is currently not possible to fully report (see discussion of model infeasibility in Section 6.3.2). However, there are instances where the combination of delay and limited options for CDR has been explored and has resulted in model infeasibilities (Luderer et al., 2013; Rogelj et al., 2013b; Riahi et al., 2014), which supports the notion that this combination presents important challenges. For example, in the AMPERE study, seven out of nine models could not produce

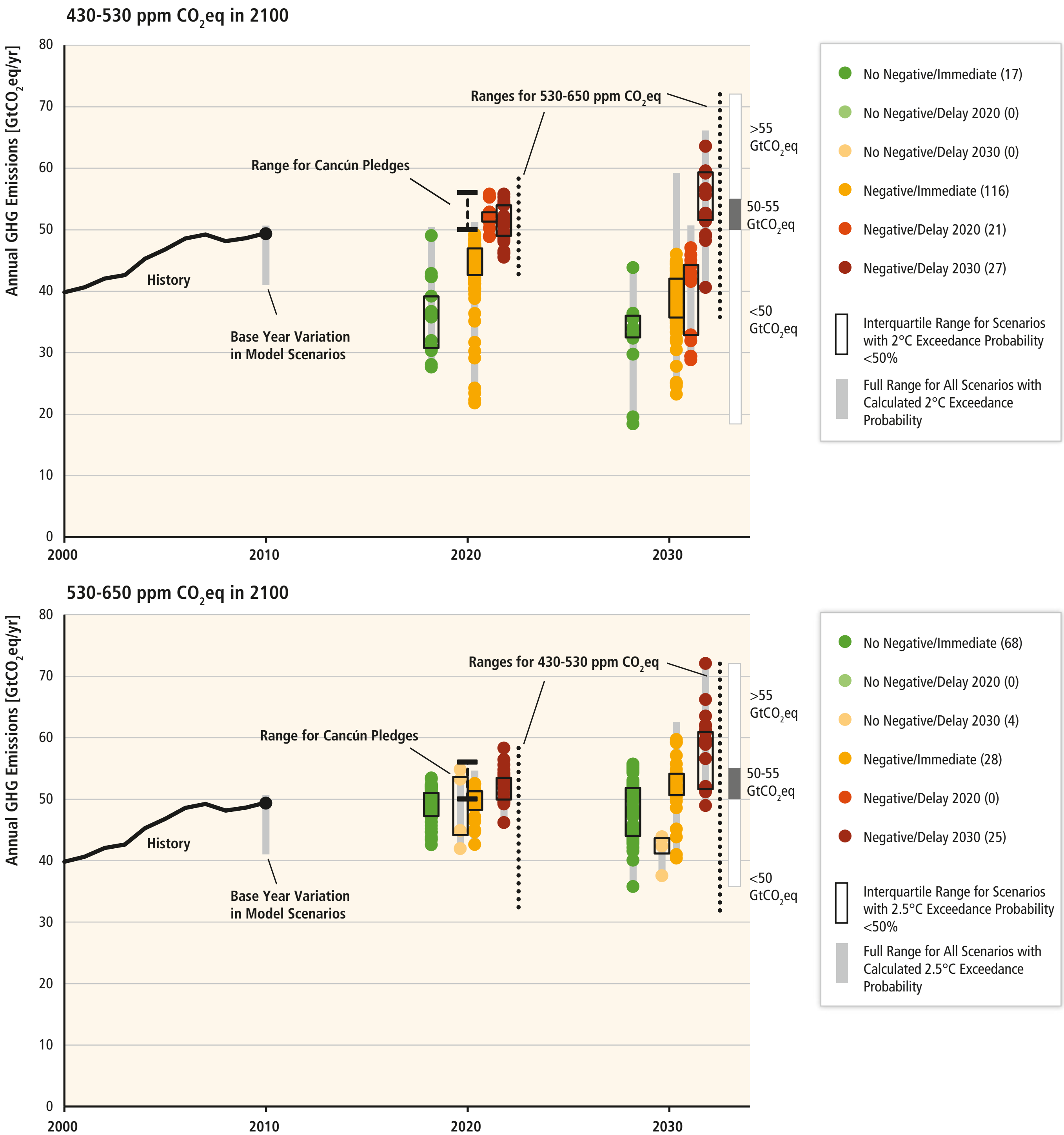


Figure 6.31 | Near-term global GHG emissions from mitigation scenarios reaching 430–530 ppm CO_2eq (top panel) and 530–650 ppm CO_2eq (bottom panel) in 2100. Includes only scenarios for which temperature exceedance probabilities were calculated (see Section 6.3.2). Individual model results are indicated with a data point when 2 °C exceedance probability, based on the MAGICC results, is below 50 % for top panel or when 2.5 °C exceedance probability is below 50 % for bottom panel. For these below-50 % scenarios the interquartile range is shown by a black rectangular frame. Colours refer to scenario classification in terms of whether net CO_2 emissions become negative before 2100 (Negative vs. No Negative) and the timing of international participation in climate mitigation (Immediate vs. Delay 2020 / 2030). Number of reported individual results is shown in legend. The range of global GHG emissions in 2020 implied by the Cancún Pledges is based on an analysis of alternative interpretations of national pledges (see Section 13.13.1.3 for details). Source: WG III AR5 Scenario Database (Annex II.10). Historic data: JRC/PBL (2013), IEA (2012a), see Annex II.9. Note: Only four reported scenarios were produced based on delayed mitigation without net negative emissions while still lying below 530 ppm CO_2eq by 2100. They do not appear in the top panel because the model had insufficient coverage of non-gas species to enable a temperature calculation (see Section 6.3.2). Delay in these scenarios extended only to 2020, and their emissions fell in the same range as the 'No Negative/Immediate' category. Note: Delayed scenarios include both delayed global action and fragmented action scenarios.

a scenario with global delay through 2030 and a restriction on CCS technology that reached 450 CO_2eq by 2100 (one of the remaining two had net negative global emissions through other channels and the other did not run past 2050). Several individual modelling team studies have also explored this space, and have found situations in which they could not reach solutions for more ambitious goals and delayed mitigation or constrained technology, including O'Neill et al. (2010), Edmonds et al. (2008), and Edmonds et al. (2013). Studies have found that delayed reductions through 2020 do not have as substantial an effect on the cost and challenge more broadly of meeting 2100 concentration levels such as 450 ppm CO_2eq as delayed reductions through 2030 (Kriegler et al., 2013b; Luderer et al., 2013; Rogelj et al., 2013b)

The implications of delayed mitigation, CDR options, and overshoot for possible temperature outcomes are also significant. Numerous studies have attempted to place the possible outcome of the Cancún Agreements in the context of longer-term climate goals (Höhne et al., 2012; UNEP, 2012). Due to the factors discussed above, but also variation in assumptions about baseline growth, mitigation costs, tradeoffs between sectors such as energy and land use, and the evolution of non-gas forcing agents, models have found that a wide range of near-term emissions could be consistent with a given long-term outcome. Among scenarios with 2100 concentrations between 430 and 530 ppm CO_2eq, focusing on those scenarios in the AR5 database for which temperature implications were calculated (see Section 6.3.2), near-term global emissions range from 22 to 56 $GtCO_2$eq in 2020 and from 18 to 66 $GtCO_2$eq in 2030 (Figure 6.31, top panel). However, based on the MAGICC results, not all pathways in this range are consistent with at least a 50 % chance of remaining below 2 °C, in particular those that rely on net negative global emissions. Pathways reaching the same 2100 concentration with higher emissions in 2030 tend to have more overshoot; when forcing stays higher for longer, the likelihood of reaching a temperature threshold increases. Based on the MAGICC results, very few scenarios in the 430–530 ppm CO_2eq range have a 50 % chance of remaining below 1.5 °C, and none with delay or limited deployment of CDR technologies; most have a probability between 0 and 25 %. A few studies have explored scenarios that lead to concentrations below 430 ppm CO_2eq in 2100 (e.g., Luderer et al., 2013, Rogelj et al., 2013a, b), some of which have been found to have more than a 66 % chance of returning to 1.5 °C by the end of the century after peaking at higher levels; these scenarios are characterized by immediate emissions reductions followed by very low mid-century emissions and extensive deployment of CDR technologies. Based on the MAGICC results, nearly all scenarios reaching 2100 concentrations in the range of 530–650 ppm CO_2eq, have a greater than 50 % chance of exceeding 2 °C by 2100, but many have a probability of less than 50 % of exceeding 2.5 °C (Figure 6.31, bottom panel). Because of the higher long-term forcing range, some growth in emissions can occur, and the preferred least-cost range is similar to the delayed range and largely consistent with the global GHG emissions reductions through 2020 implied by the Cancún Pledges (see Section 13.13.1.3).

Whether due to delayed mitigation or widespread use of CDR options or some combination of the two, higher levels of emissions in the near-term imply an emissions pathway shifted in time, resulting in steeper reductions later to remain consistent with a given long-term forcing goal. As discussed in Section 6.3.2, emissions in 2030 have been used as a rough indicator for understanding the relationship between near-term and long-term mitigation. Higher emissions in 2030 require more rapid decreases in emissions from 2030 through 2050, both to make up for the larger cumulative emissions up through 2030 and because emissions must be reduced from a higher 2030 level (Figure 6.32). Emissions decline rates for any scenario that meets 2100 concentration goals such as 450 or 550 ppm CO_2eq must at some point push beyond historical experience, because emissions have in general followed growth, with past instances of decline associated only with large-scale disruptions such as the collapse of the Soviet Union or special cases of policy intervention such as France and Sweden (see Chapter 5). Less mitigation over the coming decades will only exacerbate the required departure from the past to meet long-term goals—pathways with emissions above 55 $GtCO_2$eq in 2030 indicate decline rates between 2030 and 2050 of around 6 % for scenarios in the range of 430–530 ppm CO_2eq in 2100 (Figure 6.32).

6.4.3 The importance of near-term technological investments and development of institutional capacity

While it is clear that some mitigation effort in the near term is crucial to preserve the option of achieving low-concentration goals, whether these goals are met in the long run depends to a greater extent on the potential for deep GHG-emissions reductions several decades from now. Thus efforts to begin the transformation to lower concentrations must also be directed toward developing the technologies and institutions that will enable deep future emissions cuts rather than exclusively on meeting particular near-term goals. The way in which countries begin low-carbon technology deployment and the implementation of climate change mitigation policies may well turn out to be quite different from the approach that proves best in the long run. The benefit of beginning to create and improve technologies as well as to develop appropriate institutional capacity today is that these present-day activities create opportunities to make early and mid-course corrections.

The likelihood of a unified global policy for a deep GHG-emissions reduction is low for the near future. Rather, the expectation is that a 'mosaic' of national and regional policies will emerge over the years to come. Individual countries will bring different views and values to bear on their decisions, which will likely lead to a wide variety of policy approaches, some more economically efficient than others. Flexible market-based policies with maximal sectoral and geographic coverage are generally understood to deliver emissions reductions at the lowest economic cost (see Section 6.3.6.5 for a discussion of issues that influence the efficiency of implementation approaches). Although the added

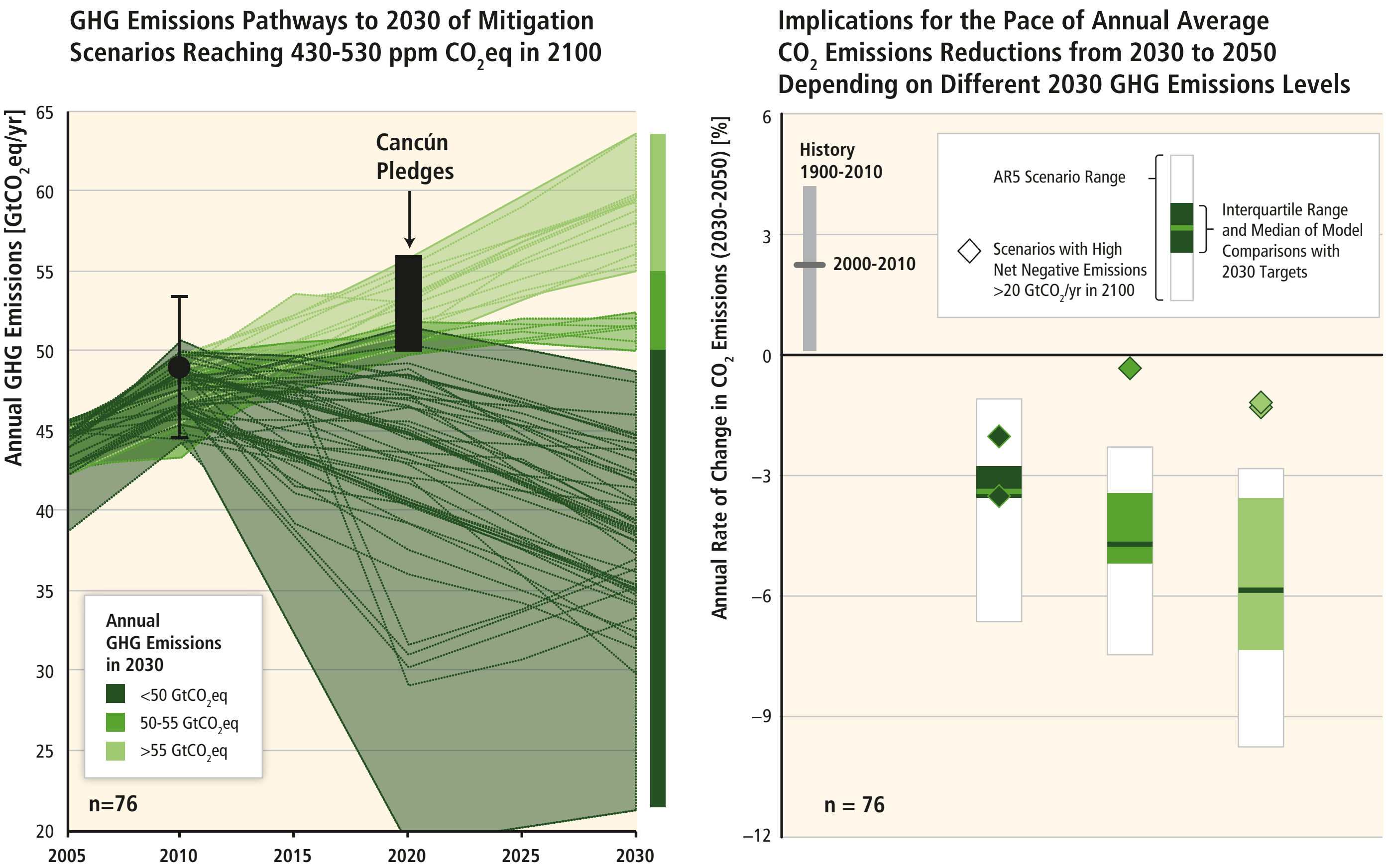


Figure 6.32 | The implications of different 2030 GHG emissions levels for the pace of CO_2 emissions reductions to 2050 in mitigation scenarios reaching 430–530 ppm CO_2eq by 2100. Left-hand panel shows the development of GHG emissions to 2030. Right-hand panel denotes the corresponding annual CO_2 emissions reduction rates for the period 2030–2050. The scenarios are grouped according to different emissions levels by 2030 (colored in dark, medium and light green). The range of global GHG emissions in 2020 implied by the Cancún Pledges is based on an analysis of alternative interpretations of national pledges (see Section 13.13.1.3 for details). The right-hand panel compares the median and interquartile range across scenarios from recent intermodelling comparisons with explicit 2030 interim goals with the range of scenarios in the WG III AR5 Scenario Database (Annex II.10). Extreme scenarios with very high net negative emissions (>20 $GtCO_2$/yr) in 2100 are reported separately as diamonds. Annual rates of historical emissions change between 1900-2010 (sustained over a period of 20 years) and average annual emissions change between 2000-2010 are shown in grey. Sources: Intermodelling comparisons with explicit interim goals (AMPERE: Riahi et al., 2013; LIMITS: Kriegler et al., 2013b; ROSE: Luderer et al., 2013) and the WG III AR5 Scenario Database (Annex II.10). Historic data: JRC/PBL (2013), IEA (2012a), see Annex II.9. Note: Only scenarios with default technology assumptions are shown. Scenarios with non-optimal timing of mitigation due to exogenous carbon price trajectories are excluded.

cost of inefficient policies in the near term may be smaller than in the long-term when mitigation requirements will be much larger, their implementation now may lead to 'institutional lock-in' if policy reform proves difficult. Thus a near-term focus on developing institutions to facilitate flexible mitigation strategies, as well as political structures to manage the large capital flows associated with carbon pricing (see e.g. Kober et al., 2014), could provide substantial benefits over the coming decades when mitigation efforts reach their full proportions.

R&D investments to bring down the costs of low-emitting technology options, combined with early deployment of mitigation technologies to improve long-term performance through learning-by-doing, are among the most important steps that can be taken in the near term (see e.g. Sagar and van der Zwaan, 2006). R&D investments are important for bringing down the costs of known low-carbon energy alternatives to the current use of predominantly fossil fuels, to develop techniques that today only exist on the drawing board, or for generating new concepts that have not yet been invented. Early deployment of climate change mitigation technologies can lead to both incremental and fundamental improvements in their long-term performance through the accumulation of experience or learning by doing. Mitigation policy is essential for spurring R&D and learning by doing, because it creates commitments to future GHG-emissions reductions that create incentives today for investments in these drivers of technological innovation, and avoids further lock-in of long-lived carbon-intensive capital stock.

Even if policies requiring GHG-emissions reductions are not implemented immediately, market participants may act in anticipation of future mitigation. Commitments to emissions reductions in the future will create incentives for investments in climate change mitigation technologies today, which can serve both to reduce current emissions and avoid further lock-in of long-lived carbon-intensive capital stock and infrastructure (see, for example, Bosetti et al., 2009c; Richels et al., 2009).

6.5 Integrating technological and societal change

Technological change occurs as innovations create new possibilities for processes and products, and market demand shifts over time in response to changes in preferences, purchasing power, and other societal factors. Societal changes can be viewed as both a requirement for and a result of global climate change mitigation. Because the use of improved and new technologies is an inherent element of society's transformation required for climate change mitigation, technological and societal changes necessarily interact. Their analysis therefore needs to be integrated.

6.5.1 Technological change

The development and deployment of technology is central to long-term mitigation, since established fossil fuel-based energy supply will need to be replaced by new low-carbon energy techniques. The importance of technological change raises key questions about whether current technology is sufficient for deep GHG-emissions reductions, the best ways to improve the technologies needed for deep emissions reductions, and the degree to which current efforts in this regard are adequate to the upcoming challenge. Essential questions also surround the appropriate timing of investments in technological change relative to other efforts to reduce GHG emissions.

A primary question regarding technological change is whether current technology is sufficient for the deep emissions reductions ultimately needed to stabilize GHG concentrations. Arguments have been made on both sides of this debate (see Hoffert et al. (2002), and Pacala and Socolow (2004), for complementary perspectives on this question). The integrated modelling literature provides limited information regarding the sufficiency of current technology, because virtually all baseline and mitigation scenarios assume that technology will improve significantly over time, especially for technologies with a large potential for advancement (see Riahi et al., 2013, and van der Zwaan et al., 2013, for two recent cross-model comparison examples). There is generally more agreement about the rate of incremental cost and performance improvements for mature technologies than for emerging technologies upon which transformation pathways may depend (see McCollum et al., 2013b, for a cross-model study on the investment dimension of this matter). Nonetheless, the literature makes clear that improvements in technology and the availability of advanced technologies can dramatically alter the costs of climate change mitigation (see also Section 6.3.6.3). The current scientific literature also emphasizes that the development and deployment of CDR technologies (see Section 6.9), are a further requirement for particular transformation pathways, for example those leading to 450 ppm CO_2eq by 2100 yet assuming substantial near-term delays in mitigation.

Various steps can be observed in the life of a technology, from invention through innovation, demonstration, commercialization, diffusion, and maturation (see e.g. Grübler et al., 1999). Both investments in R&D and the accumulation of experience through learning by doing play important roles in the mechanisms behind technological change. These forces are complemented by economies of scale. All these drivers of technological change are complementary yet and interlinked (Clarke and Weyant, 2002; Goulder and Mathai, 2000; Sagar and van der Zwaan, 2006; Stoneman, 2013).

Although technological change has received extensive attention and analysis in the context of transformation pathways (for recent examples, see IPCC, 2011; GEA, 2012), a clear systematic understanding of the subject matter is still not available. For this reason, most of the scenarios developed since the 1970s for energy and climate change analysis make exogenous assumptions about the rate of technological change. Only since the late 1990s has the effect of induced innovation been considered in a subset of integrated models used for the development of these scenarios (such as in Messner, 1997; Goulder and Schneider, 1999; van der Zwaan et al., 2002; Carraro et al., 2003). This restricted treatment is due to limitations in the ability to represent the complexity of technological change, and also results from the incomplete empirical evidence on the magnitude of the effects of technological change (Popp, 2006b). More recently, empirical data on technological change have been incorporated in some integrated models (see e.g., Fisher-Vanden, 2008), which advances the endogenous representation of technological progress. Unsettled issues remain, however, including the proper accounting for opportunity costs of climate-related knowledge generation, the treatment of knowledge spillovers and appropriability, and the empirical basis for parameterizing technological relationships (Gillingham et al., 2008).

The relation between mitigation and innovation, and the presence of market failures associated with both, raises the question of the proper combination of innovation and mitigation policy for reducing GHG emissions over the long term. The modelling literature broadly indicates that relying solely on innovation policies would not be sufficient to stabilize GHG concentrations (see e.g. Bosetti et al., 2011; Kalkuhl et al., 2013), as evidenced by the fact that although most reference scenarios assume substantial technological change, none of them lead to emissions reductions on the level of those needed to bring CO_2eq concentrations to levels such as 650 ppm CO_2eq or below by 2100 (see Section 6.3.2). Climate policies such as carbon pricing could induce significant technological change, provided the policy commitment is credible, long term, and sufficiently strong (Popp, 2006a; Bosetti et al., 2011), while at the same time contributing to emission reductions. The positive effect of climate policies on technological change, however, does not necessarily obviate the need for specific policies aimed at incentivizing R&D investments. Market failures associated with innovation provide the strongest rationale for subsidizing R&D (see Section 15.6).

The joint use of R&D subsidies and climate policies has been shown to possibly generate further advantages, with some studies indicating benefits of the order of 10–30 % overall climate control cost reductions (D. Popp, 2006; V. Bosetti et al., 2011). Climate-specific R&D instruments can step up early innovation and ultimately reduce mitigation costs (Gerlagh et al., 2009), although R&D subsidies could raise the shadow value of CO_2 in the short term because of rebound effects from stimulating innovation (Otto and Reilly, 2008) (See Section 6.3.6.5 for further discussion of combining policy instruments to reduce aggregate mitigation costs). In the absence of explicit efforts to address innovation market failures, carbon taxes might be increased or differentiated across regions to indirectly address the under provision of R&D (Golombek and Hoel, 2008; Hart, 2008; Greaker and Pade, 2009; Heal and Tarui, 2010; De Cian and Tavoni, 2012).

Although there is no definitive conclusion on the subject matter, several studies suggest that the benefits of increased technological change for climate change mitigation may be sufficiently high to justify upfront investments and policy support in innovation and diffusion of energy efficiency and low-carbon mitigation technologies (see e.g. Dowlatabadi, 1998; Newell et al., 1999; Nordhaus, 2002; Buonanno et al., 2003; Gerlagh and van der Zwaan, 2003). For example, it has been suggested that the current rates of investments are relatively low and that an average increase several times from current clean energy R&D expenditures may be closer towards optimality to stabilize GHG concentrations (Popp, 2006a; Nemet and Kammen, 2007; Bosetti et al., 2009a; IEA, 2010a; Marangoni and M. Tavoni, 2014) (Table 6.6). Bridging a possible 'R&D gap' is particularly important and challenging, given that public energy R&D investments in OECD countries have generally been decreasing as a share of total research budgets over the past 30 years (from 11 % down to 4 %, according to recent International Energy Agency (IEA) R&D statistics). On the other hand, in the private sector the rate of innovation (if measured by clean energy patents) seems to have accelerated over the past 10 years.

An unequivocal call for energy innovation policy can be questioned, however, when all inventive activities are accounted for. It might also not be straightforward to determine the overall effect of mitigation policy on technological innovation, since low-carbon energy R&D may crowd out other inventive activity and result in lower overall welfare (Goulder and Schneider, 1999). The degree of substitutability between different inputs of production has been shown to drive the outcome of scenarios from integrated models (Otto et al., 2008; Acemoglu et al., 2009; Carraro et al., 2010). Innovation is found to play an important role in attempts to hedge against future uncertainties such as related to climate change impacts, technological performance and policy implementation (Loschel, 2002; Bohringer and Löschel, 2006; Baker and Shittu, 2008; Bosetti and Tavoni, 2009).

6.5.2 Integrating societal change

Individual behaviour, social preferences, historical legacies, and institutional structures can influence the use of technologies and mitigation more generally. Technological transitions necessarily encompass more than simply improving and deploying technology. Because they co-evolve with technologies, social determinants of individual and collective behaviours can be either causes or consequences of transformation pathways. Moreover, governance and policies can influence these factors and thereby affect transformation pathways. This more complex framing of transformation pathways implies the need for a broader perspective on mitigation that explicitly considers the obstacles to deployment and mitigation more generally.

Research on these societal change elements is analytically diverse and often country-specific, which complicates comparative modelling exercises of the type reviewed in this chapter. The difficulty in representing these processes in models has meant that societal change research has often been divorced from the literature on transformation pathways. However, significant bodies of literature show how societal changes can affect the costs and acceptability of mitigation, and the interactions of climate policies and other dimensions of public policies beyond the energy sector.

Non-optimal or real world institutional conditions can influence how technological pathways evolve even under an economy-wide price on carbon. Because of the heterogeneity of the carbon impact of different sectors, the impact of a carbon price differs widely across sectors (Smale et al., 2006; Houser et al., 2009; Fischer and Fox, 2011; Monjon and Quirion, 2011) Demailly et al., 2008). Even in less energy-intensive sectors, pre-existing characteristics in the national econ-

Table 6.6 | Preliminary findings on energy efficiency and clean energy R&D investments, as suggested in the literature to date, and as needed to attain concentration goals. For reference, current public R&D expenditures are approximately 10 Billion USD/yr.

Study	Foreseen total clean energy R&D investments	Notes
Nemet and Kammen (2007) based on Davis and Owens (2003)	17–27 Billion USD/yr	For the period 2005–2015
IEA (2010a)	50–100 Billion USD/yr	To achieve the 'Blue Map' scenario in 2050. Roughly half of the investments are reserved for advanced vehicle R&D.
Bosetti et al. (2009a)	70–90 Billion USD/yr	Average to 2050 for a range of climate concentration goals. A large share is reserved for low-carbon fuel R&D.

omy—such as inflexible labour markets—can complicate the deployment of technologies (Guivarch et al., 2011). A further obstacle is the uneven impacts of a carbon price on household purchasing power, particularly for lower-income brackets (Combet et al., 2010; Grainger and Kolstad, 2010).

Policy uncertainty can have implications for low-carbon technology investment. High levels of uncertainty force risk-averse firms not to adopt technologies by merit order in terms of net present value (Kahneman and Tversky, 1979; Pindyck, 1982; Majd and Pindyck, 1987). Hallegatte et al. (2008) show the importance of the difference in investment rules in a managerial economy (Roe, 1994) and a shareholder economy (Jensen, 1986). Hadjilambrinos (2000) and Finon and Romano (2009) show how differences in regulatory regimes may explain differences in technological choices in the electricity industries. Bosetti et al. (2011) show that investment uncertainty increases the costs and reduces the pace of transformation pathways. Perceived policy risks can not only dampen investment but can also encourage perverse outcomes such as non-additionality in the CDM (Hultman et al., 2012b). This raises the potential for linking mitigation policies, energy sector regulatory reforms, and financial policies to increase the risk-averse returns of mitigation investments (Hourcade and Shukla, 2013).

Changes in institutional structures will be required to facilitate the technological change envisaged in the scenarios reviewed in this chapter. Historically, political and institutional pre-conditions, changing decision routines, and organizational skills help explain why countries with similar dependence on oil imports adopted very different energy responses to oil shocks (Hourcade and Kostopoulou, 1994; Hultman et al., 2012a). Similar issues arise in a low-carbon transition. New policies and institutional structures might be developed to manage infrastructures such as those associated with large quantities of intermittent resources on the electric grid, CO_2 transport and storage, dispersed generation or storage of electricity, or nuclear waste and materials.

Although modelling exercises have been able to assess the possible changes in the energy supply portfolio and the pressures to deploy energy efficiency technologies, such changes are difficult in practice to separate from the evolution of preference and lifestyles. The literature on energy-efficiency investments highlights the frequent incongruity between perceived economic benefits for energy efficiency and actual consumer behaviour that seems often to ignore profitable investments. Such behaviour has been shown to stem from perceived unreliability, unfounded expectations for maintenance, information failures, property rights, split incentives, and differentiation across income.

Finally, social factors influence the changes in the way energy systems couple with other large-scale systems of production such as the built environment, transportation, and agriculture. The way that energy is used and consumed in urban areas (such as in transportation, heating, and air-conditioning) is often driven by the structure and form of the urban infrastructure (Leck, 2006). Recent modelling exercises demonstrated the tradeoff between commuting costs and housing costs and their impact on the urban sprawl and the mobility needs (Gusdorf and Hallegatte, 2007; Gusdorf et al., 2008). In many cases, the price of real estate is as powerful a driver of mobility demand as the price of transportation fuel, and therefore affects the price of carbon needed for meeting a given climate objective (Waisman et al., 2012; Lampin et al., 2013). The transport contribution to carbon can be affected by, for example, just-in-time processes and geographical splits of the productive chains (Crassous and Hourcade, 2006).

6.6 Sustainable development and transformation pathways, taking into account differences across regions

Averting the adverse social and environmental effects of climate change is fundamental to sustainable development (WCED, 1987, and Chapter 4). Yet, climate change is but one of many challenges facing society in the 21st century. Others include, for instance, providing access to clean, reliable, and affordable energy services to the world's poorest; maintaining stable and plentiful employment opportunities; limiting air pollution, health damages, and water impacts from energy and agriculture; alleviating energy security concerns; minimizing energy-driven land use requirements and biodiversity loss; and maintaining the security of food supplies. A complex web of interactions and feedback effects links these various policy objectives, all of which are important for sustainable development (see Section 4.8 and Table 4.1).

Implementation of mitigation policies and measures therefore may be adequately described within a multi-objective framework and may be aligned with other objectives to maximize synergies and minimize tradeoffs. Because the relative importance of individual objectives differs among diverse stakeholders and may change over time, transparency on the multiple effects that accrue to different actors at different points of time is important for decision making (see Sections 2.4, 3.6.3, 3.7.1, and 4.8).

Although the scientific literature makes very clear that a variety of policies and measures exist for mitigating climate change, the impacts of each of these options along other, non-climate dimensions have received less attention. To the extent these mitigation side-effects are positive, they can be deemed 'co-benefits'; if adverse, they imply 'risks' with respect to the other non-climate objectives (see Annex I for definitions). Despite their importance for mitigation strategies, side-effects are often not monetized or even quantified in analyses of climate change (see e.g. Levine et al., 2007).

Table 6.7 | Potential co-benefits (green arrows ↑) and adverse side-effects (orange arrows ↑) of the main sectoral mitigation measures; arrows pointing up/down denote a positive/negative effect on the respective objective or concern; a question mark (**?**) denotes an uncertain net effect. Co-benefits and adverse side-effects depend on local circumstances as well as on the implementation practice, pace, and scale (see Tables 7.3, 8.4, 9.7, 10.5, 11.9, 11.12). Column two provides the contribution of different sectoral mitigation strategies to stringent mitigation scenarios reaching atmospheric CO_2eq concentrations of 430–530 ppm in 2100. The interquartile ranges of the scenario results for the year 2050 show that there is flexibility in the choice of mitigation strategies within and across sectors consistent with low-concentration goals (see Sections 6.4 and 6.8). Scenario results for energy supply and end-use sectors are based on the AR5 Scenario Database (see Annex II.10). For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see Sections 3.9, 6.3.6, 13.2.2.3, and 14.4.2. The uncertainty qualifiers in brackets denote the level of evidence and agreement on the respective effects. Abbreviations for evidence: l = limited, m = medium, r = robust; for agreement: l = low, m = medium, h = high.

Sectoral mitigation measures	Integrated model results for stringent mitigation scenarios			Effect on additional objectives/concerns			
	Deployment[1]		Rate of change [%/yr]	Economic	Social	Environmental	Other
Energy Supply	2010	2050		*For possible upstream effects of biomass supply for bioenergy, see AFOLU.*			
Nuclear replacing coal power	10 EJ/yr	(4–22) *17–47* EJ/yr	(−2–2) *1–4*	↑ Energy security (reduced exposure to fuel price volatility) (**m**/**m**) ↑ Local employment impact (but uncertain net effect) (**l**/**m**) ↑ Legacy cost of waste and abandoned reactors (**m**/**h**)	Health impact via ↓ Air pollution and coal mining accidents (**m**/**h**) ↑ Nuclear accidents and waste treatment, uranium mining and milling (**m**/**l**) ↑ Safety and waste concerns (**r**/**h**)	Ecosystem impact via ↓ Air pollution (**m**/**h**) and coal mining (**l**/**h**) ↑ Nuclear accidents (**m**/**m**)	Proliferation risk (**m**/**m**)
Renewable energy (wind, photovoltaic (PV), concentrated solar power (CSP), hydro, geothermal, bioenergy) replacing coal	62 EJ/yr	(66–125) *194–282* EJ/y	(0.2–2) *3–4*	↑ Energy security (resource sufficiency, diversity in the near/medium term) (**r**/**m**) ↑ Local employment impact (but uncertain net effect) (**m**/**m**) ↑ Irrigation, flood control, navigation, water availability (for multipurpose use of reservoirs and regulated rivers) (**m**/**h**) ↑ Extra measures to match demand (for PV, wind and some CSP) (**r**/**h**)	Health impact via ↓ Air pollution (except bioenergy) (**r**/**h**) ↓ Coal mining accidents (**m**/**h**) ↑ Contribution to (off-grid) energy access (**m**/**l**) **?** Project-specific public acceptance concerns (e.g., visibility of wind) (**l**/**m**) ↑ Threat of displacement (for large hydro) (**m**/**h**)	Ecosystem impact via ↓ Air pollution (except bioenergy) (**m**/**h**) ↓ Coal mining (**l**/**h**) ↑ Habitat impact (for some hydro) (**m**/**m**) ↑ Landscape and wildlife impact (for wind) **m**/**m**) ↓ Water use (for wind and PV) (**m**/**m**) ↑ Water use (for bioenergy, CSP, geothermal, and reservoir hydro) (**m**/**h**)	Higher use of critical metals for PV and direct drive wind turbines (**r**/**m**)
Fossil CCS replacing coal	0 Gt CO_2/yr stored	(0) *4–12* CO_2/yr stored	(0) *NA*	↑ Preservation vs. lock-in of human and ↑ physical capital in the fossil industry (**m**/**m**)	Health impact via ↑ Risk of CO_2 leakage (**m**/**m**) ↑ Upstream supply-chain activities (**m**/**h**) ↑ Safety concerns (CO_2 storage and transport) (**m**/**h**)	↑ Ecosystem impact via upstream supply-chain activities (**m**/**m**) ↑ Water use (**m**/**h**)	Long-term monitoring of CO_2 storage (**m**/**h**)
BECCS replacing coal	0 Gt CO_2/yr	(0) *0–6* CO_2/yr	*NA*	*See fossil CCS where applicable. For possible upstream effect of biomass supply, see agriculture, forestry, and other land use (AFOLU).*			
Methane leakage prevention, capture or treatment	NA	NA	NA	↑ Energy security (potential to use gas in some cases) (**l**/**h**)	↓ Health impact via reduced air pollution (**m**/**m**) ↑ Occupational safety at coal mines (**m**/**m**)	↓ Ecosystem impact via reduced air pollution (**l**/**m**)	

1) Deployment levels for baseline scenarios (in parentheses) and stringent mitigation scenarios leading to 430–530 ppm CO_2eq in 2100 (in italics). Ranges correspond to the 25th to 75th percentile interquartile across the scenario ensemble of the AR5 Scenario Database (for mitigation scenarios, only assuming idealized policy implementation). Data for 2010 is historic data from IEA (2012c, 2012d).

Sectoral mitigation measures	Integrated model results for stringent mitigation scenarios	Effect on additional objectives/concerns: Economic	Social	Environmental	Other
Transport	Scenario results	*For possible upstream effects of low-carbon electricity, see Energy Supply. For possible upstream effects of biomass supply, see AFOLU.*			
Reduction of fuel carbon intensity: electricity, hydrogen (H_2), compressed natural gas (CNG), biofuels	*Interquartile ranges for the whole sector in 2050 with 430–530 ppm CO_2eq concentrations in 2100 (see Figures 6.37 & 6.38):* 1) Final energy low-carbon fuel shares 27–41 % 2) Final energy reduction relative to baseline 20–45 %	↑ Energy security (diversification, reduced oil dependence and exposure to oil price volatility) **(m/m)** ↑ Technological spillovers (e.g., battery technologies for consumer electronics) **(l/l)**	Health impact via urban air pollution by ? CNG, biofuels: net effect unclear **(m/l)** ↓ Electricity, H_2: reducing most pollutants **(r/h)** ↑ Diesel: potentially increasing pollution **(l/m)** ↓ Health impact via reduced noise (electrification and fuel cell LDVs) **(l/m)** ↓ Road safety (silent electric LDVs at low speed) **(l/l)**	Ecosystem impact of electricity and hydrogen via ↓ Urban air pollution **(m/m)** ↑ Material use (unsustainable resource mining) **(l/l)** ? Ecosystem impact of biofuels: *see AFOLU*	
Reduction of energy intensity		↑ Energy security (reduced oil dependence and exposure to oil price volatility) **(m/m)**	↓ Health impact via reduced urban air pollution **(r/h)** ↑ Road safety (via increased crash-worthiness) **(m/m)**	↓ Ecosystem and biodiversity impact via reduced urban air pollution **(m/h)**	
Compact urban form and improved transport infrastructure **Modal shift**		↑ Energy security (reduced oil dependence and exposure to oil price volatility) **(m/m)** ↑ Productivity (reduced urban congestion and travel times, affordable and accessible transport) **(m/h)** ? Employment opportunities in the public transport sector vs car manufacturing jobs **(l/m)**	Health impact for non-motorized modes via ↓ Increased physical activity **(r/h)** ↑ Potentially higher exposure to air pollution **(r/h)** ↓ Noise (modal shift and travel reduction) **(r/h)** ↑ Equitable mobility access to employment opportunities, particularly in developing countries (DCs) **(r/h)** ↑ Road safety (via modal shift and/or infrastructure for pedestrians and cyclists) **(r/h)**	Ecosystem impact via reduced ↓ Urban air pollution **(r/h)** ↓ Land-use competition **(m/m)**	
Journey distance reduction and avoidance		↑ Energy security (reduced oil dependence and exposure to oil price volatility) **(r/h)** ↑ Productivity (reduced urban congestion, travel times, walking) **(r/h)**	↓ Health impact (for non-motorized transport modes) **(r/h)**	Ecosystem impact via ↓ Urban air pollution **(r/h)** ↑ New/shorter shipping routes **(r/h)** ↓ Land-use competition from transport infrastructure **(r/h)**	
Buildings	Scenario results	*For possible upstream effects of fuel switching and RES, see Energy Supply.*			
Fuel switching, incorporation of renewable energy, green roofs, and other measures reducing GHG emissions intensity	*Interquartile ranges for the whole sector in 2050 with 430–530 ppm CO_2eq concentrations in 2100 (see Figures 6.37 & 6.38):* 1) Final energy low-carbon fuel shares 51–60 % 2) Final energy reduction relative to baseline 14–35 %	↑ Energy security **(m/h)** ↑ Employment impact **(m/m)** ↑ Lower need for energy subsidies **(l/l)** ↑ Asset values of buildings **(l/m)**	Fuel poverty (residential) via ↓ Energy demand **(m/h)** ↑ Energy cost **(l/m)** ↓ Energy access (for higher energy cost) **(l/m)** ↑ Productive time for women/children (for replaced traditional cookstoves) **(m/h)**	Health impact in residential buildings via ↓ Outdoor air pollution **(r/h)** ↓ Indoor air pollution (in DCs) **(r/h)** ↓ Fuel poverty **(r/h)** ↓ Ecosystem impact (less outdoor air pollution) **(r/h)** ↑ Urban biodiversity (for green roofs) **(m/m)**	Reduced Urban Heat Island (UHI) effect **(l/m)**
Retrofits of existing buildings (e.g., cool roof, passive solar, etc.) **Exemplary new buildings** **Efficient equipment**		↑ Energy security **(m/h)** ↑ Employment impact **(m/m)** ↑ Productivity (for commercial buildings) **(m/h)** ↑ Lower need for energy subsidies **(l/l)** ↑ Asset values of buildings **(l/m)** ↑ Disaster resilience **(l/m)**	↓ Fuel poverty (for retrofits and efficient equipment) **(m/h)** ↓ Energy access (higher cost for housing due to the investments needed) **(l/m)** ↑ Thermal comfort (for retrofits and exemplary new buildings) **(m/h)** ↑ Productive time for women and children (for replaced traditional cookstoves) **(m/h)**	Health impact via ↓ Outdoor air pollution **(r/h)** ↓ Indoor air pollution (for efficient cookstoves) **(r/h)** ↓ Improved indoor environmental conditions **(m/h)** ↓ Fuel poverty **(r/h)** ↓ Insufficient ventilation **(m/m)** ↓ Ecosystem impact (less outdoor air pollution) **(r/h)** ↓ Water consumption and sewage production **(l/l)**	Reduced UHI effect (retrofits and new exemplary buildings) **(l/m)**
Behavioural changes reducing energy demand		↑ Energy security **(m/h)** ↑ Lower need for energy subsidies **(l/l)**		↓ Health impact via less outdoor air pollution **(r/h)** and improved indoor environmental conditions **(m/h)** ↓ Ecosystem impact (less outdoor air pollution) **(r/h)**	

Sectoral mitigation measures	Integrated model results for stringent mitigation scenarios	Effect on additional objectives/concerns			
		Economic	**Social**	**Environmental**	**Other**
Industry	Scenario results	*For possible upstream effects of low-carbon energy supply (incl CCS), see energy supply and of biomass supply, see AFOLU.*			
CO_2 and non-CO_2 GHG emissions intensity reduction	*Interquartile ranges for the whole sector in 2050 with 430–530 ppm CO_2eq concentrations in 2100 (see Figures 6.37 & 6.38):* 1) Final energy low-carbon fuel shares: 44–57 % 2) Final energy reduction relative to baseline: 22–38 %	↑ Competitiveness and productivity **(m/h)**	↓ Health impact via reduced local air pollution and better work conditions (for perfluorinated compounds (PFCs) from aluminium) **(m/m)**	↓ Ecosystem impact via reduced local air pollution and reduced water pollution **(m/m)** ↑ Water conservation **(l/m)**	
Technical energy efficiency improvements via new processes and technologies		↑ Energy security (via lower energy intensity) **(m/m)** ↑ Employment impact **(l/l)** ↑ Competitiveness and productivity **(m/h)** ↑ Technological spillovers in DCs (due to supply chain linkages) **(l/l)**	↓ Health impact via reduced local pollution **(l/m)** ↑ New business opportunities **(m/m)** ↑ Water availability and quality **(l/l)** ↑ Safety, working conditions and job satisfaction **(m/m)**	Ecosystem impact via ↓ Fossil fuel extraction **(l/l)** ↓ Local pollution and waste **(m/m)**	
Material efficiency of goods, recycling		↓ National sales tax revenue in medium term **(l/l)** ↑ Employment impact in waste recycling market **(l/l)** ↑ Competitiveness in manufacturing **(l/l)** ↑ New infrastructure for industrial clusters **(l/l)**	↓ Health impacts and safety concerns **(l/m)** ↑ New business opportunities **(m/m)** ↓ Local conflicts (reduced resource extraction) **(l/m)**	↓ Ecosystem impact via reduced local air and water pollution and waste material disposal **(m/m)** ↓ Use of raw/virgin materials and natural resources implying reduced unsustainable resource mining **(l/l)**	
Product demand reductions		↓ National sales tax revenue (medium term) **(l/l)**	↑ Wellbeing via diverse lifestyle choices **(l/l)**	↓ Post-consumption waste **(l/l)**	
AFOLU	Scenario results	*Note: co-benefits and adverse side-effects depend on the development context and the scale of the intervention (size).*			
Supply side: Forestry, land-based agriculture, livestock, integrated systems and bioenergy (**marked by** †) **Demand side:** Reduced losses in the food supply chain, changes in human diets, changes in demand for wood and forestry products	Ranges for cumulative land-related emissions reductions relative to baseline for CH_4, CO_2, and N_2O in idealized implementation scenarios with 450 CO_2eq ppm concentrations in 2100 (see Table 11.10): CH_4: 2–18 % CO_2: −104–423 % N_2O: 8–17 %	† Employment impact via ↑ Entrepreneurship development **(m/h)** ↓ Use of less labor-intensive **(m/m)** Technologies in agriculture ↑† Diversification of income sources and access to markets **(r/h)** ↑† Additional income to (sustainable) landscape management **(m/h)** ↑† Income concentration **(m/m)** ↑† Energy security (resource sufficiency) **(m/h)** ↑ Innovative financing mechanisms for sustainable resource management **(m/h)** ↑ Technology innovation and transfer **(m/m)**	↑† Food-crops production through integrated systems and sustainable agriculture intensification **(r/m)** ↓† Food production (locally) due to large-scale monocultures of non-food crops **(r/l)** ↑ Cultural habitats and recreational areas via (sustainable) forest management and conservation **(m/m)** ↑† Human health and animal welfare e.g., through less pesticides, reduced burning practices and practices like agroforestry and silvo-pastoral systems **(m/h)** ↓† Human health when using burning practices (in agriculture or bioenergy) **(m/m)** † Gender, intra- and inter-generational equity via ↑ Participation and fair benefit sharing **(r/h)** ↑ Concentration of benefits **(m/m)**	↑ Provision of ecosystem services via Ecosystem conservation and sustainable management as well as sustainable agriculture **(r/h)** ↑† Large-scale monocultures **(r/h)** ↑† Land use competition **(r/m)** ↑ Soil quality **(r/h)** ↓ Erosion **(r/h)** ↑ Ecosystem resilience **(m/h)** ↑ Albedo and evaporation **(r/h)**	*Institutional aspects:* ↑↓† Tenure and use rights at the local level (for indigenous people and local communities) especially when implementing activities in natural forests **(r/h)** ↑↓ Access to participative mechanisms for land management decisions **(r/h)** ↑ Enforcement of existing policies for sustainable resource management **(r/h)**
Human Settlements and Infrastructure		*For co-benefits and adverse side-effects of compact urban form and improved transport infrastructure, see also Transport.*			
Compact development and infrastructure		↑ Innovation, productivity and efficient resource use and delivery **(r/h)** ↑ Higher rents and property values **(m/m)**	↑ Health from increased physical activity: *see Transport*	↑ Preservation of open space **(m/m)**	
Increased accessibility		↑ Commute savings **(r/h)**	↑ Health from increased physical activity: *see Transport* ↑ Social interaction and mental health **(m/m)**	↑ Air quality and reduced ecosystem and health impacts **(m/h)**	
Mixed land use		↑ Commute savings **(r/h)** ↑↑ Higher rents and property values **(m/m)**	↑ Health from increased physical activity **(r/h)** ↑ Social interaction and mental health **(l/m)**	↑ Air quality and reduced ecosystem and health impacts **(m/h)**	

6.6.1 Co-benefits and adverse side-effects of mitigation measures: Synthesis of sectoral information and linkages to transformation pathways

One source of information on side-effects emerges from literature exploring the nature of individual technological or sectoral mitigation measures. These studies are covered in Chapters 7–12. Based on those assessments, Table 6.7 provides an aggregated but qualitative overview of the potential co-benefits and adverse side-effects that could be realized if certain types of mitigation measures are enacted in different sectors: energy supply-side transformations; technological and behavioural changes in the transport, buildings, and industry end-use sectors; and modified agriculture, forestry, and land use practices. These co-benefits and adverse side-effects can be classified by the nature of their sustainable development implications: economic, social, or environmental (see Sections 4.2 and 4.8 for a discussion of the three pillars of sustainable development). Other types of impacts are also possible and are highlighted in the table where relevant.

Whether or not any of these side-effects actually materialize, and to what extent, will be highly case- and site-specific, as they will depend importantly on local circumstances and the scale, scope, and pace of implementation, among other factors. Measures undertaken in an urbanized area of the industrialized world, for instance, may not yield the same impacts as when enacted in a rural part of a developing country (Barker et al., 2007). Such detailed considerations are not reflected in Table 6.7, which is meant to give an aggregated sense of the potential co-benefits and adverse side-effects throughout the world when mitigation policies are in place. Details are discussed in each of the respective sectoral chapters (see Chapters 7–12). Note that in addition to the *qualitative* information on potential side-effects summarized below, Table 6.7 also provides *quantitative* information for each sector regarding the mid-century contribution of the respective (group of) mitigation measures to reach stringent mitigation goals (see Sections 6.8, 7.11, and 11.9 for the underlying data).

The compilation of sectoral findings in Table 6.7 suggests that the potential for co-benefits clearly outweighs that of adverse side-effects in the case of energy end-use mitigation measures (transport, buildings, and industry), whereas the evidence suggests this may not be the case for all supply-side and AFOLU measures. Although no single category of mitigation measures is completely devoid of risk, Table 6.7 highlights that certain co-benefits are valid across all sectors. For instance, by contributing to a phaseout of conventional fossil fuels, nearly all mitigation measures have major health and environmental benefits for society, owing to significant reductions in both outdoor and indoor air pollution, and lead to improved energy security at the national level for most countries. In addition to the many sector-specific co-benefits and adverse side-effects, sectoral employment and productivity gains, technological spillovers, and more equitable energy/mobility access offer examples of co-benefits that are possible across all demand sectors. While energy demand reductions additionally mitigate risks associated with energy supply technologies (see also Rogelj et al., 2013b), the upstream effects of fuel switching are more complex and depend to a large extent on local circumstances (see Section 7.11).

Moreover, while nearly all mitigation measures for reducing (fuel) carbon and energy intensity have higher up-front investment requirements than conventional technologies, their often lower operating costs, and sometimes even lifecycle costs, can contribute to reduced energy service prices for consumers, depending on local and national institutional settings (see Section 7.9.1). If, on the other hand, energy prices rise as a consequence, so do the political challenges of implementation, such as those associated with the provision of universal energy access and associated economic, social, environmental, and health risks for the poorest members of society (Markandya et al., 2009; Sathaye et al., 2011; Rao, 2013). Well-designed policies are thus important to avoid perverse incentives of climate policies, including increasing traditional biomass use for heating and cooking (see Bollen et al., 2009a, b, and Section 9.7.1).

In addition to furthering the achievement of various global goals for sustainability, namely those of the major environmental conventions (e.g., the United Nations' Convention to Combat Desertification (UNCCD, 2004), Convention on Biological Diversity (CBD, 1992), 'Sustainable Energy for All' initiative, and the Millennium Development Goals (MDG)), mitigation can potentially yield positive side-effects in the impacts, adaptation, and vulnerability (IAV) dimensions (see Section 6.6.2.5 and 11.7, Haines et al., 2009; Rogelj et al., 2013c). For instance, decentralized renewable energy systems can help to build adaptive capacity in rural communities (Venema and Rehman, 2007), and sustainable agricultural practices (e.g., conservation tillage and water management) can improve drought resistance and soil conservation and fertility (Uprety et al., 2012).

6.6.2 Transformation pathways studies with links to other policy objectives

As indicated above, the overall nature and extent of the co-benefits and risks arising from global transformation pathways depends importantly on which mitigation options are implemented and how. The full systems-level welfare impacts for multi-objective decision making are therefore best viewed from an integrated perspective that permits the full accounting of the impacts of each of the objectives on social welfare (see Section 3.5.3) (Bell et al., 2008; Sathaye et al., 2011; Rao et al., 2013). Taking such a perspective poses a significant challenge, since the costs of mitigation need to be weighed against the multiple benefits and adverse side-effects for the other objectives. To complicate matters further, these other objectives are traditionally measured in different units (e.g., health benefits of reduced air pollution in terms of deaths avoided). In addition, combining the different objectives into a single overall welfare formulation implies subjective choices about the ranking or relative importance of policy priorities. Such a ranking is highly dependent on the policy context (see Sections 2.4 and 3.6.3).

Since AR4, a number of scenario studies have been conducted to shed light on the global implications of transformation pathways for other objectives. Earlier scenario literature primarily focused on the health and ecosystem benefits of mitigation via reduced air pollution; some evidence of co-benefits for employment and energy security was also presented in AR4. More recent studies have broadened their focus to include energy security, energy access, biodiversity conservation, water, and land-use requirements (see Section 11.13.7 for a review of scenario studies focusing on water and land use and implications for food security). Many of these newer analyses use globally consistent methods, meaning they employ long-term, multi-region frameworks that couple models of both bio-geophysical and human processes, thereby permitting the consideration of targeted policies for the additional objectives in their own right. While the majority of these studies focus on two-way interactions (e.g., the effect of mitigation on air pollution in a given country or across groups of countries—or vice versa), a few recent analyses have looked at three or more objectives simultaneously (Section 6.6.2.7). Important to note in this context is that many of the non-technical measures listed in Table 6.7 (e.g., behavioral changes) are not fully taken into account by models, though the state-of-the-art continues to improve.

6.6.2.1 Air pollution and health

Greenhouse gas and air pollutant emissions typically derive from the same sources, such as power plants, factories, and cars. Hence, mitigation strategies that reduce the use of fossil fuels typically result in major cuts in emissions of black carbon (BC), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and mercury (Hg), among other harmful species. Together with tropospheric ozone and its precursors (mainly deriving from AFOLU and fossil fuel production/transport processes), these pollutants separately or jointly cause a variety of detrimental health and ecosystem effects at various scales (see Section 7.9.2). The magnitude of these effects varies across pollutants and atmospheric concentrations (as well as the concentrations of pollutants created via further chemical reactions) and is due to different degrees of population exposure, whether indoor or outdoor or in urban or rural settings (see Barker et al., 2007; Bollen et al., 2009b; Markandya et al., 2009; Smith et al., 2009; Sathaye et al., 2011; GEA, 2012). The term 'fine particulate matter ($PM_{2.5}$)' is frequently used to refer to a variety of air pollutants that are extremely small in diameter and therefore cause some of the most serious health effects.

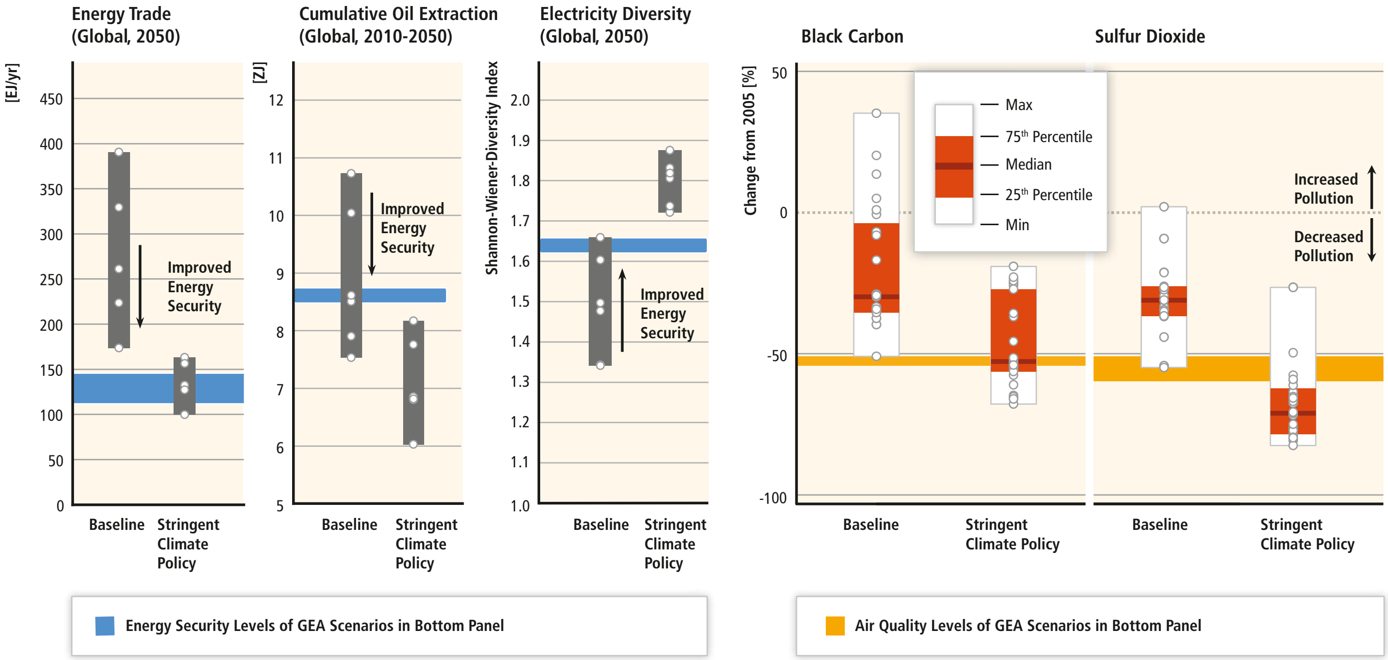
The literature assessed in AR4 focused on air pollution reductions in individual countries and regions, pointing to large methodological differences in, for example, the type of pollutants analyzed, sectoral focus, and the treatment of existing air pollution policy regimes. As confirmed by recent literature (Friel et al., 2009; Wilkinson et al., 2009; Woodcock et al., 2009; Markandya et al., 2009; Haines et al., 2009; Smith et al., 2009; Nemet et al., 2010), AR4 showed that the monetized air quality co-benefits from mitigation are of a similar order of magnitude as the mitigation costs themselves (see Sections 3.6.3 and 5.7.1). For instance, taking into account new findings on the relationship between chronic mortality and exposure to PM and ozone as well as the effect of slowing climate change on air quality, West et al. (2013) calculate global average monetized co-benefits of avoided mortality of 55–420 USD_{2010}/tCO_2. They find that the values for East Asia far exceed the marginal mitigation costs in 2030. (See Section 5.7 for a broader review of this issue, as well as a discussion of the importance of baseline conditions for these results.) Furthermore, it has been noted that reductions in certain air pollutants can potentially increase radiative forcing (see Sections 1.2.5, 5.2, and WG I Chapter 7). This is an important adverse side-effect, and one that is not discussed here due to the lack of scenario studies addressing the associated tradeoff between health and climate benefits.

The available evidence indicates that transformation pathways leading to 430–530 ppm CO_2eq in 2100 will have major co-benefits in terms of reduced air pollution (Figure 6.33, top right panel). Recent integrated modelling studies agree strongly with earlier findings by van Vuuren et al. (2006) and Bollen et al. (2009a) in this regard. For example, Rose et al. (2014b) find that national air pollution policies may no longer be binding constraints on pollutant emissions depending on the stringency of climate policies. In China, for instance, mitigation efforts consistent with a global goal of 3.7 W/m^2 (2.8 W/m^2) in 2100 result in SO_2 emissions 15 to 55 % (25–75 %) below reference levels by 2030 and 40 to 80 % (55–80 %) by 2050. Chaturvedi and Shukla (2014) find similar results for India. Globally, Rafaj et al. (2013b) calculate that stringent mitigation efforts would simultaneously lead to near-term (by 2030) reductions of SO_2, NO_x, and $PM_{2.5}$ on the order of 40 %, 30 %, and 5 %, respectively, relative to a baseline scenario. Riahi et al. (2012) find that by further exploiting the full range of opportunities for energy efficiency and ensuring access to modern forms of energy for the world's poorest (hence less indoor/household air pollution), the near-term air pollution co-benefits of mitigation could be even greater: 50 % for SO_2, 35 % for NO_x, and 30 % for $PM_{2.5}$ by 2030. Additionally, Amann et al. (2011) and Rao et al. (2013) find significant reductions in air quality control costs due to mitigation policies (see Section 6.6.2.7). Riahi et al. (2012) further estimate that stringent mitigation efforts can help to reduce globally aggregated disability-adjusted life years (DALYs) by more than 10 million by 2030, a decrease of one-third compared to a baseline scenario. The vast majority of these co-benefits would accrue in urban households of the developing world. Similarly, West et al. (2013) find that global mitigation (RCP 4.5) can avoid 0.5 ± 0.2, 1.3 ± 0.5, and 2.2 ± 0.8 million premature deaths in 2030, 2050, and 2100, relative to a baseline scenario that foresees decreasing PM and ozone (O_3) concentrations. Regarding mercury, Rafaj et al. (2013a) show that under a global mitigation regime, atmospheric releases from anthropogenic sources can be reduced by 45 % in 2050, relative to a a baseline scenario without climate measures.

Co-Benefits of Climate Change Mitigation for Energy Security and Air Quality

LIMITS Model Inter-Comparison
Impact of Climate Policy on Energy Security

IPCC AR5 Scenario Ensemble
Impact of Climate Policy on Air Pollutant Emissions (Global, 2005-2050)



Policy Costs of Achieving Different Objectives

Global Energy Assessment Scenario Ensemble (n=624)

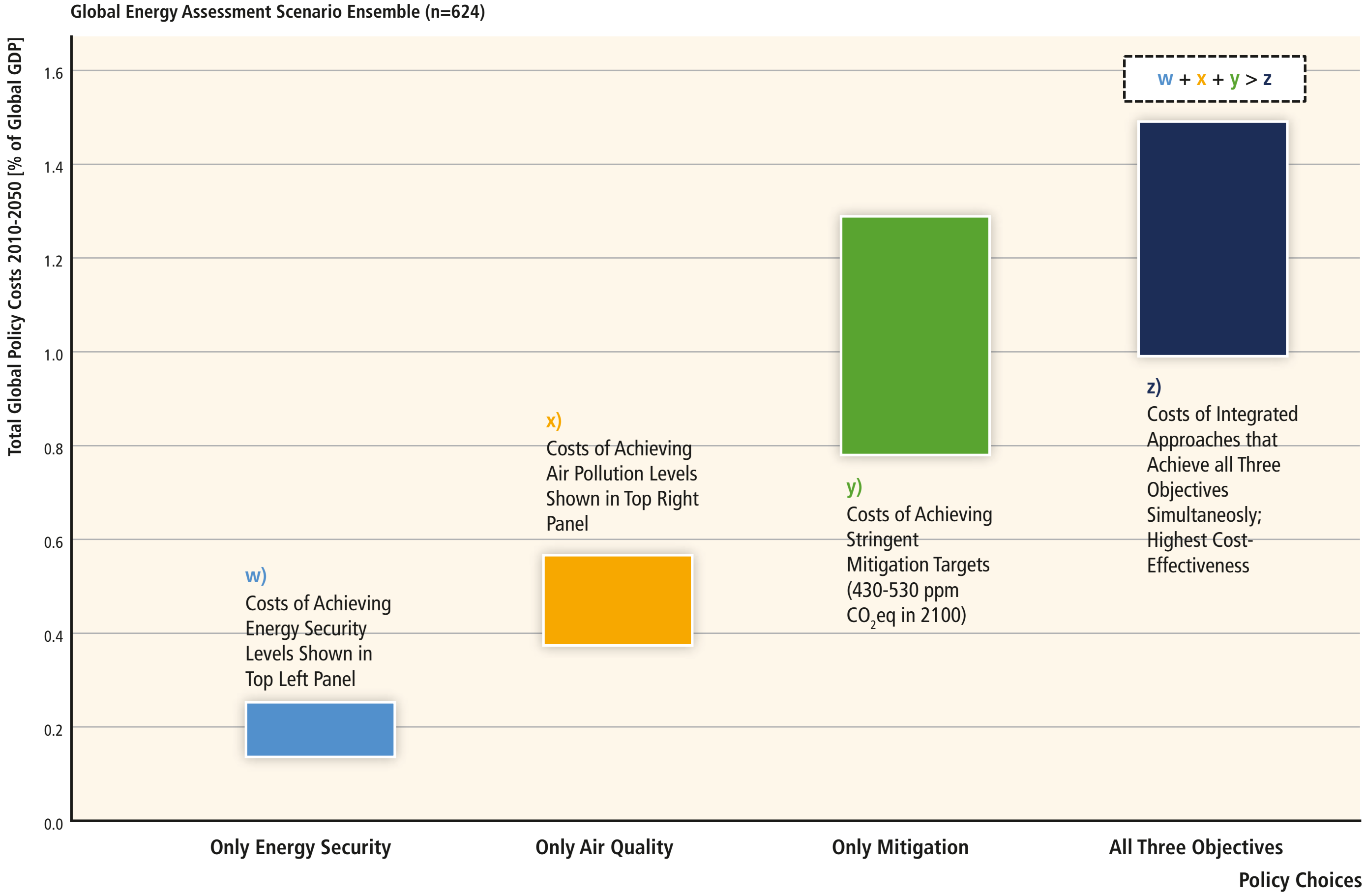


Figure 6.33 | Co-benefits of mitigation for energy security and air quality in scenarios with stringent climate policies (reaching 430–530 ppm CO_2eq concentrations in 2100). Upper panels show co-benefits for different energy security indicators and air pollutant emissions. Lower panel shows related global policy costs of achieving the energy security, air quality, and mitigation objectives, either alone (w, x, y) or simultaneously (z). Integrated approaches that achieve these objectives simultaneously show the highest cost-effectiveness due to synergies (w+x+y>z). Policy costs are given as the increase in total energy system costs relative to a no-policy baseline; hence, they only capture the mitigation component and do not include the monetized co-benefits of, for example, reduced health impacts or climate damages. In this sense, costs are indicative and do not represent full uncertainty ranges. Sources: LIMITS model intercomparison (Jewell et al., 2013; Tavoni et al., 2013), WGIII AR5 Scenario Database (Annex II.10, includes only scenarios based on idealized policy implementation and full technology availability), Global Energy Assessment (GEA) scenarios (Riahi et al., 2012; McCollum et al., 2013a).

Several studies published since AR4 have analyzed the potential climate impacts of methane mitigation and local air pollutant emissions control (West et al., 2006, 2007; Shine et al., 2007; Reilly et al., 2007; Ramanathan and Carmichael, 2008; Jerrett et al., 2009; Anenberg et al., 2012). For instance, Shindell et al. (2012) identify 14 different methane and BC mitigation measures that, in addition to slowing the growth in global temperatures in the medium term (~0.5 °C lower by 2050, central estimate), lead to important near-term (2030) co-benefits for health (avoiding 0.7 to 4.7 million premature deaths from outdoor air pollution globally) and food security (increasing annual crop yields globally by 30 to 135 million metric tons due to ozone reductions; see Section 11.13.7 for a further discussion of the relationship between mitigation and food security). Smith and Mizrahi (2013) also acknowledge the important co-benefits of reducing certain short-lived climate forcers (SLCF) but at the same time conclude that (1) the near-to-medium term climate impacts of these measures are likely to be relatively modest (0.16 °C lower by 2050, central estimate; 0.04–0.35 °C considering the various uncertainties), and (2) the additional climate benefit of targeted SLCF measures after 2050 is comparatively low.

6.6.2.2 Energy security

A number of analyses have studied the relationship between mitigation and energy security. The assessment here focuses on energy security concerns that relate to (1) the sufficiency of resources to meet national energy demand at competitive and stable prices, and (2) the resilience of energy supply (see Section 7.9.1 for a broader discussion). A number of indicators have been developed to quantitatively express these concerns (Kruyt et al., 2009; Jewell, 2011; Jewell et al., 2014). The most common indicators of sufficiency of energy supply are energy imports (see SRREN (IPCC, 2011) Figure 9.6) and the adequacy of the domestic resource base (Gupta, 2008; Kruyt et al., 2009; Le Coq and Paltseva, 2009; IEA, 2011; Jewell, 2011; Jewell et al., 2013). Resilience of energy systems is commonly measured by the diversity of energy sources and carriers (Stirling, 1994, 2010; Grubb et al., 2006; Bazilian and Roques, 2009; Skea, 2010) and the energy intensity of GDP (Gupta, 2008; Kruyt et al., 2009; Jewell, 2011; Cherp et al., 2012).

Recent studies show that mitigation policies would likely increase national energy sufficiency and resilience (Figure 6.33, top left panel). Mitigation policies lead to major reductions in the import dependency of many countries, thus making national and regional energy systems less vulnerable to price volatility and supply disruptions (Criqui and Mima, 2012; Shukla and Dhar, 2011; Jewell et al., 2013). One multi-model study finds that in stringent mitigation scenarios, global energy trade would be 10–70 % lower by 2050 and 40–74 % by 2100 than in the baseline scenario (Jewell et al., 2013). Most of the decrease in regional import dependence would appear after 2030 since mitigation decreases the use of domestic coal in the short term, which counteracts the increase in domestic renewables (Akimoto et al., 2012; Jewell et al., 2013). At the same time mitigation leads to much lower extraction rates for fossil resources (Kruyt et al., 2009; Jewell et al., 2013; McCollum et al., 2014a). The IEA, for example, finds that rapid deployment of energy efficiency technologies could reduce oil consumption by as much as 13 million barrels a day (IEA, 2012). Mitigation actions could thus alleviate future energy price volatility, given that perceptions of resource scarcity are a key driver of rapid price swings. This would mean that domestic fossil resources could act as a 'buffer of indigenous resources' (Turton and Barreto, 2006). Improved energy security of importers, however, could adversely impact the 'demand security' of exporters (Luft, 2013); indeed, most of the modeling literature indicates that climate mitigation would decrease oil export revenues of oil exporters (IEA, 2009; Haurie and Vielle, 2010; Bauer et al., 2014a, 2014b; Tavoni et al., 2013; McCollum et al., 2013a). However, three recent studies argue that if the cost of alternatives to conventional oil is high enough, conventional oil exporters could benefit from climate policies, particularly in the near term (Persson et al. 2007; Johansson et al. 2009; Nemet and Brandt, 2012). Although there is broad agreement in the literature about the overall negative effect on oil export revenues, the distribution of this effect will differ between exporters of conventional vs unconventional oil exporters. (See Section 6.3.6.6 regarding the impacts that these trade shifts would have on major energy exporters.)

Studies also indicate that mitigation would likely increase the resilience of energy systems (Figure 6.33, top left panel). The diversity of energy sources used in the transport and electricity sectors would rise relative to today and to a baseline scenario in which fossils remain dominant (Grubb et al., 2006; Riahi et al., 2012; Cherp et al., 2014; Jewell et al., 2013). Additionally, energy trade would be much less affected by fluctuations in GDP growth and by uncertainties in fossil resource endowments and energy demand growth (Cherp et al., 2014; Jewell et al., 2013). These developments (mitigation and energy-efficiency improvements) would make energy systems more resilient to various types of shocks and stresses and would help insulate economies from price volatility and supply disruptions (see Chapters 8–10).

6.6.2.3 Energy access

According to the literature, providing universal energy access (see Section 7.9.1 for a broader discussion) would likely result in negligible impacts on GHG emissions globally (PBL, 2012; Riahi et al., 2012). Rogelj et al (2013c) find that the United Nation's (UN) energy access goals for 2030 are fully consistent with stringent mitigation measures while other scenario analyses indicate that deployment of renewable energy in LDCs can help to promote access to clean, reliable, and affordable energy services (Kaundinya et al., 2009; Reddy et al., 2009). In addition, a number of recent integrated modelling studies ensure, by design, that developing country household final energy consumption levels are compatible with minimal poverty thresholds (Ekholm et al., 2010a; van Ruijven et al., 2011; Daioglou et al., 2012; Narula et al., 2012; Krey et al., 2012). An important message from these studies is that the provision of energy access in developing countries should not be confused with broader economic growth. The latter could have a pronounced GHG affect, particularly in today's emerging economies (see Section 6.3.1.3).

The primary risk from mitigation is that an increase in energy prices for the world's poor could potentially impair the transition to universal energy access by making energy less affordable (see Sections 6.6.1 and 7.9.1). A related concern is that increased energy prices could also delay structural changes and the build-up of physical infrastructure (Goldemberg et al., 1985; Steckel et al., 2013; Jakob and Steckel, 2014). Isolating these effects has proven to be difficult in the integrated modelling context because these models typically aggregate consumption losses from climate policies (see Section 6.3.6).

6.6.2.4 Employment

The potential consequences of climate policies on employment are addressed in the scientific literature in different ways. One strand of literature analyzes the employment impacts associated with the deployment of specific low-carbon technologies, such as renewables or building retrofits (see Sections 7.9.1 and 9.7.2.1). This literature often finds a significant potential for *gross* job creation, either directly or indirectly; however, a number of issues are left unresolved regarding the methodologies used in computing those impacts on one hand and the gap between this potential and *net* employment impacts in a particular sector on the other hand (see Wei et al., 2010). The net effect is typically addressed in general equilibrium literature. Although many integrated models used to develop long-term scenarios are general equilibrium models, they usually assume full employment and are therefore not well-suited to addressing gross versus net employment-related questions.

According to the literature, employment benefits from mitigation depend on the direction and strength of income/output and substitution impacts of mitigation. These impacts are governed by two interrelated sets of factors related to mitigation technologies and general equilibrium effects. One set involves the characteristics of mitigation technologies, including (1) their costs per job created, which determines the crowding out of jobs in other sectors when capital is constrained (Frondel et al., 2010); (2) the portion of the low-carbon technologies that is imported, which determines domestic job creation and the net positive impact on the trade balance; and (3) the availability of skills in the labor force, as well as its capacity to adapt (Babiker and Eckaus, 2007; Fankhauser et al., 2008; Guivarch et al., 2011), which determines the pace of job creation and the real cost of low-carbon technology deployment in terms of increased wages due to skilled labor scarcities.

A second set of factors encompasses all the general equilibrium effects, some of which are triggered by the above parameters and others by the net income effects of higher carbon prices (see Section 3.6.3). Recycling the revenues from carbon pricing and subsequently lowering labor taxes changes the relative prices of labor and energy (and to a lesser extent the costs of production inputs), which in turn leads to a redirection of technology choices and innovation towards more labor-intensive techniques. In addition, by contributing to higher energy costs, climate policies change the relative prices of energy- and non-energy intensive goods and services, thereby causing households to consume more of the latter. These mechanisms operate differently in developed, emerging, and developing economies, particularly with respect to the various forms of informal labor. Some of the mechanisms operate over the medium (more labor-intensive techniques) and long term (structural change) (Fankhauser et al., 2008). Others, however, operate over the short term and might therefore be influenced by near-term mitigation policies.

6.6.2.5 Biodiversity conservation

The concept of biodiversity can be interpreted in different ways. Measuring it therefore presents a challenge. One indicator that has been used in the integrated modelling literature for assessing the biodiversity implications of global transformation pathways is that of mean species abundance (MSA), which uses the species composition and abundance of the original ecosystem as a reference situation. According to PBL (2012), globally averaged MSA declined continuously from approximately 76 % in 1970 to 68 % in 2010 (relative to the undisturbed states of ecosystems). This was mostly due to habitat loss resulting from conversion of natural systems to agriculture uses and urban areas.

The primary biodiversity-related side-effects from mitigation involve the potentially large role of reforestation and afforestation efforts and of bioenergy production. These elements of mitigation strategy could either impose risks or lead to co-benefits, depending on where and how they are implemented (see Table 6.7). The integrated modelling literature does not at this time provide an explicit enough treatment of these issues to effectively capture the range of transformation pathways. One study (PBL, 2012) suggests that it is possible to stabilize average global biodiversity at the 2020/2030 level (MSA =

65 %) by 2050 even if land-use mitigation measures are deployed. Such an achievement represents more than a halving of all biodiversity loss projected to occur by mid-century in the baseline scenario and is interpreted to be in accordance with the Aichi Biodiversity Targets (CBD, 2010). Of critical importance in this regard are favourable institutional and policy mechanisms for reforestation/afforestation and bioenergy that complement mitigation actions (as described in Section 11.13).

6.6.2.6 Water use

The last decades have seen the world's freshwater resources come under increasing pressure. Almost three billion people live in water-scarce regions (Molden, 2007), some two billion in areas of severe water stress in which demand accounts for more than 40 % of total availability (PBL, 2012). Water withdrawals for energy and industrial processes (currently 20 % globally) and municipal applications (10 %) are projected to grow considerably over the next decades, jointly surpassing irrigation (70 %) as the primary water user by 2050 (Alcamo and Henrichs, 2002; Shiklomanov and Rodda, 2003; Molden, 2007; Fischer et al., 2007; Shen et al., 2008; Bruinsma, 2011). This growth is projected to be greatest in areas already under high stress, such as South Asia.

Renewable energy technologies such as solar PV and wind power will reduce freshwater withdrawals for thermal cooling relative to fossil alternatives. On the other hand, CCS and some forms of renewable energy, especially bioenergy, could demand a significant amount of water (see Table 6.7 and Section 7.9.2). For bioenergy in particular, the overall effect will depend importantly on which feedstocks are grown, where, and if they require irrigation (see Section 11.13.7). Similarly, reforestation and afforestation efforts, as well as attempts to avoid deforestation, will impact both water use and water quality. The net effects could be either positive (Townsend et al., 2012) or negative (Jackson et al., 2005), depending on the local situation (see Section 11.7).

When accounting for the system dynamics and relative economics between alternative mitigation options (both in space and time), recent integrated modelling scenarios generally indicate that stringent mitigation actions, combined with heightened water-use efficiency measures, could lead to significant reductions in global water demand over the next several decades. PBL (2012), for instance, calculates a 25 % reduction in total demand by 2050, translating to an 8 % decline in the number of people living in severely water-stressed regions worldwide. Other studies by Hanasaki et al. (2013) and Hejazi et al. (2013) find the co-benefits from mitigation to be of roughly the same magnitude: reductions of 1.0–3.9 % and 1.2–5.5 %, respectively, in 2050. Hejazi et al. (2013) note, however, that water scarcity could be exacerbated if mitigation leads to more intensive production of bioenergy crops. In contrast, Akimoto et al. (2012) find that stringent mitigation increases water-stressed populations globally (+3 % in 2050) as a result of decreases in annual water availability in places like South Asia.

6.6.2.7 Integrated studies of multiple objectives

Integrated scenario research is just beginning to assess multiple sustainable development objectives in parallel. This emerging literature generally finds that mitigation goals can be achieved more cost-effectively if the objectives are integrated and pursued simultaneously rather than in isolation. Recent examples of such studies include Bollen et al. (2010) and the Global Energy Assessment (GEA) (McCollum et al., 2011, 2013a; Riahi et al., 2012). These two analyses are unique from other integrated studies (see e.g., Shukla et al., 2008; Skea and Nishioka, 2008; Strachan et al., 2008; IEA, 2011; Shukla and Dhar, 2011; PBL, 2012; Akimoto et al., 2012; Howells et al., 2013) because they attempt to quantify key interactions in economic terms on a global scale, employing varying methodologies to assess the interactions between climate change, air pollution, and energy security policies. Bollen et al. (2010) employ a cost-benefit social welfare optimization approach while the GEA study employs a cost-effectiveness approach (see Section 3.7.2.1). Despite these differences, the two studies provide similar insights. Both suggest that near-term synergies can be realized through decarbonization and energy efficiency and that mitigation policy may be seen as a strategic entry point for reaping energy security and air quality co-benefits. The GEA study in particular finds major cost savings from mitigation policy in terms of reduced expenditures for imported fossil fuels and end-of-pipe air pollution control equipment (see bottom panel of Figure 6.33). The magnitude of these co-benefits depends importantly on the future stringency of energy security and air pollution policies in the absence of mitigation policy. If these are more aggressive than currently planned, then the co-benefits would be smaller.

Another class of sustainable development scenarios are the Low-Carbon Society (LCS) assessments (Kainuma et al., 2012), which collectively indicate that explicit inclusion of mitigation co-benefits in the cost calculation results in a lower-carbon price in the LCS scenarios than in a scenario that only considers mitigation costs (Shukla et al., 2008). A key message from these studies is that co-benefits are neither automatic nor assured, but result from conscious and carefully coordinated policies and implementation strategies, such as lifestyle changes, green manufacturing processes, and investments into energy efficient devices, recycling measures, and other targeted actions (Shukla and Chaturvedi, 2012).

Finally, studies suggest that co-benefits could influence the incentives for global climate agreements discussed in Section 13.3 (Pittel and Rübbelke, 2008; Bollen et al., 2009b; Wagner, 2012). At the present time, however, international policy regimes for mitigation and its important co-benefits remain separate (Holloway et al., 2003; Swart et al., 2004; Nemet et al., 2010; Rao et al., 2013). Dubash et al. (2013) propose a methodology for operationalizing co-benefits in mitigation policy formulation, thus helping to bring the varied policy objectives closer together (see Section 15.2).

6.7 Risks of transformation pathways

Mitigation will be undertaken within the context of a broad set of policy objectives, existing societal structures, institutional frameworks, and physical infrastructures. The relationship between these broader characteristics of human societies and the particular implications of mitigation activities will be both complex and uncertain. Mitigation will also take place under uncertainty about the underlying physical processes that govern the climate. All of these indicate that there is a range of different risks associated with different transformation pathways.

The various risks associated with transformation pathways can be grouped into several categories, and many of these are discussed elsewhere in this chapter. One set of risks is associated with the linkage of mitigation with other policy objectives, such as clean air, energy security, or energy access. These linkages may be positive (co-benefits) or negative (risks). These relationships are discussed in Section 6.6. Another set of risks is associated with the possibility that particular mitigation measures might be taken off the table because of perceived negative side-effects and that stabilization will prove more challenging that what might have been expected (Strachan and Usher, 2012). These issues are discussed in Section 6.3 as well as elsewhere in the chapter, including Section 6.9 for CDR options. Another risk is that the economic costs may be higher or lower than anticipated, because the implications of mitigation cannot be understood with any degree of certainty today, for a wide range of reasons. This issue is discussed in Section 6.3.6. It is important to emphasize that both the economic costs and the economic benefits of mitigation are uncertain. One of the most fundamental risks associated with mitigation is that any transformation pathway may not maintain temperatures below a particular threshold, such as 2 °C or 1.5 °C above preindustrial levels due to limits in our understanding of the relationship between emissions and concentrations and, more importantly, the relationship between GHG concentrations and atmospheric temperatures. This topic is discussed in Section 6.3.2.

A broad risk that underpins all the mitigation scenarios in this chapter is that every long-term pathway depends crucially not just on actions by today's decision makers, but also by future decision-makers and future generations. Indeed, mitigation must be framed within a sequential-decision making not just because it is good practice, but more fundamentally because decision makers today cannot make decisions for those in the future. A consistent risk is that future decision makers may not undertake the mitigation that is required to meet particular long-term goals. In this context, actions today can be seen as creating or limiting options to manage risk rather than leading to particular goals. This topic is discussed in Sections 6.3 and 6.4 through the exploration of the consequences of different levels of near-term mitigation. This issue is particularly important in the context of scenarios that lead to concentration goals such as 450 ppm CO_2eq by 2100. The vast majority of these scenarios temporarily overshoot the long-term goal and then descend to it by the end of the century through increasing emissions reductions. When near-term mitigation is not sufficiently strong, future mitigation must rely heavily on CDR technologies such as BECCS, putting greater pressure on future decision makers and highlighting any uncertainties and risks surrounding these technologies. While these scenarios are possible in a physical sense, they come with a very large risk that future decision makers will not take on the ambitious action that would ultimately be required. Indeed, studies have shown that delayed and fragmented mitigation can lead to a relaxation of long-term goals if countries that delay their participation in a global mitigation strategy are not willing or unable to pick up the higher costs of compensating higher short-term emissions (Blanford et al., 2014; Kriegler et al., 2014c).

6.8 Integrating sector analyses and transformation scenarios

6.8.1 The sectoral composition of GHG emissions along transformation pathways

Options for reducing GHG emissions exist across a wide spectrum of human activities. The majority of these options fall into three broad areas: energy supply, energy end-use, and AFOLU. The primary focus of energy supply options is to provide energy from low- or zero-carbon energy sources; that is, to decarbonize energy supply. Options in energy end-use sectors focus either on reducing the use of energy and/or on using energy carriers produced from low-carbon sources, including electricity generated from low-carbon sources. Direct options in AFOLU involve storing carbon in terrestrial systems (for example, through afforestation). This sector is also the source of bioenergy. Options to reduce non-CO_2 emissions exist across all these sectors, but most notably in agriculture, energy supply, and industry.

These sectors and the associated options are heavily interlinked. For example, energy demand reductions may be evident not only as direct emissions reductions in the end-use sectors but also as emissions reductions from the production of energy carriers such as electricity ('indirect emissions', see Annex A.II.5). Replacing fossil fuels in energy supply or end-use sectors by bioenergy reduces emissions in these sectors, but may increase land-use emissions in turn (see Chapter 11, Bioenergy Appendix). In addition, at the most general level, sectoral mitigation actions are linked by the fact that reducing emissions through a mitigation activity in one sector reduces the required reductions from mitigation activities in other sectors to meet a long-term CO_2-equivalent concentration goal.

The precise set of mitigation actions taken in any sector will depend on a wide range of factors, including their relative economics, policy structures, and linkages to other objectives (see Section 6.6) and interactions among measures across sectors. Both integrated models, such as those assessed in this chapter, and sectorally focused research, such as that assessed in Chapters 7–11, offer insights into the options for mitigation across sectors. The remainder of this section first assesses the potential for mitigation within the sectors based on integrated studies and then in each of the emitting sectors based on the combined assessments from sectoral and integrated studies. Important questions are how consistent the results from integrated modelling studies are with sectorally-focused literature and how they complement each other.

6.8.2 Mitigation from a cross-sectoral perspective: Insights from integrated models

Integrated models are a key source of research on the tradeoffs and synergies in mitigation across sectors. In scenarios from these models, energy sector emissions are the dominant source of GHG emissions in baseline scenarios, and these emissions continue to grow over time relative to net AFOLU CO_2 emissions and non-CO_2 GHG emissions (Section 6.3.1 and Figure 6.34). Within the energy sector, direct emissions from energy supply, and electricity generation in particular, are larger than the emissions from any single end-use sector (Figure 6.34). Direct emissions, however, do not provide a full representation of the importance of different activities causing the emissions, because the consumption of energy carriers such as electricity by the end-use sectors, leads to indirect emissions from the production of those energy carriers (consumption-based approach). An alternative perspective is to allocate these indirect energy supply emissions to the end-use sectors that use these supplies (see, for example, in Figure 6.34). At present, indirect emissions from electricity use are larger than direct emissions in buildings and constitute an important share of industrial emissions while they are small in transport compared to direct CO_2 emissions.

In mitigation scenarios from integrated models, decarbonization of the electricity sector takes place at a pace more rapid than reduction of direct emissions in the energy end-use sectors (see Sections 7.11.3 and Figure 6.35). For example, in 450 ppm CO_2eq scenarios, the electricity sector is largely decarbonized by 2050, whereas deep reductions in direct emissions in the end-use sectors largely arise beyond mid-century. More so than any other energy supply technology, the availability of BECCS and its role as a primary CDR technology (Sections 6.3.2 and 6.9) has a substantial effect on this dynamic, allowing for energy supply sectors to serve as a net negative emissions source by mid-century and allowing for more gradual emissions reductions in other sectors. In contrast, sectoral studies show available pathways to deep reductions in emissions (both direct and indirect) already by mid-century (see, e.g., Chapter 9).

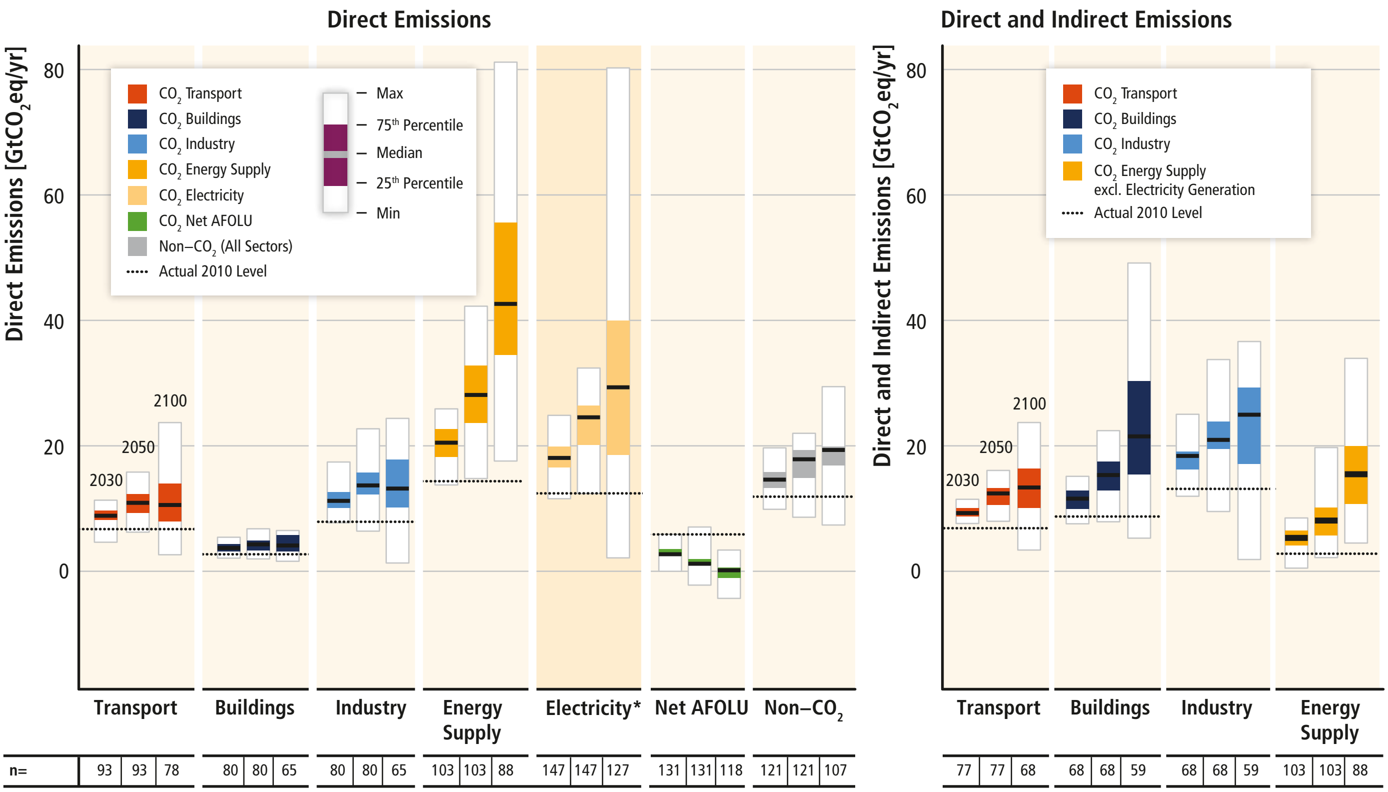


Figure 6.34 | Direct (left panel) and direct and indirect emissions (right panel) of CO_2 and non-CO_2 GHGs across sectors in baseline scenarios. Note that in the case of indirect emissions, only electricity emissions are allocated from energy supply to end-use sectors. In the left panel electricity sector emissions are shown ("Electricity*") in addition to energy supply sector emissions which they are part of, to illustrate their large role on the energy supply side. The numbers at the bottom refer to the number of scenarios included in the ranges that differ across sectors and time due to different sectoral resolution and time horizon of models. Source: WG III AR5 Scenario Database (Annex II.10). Includes only baseline scenarios. Note that scenarios from the AMPERE study were excluded due to large overlap with the EMF27 study. Historical data: JRC/PBL (2013), IEA (2012), see Annex II.9 and Annex II.5.

Within the end-use sectors, deep emissions reductions in transport are generally the last to emerge in integrated modelling studies because of the assumption that options to switch to low-carbon energy carriers in transport are more limited than in buildings and industry, and also because of the expected high growth for mobility and freight transport (Section 8.9.1). In the majority of baseline scenarios from integrated models, net AFOLU CO_2 emissions largely disappear by mid-century, with some models projecting a net sink after 2050 (Section 6.3.1.4). There is a wide uncertainty in the role of afforestation and reforestation in mitigation, however. In some mitigation scenarios the AFOLU sectors can become a significant carbon sink (Section 6.3.2.4).

6.8.3 Decarbonizing energy supply

Virtually all integrated modelling studies indicate that decarbonization of electricity is critical for mitigation, but there is no general consensus regarding the precise low-carbon technologies that might support this decarbonization (Fischedick et al., 2011; Clarke et al., 2012) (Section 7.11.3). These studies have presented a wide range of combinations of renewable energy sources (Krey and Clarke, 2011; Luderer et al., 2014b), nuclear power (Bauer et al., 2012; Rogner and Riahi, 2013), and CCS-based technologies (McFarland et al., 2009; Bauer et al., 2014a; McCollum et al., 2014a; van der Zwaan et al., 2014) as both viable and cost-effective (see Section 7.11). The breadth of different, potentially cost-effective strategies raises the possibility not only that future costs and performances of competing electricity technologies are uncertain today, but also that regional circumstances, including both energy resources and links to other regional objectives (e.g., national security, local air pollution, energy security, see Section 6.6), might be as important decision making factors as economic costs (Krey et al., 2014). The one exception to this flexibility in energy supply surrounds the use of BECCS. CDR technologies such as BECCS are fundamental to many scenarios that achieve low-CO_2eq concentrations, particularly those based on substantial overshoot as might occur if near-term mitigation is delayed (Sections 6.3.2 and 6.4). In contrast to the electricity sector, decarbonization of the non-electric energy-supply sector (e.g., liquid fuels supply) is progressing typically at much lower pace (Section 7.11.3, Figures 7.14 and 7.15) and could therefore constitute a bottleneck in the transformation process.

6.8.4 Energy demand reductions and fuel switching in end-use sectors

The two major groups of options in energy end-use sectors are those that focus on reducing the use of energy and/or those that focus on using energy carriers produced from low-carbon sources. Three important issues are therefore the potential for fuel switching, the potential

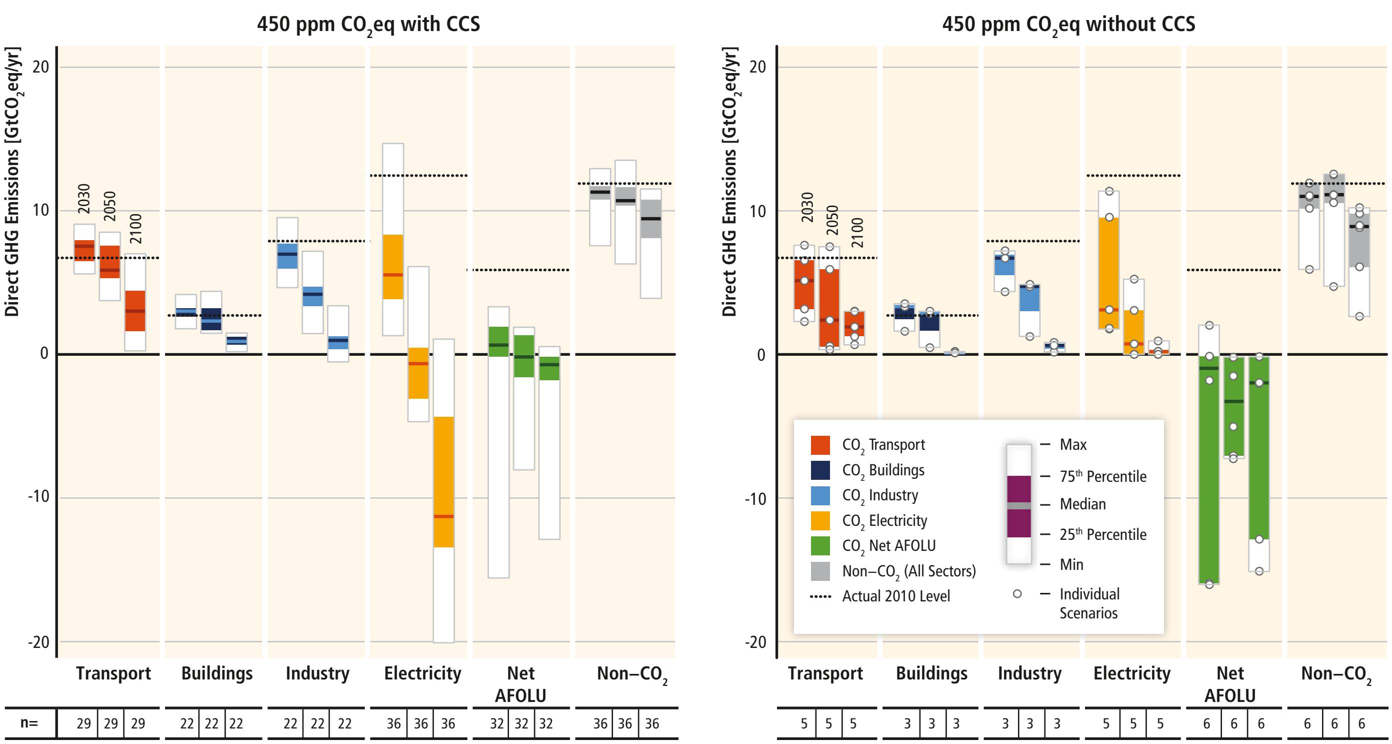


Figure 6.35 | Direct emissions of CO_2 and non-CO_2 GHGs across sectors in mitigation scenarios that reach around 450 (430–480) ppm CO_2eq concentrations in 2100 with using CCS (left panel) and without using CCS (right panel). The numbers at the bottom of the graphs refer to the number of scenarios included in the ranges that differ across sectors and time due to different sectoral resolution and time horizon of models. White dots in the right panel refer to emissions of individual scenarios to give a sense of the spread within the ranges shown due to the small number of scenarios. Source: WG III AR5 Scenario Database (Annex II.10). Includes only scenarios based on idealized policy implementation that provide emissions at the sectoral level. Note that scenarios from the AMPERE study were excluded due to large overlap with the EMF27 study. Historical data: JRC/PBL (2013), IEA (2012), see Annex II.9.

for reductions of energy use per unit of output/service, and the relationship and timing between the two. In general, as discussed in Section 6.3.4, integrated studies indicate that energy intensity (per unit of GDP) reductions outweigh decarbonization of energy supply in the near term when the energy-supply system is still heavily reliant on largely carbon-intensive fossil fuels (Figure 6.17). Over time, the mitigation dynamic switches to one focused on carbon-intensity reductions (see AR4, Fisher et al., 2007, Section 3.3.5.2). From the perspective of end-use sectors, decarbonization of energy involves both the decarbonization of existing sources, for example, by producing electricity from low-carbon sources or using liquid fuels made from bioenergy, and an increase in the use of lower-carbon fuels, for example, through an increase in the use of electricity (Edmonds et al., 2006; Kyle et al., 2009; Sugiyama, 2012; Williams et al., 2012; Krey et al., 2014; Yamamoto et al., 2014). It should be noted that there is generally an autonomous increase in electrification in baseline scenarios that do not assume any climate policies, which reflects a trend toward more convenient grid-based fuels due to higher affluence (Nakicenovic et al., 1998; Schäfer, 2005), as well as electricity typically showing a slower cost increase over time compared to other energy carriers (Edmonds et al., 2006; Krey et al., 2014).

The comparison between integrated and sectoral studies is difficult with regard to the timing and tradeoffs between fuel switching and energy reduction, because few sectoral studies have attempted to look concurrently at both fuel switching and energy-reduction strategies. Instead, the majority of sectoral studies have focused most heavily on energy reduction, asking how much energy use for a particular activity can be reduced with state-of-the-art technology. One reason for this focus on energy reduction is that sectoral research is more commonly focused on near-term actions based on available mitigation technologies and, in the near-term, major fuel sources such as liquid fuels and electricity may have high-carbon intensities. This means that energy reductions will have substantial near-term mitigation effects. In the longer term, however, these fuel sources will be largely decarbonized along low-concentration transformation pathways, meaning that energy reductions will not so clearly lead to reductions in indirect emissions (note that this does not mean they do not continue to be important, because they decrease the need for utilizing energy sources and the associated co-benefits and risks, see Section 6.6).

This evolution can be clearly seen through a comparison of direct and indirect emissions in end-use sectors in integrated modelling scenarios (Figure 6.36). In 2010, the largest part of emissions from the buildings sector are the indirect emissions from electricity. This trend continues in baseline scenarios (Figure 6.36). However, in deep emission-reduction scenarios, indirect emissions from electricity are largely eliminated by 2050, and in many scenarios, the electricity sector even becomes a sink for CO_2 through the use of BECCS (Figure 6.35, left panel). There are only minimal indirect emissions from electricity in the transport sector today and by 2050 in mitigation scenarios. Those scenarios that decarbonize the transportation sector through electrification do so by taking advantage of a largely decarbonized electricity sector. The industrial sector lies between the buildings and transport sectors. Of importance, the observed trends can be very regional in character. For example, the value of electrification will be higher in countries or regions that already have low-carbon electricity portfolios.

The primary distinction between sectoral studies and integrated modelling studies with regard to end-use options for fuel switching and end-use reductions is that integrated models typically represent end-use options at a more aggregated scale than sectoral studies. In addition, however, there is an important difference in the way that the two types of studies attempt to ascertain opportunities (see Section 8.9). Long-term mitigation scenarios from integrated models achieve reductions from baseline emissions based almost exclusively on the imposition of a carbon price and generally assume functioning markets and may not

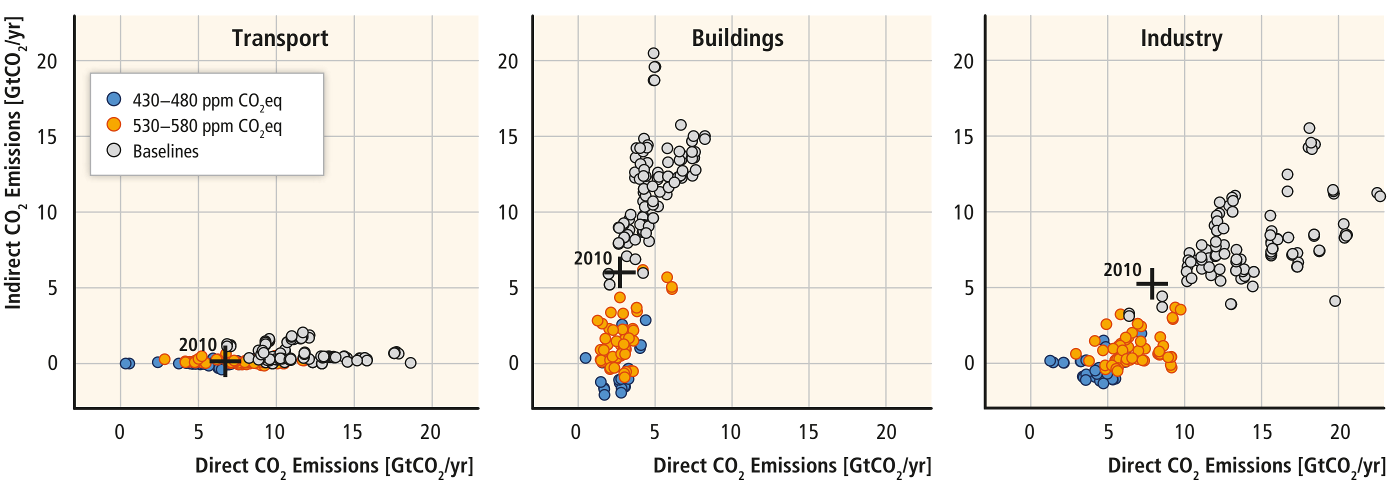


Figure 6.36 | Direct CO_2 emissions vs. indirect CO_2 emissions from electricity in the transport, buildings, and industry sectors in 2050 for baseline and mitigation scenarios reaching 430–480 ppm and 530–580 ppm CO_2eq in 2100. Source: WG III AR5 Scenario Database (Annex II.10). Includes only scenarios based on idealized policy implementation that provide emissions at the sectoral level. Historical data from JRC/PBL (2013), IEA (2012a), see Annex II.9.

fully represent existing barriers, in particular in end-use sectors. In contrast, sectoral studies explore options for energy-demand reduction based on engineering and/or local details and do so based on cost-effectiveness calculations regarding a typically much richer portfolio of tailored options. They also recognize that there are many boundaries to consumer rationality and thus not all options that are cost-effective happen automatically in a baseline, but are mobilized by mitigation policies. It is also challenging to compare the potential for energy reductions across sectoral and integrated studies, because of difficulties to discern the degree of mitigation that has occurred in the baseline itself in these studies. Therefore any comparisons must be considered approximate at best. It is important to note that the emphasis on economic instruments like carbon pricing in integrated studies leads to a negative correlation between energy-demand reduction and the option of switching to low-carbon energy carriers at modest cost. Therefore, integrated studies that foresee a significant potential for switching to electricity, for example, in an end-use sector at modest costs, usually show a lower need for reducing energy demand in this sector and the other way around. It should also be noted that there is not always a clear cut distinction between sectoral and integrated studies. Some sectoral studies, in particular those that provide estimates for both energy savings and fuel switching, are in fact integrated studies with considerable sectoral detail such as the IEA World Energy Outlook (IEA, 2010b, 2012b) or the Energy Technology Perspectives report (IEA, 2008, 2010c) (see Annex II.10).

In general, in the transport sector, the opportunities for energy-use reductions and fuel switching are broadly consistent between integrated and sectoral studies (Figures 6.37 and 6.38, Section 8.9). However, the underlying mechanisms utilized in these studies may be different. Comprehensive transport sector studies tend to include technical efficiency measures, switching to low-carbon fuels, behavioural changes that affect both the modal split and the amount of transport services demanded, and a broader set of infrastructural characteristics such as compact cities. In integrated studies, these factors are not always addressed explicitly, and the focus is usually on technical efficiency measures, fuel switching and service demand reduction. Regarding fuel choice, the majority of integrated studies indicate a continued reliance on liquid and gaseous fuels, supported by an increase in the use of bioenergy up to 2050. Many integrated studies also include substantial shares of electricity through, for example, the use of electric vehicles for light-duty transportation, usually during the second-half of the century. Hydrogen has also been identified by numerous studies as a potential long-term solution should storage, production, and distribution challenges be overcome (Section 8.9.1). While electricity and hydrogen achieve substantial shares in some scenarios, many integrated modelling scenarios show no dominant transport fuel source in 2100. This prevails in scenarios leading to 430–530 ppm CO_2eq concentration levels in 2100 with the median values for the share of electricity and hydro-

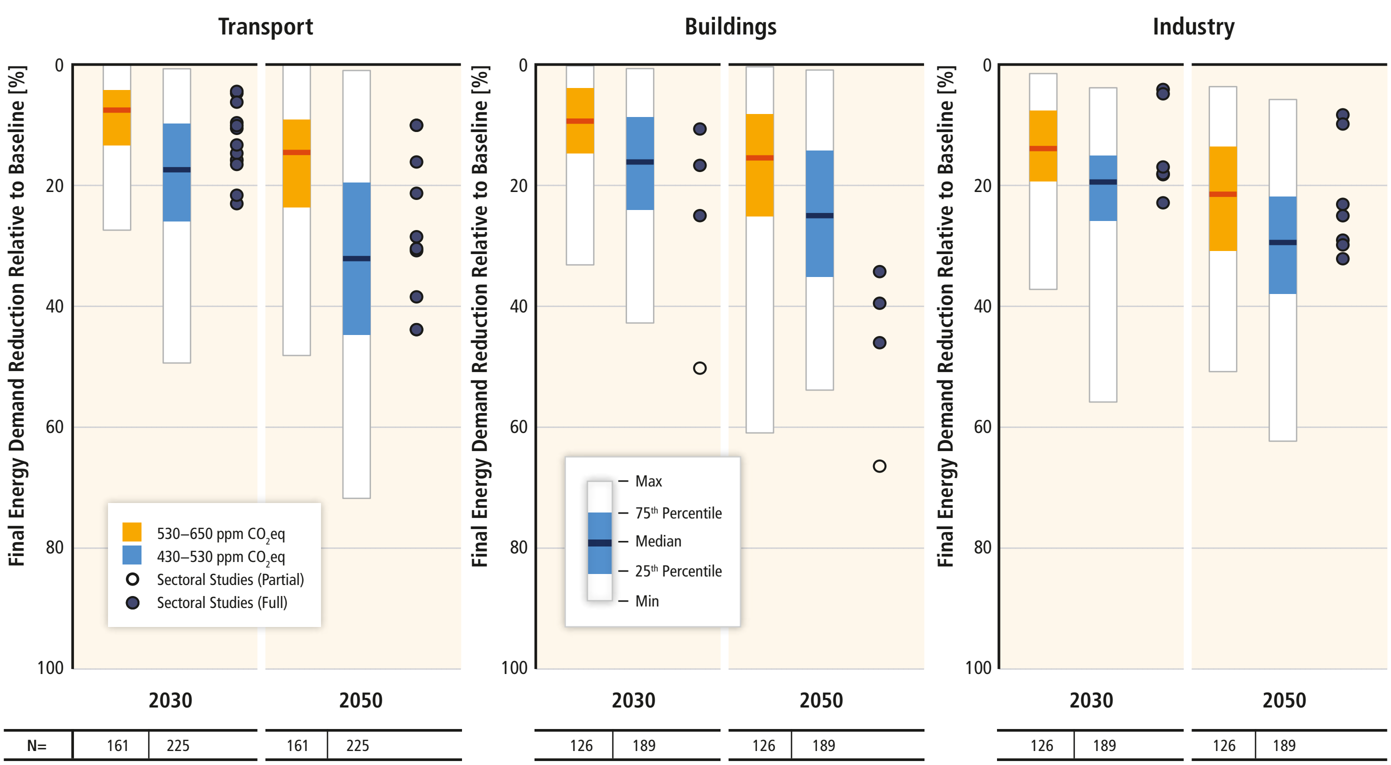


Figure 6.37 | Sectoral final energy demand reduction relative to baseline in the energy end-use sectors, transport, buildings, and industry by 2030 and 2050 in mitigation scenarios reaching 430–530 ppm and 530–650 ppm CO_2eq in 2100 (see Section 6.3.2) compared to sectoral studies assessed in Chapters 8–10. Filled circles correspond to sectoral studies with full sectoral coverage while empty circles correspond to studies with only partial sectoral coverage (e.g., heating and cooling only for buildings). Source: WG III AR5 Scenario Database (Annex II.10). Includes only scenarios based on idealized policy implementation. Sectoral studies as provided by Chapters 8, 9, and 10, see Annex II.10.

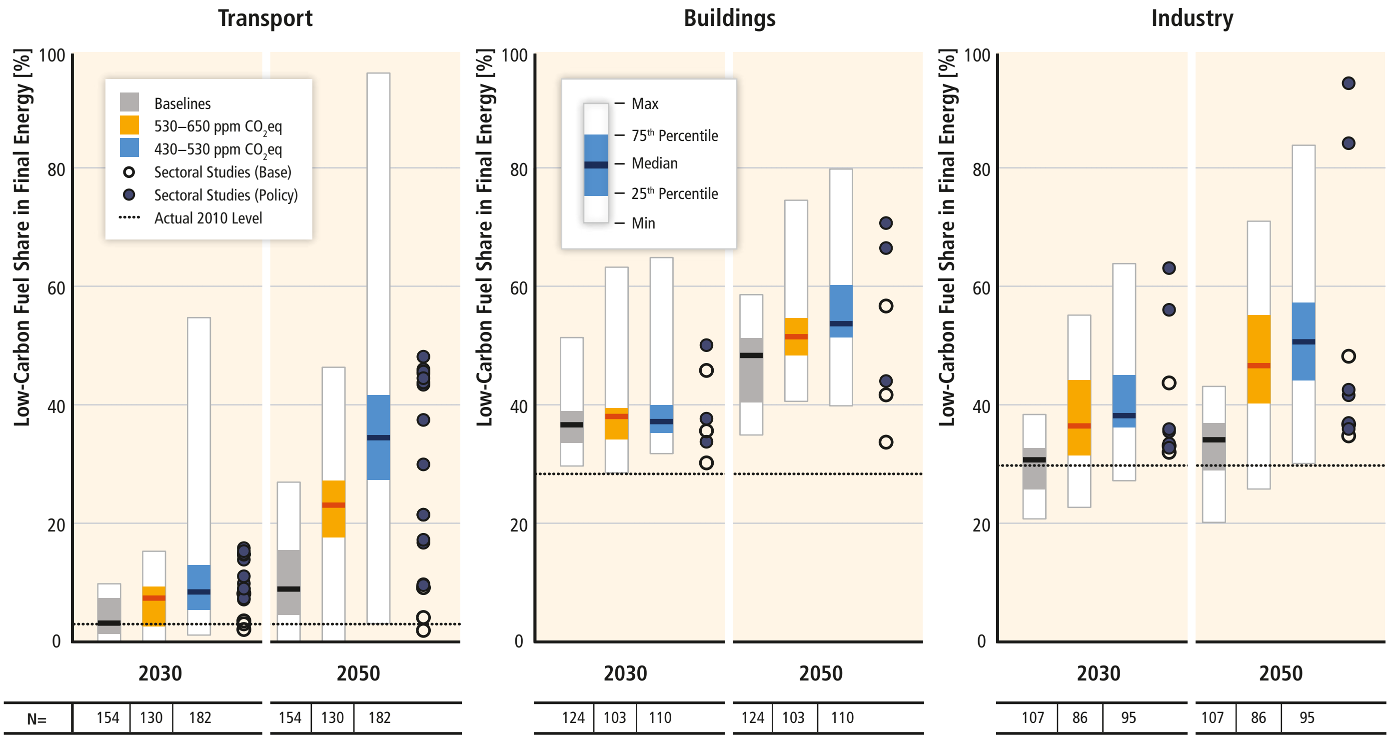


Figure 6.38 | Development of final energy low-carbon fuel shares in the energy end-use sectors transport, buildings, and industry by 2030 and 2050 in baseline and mitigation scenarios reaching 430–530 ppm and 530–650 ppm CO_2eq in 2100 (see Section 6.3.2) compared to sectoral studies assessed in Chapters 8–10. Low-carbon fuels include electricity, hydrogen, and liquid biofuels in transport, electricity in buildings and electricity, heat, hydrogen, and bioenergy in industry. Filled symbols correspond to sectoral studies with additional climate policies whereas empty symbols correspond to studies with baseline assumptions. Source: WG III AR5 Scenario Database (Annex II.10). Includes only scenarios based on idealized policy implementation. Sectoral studies as provided by Chapters 8, 9, and 10, see Annex II.10. Historical data from IEA (2012c; d).

gen in 2100 being 22 % and 25 % of final energy, respectively (Section 8.9.1, Figure 8.9.4).

Detailed building sector studies indicate energy savings potential by 2050 on the upper end of what integrated studies show (Section 9.8.2, Figure 9.19), and both sectoral and integrated studies show modest opportunities for fuel switching due to the already high level of electricity consumption in the buildings sector, particularly in developed countries (Figures 6.37 and 6.38). Building sector studies have focused largely on identifying options for saving energy whereas fuel switching as a means for reducing emissions is not considered in detail by most studies. In general, both sectoral and integrated studies indicate that electricity will supply a dominant share of building energy demand over the long term, especially if heating demand decreases due to a combination of efficiency gains, better architecture and climate change. Best case new buildings can reach 90 % lower space heating and cooling energy use compared to the existing stock (Section 9.3.3), while for existing buildings, deep retrofits can achieve heating and cooling energy savings in the range of 50–90 % (Section 9.3.4).

Detailed industry sector studies tend to be more conservative regarding savings in industrial final energy compared to baseline, but on the other hand foresee a greater potential for switching to low-carbon fuels, including electricity, heat, hydrogen and bioenergy than integrated studies (Figures 6.37 and 6.38). Sectoral studies, which are often based on micro unit-level analyses, indicate that the broad application of best available technologies for energy reduction could lead to about 25 % of energy savings in the sector with immediate deployment and similar contributions could be achieved with new innovations and deployment across a large number of production processes (Section 10.4). Integrated models in general (with exceptions, see Section 10.10.1) treat the industry sector in a more aggregated fashion and mostly do not provide detailed sub-sectoral material flows, options for reducing material demand, and price-induced inter-input substitution possibilities explicitly (Section 10.10.1). Similar to the transportation sector, there is no single perceived near- or long-term configuration for industrial energy (see Sections 10.4 and 10.7). Multiple pathways may be pursued or chosen depending on process selection and technology development. For the industry sector to achieve near-zero emission with carbonaceous energy, carriers will need CCS facilities though market penetration of this technology is still highly uncertain and only limited examples are in place so far. Some integrated studies indicate a move toward electricity whereas others indicate a continued reliance on liquid or solid fuels, largely supported through bioenergy (Section 10.10.1, Figure 10.14). Due to the heterogeneous character of the industry sector a coherent comparison between sectoral and integrated studies remains difficult.

6.8.5 Options for bioenergy production, reducing land-use change emissions, and creating land-use GHG sinks

As noted in Section 6.3.5, land use has three primary roles in mitigation: bioenergy production, storage of carbon in terrestrial systems, mitigation of non-CO_2 GHGs. It also influences mitigation through biogeophysical factors such as albedo. Integrated modelling studies are the primary means by which the tradeoffs and synergies between these different roles, in particular the first two, might unfold over the rest of the century. The integrated modelling studies sketch out a wide range of ways in which these forces might affect the land surface, from widespread afforestation under comprehensive climate policies to widespread deforestation if carbon storage on land is not included in the mitigation policy (Sections 6.3.5 and 11.9).

Sectoral studies complement integrated modelling studies by exploring the ability of policy and social structures to support broad changes in land-use practices over time (Section 11.6). In general, sectoral studies point to the challenges associated with making large-scale changes to the land surface in the name of mitigation, such as challenges associated with institutions, livelihoods, social and economic concerns, and technology and infrastructure. These challenges raise questions about transformation pathways (Section 11.6). For example, although increasing the land area covered by natural forests could enhance biodiversity and a range of other ecosystem services, afforestation occurring through large-scale plantations could negatively impact biodiversity, water, and other ecosystem services (Sections 11.7 and 11.13.6). Similarly, the use of large land areas for afforestation or dedicated feedstocks for bioenergy could increase food prices and compromise food security if land normally used for food production is converted to bioenergy or forests (Section 11.4). The degree of these effects is uncertain and depends on a variety of sector-specific details regarding intensification of land use, changes in dietary habits, global market interactions, and biophysical characteristics and dynamics. The implications of transformation pathways that rely heavily on reductions of non-CO_2 GHGs from agriculture depend on whether mitigation is achieved through reduced absolute emissions, or through reduced emissions per unit of agricultural product (Section 11.6), and the role of large-scale intensive agriculture, which has often not been implemented sustainably (e. g., large areas of monoculture food or energy crops or intensive livestock production, potentially damaging ecosystem services). Furthermore, sector studies are beginning to elucidate implementation issues, such as the implications of staggered and/or partial regional adoption of land mitigation policies, as well as institutional design. For example, realizing large-scale bioenergy without compromising the terrestrial carbon stock might require strong institutional conditions, such as an implemented and enforced global price on land carbon. Finally, sector studies will continue to provide revised and new characterizations of mitigation technologies that can be evaluated in a portfolio context (Section 11.9).

6.9 Carbon and radiation management and other geo-engineering options including environmental risks

Some scientists have argued that it might be useful to consider, in addition to mitigation and adaptation measures, various intentional interventions into the climate system as part of a broader climate policy strategy (Keith, 2000; Crutzen, 2006). Such technologies have often been grouped under the blanket term 'geoengineering' or, alternatively, 'climate engineering' (Keith, 2000; Vaughan and Lenton, 2011). Calls for research into these technologies have increased in recent years (Caldeira and Keith, 2010; Science and Technology Committee, 2010), and several assessments have been conducted (Royal Society, 2009; Edenhofer et al., 2011; Ginzky et al., 2011; Rickels et al., 2011). Two categories of geoengineering are generally distinguished. Removal of GHGs, in particular carbon dioxide termed 'carbon dioxide removal' or CDR, would reduce atmospheric GHG concentrations. The boundary between some mitigation and some CDR methods is not always clear (Boucher et al., 2011, 2013). 'Solar radiation management' or SRM technologies aim to increase the reflection of sunlight to cool the planet and do not fall within the usual definitions of mitigation and adaptation. Within each of these categories, there is a wide range of techniques that are addressed in more detail in Sections 6.5 and 7.7 of the WG I report.

Many geoengineering technologies are presently only hypothetical. Whether or not they could actually contribute to the avoidance of future climate change impacts is not clear (Blackstock et al., 2009; Royal Society, 2009). Beyond open questions regarding environmental effects and technological feasibility, questions have been raised about the socio-political dimensions of geoengineering and its potential implications for climate politics (Barrett, 2008; Royal Society, 2009; Rickels et al., 2011). In the general discussion, geoengineering has been framed in a number of ways (Nerlich and Jaspal, 2012; Macnaghten and Szerszynski, 2013; Luokkanen et al., 2013; Scholte et al., 2013), for instance, as a last resort in case of a climate emergency (Blackstock et al., 2009; McCusker et al., 2012), or as a way to buy time for implementing conventional mitigation (Wigley, 2006; Institution of Mechanical Engineers, 2009; MacCracken, 2009). Most assessments agree that geoengineering technologies should not be treated as a replacement for conventional mitigation and adaptation due to the high costs involved for some techniques, particularly most CDR methods, and the potential risks, or pervasive uncertainties involved with nearly all techniques (Royal Society, 2009; Rickels et al., 2011). The potential role of geoengineering as a viable component of climate policy is yet to be determined, and it has been argued that geoengineering could become a distraction from urgent mitigation and adaptation measures (Lin; Preston, 2013).

6.9.1 Carbon dioxide removal

6.9.1.1 Proposed carbon dioxide removal methods and characteristics

Proposed CDR methods involve removing CO_2 from the atmosphere and storing the carbon in land, ocean, or geological reservoirs. These methods vary greatly in their estimated costs, risks to humans and the environment, potential scalability, and notably in the depth of research about their potential and risks. Some techniques that fall within the definition of CDR are also regarded as mitigation measures such as afforestation and BECCS (see Glossary). The term 'negative emissions technologies' can be used as an alternative to CDR (McGlashan et al., 2012; McLaren, 2012; Tavoni and Socolow, 2013).

The WG I report (Section 6.5.1) provides an extensive but not exhaustive list of CDR techniques (WG I Table 6.14). Here only techniques that feature more prominently in the literature are covered. This includes (1) increased land carbon sequestration by reforestation and afforestation, soil carbon management, or biochar (see WG III Chapter 11); (2) increased ocean carbon sequestration by ocean fertilization; (3) increased weathering through the application of ground silicates to soils or the ocean; and (4) chemical or biological capture with geological storage by BECCS or direct air capture (DAC). CDR techniques can be categorized in alternative ways. For example, they can be categorized (1) as industrial technologies versus ecosystem manipulation; (2) by the pathway for carbon dioxide capture (e.g. McLaren, 2012; Caldeira et al., 2013); (3) by the fate of the stored carbon (Stephens and Keith, 2008); and (4) by the scale of implementation (Boucher et al., 2013). Removal of other GHGs, e.g., CH_4 and N_2O, have also been proposed (Boucher and Folberth, 2010; de Richter and Caillol, 2011; Stolaroff et al., 2012).

All CDR techniques have a similar slow impact on rates of warming as mitigation measures (van Vuuren and Stehfest, 2013) (see WG I Section 6.5.1). An atmospheric 'rebound effect' (see WG I Glossary) dictates that CDR requires roughly twice as much CO_2 removed from the atmosphere for any desired net reduction in atmospheric CO_2 concentration, as some CO_2 will be returned from the natural carbon sinks (Lenton and Vaughan, 2009; Matthews, 2010). Permanence of the storage reservoir is a key consideration for CDR efficacy. Permanent (larger than tens of thousands of years) could be geological reservoirs while non-permanent reservoirs include oceans and land (the latter could, among others, be affected by the magnitude of future climate change) (see WG I Section 6.5.1). Storage capacity estimates suggest geological reservoirs could store several thousand GtC; the oceans a few thousand GtC in the long term, and the land may have the potential to store the equivalent to historical land-use loss of 180 ± 80 GtC (also see Table 6.15 of WG I)(IPCC, 2005; House et al., 2006; Orr, 2009; Matthews, 2010).

Ocean fertilization field experiments show no consensus on the efficacy of iron fertilization (Boyd et al., 2007; Smetacek et al., 2012). Modelling studies estimate between 15 ppm and less than 100 ppm drawdown of CO_2 from the atmosphere over 100 years (Zeebe and Archer, 2005; Cao and Caldeira, 2010) while simulations of mechanical upwelling suggest 0.9 Gt/yr (Oschlies et al., 2010). The latter technique has not been field tested. There are a number of possible risks including downstream decrease in productivity, expanded regions of low-oxygen concentration, and increased N_2O emissions (See WG I Section 6.5.3.2) (low confidence). Given the uncertainties surrounding effectiveness and impacts, this CDR technique is at a research phase with no active commercial ventures. Furthermore, current international governance states that marine geoengineering including ocean fertilization is to be regulated under amendments to the London Convention/London Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, only allowing legitimate scientific research (Güssow et al., 2010; International Maritime Organization, 2013).

Enhanced weathering on land using silicate minerals mined, crushed, transported, and spread on soils has been estimated to have a potential capacity, in an idealized study, of 1 GtC/yr (Köhler et al., 2010). Ocean-based weathering CDR methods include use of carbonate or silicate minerals processed or added directly to the ocean (see WG I Section 6.5.2.3). All of these measures involve a notable energy demand through mining, crushing, and transporting bulk materials. Preliminary hypothetical cost estimates are in the order of 23–66 USD/tCO_2 (Rau and Caldeira, 1999; Rau et al., 2007) for land and 51–64 USD/tCO_2 for ocean methods (McLaren, 2012). The confidence level on the carbon cycle impacts of enhanced weathering is low (WG I Section 6.5.3.3).

The use of CCS technologies (IPCC, 2005) with biomass energy also creates a carbon sink (Azar et al., 2006; Gough and Upham, 2011). BECCS is included in the RCP 2.6 (van Vuuren et al., 2007, 2011b) and a wide range of scenarios reaching similar and higher concentration goals. From a technical perspective, BECCS is very similar to a combination of other techniques that are part of the mitigation portfolio: the production of bio-energy and CCS for fossil fuels. Estimates of the global technical potential for BECCS vary greatly ranging from 3 to more than 10 GtCO_2/yr (Koornneef et al., 2012; McLaren, 2012; van Vuuren et al., 2013), while initial cost estimates also vary greatly from around 60 to 250 USD/tCO_2 (McGlashan et al., 2012; McLaren, 2012). Important limiting factors for BECCS include land availability, a sustainable supply of biomass and storage capacity (Gough and Upham, 2011; McLaren, 2012). There is also a potential issue of competition for biomass under bioenergy-dependent mitigation pathways.

Direct air capture uses a sorbent to capture CO_2 from the atmosphere and the long-term storage of the captured CO_2 in geological reservoirs (GAO, 2011; McGlashan et al., 2012; McLaren, 2012). There are a number of proposed capture methods including adsorption of CO_2 using amines in a solid form and the use of wet scrubbing systems based on calcium or sodium cycling. Current research efforts focus on capture methodologies (Keith et al., 2006; Baciocchi et al., 2006; Lackner, 2009; Eisenberger et al., 2009; Socolow et al., 2011) with storage technologies assumed to be the same as CCS (IPCC, 2005). A U.S. Government Accountability Office (GAO) (2011) technology assessment concluded that all DAC methods were currently immature. A review of initial hypothetical cost estimates, summarizes 40–300 USD/tCO_2 for supported amines and 165–600 USD/tCO_2 for sodium or calcium scrubbers (McLaren, 2012) reflecting an ongoing debate across very limited literature. Carbon dioxide captured through CCS, BECCS, and DAC are all intended to use the same storage reservoirs (in particular deep geologic reservoirs), potentially limiting their combined use under a transition pathway.

6.9.1.2 Role of carbon dioxide removal in the context of transformation pathways

Two of the CDR techniques listed above, BECCS and afforestation, are already evaluated in the current integrated models. For concentration goals on the order of 430–530 ppm CO_2eq by 2100, BECCS forms an essential component of the response strategy for climate change in the majority of scenarios in the literature, particularly in the context of concentration overshoot. As discussed in Section 6.2.2, BECCS offers additional mitigation potential, but also an option to delay some of the drastic mitigation action that would need to happen to reach lower GHG-concentration goals by the second half of the century. In scenarios aiming at such low-concentration levels, BECCS is usually competitive with conventional mitigation technologies, but only after these have been deployed at very large scale (see Azar et al., 2010; Tavoni and Socolow, 2013). At same time, BECCS applications do not feature in less ambitious mitigation pathways (van Vuuren et al., 2011a). Key implications of the use of BECCS in transition pathways is that emission reduction decisions are directly related to expected availability and deployment of BECCS in the second half of the century and that scenarios might temporarily overshoot temperature or concentration goals.

The vast majority of scenarios in the literature show CO_2 emissions of LUC become negative in the second half of the century—even in the absence of mitigation policy (see Section 6.3.2). This is a consequence of demographic trends and assumptions on land-use policy. Additionally afforestation as part of mitigation policy is included in a smaller set of models. In these models, afforestation measures increase for lower-concentration categories, potentially leading to net uptake of carbon of around 10 GtCO_2/yr.

There are broader discussions in the literature regarding the technological challenges and potential risks of large-scale BECCS deployment. The potential role of BECCS will be influenced by the sustainable supply of large-scale biomass feedstock and feasibility of capture, transport, and long-term underground storage of CO_2 as well as the perceptions of these issues. The use of BECCS faces large challenges in financing, and currently no such plants have been built and tested at scale. Integrated modeling studies have therefore explored the sensitivities regarding the availability of BECCS in the technology portfolio by limiting bioenergy supply or CCS storage (Section 6.3.6.3).

Only a few papers have assessed the role of DAC in mitigation scenarios (e.g. Keith et al., 2006; Keller et al., 2008a; Pielke Jr, 2009; Nemet and Brandt, 2012; Chen and Tavoni, 2013). These studies generally show that the contribution of DAC hinges critically on the stringency of the concentration goal, the costs relative to other mitigation technologies, time discounting and assumptions about scalability. In these models, the influence of DAC on the mitigation pathways is similar to that of BECCS (assuming similar costs). That is, it leads to a delay in short-term emission reduction in favour of further reductions in the second half of the century. Other techniques are even less mature and currently not evaluated in integrated models.

There are some constraints to the use of CDR techniques as emphasized in the scenario analysis. First of all, the potential for BECCS, afforestation, and DAC are constrained on the basis of available land and/or safe geologic storage potential for CO_2. Both the potential for sustainable bio-energy use (including competition with other demands, e.g., food, fibre, and fuel production) and the potential to store > 100 GtC of CO_2 per decade for many decades are very uncertain (see previous section) and raise important societal concerns. Finally, the large-scale availability of CDR, by shifting the mitigation burden in time, could also exacerbate inter-generational impacts.

6.9.2 Solar radiation management

6.9.2.1 Proposed solar radiation management methods and characteristics

SRM geoengineering technologies aim to lower the Earth's temperature by reducing the amount of sunlight that is absorbed by the Earth's surface, and thus countering some of the GHG induced global warming. Most techniques work by increasing the planetary albedo, thus reflecting a greater fraction of the incoming sunlight back to space. A number of SRM methods have been proposed:

- Mirrors (or sunshades) placed in a stable orbit between the Earth and Sun would directly reduce the insolation the Earth receives (Early, 1989; Angel, 2006). Studies suggest that such a technology is unlikely to be feasible within the next century (Angel, 2006).

- Stratospheric aerosol injection would attempt to imitate the global cooling that large volcanic eruptions produce (Budyko and Miller, 1974; Crutzen, 2006; Rasch et al., 2008). This might be achieved by lofting sulphate aerosols (or other aerosol species) or their precursors to the stratosphere to create a high-altitude reflective layer that would need to be continually replenished. Section 7.7.2.1 of WG I assessed that there is medium confidence that up to 4 W/m^2 of forcing could be achieved with this approach.

- Cloud brightening might be achieved by increasing the albedo of certain marine clouds through the injection of cloud condensation nuclei, most likely sea salt, producing an effect like that seen when ship-tracks of brighter clouds form behind polluting ships (Latham, 1990; Latham et al., 2008, 2012). Section 7.7.2.2 of WG I assessed that too little was known about marine cloud brightening to provide a definitive statement on its potential efficacy, but noted that it might be sufficient to counter the radiative forcing that would result from a doubling of CO_2 levels.

- Various methods have been proposed that could increase the albedo of the planetary surface, for example in urban, crop, and desert regions (President's Science Advisory Committee. Environmental Pollution Panel, 1965; Gaskill, 2004; Hamwey, 2007; Ridgwell et al., 2009). These methods would likely only be possible on a much smaller scale than those listed above. Section 7.7.2.3 of WG I discusses these approaches.

This list is non-exhaustive and new proposals for SRM methods may be put forward in the future. Another method that is discussed alongside SRM methods aims to increase outgoing thermal radiation through the modification of cirrus clouds (Mitchell and Finnegan, 2009) (see WG I Section 7.7.2.4).

As SRM geoengineering techniques only target the solar radiation budget of the Earth, the effects of CO_2 and other GHGs on the Earth System would remain, for example, greater absorption and re-emission of thermal radiation by the atmosphere (WG I Section 7.7), an enhanced CO_2 physiological effect on plants (WG I Section 6.5.4), and increased ocean acidification (Matthews et al., 2009). Although SRM geoengineering could potentially reduce the global mean surface air temperature, no SRM technique could fully return the climate to a pre-industrial or low-CO_2-like state. One reason for this is that global mean temperature and global mean hydrological cycle intensity cannot be simultaneously returned to a pre-industrial state (Govindasamy and Caldeira, 2000; Robock et al., 2008; Schmidt et al., 2012; Kravitz et al., 2013; MacMartin et al., 2013; Tilmes et al., 2013). Section 7.7.3 of WG I details the current state of knowledge on the potential climate consequences of SRM geoengineering. In brief, simulation studies suggest that some SRM geoengineering techniques applied to a high-CO_2 climate could create climate conditions more like those of a low-CO_2 climate (Moreno-Cruz et al., 2011; MacMartin et al., 2013), but the annual mean, seasonality, and interannual variability of climate would be modified compared to the pre-industrial climate (Govindasamy and Caldeira, 2000; Lunt et al., 2008; Robock et al., 2008; Ban-Weiss and Caldeira, 2010; Moreno-Cruz et al., 2011; Schmidt et al., 2012; Kravitz et al., 2013; MacMartin et al., 2013). SRM geoengineering that could reduce global mean temperatures would reduce thermosteric sea-level rise and would likely also reduce glacier and ice-sheet contributions to sea-level rise (Irvine et al., 2009, 2012; Moore et al., 2010).

Model simulations suggest that SRM would result in substantially altered global hydrological conditions, with uncertain consequences for specific regional responses such as precipitation and evaporation in monsoon regions (Bala et al., 2008; Schmidt et al., 2012; Kravitz et al., 2013; Tilmes et al., 2013). In addition to the imperfect cancellation of GHG-induced changes in the climate by SRM, CO_2 directly affects the opening of plant stomata, and thus the rate of transpiration of plants and in turn the recycling of water over continents, soil moisture, and surface hydrology (Bala et al., 2007; Betts et al., 2007; Boucher et al., 2009; Spracklen et al., 2012).

Due to these broadly altered conditions that would result from an implementation of geoengineering, and based on experience from studies of the detection and attribution of climate change, it may take many decades of observations to be certain whether SRM is responsible for a particular regional trend in climate (Stone et al., 2009; MacMynowski et al., 2011). These detection and attribution problems also imply that field testing to identify some of the climate consequences of SRM geoengineering would require deployment at a sizeable fraction of full deployment for a period of many years or even decades (Robock et al., 2010; MacMynowski et al., 2011).

It is important to note that in addition to affecting the planet's climate, many SRM methods could have serious non-climatic side-effects. Any stratospheric aerosol injection would affect stratospheric chemistry and has the potential to affect stratospheric ozone levels. Tilmes et al. (2009) found that sulphate aerosol geoengineering could delay the recovery of the ozone hole by decades (WG I Section 7.7.2.1). Stratospheric aerosol geoengineering would scatter light, modifying the optical properties of the atmosphere. This would increase the diffuse-to-direct light ratio, which would make the sky appear hazier (Kravitz et al., 2012), reduce the efficacy of concentrated solar power facilities (Murphy, 2009), and potentially increase the productivity of some plant species, and preferentially those below the canopy layer, with unknown long-term ecosystem consequences (Mercado et al., 2009). The installations and infrastructure of SRM geoengineering techniques may also have some negative effects that may be particularly acute for techniques that are spatially extensive, such as desert albedo geoengineering. SRM would have very little effect on ocean acidification and the other direct effects of elevated CO_2 concentrations that are likely to pose significant risks (see WG I Section 6.5.4).

6.9.2.2 The relation of solar radiation management to climate policy and transformation pathways

A key determinant of the potential role, if any, of SRM in climate policy is that some methods might act relatively quickly. For example, stratospheric aerosol injection could be deployable within months to years, if and when the technology is available, and the climate response to the resulting changes in radiative forcing could occur on a timescale of a decade or less (e.g. Keith, 2000; Matthews and Caldeira, 2007; Royal Society, 2009; Swart and Marinova, 2010; Goes et al., 2011). Mitigating GHG emissions would affect global mean temperatures only on a multi-decadal to centennial time-scale because of the inertia in the carbon cycle (van Vuuren and Stehfest, 2013). Hence, it has been argued that SRM technologies could potentially complement mitigation activities, for example, by countering global GHG radiative forcing while mitigation activities are being implemented, or by providing a back-up strategy for a hypothetical future situation where short-term reductions in radiative forcing may be desirable (Royal Society, 2009; Rickels et al., 2011). However, the relatively fast and strong climate response expected from some SRM techniques would also impose risks. The termination of SRM geoengineering forcing either by policy choice or through some form of failure would result in a rapid rise of global mean temperature and associated changes in climate, the magnitude of which would depend on the degree of SRM forcing that was being exerted and the rate at which the SRM forcing was withdrawn (Wigley, 2006; Matthews and Caldeira, 2007; Goes et al., 2011; Irvine et al., 2012; Jones et al., 2013). It has been suggested that this risk could be minimized if SRM geoengineering was used moderately and combined with strong CDR geoengineering and mitigation efforts (Ross and Matthews, 2009; Smith and Rasch, 2012). The potential of SRM to significantly impact the climate on short time-scales, at potentially low cost, and the uncertainties and risks involved in this raise important socio-political questions in addition to natural scientific and technological considerations in the section above.

The economic analysis of the potential role of SRM as a climate change policy is an area of active research and has, thus far, produced mixed and preliminary results (see Klepper and Rickels, 2012). Estimates of the direct costs of deploying various proposed SRM methods differ significantly. A few studies have indicated that direct costs for some SRM methods might be considerably lower than the costs of conventional mitigation, but all estimates are subject to large uncertainties because of questions regarding efficacy and technical feasibility (Coppock, 1992; Barrett, 2008; Blackstock et al., 2009; Robock et al., 2009; Pierce et al., 2010; Klepper and Rickels, 2012; McClellan et al., 2012).

However, SRM techniques would carry uncertain risks, do not directly address some impacts of anthropogenic GHG emissions, and raise a range of ethical questions (see WG III Section 3.3.8) (Royal Society, 2009; Goes et al., 2011; Moreno-Cruz and Keith, 2012; Tuana et al., 2012). While costs for the implementation of a particular SRM method might potentially be low, a comprehensive assessment would need to consider all intended and unintended effects on ecosystems and societies and the corresponding uncertainties (Rickels et al., 2011; Goes et al., 2011; Klepper and Rickels, 2012). Because most proposed SRM methods would require constant replenishment and an increase in their implementation intensity if emissions of GHGs continue, the result of any assessment of climate policy costs is strongly dependent on assumptions about the applicable discount rate, the dynamics of deployment, the implementation of mitigation, and the likelihood of risks and side-effects of SRM (see Bickel and Agrawal, 2011; Goes et al., 2011). While it has been suggested that SRM technologies may 'buy time' for emission reductions (Rickels et al., 2011), they cannot substitute for emission reductions in the long term because they do not address concentrations of GHGs and would only partially and imperfectly compensate for their impacts.

The acceptability of SRM as a climate policy in national and international socio-political domains is uncertain. While international commitment is required for effective mitigation, a concern about SRM is that direct costs might be low enough to allow countries to unilaterally alter the global climate (Bodansky, 1996; Schelling, 1996; Barrett, 2008). Barrett (2008) and Urpelainen (2012) therefore argue that SRM technologies introduce structurally obverse problems to the 'free-rider' issue in climate change mitigation. Some studies suggest that deployment of SRM hinges on interstate cooperation, due to the complexity of the climate system and the unpredictability of outcomes if states do not coordinate their actions (Horton, 2011). In this case, the political feasibility of an SRM intervention would depend on the ability of state-level actors to come to some form of agreement.

The potential for interstate cooperation and conflict will likely depend on the institutional context in which SRM is being discussed, as well as on the relative importance given to climate change issues at the national and international levels. Whether a broad international agreement is possible is a highly contested subject (see Section 13.4.4) (SRMGI, 2012). Several researchers suggest that a UN-based institutional arrangement for decision making on SRM would be most effective (Barrett, 2008; Virgoe, 2009; Zürn and Schäfer, 2013). So far there are no legally binding international norms that explicitly address SRM, although certain general rules and principles of international law are applicable (see WG II, Chapter 13, p.37). States parties to the UN Convention on Biological Diversity have adopted a non-binding decision on geoengineering that establishes criteria that could provide guidance for further development of international regulation and governance (CBD Decision IX/16 C (ocean fertilization) and Decision X/33(8)(w); see also LC/LP Resolutions LC-LP.1(2008) and LC-LP.2(2010), preamble).

Commentators have identified the governance of SRM technologies as a significant political and ethical challenge, especially in ensuring legitimate decision making, monitoring, and control (Victor, 2008; Virgoe, 2009; Bodansky, 2012). Even if SRM would largely reduce the global temperature rise due to anthropogenic climate change, as current modelling studies indicate, it would also imply a spatial and temporal redistribution of risks. SRM thus introduces important questions of intra- and intergenerational justice, both distributive and procedural (see Wigley, 2006; Matthews and Caldeira, 2007; Goes et al., 2011; Irvine et al., 2012; Tuana et al., 2012; Bellamy et al., 2012; Preston, 2013). Furthermore, since the technologies would not remove the need for emission reductions, in order to to effectively ameliorate climate change over a longer-term SRM regulation would need to be based on a viable relation between mitigation and SRM activities, and consider the respective and combined risks of increased GHG concentrations and SRM interventions. The concern that the prospect of a viable SRM technology may reduce efforts to mitigate and adapt has featured prominently in discussions to date (Royal Society, 2009; Gardiner, 2011; Preston, 2013).

Whether SRM field research or even deployment would be socially and politically acceptable is also dependent on the wider discursive context in which the topic is being discussed. Bellamy et al. (2013) show that the success of mitigation policies is likely to have an influence on stakeholder acceptability of SRM. While current evidence is limited to few studies in a very narrow range of cultural contexts, in a first review of early studies on perceptions of geoengineering, Corner et al. (2012) find that participants of different studies tend to prefer CDR over SRM and mitigation over geoengineering. Considerations that influence opinions are, amongst others, the perceived 'naturalness' of a technology, its reversibility, and the capacity for responsible and transparent governance (Corner et al., 2012). Furthermore, the way that the topic is framed in the media and by experts plays an important role in influencing opinions on SRM research or deployment (Luokkanen et al., 2013; Scholte et al., 2013). The direction that future discussions may take is impossible to predict, since deepened and highly differentiated information is rapidly becoming available (Corner et al., 2012; Macnaghten and Szerszynski, 2013).

6.9.3 Summary

Despite the assumption of some form of negative CO_2 emissions in many scenarios, including those leading to 2100 concentrations approaching 450 ppm CO_2eq, whether proposed CDR or SRM geoengineering techniques can actually play a useful role in transformation pathways is uncertain as the efficacy and risks of many techniques are poorly understood at present. CDR techniques aim to reduce CO_2 (or potentially other GHG) concentrations. A broad definition of CDR would cover afforestation and BECCS, which are sometimes classified as mitigation techniques, but also proposals that are very distinct from mitigation in terms of technical maturity, scientific understanding, and risks such as ocean iron fertilization. The former are often included in current integrated models and scenarios and are, in terms of their impact on the climate, directly comparable with techniques that are considered to be conventional mitigation, notably fossil CCS and bio-energy use. Both BECCS and afforestation may play a key role in reaching low-GHG concentrations, but at a large scale have substantial land-use demands that may conflict with other mitigation strategies and societal needs such as food production. Whether other CDR techniques would be able to supplement mitigation at any significant scale in the future depends upon efficacy, cost, and risks of these techniques, which at present are highly uncertain. The properties of potential carbon storage reservoirs are also critically important, as limits to reservoir capacity and longevity will constrain the quantity and permanence of CO_2 storage. Furthermore, some CDR techniques such as ocean iron fertilization may pose transboundary risks. The impacts of CDR would be relatively slow: climate effects would unfold over the course of decades.

In contrast to CDR, SRM would aim to cool the climate by shielding sunlight. These techniques would not reduce elevated GHG concentrations, and thus not affect other consequences of high-GHG concentrations, such as ocean acidification. Some SRM proposals could potentially cause a large cooling within years, much quicker than mitigation or CDR, and a few studies suggest that costs might be considerably lower than CDR for some SRM techniques. It has thus been suggested that SRM could be used to quickly reduce global temperatures or to limit temperature rise while mitigation activities are being implemented. However, to avoid warming, SRM would need to be maintained as long as GHG concentrations remain elevated. Modelling studies show that SRM may be able to reduce global average temperatures but would not perfectly reverse all climatic changes that occur due to elevated GHG concentrations, especially at local to regional scales. For example, SRM is expected to weaken the global hydrological cycle with consequences for regional precipitation patterns and surface hydrology, and is expected to change the seasonality and variability of climate. Because the potential climate impacts of any SRM intervention are uncertain and evidence is very limited, it is too early to conclude how effective SRM would be in reducing climate risks. SRM approaches may also carry significant non-climatic side-effects. For example, sulphate aerosol injection would modify stratospheric chemistry, potentially reducing ozone levels, and would change the appearance of the sky. The risks of SRM interventions and large-scale experiments, alongside any potential benefits, raise a number of ethical and political questions that would require public engagement and international cooperation to address adequately.

6.10 Gaps in knowledge and data

The questions that motivate this chapter all address the broad characteristics of possible long-term transformation pathways toward stabilization of GHG concentrations. The discussion has not focused on today's global or country-specific technology strategies, policy strategies, or other elements of a near-term strategy. It is therefore within this long-term strategic context that gaps in knowledge and data should be viewed.

Throughout this chapter, a number of areas of further development have been highlighted. Several areas would be most valuable to further the development of information and insights regarding long-term transformation pathways. These include the following: development of a broader set of socioeconomic and technological storylines to support the development of future scenarios; scenarios pursuing a wider set of climate goals including those related to temperature change; more mitigation scenarios that include impacts from, and adaptations to, a changing climate, including energy and land-use systems critical for mitigation; expanded treatment of the benefits and risks of CDR and SRM options; expanded treatment of co-benefits and risks of mitigation pathways; improvements in the treatment and understanding of mitigation options and responses in end-use sectors in transformation pathways; and more sophisticated treatments of land use and land use-based mitigation options in mitigation scenarios. In addition, a major weakness of the current integrated modelling suite is that regional definitions are often not comparable across models. An important area of advancement would be to develop some clearly defined regional definitions that can be met by most or all models.

6.11 Frequently Asked Questions

FAQ 6.1 Is it possible to bring climate change under control given where we are and what options are available to us? What are the implications of delaying mitigation or limits on technology options?

Many commonly discussed concentration goals, including the goal of reaching 450 ppm CO_2eq by the end of the 21st century, are both physically and technologically possible. However, meeting long-term climate goals will require large-scale transformations in human societies, from the way that we produce and consume energy to how we use the land surface, that are inconsistent with both long-term and short-term trends. For example, to achieve a 450 ppm CO_2eq concentration by 2100, supplies of low-carbon energy—energy from nuclear power, solar power, wind power, hydroelectric power, bioenergy, and fossil resources with carbon dioxide capture and storage—might need to increase five-fold or more over the next 40 years. The possibility of meeting any concentration goal therefore depends not just on the available technologies and current emissions and concentrations, but also on the capacity of human societies to bear the associated economic implications, accept the associated rapid and large-scale deployment of technologies, develop the necessary institutions to manage the transformation, and reconcile the transformation with other policy priorities such as sustainable development. Improvements in the costs and performance of mitigation technologies will ease the burden of this transformation. If the world's countries cannot take on sufficiently ambitious mitigation over the next 20 years, or obstacles impede the deployment of important mitigation technologies at large scale, goals such as 450 ppm CO_2eq by 2100 may no longer be possible.

FAQ 6.2 What are the most important technologies for mitigation? Is there a silver bullet technology?

Limiting CO_2eq concentrations will require a portfolio of options, because no single option is sufficient to reduce CO_2eq concentrations and eventually eliminate net CO_2 emissions. A portfolio approach can be tailored to local circumstances to take into account other priorities such as those associated with sustainable development. Technology options include a range of energy supply technologies such as nuclear power, solar energy, wind power, and hydroelectric power, as well as bioenergy and fossil resources with carbon dioxide capture and storage. In addition, a range of end-use technologies will be needed to reduce energy consumption, and therefore the need for low-carbon energy, and to allow the use of low-carbon fuels in transportation, buildings, and industry. Halting deforestation and encouraging an increase in forested land will help to halt or reverse LUC CO_2 emissions. Furthermore, there are opportunities to reduce non-CO_2 emissions from land use and industrial sources. Many of these options must be deployed to some degree to stabilize CO_2eq concentrations. At the same time, although a portfolio approach is necessary, if emissions reductions are too modest over the coming two decades, it may no longer be possible to reach a goal of 450 ppm CO_2eq by the end of the century without large-scale deployment of carbon dioxide removal technologies. Thus, while no individual technology is sufficient, carbon dioxide removal technologies could become necessary in such a scenario.

FAQ 6.3 How much would it cost to bring climate change under control?

Aggregate economic mitigation cost metrics are an important criterion for evaluating transformation pathways and can indicate the level of difficulty associated with particular pathways. However, the broader socio-economic implications of mitigation go beyond measures of aggregate economic costs, as transformation pathways involve a range of tradeoffs that link to other policy priorities. Global mitigation cost estimates vary widely due to methodological differences along with differences in assumptions about future emissions drivers, technologies, and policy conditions. Most scenario studies collected for this assessment that are based on the idealized assumptions that all countries of the world begin mitigation immediately, there is a single global carbon price applied to well-functioning markets, and key technologies are available, find that meeting a 430–480 ppm CO_2eq goal by century's end would entail a reduction in the amount global consumers spend of 1–4 % in 2030, 2–6 % in 2050, and 3–11 % in 2100 relative to what would happen without mitigation. To put these losses in context, studies assume that consumption spending might grow from four- to over ten-fold over the century without mitigation. Less ambitious goals are associated with lower costs this century. Substantially higher and lower estimates have been obtained by studies that consider interactions with pre-existing distortions, non-climate market failures, and complementary policies. Studies explicitly exploring the implications of less-idealized policy approaches and limited technology performance or availability have consistently produced higher cost estimates. Delaying mitigation would reduce near-term costs; however subsequent costs would rise more rapidly to higher levels.

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7

Energy Systems

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Executive Summary

The *energy systems* chapter addresses issues related to the mitigation of greenhouse gas emissions (GHG) from the *energy supply sector*. The energy supply sector, as defined in this report, comprises all energy extraction, conversion, storage, transmission, and distribution processes that deliver *final energy* to the end-use sectors (industry, transport, and building, as well as agriculture and forestry). Demand side measures in the energy end-use sectors are discussed in chapters 8–11.

The energy supply sector is the largest contributor to global greenhouse gas emissions (*robust evidence, high agreement*). In 2010, the energy supply sector was responsible for approximately 35 % of total anthropogenic GHG emissions. Despite the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, GHG emissions grew more rapidly between 2000 and 2010 than in the previous decade. Annual GHG-emissions growth in the global energy supply sector accelerated from 1.7 % per year from 1990–2000 to 3.1 % per year from 2000–2010. The main contributors to this trend were a higher energy demand associated with rapid economic growth and an increase of the share of coal in the global fuel mix. [7.2, 7.3]

In the baseline scenarios assessed in AR5, direct CO_2 emissions of the energy supply sector increase from 14.4 $GtCO_2$/yr in 2010 to 24–33 $GtCO_2$/yr in 2050 (25–75th percentile; full range 15–42 $GtCO_2$/yr), with most of the baseline scenarios assessed in AR5 showing a significant increase (*medium evidence, medium agreement*). The lower end of the full range is dominated by scenarios with a focus on energy intensity improvements that go well beyond the observed improvements over the past 40 years. The availability of fossil fuels alone will not be sufficient to limit CO_2-equivalent (CO_2eq) concentrations to levels such as 450 ppm, 550 ppm, or 650 ppm. [6.3.4, Figures 6.15, 7.4, 7.11.1, Figure TS 15]

Multiple options exist to reduce energy supply sector GHG emissions (*robust evidence, high agreement*). These include energy efficiency improvements and fugitive emission reductions in fuel extraction as well as in energy conversion, transmission, and distribution systems; fossil fuel switching; and low-GHG energy supply technologies such as renewable energy (RE), nuclear power, and carbon dioxide capture and storage (CCS). [7.5, 7.8.1, 7.11]

The stabilization of GHG concentrations at low levels requires a fundamental transformation of the energy supply system, including the long-term substitution of unabated[1] fossil fuel conversion technologies by low-GHG alternatives (*robust evidence, high agreement*). Concentrations of CO_2 in the atmosphere can only be stabilized if global (net) CO_2 emissions peak and decline toward zero in the long term. Improving the energy efficiencies of fossil power plants and/or the shift from coal to gas will not by itself be sufficient to achieve this. Low-GHG energy supply technologies are found to be necessary if this goal is to be achieved. [7.5.1, 7.8.1, 7.11]

Decarbonizing (i.e. reducing the carbon intensity of) electricity generation is a key component of cost-effective mitigation strategies in achieving low-stabilization levels (430–530 ppm CO_2eq); in most integrated modelling scenarios, decarbonization happens more rapidly in electricity generation than in the industry, buildings and transport sectors (*medium evidence, high agreement*). In the majority of low-stabilization scenarios, the share of low-carbon electricity supply (comprising RE, nuclear and CCS) increases from the current share of approximately 30 % to more than 80 % by 2050, and fossil fuel power generation without CCS is phased out almost entirely by 2100. [7.11]

Since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), many RE technologies have demonstrated substantial performance improvements and cost reductions, and a growing number of RE technologies have achieved a level of maturity to enable deployment at significant scale (*robust evidence, high agreement*). Some technologies are already economically competitive in various settings. While the levelized cost of photovoltaic (PV) systems fell most substantially between 2009 and 2012, a less marked trend has been observed for many other RE technologies. Regarding electricity generation alone, RE accounted for just over half of the new electricity-generating capacity added globally in 2012, led by growth in wind, hydro, and solar power. Decentralized RE supply to meet rural energy needs has also increased, including various modern and advanced traditional biomass options as well as small hydropower, PV, and wind.

RE technology policies have been successful in driving the recent growth of RE. Nevertheless many RE technologies still need direct support (e.g., feed-in tariffs, RE quota obligations, and tendering/bidding) and/or indirect support (e.g., sufficiently high carbon prices and the internalization of other externalities) if their market shares are to be significantly increased. Additional enabling policies are needed to address issues associated with the integration of RE into future energy systems (*medium evidence, medium agreement*). [7.5.3, 7.6.1, 7.8.2, 7.12, 11.13]

There are often co-benefits from the use of RE, such as a reduction of air pollution, local employment opportunities, few severe accidents compared to some other forms of energy supply, as well as improved energy access and security (*medium evidence, medium agreement*). At the same time, however, some RE technologies can have technology- and location-specific adverse side-effects, though those can be reduced to a degree through appropriate technology selection, operational adjustments, and siting of facilities. [7.9]

[1] These are fossil fuel conversion technologies not using carbon dioxide capture and storage technologies.

Infrastructure and integration challenges vary by RE technology and the characteristics of the existing background energy system (*medium evidence, medium agreement*). Operating experience and studies of medium to high penetrations of RE indicate that these issues can be managed with various technical and institutional tools. As RE penetrations increase, such issues are more challenging, must be carefully considered in energy supply planning and operations to ensure reliable energy supply, and may result in higher costs. [7.6, 7.8.2]

Nuclear energy is a mature low-GHG emission source of baseload power, but its share of global electricity generation has been declining (since 1993). Nuclear energy could make an increasing contribution to low-carbon energy supply, but a variety of barriers and risks exist (*robust evidence, high agreement*). Its specific emissions are below 100 gCO_2eq per kWh on a lifecycle basis and with more than 400 operational nuclear reactors worldwide, nuclear electricity represented 11 % of the world's electricity generation in 2012, down from a high of 17 % in 1993. Pricing the externalities of GHG emissions (carbon pricing) could improve the competitiveness of nuclear power plants. [7.2, 7.5.4, 7.8.1, 7.12]

Barriers to and risks associated with an increasing use of nuclear energy include operational risks and the associated safety concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapon proliferation concerns, and adverse public opinion (*robust evidence, high agreement*). New fuel cycles and reactor technologies addressing some of these issues are under development and progress has been made concerning safety and waste disposal (*medium evidence, medium agreement*). [7.5.4, 7.8.2, 7.9, 7.11]

Carbon dioxide capture and storage technologies could reduce the lifecycle GHG emissions of fossil fuel power plants (*medium evidence, medium agreement*). While all components of integrated CCS systems exist and are in use today by the fossil fuel extraction and refining industry, CCS has not yet been applied at scale to a large, commercial fossil fuel power plant. A variety of pilot and demonstrations projects have led to critical advances in the knowledge of CCS systems and related engineering, technical, economic and policy issues. CCS power plants could be seen in the market if they are required for fossil fuel facilities by regulation or if they become competitive with their unabated counterparts, for instance, if the additional investment and operational costs, caused in part by efficiency reductions, are compensated by sufficiently high carbon prices (or direct financial support). Beyond economic incentives, well-defined regulations concerning short- and long-term responsibilities for storage are essential for a large-scale future deployment of CCS. [7.5.5, 7.8.1]

Barriers to large-scale deployment of CCS technologies include concerns about the operational safety and long-term integrity of CO_2 storage as well as transport risks (*limited evidence, medium agreement*). There is, however, a growing body of literature on how to ensure the integrity of CO_2 wells, on the potential consequences of a pressure buildup within a geologic formation caused by CO_2 storage (such as induced seismicity), and on the potential human health and environmental impacts from CO_2 that migrates out of the primary injection zone (*limited evidence, medium agreement*). [7.5.5, 7.9]

Combining bioenergy with CCS (BECCS) offers the prospect of energy supply with large-scale net negative emissions, which plays an important role in many low-stabilization scenarios, while it entails challenges and risks (*limited evidence, medium agreement*). These challenges and risks include those associated with the upstream provision of the biomass that is used in the CCS facility as well as those associated with the CCS technology itself. BECCS faces large challenges in financing and currently no such plants have been built and tested at scale. [7.5.5, 7.8.2, 7.9, 7.12, 11.13]

GHG emissions from energy supply can be reduced significantly by replacing current world average coal-fired power plants with modern, highly efficient natural gas combined-cycle (NGCC) power plants or combined heat and power (CHP) plants, provided that natural gas is available and the fugitive emissions associated with its extraction and supply are low or mitigated (*robust evidence, high agreement*). Lifecycle assessments indicate a reduction of specific GHG emissions of approximately 50 % for a shift from a current world-average coal power plant to a modern NGCC plant depending on natural gas upstream emissions. Substitution of natural gas for renewable energy forms increases emissions. Mitigation scenarios with low-GHG concentration targets (430–530 ppm CO_2eq) require a fundamental transformation of the energy system in the long term. In mitigation scenarios reaching about 450 ppm CO_2eq by 2100, natural gas power generation without CCS typically acts as a bridge technology, with deployment increasing before peaking and falling to below current levels by 2050 and declining further in the second half of the century (*robust evidence, high agreement*). [7.5.1, 7.8, 7.9, 7.11]

Direct GHG emissions from the fossil fuel chain can be reduced through various measures (*medium evidence, high agreement*). These include the capture or oxidation of coal bed methane, the reduction of venting and flaring in oil and gas systems, as well as energy efficiency improvements and the use of low-GHG energy sources in the fuel chain. [7.5.1]

Greenhouse gas emission trading and GHG taxes have been enacted to address the market externalities associated with GHG emissions (*high evidence, high agreement*). In the longer term, GHG pricing can support the adoption of low-GHG energy technologies due to the resulting fuel- and technology-dependent mark up in marginal costs. Technology policies (e.g., feed-in tariffs, quotas, and tendering/bidding) have proven successful in increasing the share of RE technologies (*medium evidence, medium agreement*). [7.12]

The success of energy policies depends on capacity building, the removal of financial barriers, the development of a solid legal

framework, and sufficient regulatory stability (*robust evidence, high agreement*). Property rights, contract enforcement, and emissions accounting are essential for the successful implementation of climate policies in the energy supply sector. [7.10, 7.12]

The energy infrastructure in developing countries, especially in Least Developed Countries (LDCs), is still undeveloped and not diversified (*robust evidence, high agreement*). There are often co-benefits associated with the implementation of mitigation energy technologies at centralized and distributed scales, which include local employment creation, income generation for poverty alleviation, as well as building much-needed technical capability and knowledge transfer. There are also risks in that the distributive impacts of higher prices for low-carbon energy might become a burden on low-income households, thereby undermining energy-access programmes, which can, however, be addressed by policies to support the poor. [7.9, 7.10]

Although significant progress has been made since AR4 in the development of mitigation options in the energy supply sector, important knowledge gaps still exist that can be reduced with further research and development (R&D). These especially comprise the technological challenges, risks, and co-benefits associated with the upscaling and integration of low-carbon technologies into future energy systems, and the resulting costs. In addition, research on the economic efficiency of climate-related energy policies, and especially concerning their interaction with other policies applied in the energy sector, is limited. [7.13]

7.1 Introduction

The energy supply sector is the largest contributor to global greenhouse gas (GHG) emissions. In 2010, approximately 35 % of total anthropogenic GHG emissions were attributed to this sector. Despite the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, annual GHG-emissions growth from the global energy supply sector accelerated from 1.7 % per year in 1990–2000 to 3.1 % in 2000–2010 (Section 7.3). Rapid economic growth (with the associated higher demand for power, heat, and transport services) and an increase of the share of coal in the global fuel mix were the main contributors to this trend.

The *energy supply sector*, as defined in this chapter (Figure 7.1), comprises all energy extraction, conversion, storage, transmission, and distribution processes with the exception of those that use final energy to provide energy services in the end-use sectors (industry, transport, and building, as well as agriculture and forestry). Concerning *energy statistics data* as reported in Sections 7.2 and 7.3, power, heat, or fuels that are generated on site for own use exclusively are not accounted for in the assessment of the energy supply sector. Note that many scenarios in the literature do not provide a sectoral split of energy-related emissions; hence, the discussion of transformation pathways in Section 7.11 focuses on aggregated *energy-related emissions* comprising the supply and the end-use sectors.

The allocation of cross-cutting issues among other chapters allows for a better understanding of the Chapter 7 boundaries (see Figure 7.1). The importance of energy for social and economic development is reviewed in Chapters 4 and 5 and to a lesser degree in Section 7.9 of this chapter. Chapter 6 presents long-term transformation pathways and futures for energy systems.

Transport fuel supply, use in vehicles, modal choice, and the local infrastructure are discussed in Chapter 8. Building integrated power and heat generation as well as biomass use for cooking are addressed in Chapter 9. Responsive load issues are dealt with by chapters 8–10. Chapter 7 considers mitigation options in energy-extraction industries (oil, gas, coal, uranium, etc.), while other extractive industries are addressed in Chapter 10. Together with aspects related to bioenergy usage, provision of biomass is discussed in Chapter 11, which covers land uses including agriculture and forestry. Only energy supply sector-related policies are covered in Chapter 7 while the broader and more-detailed climate policy picture is presented in Chapters 13–15.

The derivation of least-cost mitigation strategies must take into account the interdependencies between energy demand and supply. Due to the selected division of labor described above, Chapter 7 does not discuss demand-side measures from a technological point of view. Tradeoffs between demand- and supply-side options, however, are considered by the integrated models (IAM) that delivered the transformation pathways collected in the WGIII AR5 Scenario Database (see Annex II.10 and, concerning energy supply aspects, Section 7.11).

Chapter 7 assesses the literature evolution of energy systems from earlier Intergovernmental Panel on Climate Change (IPCC) reports, comprising the Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005), the Fourth Assessment Report (AR4) (IPCC, 2007), and the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (IPCC, 2011a). Section 7.2 describes the current status of global and regional energy markets. Energy-related GHG-emissions trends together with associated drivers are presented in Section 7.3. The next section provides data on energy resources. Section 7.5 discusses advances in the field of mitigation technologies. Issues related to the integration of low-carbon technologies are covered in Section 7.6, while Section 7.7 describes how climate change may impact energy demand and supply. Section 7.8 discusses emission-reduction potentials and related costs. Section 7.9 covers issues of co-benefits and adverse side effects of mitigation options. Mitigation barriers are dealt with in Section 7.10. The implications of various transformation pathways for the energy sector are covered in Section 7.11. Section 7.12 presents energy supply sector-specific policies. Section 7.13 addresses knowledge gaps and Section 7.14 summarizes frequently asked questions (FAQ).

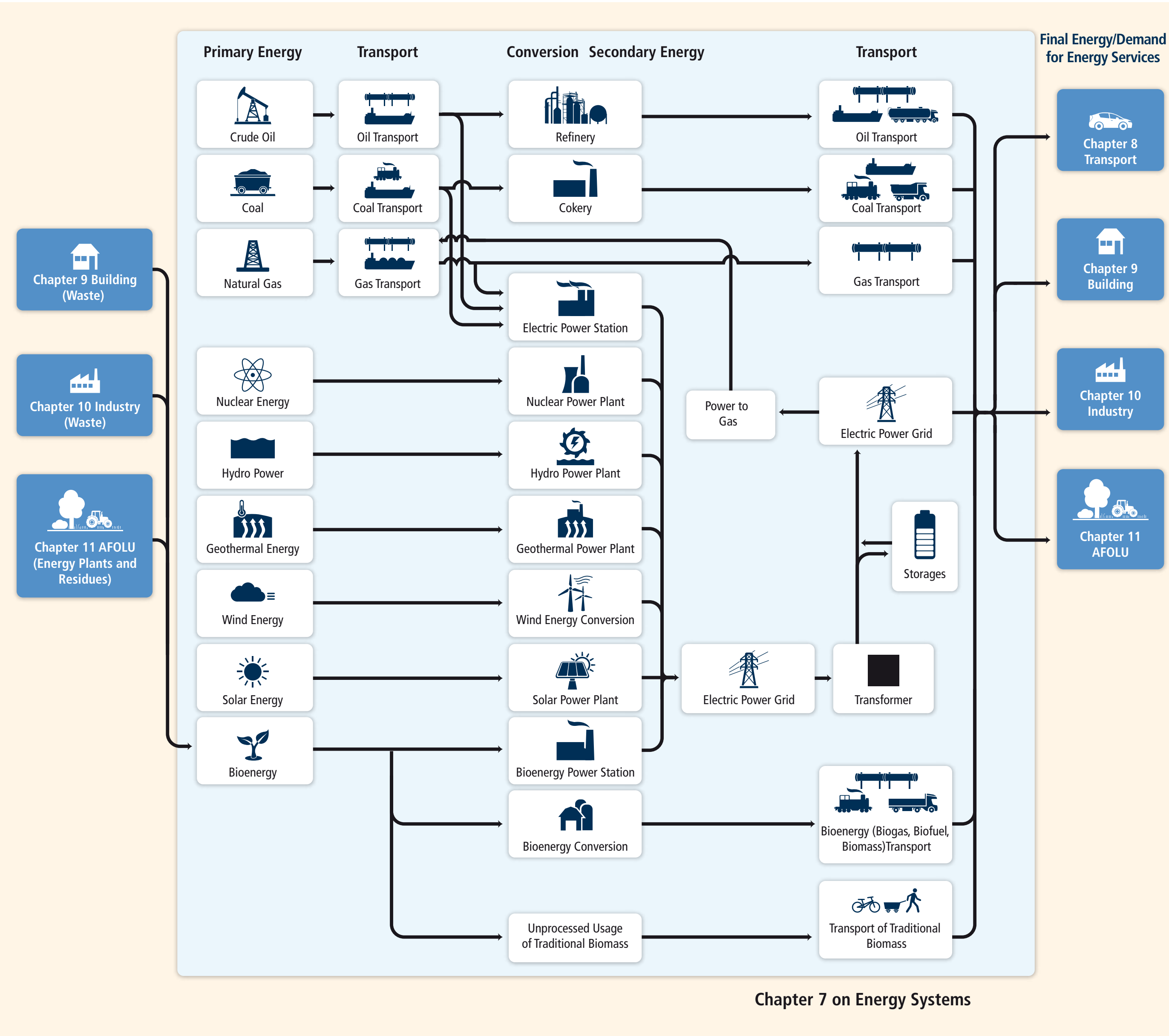


Figure 7.1 | Illustrative energy supply paths shown in order to illustrate the boundaries of the energy supply sector as defined in this report. The self-generation of heat and power in the end-use sectors (i.e., transport, buildings, industry, and Agriculture, Forestry, and Other Land Use (AFOLU)) is discussed in Chapters 8–11.

7.2 Energy production, conversion, transmission and distribution

The energy supply sector converts over 75 % of total primary energy supply (TPES) into other forms, namely, electricity, heat, refined oil products, coke, enriched coal, and natural gas. Industry (including non-energy use) consumes 84 % of final use of coal and peat, 26 % of petroleum products, 47 % of natural gas, 40 % of electricity, and 43 % of heat. Transportation consumes 62 % of liquid fuels final use. The building sector is responsible for 46 % of final natural gas consumption, 76 % of combustible renewables and waste, 52 % of electricity use, and 51 % of heat (Table 7.1). Forces driving final energy-consumption evolution in all these sectors (Chapters 8–11) have a significant impact on the evolution of energy supply systems, both in scale and structure.

The energy supply sector is itself the largest energy user. Energy losses assessed as the difference between the energy inputs to (78 % of the TPES) and outputs from this sector (48.7 % of TPES) account for 29.3 % of TPES (Table 7.1). The TPES is not only a function of end users' demand for higher-quality energy carriers, but also the relatively low average global efficiency of energy conversion, transmission, and distribution processes (only 37 % efficiency for fossil fuel power and just 83 % for fossil fuel district heat generation). However, low efficiencies and large own energy use of the energy sector result in high

Table 7.1 | 2010 World Energy Balance (EJ on a net calorific value basis applying the *direct equivalent method*).
Source: See IEA (2012a) for data, methodology, and definitions. International Energy Agency (IEA) data were modified to convert to primary energy by applying the *direct equivalent method* (see Annex II.4). Negative numbers in energy sector reflect energy spent or lost, while positive ones indicate that specific forms of energy were generated.

Supply and consumption	Coal and peat	Crude oil	Oil products	Gas	Nuclear	Hydro	Geo-thermal. Solar, etc.	Com-bustible renew-ables and waste	Electricity	Heat	Total*	*Share in TPES (%)*	*Share in FEC (%)*	*Conversion efficiency* and losses (%)*
Production	**150.56**	**170.38**	**0.00**	**113.84**	**9.95**	**12.38**	**2.91**	**53.47**	**0**	**0.04**	**513.52**	***101.20 %***		
Imports	26.83	96.09	44.12	34.21				0.45	2.12	0.00	203.81	*39.92 %*		
Exports	−28.52	−92.59	−46.55	−34.60				−0.39	−2.08	0.00	−204.73	*−40.10 %*		
Stock Changes	−3.34	0.27	0.26	0.75				−0.02			−2.09	*−0.41 %*		
Total Primary Energy Supply (TPES)	**145.52**	**174.14**	**−2.17**	**114.20**	**9.95**	**12.38**	**2.91**	**53.51**	**0.04**	**0.04**	**510.52**	***100.00 %***		
Share in total TPES (%)	*28.51 %*	*34.11 %*	*−0.43 %*	*22.37 %*	*1.95 %*	*2.42 %*	*0.57 %*	*10.48 %*	*0.01 %*		*100.00 %*			
Transfers	0.00	−6.56	7.51					0.00			0.95	*−0.19 %*		
Statistical Differences	−2.07	0.47	−1.13	−0.07			−0.01	−0.02	0.28	0.00	−2.55	*0.50 %*		
Electricity Plants	−82.68	−1.45	−8.44	−29.54	−9.89	−12.38	−1.61	−2.65	65.37	−0.01	−83.28	*16.31 %*		*37.13 %*
Combined Heat and Power Plants	−6.75		−0.94	−12.76	−0.06	0	−0.02	−1.47	6.85	5.86	−9.31	*1.82 %*		*57.72 %*
Electricity generation (TWh)	*8698*	*28*	*961*	*4768*	*2756*	*3437*	*450*	*332*		*2*	*21431*			
Share in electricity generation (%)	*40.58 %*	*0.13 %*	*4.49 %*	*22.25 %*	*12.86 %*	*16.04 %*	*2.10 %*	*1.55 %*		*0.01 %*	*100.00 %*			
Heat Plants	−4.34	−0.03	−0.54	−3.77			−0.34	−0.44	−0.01	7.05	−2.42	*0.47 %*		*83.28 %*
Gas Works	−0.37		−0.15	0.12							−0.40	*0.08 %*		*22.79 %*
Oil Refineries		−164.70	162.86	−0.03							−1.87	*0.37 %*		*98.86 %*
Coal Transformation	−9.19	0.00	−0.13	0.00				0.00			−9.33	*1.83 %*		
Liquefaction Plants	−0.68	0.33	0.00	−0.30							−0.65	*0.13 %*		*33.69 %*
Other Transformation	0.00	0.01	−0.01	−0.09				−2.22		−0.01	−2.33			*0.30 %*
Energy Industry Own Use	−3.61	−0.42	−8.81	−11.53			−0.01	−0.56	−6.10	−1.43	−32.46	*6.36 %*		*6.36 %*
Losses	−0.11	−0.34	−0.02	−1.03			−0.01	−0.01	−6.08	−0.89	−8.49	*1.66 %*		*1.66 %*
Total energy sector	**−107.73**	**−173.18**	**151.33**	**−58.94**	**−9.95**	**−12.38**	**−1.98**	**−7.35**	**60.02**	**10.56**	**−149.60**	***29.30 %***		
Share of energy sector in TPES by fuels (%)	*74.03 %*	*99.45 %*	*7.08 %*	*51.61 %*	*100.00 %*	*100.00 %*	*68.00 %*	*13.74 %*	*8.17 %*	*18.21 %*	*−29.30 %*			
Total Final Consumption (TFC)	**35.72**	**1.44**	**148.02**	**55.19**	**0.00**	**0.00**	**0.92**	**46.14**	**60.35**	**10.60**	**358.37**	***70.20 %***	***100.0 %***	
Share of energy carriers in TFC (%)	*9.97 %*	*0.40 %*	*41.30 %*	*15.40 %*	*0.00 %*	*0.00 %*	*0.26 %*	*12.87 %*	*16.84 %*	*2.96 %*	*100.00 %*			
Industry	28.38	0.52	12.98	19.42			0.02	8.20	24.26	4.61	98.39	*19.27 %*	*27.46 %*	
Transport	0.14	0.00	91.94	3.73				2.41	0.97	0.00	99.20	*19.43 %*	*27.68 %*	
Buildings	4.25	0.03	13.13	25.15			0.48	35.10	31.46	5.37	114.96	*22.52 %*	*32.08 %*	
Agriculture/forestry/fishing	0.46	0.00	4.51	0.25			0.03	0.31	1.58	0.14	7.29	*1.43 %*	*2.03 %*	
Non-Specified	0.98	0.25	0.60	0.26			0.39	0.11	2.07	0.49	5.15	*1.01 %*	*1.44 %*	
Non-Energy Use	1.51	0.63	24.87	6.38							33.38	*6.54 %*	*9.32 %*	

*Only for fossil fuel-powered generation. Totals may not add up due to rounding.

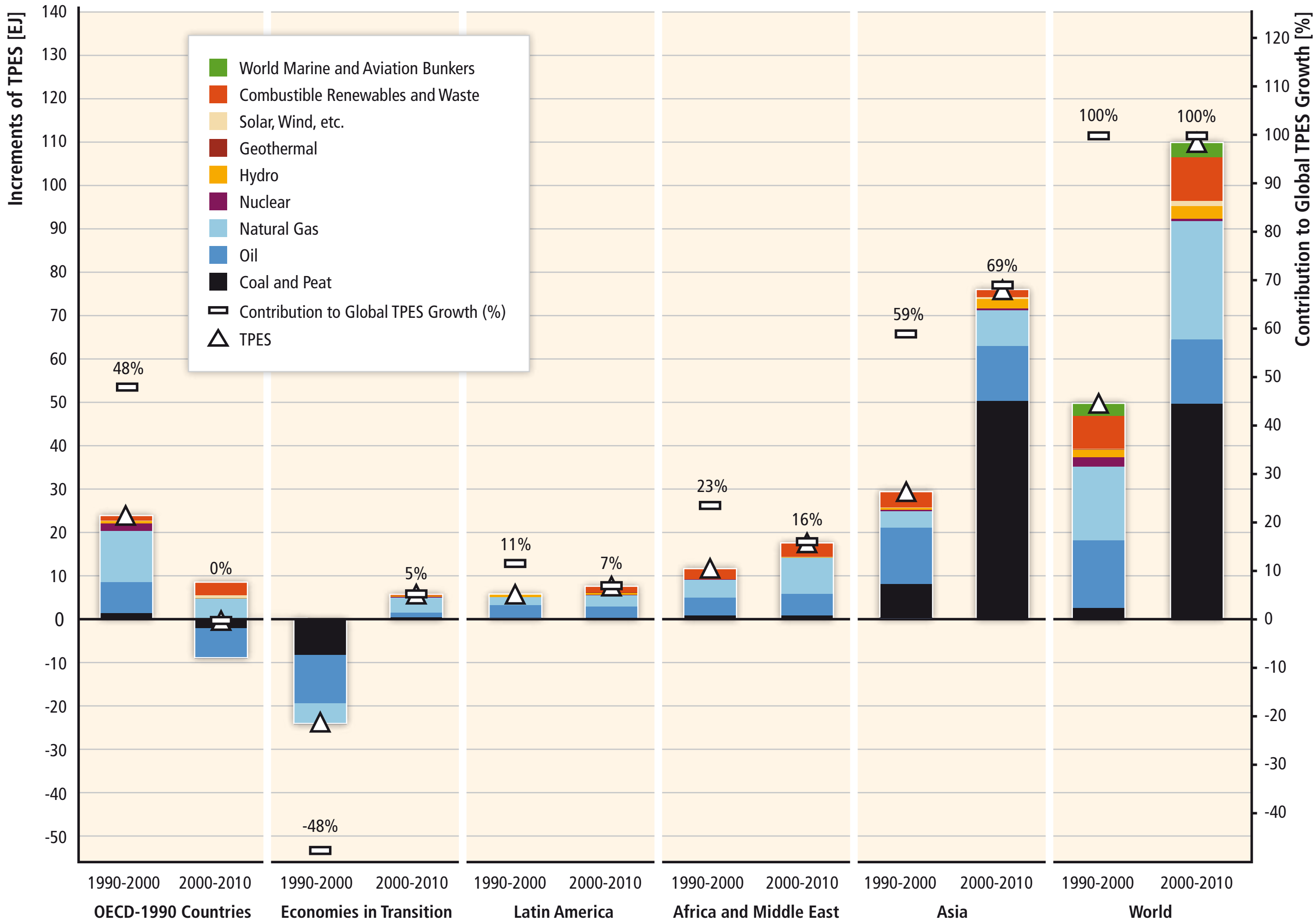


Figure 7.2 | Contribution of energy sources to global and regional primary energy use *increments*. Notes: Modern biomass contributes 40 % of the total biomass share. Underlying data from IEA (2012a) for this figure have been converted using the direct equivalent method of accounting for primary energy (see Annex.II.4). Legend: OECD-1990 (OECD-1990), Asia (ASIA), Economies in Transition (EIT), Middle East and Africa (MAF), and Latin America (LAM),total primary energy supply (TPES).

indirect multiplication effects of energy savings from end users. One argument (Bashmakov, 2009) is that in estimating indirect energy efficiency effects, transformation should be done not only for electricity, for which it is regularly performed, but also for district heating as well as for any activity in the energy supply sector, and even for fuels transportation. Based on this argument, global energy savings multiplication factors are much higher if assessed comprehensively and are equal to 1.07 for coal and petroleum products, 4.7 for electricity, and 2.7 for heat.

Between 2000–2010, TPES grew by 27 % globally (2.4 % per annum), while for the regions it was 79 % in Asia, 47 % in Middle East and Africa (MAF), 32 % in Latin America (LAM), 13 % in Economies in Transition (EIT), and it was nearly stable for the countries of the Organisation for Economic Co-operation and Development 1990 (OECD90)[2] (IEA, 2012a). After 2010, global TPES grew slower (close to 2 % per annum over 2010–2012) with Asia, MAF, and LAM showing nearly half their 2000–2010 average annual growth rates and declining energy use in EIT and OECD90 (BP, 2013; Enerdata, 2013). Thus all additional energy demand after 2000 was generated outside of the OECD90 (Figure 7.2). The dynamics of the energy markets evolution in Asia differs considerably from the other markets. This region accounted for close to 70 % of the global TPES increment in 2000–2010 (over 90 % in 2010–2012), for all additional coal demand, about 70 % of additional oil demand, over 70 % of additional hydro, and 25 % of additional wind generation (IEA, 2012a; BP, 2013; Enerdata, 2013). Between 2000–2010, China alone more than doubled its TPES and contributed to over half of the global TPES increment, making it now the leading energy-consuming nation.

Led by Asia, global coal consumption grew in 2000–2010 by over 4 % per annum and a slightly slower rate in 2010–2012. Coal contributed 44 % of the growth in energy use and this growth alone matched the total increase in global TPES for 1990–2000 (Figure 7.2). Power generation remains the main global coal renaissance driver (US DOE, 2012). China is the leading coal producer (47 % of world 2012 production), followed by the United States, Australia, Indonesia, and India (BP,

[2] For regional aggregation, see Annex II.2

2013). Competitive power markets flexible to gas and coal price spreads are creating stronger links between gas and coal markets driving recent coal use down in the USA, but up in EU (IEA, 2012b).

Although use of liquid fuels has grown in non-OECD countries (mostly in Asia and the MAF), falling demand in the OECD90 has seen oil's share of global energy supply continue to fall in 2000–2012. Meeting demand has required mobilization of both conventional and unconventional liquid supplies. Relatively low transportation costs have given rise to a truly global oil market with 55 % of crude consumption and 28 % of petroleum products being derived from cross-border trade (Table 7.1). The Organization of the Petroleum Exporting Countries (OPEC) in 2012 provided 43 % of the world's total oil supply keeping its share above its 1980 level; 33 % came from the Middle East (BP, 2013). The most significant non-OPEC contributors to production growth since 2000 were Russia, Canada, United States, Kazakhstan, Brazil, and China (GEA, 2012; IEA, 2012b; US DOE, 2012; BP, 2013). Growing reliance on oil imports raises concerns of Asia and other non-OECD regions about oil prices and supply security (IEA, 2012b).

In the global gas balance, the share of unconventional gas production (shale gas, tight gas, coal-bed methane, and biogas) grew to 16 % in 2011 (IEA, 2012c). The shale gas revolution put the United States (where the share of unconventional gas more than doubled since 2000, and reached 67 % in 2011) on top of the list of major contributors to additional (since 2000) gas supply, followed by Qatar, Iran, China, Norway, and Russia (BP, 2013; US DOE, 2013a). Although the 2000–2010 natural gas consumption increments are more widely distributed among the regions than for oil and coal, gas increments in Asia and the MAF dominate. The low energy density of gas means that transmission and storage make up a large fraction of the total supply chain costs, thus limiting market development. Escalation of Liquefied Natural Gas (LNG) markets to 32 % of international gas trade in 2012 (BP, 2013) has, however, created greater flexibility and opened the way to global trade in gas (MIT, 2011). Growth in United States natural gas production and associated domestic gas prices decline have resulted in the switching of LNG supplies to markets with higher prices in South America, Europe, and Asia (IEA, 2012b). Nevertheless, natural gas supply by pipelines still delivers the largest gas volumes in North America and in Europe (US DOE, 2012; BP, 2013).

Renewables contributed 13.5 % of global TPES in 2010 (Table 7.1). The share of renewables in global electricity generation approached 21 % in 2012 (BP, 2013; Enerdata, 2013), making them the third-largest contributor to global electricity production, just behind coal and gas, with large chances to become the second-largest contributor well before 2020. Greatest growth during 2005–2012 occurred in wind and solar with generation from wind increasing 5-fold, and from solar photovoltaic, which grew 25-fold. By 2012, wind power accounted for over 2 % of world electricity production (gaining 0.3 % share each year since 2008). Additional energy use from solar and wind energy was driven mostly by two regions, OECD90 and Asia, with a small contribution from the rest of the world (IEA, 2012d). In 2012, hydroelectricity supplied 16.3 % of world electricity (BP, 2013).

New post-2000 trends were registered for nuclear's role in global energy systems. In recent years, the share of nuclear energy in world power generation has declined. Nuclear electricity represented 11 % of the world's electricity generation in 2012, down from a high of 17 % in 1993; its contribution to global TPES is declining since 2002 (IEA, 2012b; BP, 2013). Those trends were formed well before the incident at the Fukushima nuclear plants in March 2011 and following revision of policies towards nuclear power by several governments (IEA, 2012e). Growing nuclear contribution to TPES after 2000 was observed only in EIT and Asia (mostly in Russia and China).

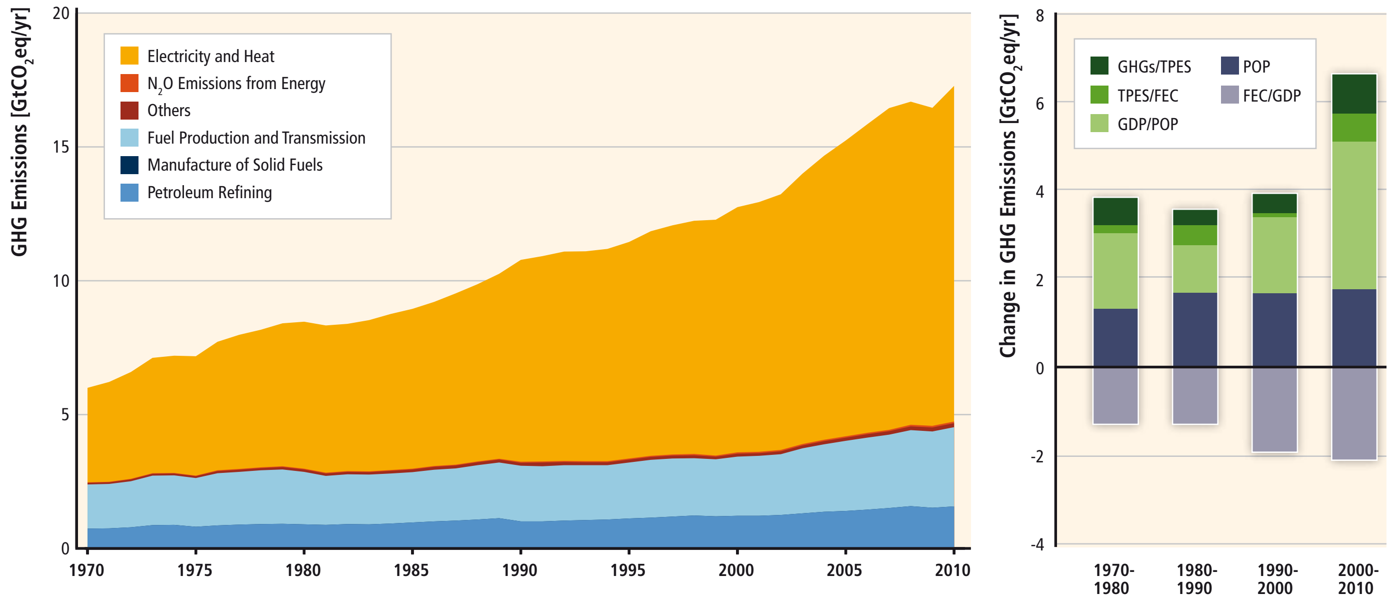
Additional information on regional total and per-capita energy consumption and emissions, historic emissions trends and drivers, and embedded (consumption-based) emissions is reported in Chapter 5.

7.3 New developments in emission trends and drivers

In 2010, the energy supply sector accounts for 49 % of all energy-related GHG emissions[3] (JRC/PBL, 2013) and 35 % of anthropogenic GHG emissions, up 13 % from 22 % in 1970, making it the largest sectoral contributor to global emissions. According to the Historic Emission Database, Emissions Database for Global Atmospheric Research (EDGAR)/International Energy Agency (IEA) dataset, 2000–2010 global energy supply sector GHG emissions increased by 35.7 % and grew on average nearly 1 % per year faster than global anthropogenic GHG emissions. Despite the UNFCCC and the Kyoto Protocol, GHG emissions grew more rapidly between 2000 and 2010 than in the previous decade. Growth in the energy supply sector GHG emissions accelerated from 1.7 % per year from 1990–2000 to 3.1 % per year from 2000–2010 (Figure 7.3). In 2012, the sector emitted 6 % more than in 2010 (BP, 2013), or over 18 $GtCO_2eq$. In 2010, 43 % of CO_2 emissions from fuel combustion were produced from coal, 36 % from oil, and 20 % from gas (IEA, 2012f).

Emissions from electricity and heat generation contributed 75 % of the last decade increment followed by 16 % for fuel production and transmission and 8 % for petroleum refining. Although sector emissions were predominantly CO_2, also emitted were methane (of which 31 % is attributed to mainly coal and gas production and transmission), and

[3] The remaining energy-related emissions occur in the consumer sectors (see Figure 7.1). The IEA reports energy sector share at 46 % (IEA, 2012f).



	Average Annual Growth Rates				Shares (%)		
	70s	80s	90s	00s	1970	1990	2010
Electricity & Heat	4.51%	3.22%	1.96%	3.19%	58.9	69.9	72.6
Petroleum Refining	2.09%	1.11%	1.88%	2.58%	12.3	9.4	9.1
Manufacture of Solid Fuels	4.26%	8.26%	1.16%	5.05%	0.0	0.0	0.0
Fuel Production and Transmission	1.78%	0.59%	0.60%	2.94%	27.5	19.3	17.1
Others	3.77%	2.00%	-0.48%	3.72%	1.1	1.0	0.9
N_2O Emissions from Energy	4.74%	2.19%	2.17%	2.66%	0.3	0.3	0.3
Total Energy Sector	**3.53%**	**2.43%**	**1.68%**	**3.10%**	**100.0**	**100.0**	**100.0**

Figure 7.3 | Energy supply sector GHG emissions by subsectors. Table shows average annual growth rates of emissions over decades and the shares (related to absolute emissions) of different emission sources. Right-hand graph displays contribution of different drivers (POP = population, GDP = gross domestic product, FEC = final energy consumption, TPES = total primary energy supply) to energy supply sector GHG (GHGs) decadal emissions increments. It is based on (IEA, 2012a). The large graph and table are based on the Historic Emission Database EDGAR/IEA dataset (IEA, 2012g; JRC/PBL, 2013).

indirect nitrous oxide (of which 9 % comes from coal and fuel-wood combustion) (IEA, 2012f).[4]

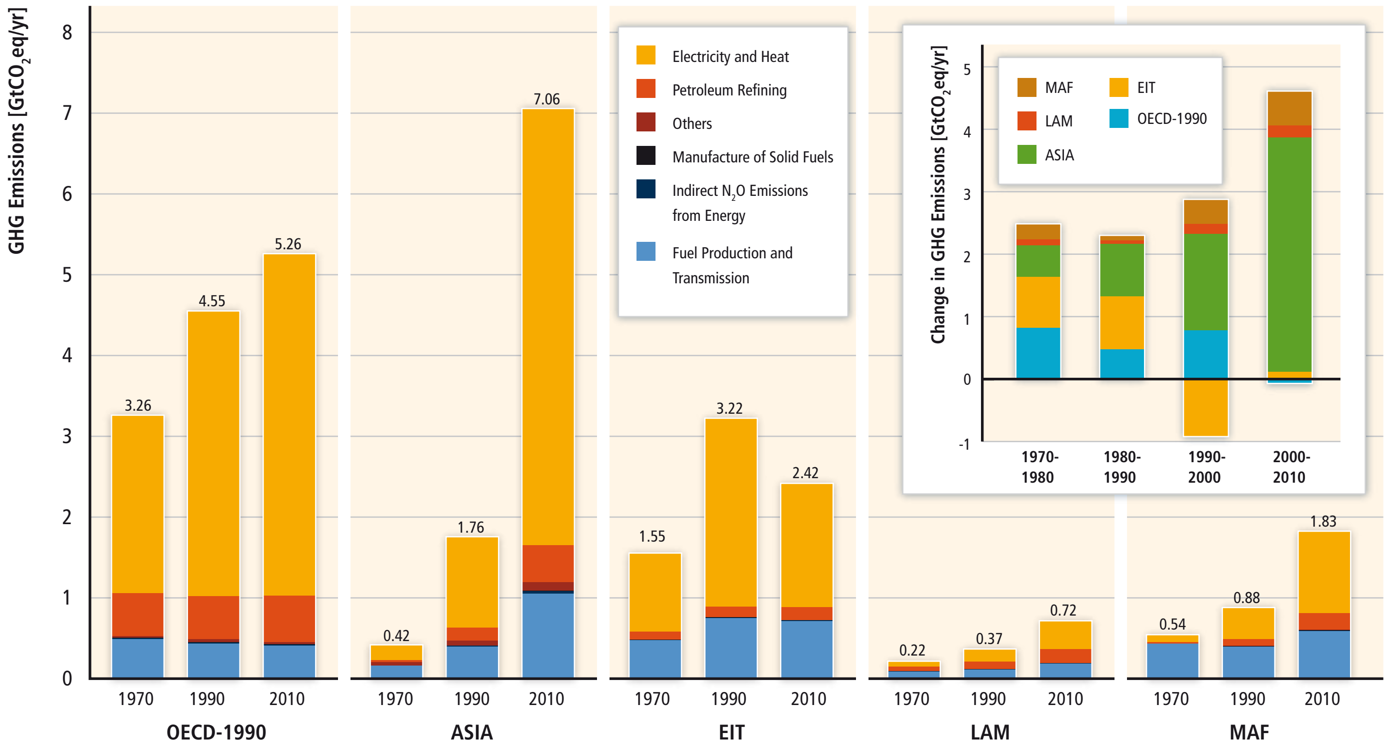
Decomposition analysis (Figure 7.3), shows that population growth contributed 39.7 % of additional sector emissions in 2000–2010, with Gross Domestic Product (GDP) per capita 72.4 %. Over the same period, energy intensity decline (final energy consumption (FEC) per unit of GDP) reduced the emissions increment by 45.4 %. Since electricity production grew by 1 % per year faster than TPES, the ratio of TPES/FEC increased contributing 13.1 % of the additional emissions. Sector carbon intensity relative to TPES was responsible for 20.2 % of additional energy supply sector GHG emissions.

[4] As in the case with energy, there is some disagreement on the historical level of global energy- related GHG emissions (See Andres et al., 2012). Moreover, emission data provided by IEA or EDGAR often do not match data from national communications to UNFCCC. For example, Bashmakov and Myshak (2012) argue that EDGAR does not provide adequate data for Russian GHG emissions: according to national communication, energy-related CO_2 emissions in 1990–2010 are 37 % down while EDGAR reports only a 28 % decline.

In addition to the stronger TPES growth, the last decade was marked by a lack of progress in the decarbonization of the global fuel mix. With 3.1 % annual growth in energy supply sector emissions, the decade with the strongest-ever mitigation policies was the one with the strongest emissions growth in the last 30 years.

Carbon intensity decline was fastest in OECD90 followed closely by EIT in 1990–2000, and by LAM in 2000–2010 (IEA, 2012a; US DOE, 2012); most developing countries show little or no decarbonization. Energy decarbonization progress in OECD90 (–0.4 % per annum in 2000–2010) was smaller than the three previous decades, but enough to compensate their small TPES increment keeping 2010 emissions below 2000 levels. In non-OECD90 countries, energy-related emissions increased on average from 1.7 % per year in 1990–2000 to 5.0 % in 2000–2010 due to TPES growth accompanied by a 0.6 % per annum growth in energy carbon intensity, driven largely by coal demand in Asia (IEA, 2012b). As a result, in 2010 non-OECD90 countries' energy supply sector GHG emissions were 2.3fold that for OECD90 countries.

In 1990, OECD90 was the world's highest emitter of energy supply sector GHGs (42 % of the global total), followed by the EIT region (30 %).



Average Annual Growth Rates

	70s	80s	90s	00s
Total world	3.53%	2.43%	1.68%	3.10%
OECD-1990	2.26%	1.10%	1.59%	-0.13%
EIT	4.31%	3.12%	-3.31%	0.49%
ASIA	8.23%	6.64%	6.52%	7.89%
LAM	3.67%	1.77%	3.64%	3.13%
MAF	3.89%	1.00%	3.76%	3.66%

Per Capita Energy Sector Emission [tCO_2eq/yr]

	1980	1990	2000	2010
Total world	1.91	2.03	2.08	2.50
OECD-1990	5.10	5.32	5.81	5.34
EIT	6.18	7.80	5.61	5.93
ASIA	0.40	0.62	1.00	1.92
LAM	0.85	0.83	1.00	1.21
MAF	1.39	1.15	1.30	1.46

Figure 7.4 | Energy supply sector GHG emissions by subsectors and regions: OECD90, ASIA countries, Economies in Transition (EIT), Africa and the Middle East (MAF), and Latin America (LAM). Right-hand graph shows contribution of different regions to decadal emissions increments. Source: Historic Emission Database EDGAR/IEA (IEA, 2012g; JRC/PBL, 2013).

By 2010, Asia had become the major emitter with 41 % share. China's emissions surpassed those of the United States, and India's surpassed Russia's (IEA, 2012f). Asia accounted for 79 % of additional energy supply sector emissions in 1990–2000 and 83 % in 2000–2010, followed well behind by the MAF and LAM regions (Figure 7.4). The rapid increase in energy supply sector GHG emissions in developing Asia was due to the region's economic growth and increased use of fossil fuels. The per-capita energy supply sector GHGs emissions in developing countries are below the global average, but the gap is shrinking, especially for Asia (Figure 7.4). The per-capita energy supply sector CO_2 emissions of Asia (excluding China) in 2010 was only 0.75 tCO_2, against the world average of 2.06 tCO_2, while the 2010 Chinese energy supply sector CO_2 emissions per capita of 2.86 tCO_2 exceeded the 2.83 tCO_2 of OECD-Europe (IEA, 2012f).

Another region with large income-driven energy supply sector GHG emissions in 2000–2010 was EIT, although neutralized by improvements in energy intensity there. This region was the only one that managed to decouple economic growth from energy supply sector emissions; its GDP in 2010 being 10 % above the 1990 level, while energy supply sector GHG emissions declined by 29 % over the same period. Additional information on regional total and per-capita emissions, historic emissions trends and drivers and embedded (consumption based) emissions is reported in Chapter 5.

7.4 Resources and resource availability

7.4.1 Fossil fuels

Table 7.2 provides a summary of fossil fuel resource estimates in terms of energy and carbon contents. Fossil fuel resources are not fixed; they are a dynamically evolving quantity. The estimates shown span quite a range reflecting the general uncertainty associated with limited knowl-

Table 7.2 | Estimates of fossil reserves and resource, and their carbon content. Source: (Rogner et al. 2012)*.

	Reserves		Resources	
	[EJ]	[Gt C]	[EJ]	[Gt C]
Conventional oil	4,900–7,610	98–152	4,170–6,150	83–123
Unconventional oil	3,750–5,600	75–112	11,280–14,800	226–297
Conventional gas	5,000–7,100	76–108	7,200–8,900	110–136
Unconventional gas	20,100–67,100	307–1,026	40,200–121,900	614–1,863
Coal	17,300–21,000	446–542	291,000–435,000	7,510–11,230
Total	51,050–108,410	1 002–1,940	353,850–586,750	8,543–13,649

* Reserves are those quantities able to be recovered under existing economic and operating conditions (BP, 2011); resources are those where economic extraction is potentially feasible (UNECE, 2010a).

edge and boundaries. Changing economic conditions, technological progress, and environmental policies may expand or contract the economically recoverable quantities altering the balance between future reserves and resources.

Coal reserve and resource estimates are subject to uncertainty and ambiguity, especially when reported in mass units (tonnes) and without a clear distinction of their specific energy contents, which can vary considerably. For both reserves and resources, the quantity of hard (black) coal significantly outnumbers the quantity of lignite (brown coal), and despite resources being far greater than reserves, the possibility for resources to cross over to reserves is expected to be limited since coal reserves are likely to last around 100 years at current rates of production (Rogner et al., 2012).

Cumulative past production of *conventional* oil falls between the estimates of the remaining reserves, suggesting that the peak in conventional oil production is imminent or has already been passed (Höök et al., 2009; Owen et al., 2010; Sorrell et al., 2012). Including resources extends conventional oil availability considerably. However, depending on such factors as demand, the depletion and recovery rates achievable from the oil fields (IEA, 2008a; Sorrell et al., 2012), even the higher range in reserves and resources will only postpone the peak by about two decades, after which global conventional oil production is expected to begin to decline, leading to greater reliance on unconventional sources.

Unconventional oil resources are larger than those for conventional oils. Large quantities of these in the form of shale oil, heavy oil, bitumen, oil (tar) sands, and extra-heavy oil are trapped in sedimentary rocks in several thousand basins around the world. Oil prices in excess of USD_{2010} 80/barrel are probably needed to stimulate investment in unconventional oil development (Engemann and Owyang, 2010; Rogner et al., 2012; Maugeri, 2012).

Unlike oil, natural gas reserve additions have consistently outpaced production volumes and resource estimations have increased steadily since the 1970s (IEA, 2011a). The global natural gas resource base is vast and more widely dispersed geographically than oil. Unconventional natural gas reserves, i.e., coal bed methane, shale gas, deep formation and tight gas are now estimated to be larger than conventional reserves and resources combined. In some parts of the world, supply of unconventional gas now represents a significant proportion of gas withdrawals, see Section 7.2.

For climate change, it is the CO_2 emitted to the atmosphere from the burning of fossil fuels that matters. When compared to the estimated CO_2 budgets of the emission scenarios presented in Chapter 6 (Table 6.2), the estimate of the total fossil fuel reserves and resources contains sufficient carbon, if released, to yield radiative forcing above that required to limit global mean temperature change to less than 2 °C. The scenario analysis carried out in Section 6.3.4 illustrates in detail that the availability of fossil fuels alone will not be sufficient to limit CO_2eq concentration to levels such as 450 ppm, 550 ppm, or 650 ppm [Figure 6.15]. Mitigation scenarios are further discussed in Section 7.11 and Chapter 6.

7.4.2 Renewable energy

For the purpose of AR5, renewable energy (RE) is defined as in the SRREN (IPCC, 2011a) to include bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy, and wind energy.[5] The technical potential for RE is defined in Verbruggen et al. (2011) as "the amount of renewable energy output obtainable by full implementation of demonstrated technologies or practices." A variety of practical, land use, environmental, and/or economic constraints are sometimes used in estimating the technical potential of RE, but with little uniformity across studies in the treatment of these factors, including costs. Definitions of technical potential therefore vary by study (e.g., Verbruggen et al., 2010), as do the data, assumptions, and methods used to estimate it (e.g., Angelis-Dimakis et al., 2011). There have also been ques-

[5] Note that, in practice, the RE sources as defined here are sometimes extracted at a rate that exceeds the natural rate of replenishment (e.g., some forms of biomass and geothermal energy). Most, but not all, RE sources impose smaller GHG burdens than do fossil fuels when providing similar energy services (see Section 7.8.1).

tions raised about the validity of some of the 'bottom up' estimates of technical potential for RE that are often reported in the literature, and whether those estimates are consistent with real physical limits (e.g., de Castro et al., 2011; Jacobson and Archer, 2012; Adams and Keith, 2013). Finally, it should be emphasized that technical potential estimates do not seek to address all practical or economic limits to deployment; many of those additional limits are noted at the end of this section, and are discussed elsewhere in Chapter 7.

Though comprehensive and consistent estimates for each individual RE source are not available, and reported RE technical potentials are not always comparable to those for fossil fuels and nuclear energy due to differing study methodologies, the SRREN (IPCC, 2011a) concludes that the aggregated global technical potential for RE as a whole is significantly higher than global energy demands. Figure 7.12 (shown in Section 7.11) summarizes the ranges of global technical potentials as estimated in the literature for the different RE sources, as reported in IPCC (2011a). The technical potential for solar is shown to be the largest by a large magnitude, but sizable potential exists for many forms of RE. Also important is the regional distribution of the technical potential. Though the regional distribution of each source varies (see, e.g., IPCC, 2011a), Fischedick et al. (2011) reports that the technical potential of RE as a whole is at least 2.6 times as large as the 2007 total primary energy demand in all regions of the world.

Considering all RE sources *together*, the estimates reported by this literature suggest that global and regional technical potentials are unlikely to pose a physical constraint on the combined contribution of RE to the mitigation of climate change (also see GEA, 2012). Additionally, as noted in IPCC (2011b), "Even in regions with relatively low levels of technical potential for any individual renewable energy source, there are typically significant opportunities for increased deployment compared to current levels". Moreover, as with other energy sources, all else being equal, continued technological advancements can be expected to increase estimates of the technical potential for RE in the future, as they have in the past (Verbruggen et al., 2011).

Nonetheless, the long-term percentage contribution of some *individual* RE sources to climate change mitigation may be limited by the available technical potential if deep reductions in GHG emissions are sought (e.g., hydropower, bioenergy, and ocean energy), while even RE sources with seemingly higher technical potentials (e.g., solar, wind) will be constrained in certain regions (see Fischedick et al., 2011). Additionally, as RE deployment increases, progressively lower-quality resources are likely to remain for incremental use and energy conversion losses may increase, e.g., if conversion to alternative carriers such as hydrogen is required (Moriarty and Honnery, 2012). Competition for land and other resources among different RE sources may impact aggregate technical potentials, as might concerns about the carbon footprint and sustainability of the resource (e.g., biomass) as well as materials demands (cf. Annex Bioenergy in Chapter 11; de Vries et al., 2007; Kleijn and van der Voet, 2010; Graedel, 2011). In other cases, economic factors, environmental concerns, public acceptance, and/or the infrastructure required to manage system integration (e.g., investments needed to accommodate variable output or transmit renewable electricity to load centres) are likely to limit the deployment of individual RE technologies before absolute technical resource potential limits are reached (IPCC, 2011a).

7.4.3 Nuclear energy

The average uranium (U) concentration in the continental Earth's crust is about 2.8 ppm, while the average concentration in ocean water is 3 to 4 ppb (Bunn et al., 2003). The theoretically available uranium in the Earth's crust is estimated at 100 teratonnes (Tt) U, of which 25 Tt U occur within 1.6 km of the surface (Lewis, 1972). The amount of uranium dissolved in seawater is estimated at 4.5 Gt (Bunn et al., 2003). Without substantial research and development (R&D) efforts to develop vastly improved and less expensive extraction technologies, these occurrences do not represent practically extractable uranium. Current market and technology conditions limit extraction of conventional uranium resources to concentrations above 100 ppm U.

Altogether, there are 4200 EJ (or 7.1 MtU) of identified conventional uranium resources available at extraction costs of less than USD 260/kgU (current consumption amounts to about 53,760 tU per year). Additional conventional uranium resources (yet to be discovered) estimated at some 4400 EJ can be mobilized at costs larger than USD 260/kgU (NEA and IAEA, 2012). Present uranium resources are sufficient to fuel existing demand for more than 130 years, and if all conventional uranium occurrences are considered, for more than 250 years. Reprocessing of spent fuel and recycling of uranium and plutonium in used fuel would double the reach of each category (IAEA, 2009). Fast breeder reactor technology can theoretically increase uranium utilization 50-fold or even more with corresponding reductions in high-level waste (HLW) generation and disposal requirements (IAEA, 2004). However, reprocessing of spent fuel and recycling is not economically competitive below uranium prices of USD_{2010} 425/kgU (Bunn et al., 2003). Thorium is a widely distributed slightly radioactive metal. Although the present knowledge of the world's thorium resource base is poor and incomplete, it is three to four times more abundant than uranium in the Earth's outer crust (NEA, 2006). Identified thorium resource availability is estimated at more than 2.5 Mt at production costs of less than USD_{2010} 82/kgTh (NEA, 2008).

Further information concerning reactor technologies, costs, risks, co-benefits, deployment barriers and policy aspects can be found in Sections 7.5.4, 7.8.2, 7.9, 7.10, and 7.12, respectively.

7.5 Mitigation technology options, practices and behavioral aspects

Climate change can only be mitigated and global temperature be stabilized when the total amount of CO_2 emitted is limited and emissions eventually approach zero (Allen et al., 2009; Meinshausen et al., 2009). Options to reduce GHG emissions in the energy supply sector reduce the lifecycle GHG-emissions intensity of a unit of final energy (electricity, heat, fuels) supplied to end users. Section 7.5 therefore addresses options to replace unabated fossil fuel usage with technologies without direct GHG emissions, such as renewable and nuclear energy sources, and options to mitigate GHG emissions from the extraction, transport, and conversion of fossil fuels through increased efficiency, fuel switching, and GHG capture. In assessing the performance of these options, lifecycle emissions have to be considered. Appropriate policies need to be in place to ensure that the adoption of such options leads to a reduction and ultimate phaseout of freely emitting (i.e., unabated) fossil technologies and not only to reduced additional energy consumption, as indicated in Section 7.12.

Options discussed in this section put some emphasis on electricity production, but many of the same options could be used to produce heat or transport fuels or deliver heating and transportation services through electrification of those demands. The dedicated provision of transport fuels is treated in Chapter 8, of heat for buildings is covered in Chapter 9, and of heat for industrial processes in Chapter 10. Options to reduce final energy demand are addressed in Chapters 8–12. Options covered in this section mainly address technology solutions. Behavioural issues in the energy supply sector often concern the selection of and investment in technology, and these issues are addressed in Sections 7.10, 7.11, and 7.12. Costs and emission-reduction potentials associated with the options are discussed in Section 7.8, whereas co-benefits and risks are addressed in Section 7.9.

7.5.1 Fossil fuel extraction, conversion, and fuel switching

Several important trends shape the opportunity to mitigate emissions associated with the extraction, transport, and conversion of fossil fuels: (1) new technologies that make accessible substantial reservoirs of shale gas and unconventional oil; (2) a renewed focus on fugitive methane emissions, especially those associated with gas production; (3) increased effort required to find and extract oil; and (4) improved technologies for energy efficiency and the capture or prevention of methane emissions in the fuel supply chain. Carbon dioxide capture technologies are discussed in Section 7.5.5.

A key development since AR4 is the rapid deployment of hydraulic-fracturing and horizontal-drilling technologies, which has increased and diversified the gas supply and allowed for a more extensive switching of power and heat production from coal to gas (IEA, 2012b); this is an important reason for a reduction of GHG emissions in the United States. At the same time, the increasing utilization of gas has raised the issue of fugitive emissions of methane from both conventional and shale gas production. While some studies estimate that around 5 % of the produced gas escapes in the supply chain, other analyses estimate emissions as low as 1 % (Stephenson et al., 2011; Howarth et al., 2011; Cathles et al., 2012). Central emission estimates of recent analyses are 2 %—3 % (+/– 1 %) of the gas produced, where the emissions from conventional and unconventional gas are comparable (Jaramillo et al., 2007; O'Sullivan and Paltsev, 2012; Weber and Clavin, 2012). Fugitive emissions depend to a significant degree on whether low-emission practices, such as the separation and capture of hydrocarbons during well completion and the detection and repair of leaks throughout gas extraction and transport, are mandated and how they are implemented in the field (Barlas, 2011; Wang et al., 2011; O'Sullivan and Paltsev, 2012). Empirical research is required to reduce uncertainties and to better understand the variability of fugitive gas emissions (Jackson et al., 2013) as well as to provide a more-global perspective. Recent empirical research has not yet resolved these uncertainties (Levi, 2012; Petron et al., 2012). The main focus of the discussion has been drilling, well completion, and gas product, but gas grids (Ryerson et al., 2013) and liquefaction (Jaramillo et al., 2007) are also important.

There has also been some attention to fugitive emissions of methane from coal mines (Su et al., 2011; Saghafi, 2012) in connection with opportunities to capture and use or treat coal-seam gas (Karacan et al., 2011). Emission rates vary widely based on geological factors such as the age of the coal and previous leakage from the coal seam (Moore, 2012).

Taking into account revised estimates for fugitive methane emissions, recent lifecycle assessments indicate that specific GHG emissions are reduced by one half (on a per-kWh basis) when shifting from the current world-average coal-fired power plant to a modern natural gas combined-cycle (NGCC) power plant, evaluated using the 100-year global warming potentials (GWP) (Burnham et al., 2012), as indicated in Figure 7.6 (Section 7.8). This reduction is the result of the lower carbon content of natural gas (15.3 gC/MJ compared to, e.g., 26.2 gC/MJ for sub-bituminous coal) and the higher efficiency of combined-cycle power plants (IEA, 2011a). A better appreciation of the importance of fugitive emissions in fuel chains since AR4 has resulted in a downward adjustment of the estimated benefit from fuel switching. More modest emissions reductions result when shifting from current average coal plants to the best available coal technology or less-advanced gas power plants. Climate mitigation consistent with the Cancun Agreement requires a reduction of emissions rates below that of NGCC plants by the middle of this century (Figure 7.7, Section 7.8.2 and Figure 7.9, Section 7.11), but natural gas may play a role as a transition fuel in combination with variable renewable sources (Levi, 2013).

Combined heat and power (CHP) plants are capable of recovering a share of the waste heat that is otherwise released by power plants that generate only electricity. The global average efficiency of fossil-fuelled power plants is 37 %, whereas the global average efficiency of CHP units is 58 % if both power and the recovered heat are taken into account (see Table 7.1 in 7.2). State of the art CHP plants are able to approach efficiencies over 85 % (IEA, 2012b). The usefulness of decentralized cogeneration units is discussed in (Pehnt, 2008). Further emissions reductions from fossil fuel systems are possible through CO_2 capture and storage (Section 7.5.5).

Producing oil from unconventional sources and from mature conventional oil fields requires more energy than producing it from virgin conventional fields (Brandt and Farrell, 2007; Gagnon, Luc et al., 2009; Lechtenböhmer and Dienst, 2010). Literature indicates that the net energy return on investment has fallen steadily for conventional oil to less than 10 GJ/GJ (Guilford et al.; Brandt et al., 2013). For oil sands, the net energy return ratio of the product delivered to the customer is about 3 GJ/GJ invested (Brandt et al., 2013), with similar values expected for oil shale (Dale et al., 2013). As a result, emissions associated with synthetic crude production from oil sands are higher than those from most conventional oil resources (Charpentier et al., 2009; Brandt, 2011). These emissions are related to extra energy requirements, fugitive emissions from venting and flaring (Johnson and Coderre, 2011), and land use (Rooney et al., 2012). Emissions associated with extraction of oil sands and refining to gasoline are estimated to be 35–55 gCO_2eq/MJ fuel, compared to emissions of 20 gCO_2eq/MJ for the production and refining of regular petroleum and 70 gCO_2eq/MJ associated with combusting this fuel (Burnham et al., 2012). Overall, fossil fuel extraction and distribution are currently estimated to contribute 5 %–10 % of total fossil-fuel-related GHG emissions (Alsalam and Ragnauth, 2011; IEA, 2011a; Burnham et al., 2012). Emissions associated with fuel production and transmission can be reduced through higher energy efficiency and the use of lower-carbon energy sources in mines, fields, and transportation networks (IPIECA and API, 2007; Hasan et al., 2011), the capture and utilization (UNECE, 2010b), or treatment (US EPA, 2006; IEA, 2009a; Karacan et al., 2011; Karakurt et al., 2011; Su et al., 2011) of methane from coal mining, the reduction of venting and flaring from oil and gas production (IPIECA and API, 2009; Johnson and Coderre, 2011), and leak detection and repair for natural gas systems (Goedbloed, 2011; Wilwerding, 2011).

7.5.2 Energy efficiency in transmission and distribution

Electrical losses associated with the high-voltage transmission system are generally less than losses within the lower-voltage distribution system mainly because the total length of transmission lines is far less than that for distribution in most power systems, and that currents and thus losses are lower at high voltages. These losses are due to a combination of cable or line losses and transformer losses and vary with the nature of the power system, particularly its geographical layout. Losses as a fraction of power generated vary considerably between countries, with developed countries tending to have lower losses, and a number of developing countries having losses of over 20 % in 2010 according to IEA online data (IEA, 2010a). Combined transmission and distribution losses for the OECD countries taken together were 6.5 % of total electricity output in 2000 (IEA, 2003a), which is close to the EU average (European Copper Institute, 1999).

Approximately 25 % of all losses in Europe, and 40 % of distribution losses, are due to distribution transformers (and these losses will be similar in OECD countries); therefore, use of improved transformer designs can make a significant impact (see European Copper Institute, 1999 and in particular Appendix A therein). Roughly a further 25 % of losses are due to the distribution system conductors and cables. An increase in distributed generation can reduce these losses since generation typically takes place closer to loads than with central generation and thus the electricity does not need to travel so far (Méndez Quezada et al., 2006; Thomson and Infield, 2007). However, if a large amount of distributed power generation is exported back into the main power system to meet more distant loads, then losses can increase again. The use of greater interconnection to ease the integration of time varying renewables into power systems would be expected to increase the bulk transfer of power over considerable distances and thus the losses (see Section 7.6.1). High-voltage direct current transmission (HVDC) has the potential to reduce transmission losses and is cost-effective for very long above-ground lines. However, sub-sea HVDC has lower losses over 55 to 70 kms (Barberis Negra et al., 2006) and will most likely be used for the connection of large offshore wind farms due to the adverse reactive power characteristics of long sub-sea alternating current (AC) transmission cables.

Crude oil transportation from upstream production facilities to refineries and subsequent moving of petroleum products to service stations or end user is an energy-consuming process if it is not effectively performed (PetroMin Pipeliner, 2010). Pipelines are the most efficient means to transport fluids. Additives can ease the flow of oil and reduce the energy used (Bratland, 2010). New pumps technology, pipeline pigging facilities, chemicals such as pour point depressants (for waxy crude oil), and drag-reducing agents are good examples of these technologies that increase the pipeline throughput.

Finally, it is worth noting that the decarbonization of heat through heat pumps and transport through an increased use of electric vehicles (EVs), could require major additions to generation capacity and aligned with this, an improved transmission and distribution infrastructure. Exactly how much will depend on whether these new loads are controlled and rescheduled through the day by demand-side management (see Section 8.3.4.2 for more detail).

7.5.3 Renewable energy technologies

Only a small fraction of the renewable energy (RE) technical potential has been tapped so far (see Section 7.4.2; IPCC 2011a), and most—but not all—forms of RE supply have low lifecycle GHG emissions in comparison to fossil fuels (see Section 7.8.1). Though RE sources are often discussed together as a group, the specific conversion technologies used are numerous and diverse. A comprehensive survey of the literature is available in IPCC (2011a). Renewable energy sources are capable of supplying electricity, but some sources are also able to supply thermal and mechanical energy, as well as produce fuels that can satisfy multiple energy service needs (Moomaw et al., 2011b).

Many RE sources are primarily deployed within larger, centralized energy networks, but some technologies can be—and often are—deployed at the point of use in a decentralized fashion (Sathaye et al., 2011; Sims et al., 2011; REN21, 2013). The use of RE in the transport, buildings, and industrial sectors—as well as in agriculture, forestry, and human settlements—is addressed more fully in Chapters 8–12.

Fischedick et al. (2011) find that, while there is no obvious single dominant RE technology likely to be deployed at a global level, bioenergy, wind, and solar may experience the largest incremental growth. The mix of RE technologies suited to a specific location, however, will depend on local conditions, with hydropower and geothermal playing a significant role in certain countries.

Because some forms of RE are primarily used to produce electricity (e.g., Armaroli and Balzani, 2011), the ultimate contribution of RE to overall energy supply may be dictated in part by the future electrification of transportation and heating/cooling or by using RE to produce other energy carriers, e.g., hydrogen (Sims et al., 2011; Jacobson and Delucchi, 2011; see also other chapters of AR5).

The performance and cost of many RE technologies have advanced substantially in recent decades and since AR4 (e.g., IPCC, 2011a; Arent et al., 2011). For example, improvements in photovoltaic (PV) technologies and manufacturing processes, along with changed market conditions (i.e., manufacturing capacity exceeding demand) and reduced non-hardware costs, have substantially reduced PV costs and prices. Continued increases in the size and therefore energy capture of individual wind turbines have reduced the levelized cost of land-based wind energy and improved the prospects for future reductions in the cost of offshore wind energy. Concentrated solar thermal power (CSP) technologies, some together with thermal storage or as gas/CSP hybrids, have been installed in a number of countries. Research, development, and demonstration of enhanced geothermal systems has continued, enhancing the prospects for future commercial deployments. Performance improvements have also been made in cropping systems, logistics, and multiple conversion technologies for bioenergy (see 11.13). IPCC (2011a) provides further examples from a broader array of RE technologies.

As discussed in IPCC (2011a), a growing number of RE technologies have achieved a level of technical and economic maturity to enable deployment at significant scale (with some already being deployed at significant scale in many regions of the world), while others are less mature and not yet widely deployed. Most hydropower technologies, for example, are technically and economically mature. Bioenergy technologies, meanwhile, are diverse and span a wide range; examples of mature technologies include conventional biomass-fuelled power plants and heating systems as well as ethanol production from sugar and starch, while many lignocellulose-based transport fuels are at a pre-commercial stage (see Section 11.13). The maturity of solar energy ranges from the R&D stage (e.g., fuels produced from solar energy), to relatively more technically mature (e.g., CSP), to technically mature (e.g., solar heating and wafer-based silicon PV); however, even the technologies that are more technically mature have not all reached a state of economic competitiveness. Geothermal power and heat technologies that rely on hydrothermal resources use mature technologies (though reservoir risks remain substantial), whereas enhanced geothermal systems continue to undergo R&D with some limited demonstration plants now deployed. Except for certain types of tidal barrages, ocean energy technologies are also at the demonstration phase and require additional R&D. Traditional land-based wind technologies are mature, while the use of wind energy in offshore locations is increasing but is typically more costly than land-based wind.

With regard to traditional biomass, the conversion of wood to charcoal in traditional kilns results in low-conversion efficiencies. A wide range of interventions have tried to overcome this challenge by promoting more efficient kilns, but the adoption rate has been limited in many countries, particularly in sub-Saharan Africa (Chidumayo and Gumbo, 2013). Although not yielding large GHG savings in global terms, increasing the efficiency of charcoal production offers local benefits such as improved charcoal delivery and lower health and environmental impacts (FAO, 2010).

Because the cost of energy from many (but not all) RE technologies has historically been higher than market energy prices (e.g. Fischedick et al., 2011; Section 7.8), public R&D programmes have been important, and government policies have played a major role in defining the amount and location of RE deployment (IEA, 2011b; Mitchell et al., 2011; REN21, 2013). Additionally, because RE relies on natural energy flows, some (but not all) RE technologies must be located at or near the energy resource, collect energy from diffuse energy flows, and produce energy output that is variable and—though power-output forecasting has improved—to some degree unpredictable (IPCC, 2011b).

The implications of these characteristics for infrastructure development and network integration are addressed in Section 7.6.1.

Renewable energy currently constitutes a relatively small fraction of global energy supply, especially if one excludes traditional biomass. However, RE provided almost 21 % of global electricity supply in 2012, and RE deployment has increased significantly since the AR4 (see Section 7.2). In 2012, RE power capacity grew rapidly: REN21 (2013) reports that RE accounted for just over half of the new electricity-gen-

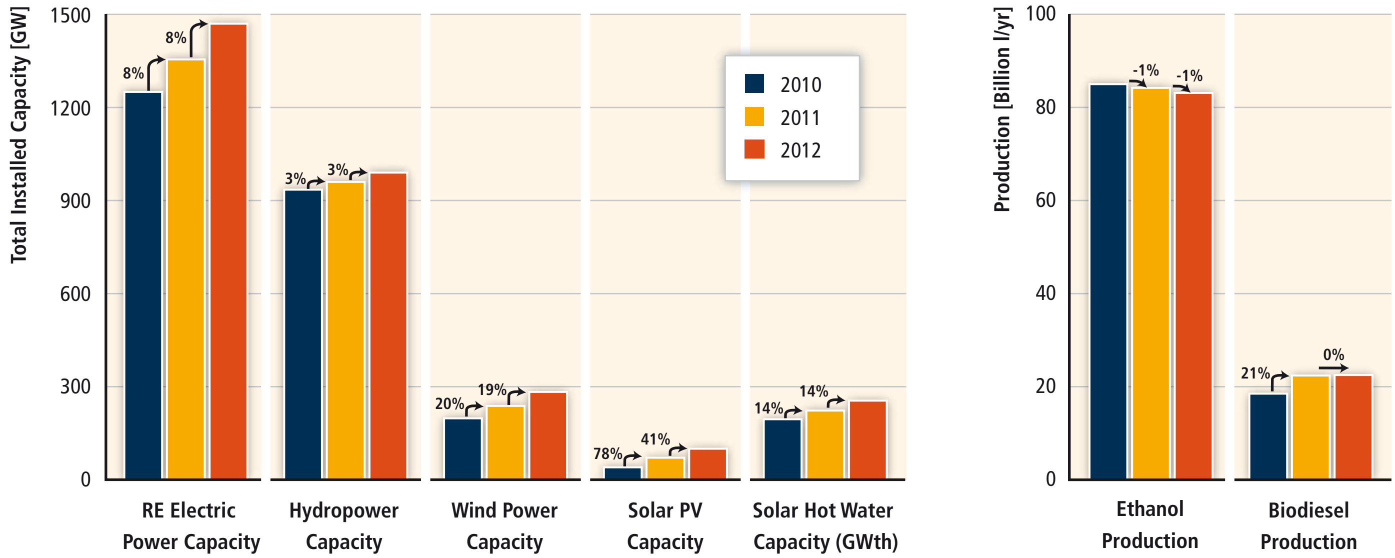


Figure 7.5 | Selected indicators of recent global growth in RE deployment (REN21, 2013). Note: A better metric of the relative contribution of RE would be based on energy supply, not installed capacity, especially because of the relatively low capacity factors of some RE sources. Energy supply statistics for power plants constructed in the most recent years, however, are not available.

erating capacity added globally in 2012.[6] As shown in Figure 7.5, the fastest-growing sources of RE power capacity included wind power (45 GW added in 2012), hydropower (30 GW), and PV (29 GW).[7]

In aggregate, the growth in cumulative renewable electricity capacity equalled 8 % from 2010 to 2011 and from 2011 to 2012 (REN21, 2013). Biofuels accounted for 3.4 % of global road transport fuel demand in 2012 (REN21, 2013); though growth was limited from 2010 to 2012, growth since the IPCC's AR4 has been substantial. By the end of 2012, the use of RE in hot water/heating markets included 293 GWth of modern biomass, 255 GWth of solar, and 66 GWth of geothermal heating (REN21, 2013).

Collectively, developing countries host a substantial fraction of the global renewable electricity generation capacity, with China adding more capacity than any other country in 2012 (REN21, 2013). Cost reductions for PV have been particularly sizable in recent years, resulting in and reflecting strong percentage growth rates (albeit from a small base), with the majority of new installations through 2012 coming from Europe (and to a lesser degree Asia and North America) but with manufacturing shifting to Asia (REN21, 2013; see also Section 7.8). The United States and Brazil accounted for 61 % and 26 %, respectively, of global bioethanol production in 2012, while China led in the use of solar hot water (REN21, 2013).

Decentralized RE to meet rural energy needs, particularly in the less-developed countries, has also increased, including various modern and advanced traditional biomass options as well as small hydropower, PV, and wind, thereby expanding and improving energy access (IPCC, 2011a; REN21, 2013).

7.5.4 Nuclear energy

Nuclear energy is utilized for electricity generation in 30 countries around the world (IAEA, 2013a). There are 434 operational nuclear reactors with a total installed capacity of 371 GWe as of September 2013 (IAEA, 2013a). Nuclear electricity represented 11 % of the world's electricity generation in 2012, with a total generation of 2346 TWh (IAEA, 2013b). The 2012 share of global nuclear electricity generation is down from a high of 17 % in 1993 (IEA, 2012b; BP, 2013). The United States, France, Japan, Russia, and Korea (Rep. of)—with 99, 63, 44, 24, and 21 GW_e of nuclear power, respectively—are the top five countries in installed nuclear capacity and together represent 68 % of total global nuclear capacity as of September 2013 (IAEA, 2013a). The majority of the world's reactors are based on light-water technology of similar concept, design, and fuel cycle. Of the reactors worldwide, 354 are light-water reactors (LWR), of which 270 are pressurized water reactors (PWR) and 84 are boiling water reactors (BWR) (IAEA, 2013a). The remaining reactor types consist of 48 heavy-water reactors (PHWR), 15 gas-cooled reactors (GCR), 15 graphite-moderated reactors (RBMK/LWGR), and 2 fast breeder reactors (FBR) (IAEA, 2013a). The choice of reactor technologies has implications for safety, cost, and nuclear fuel cycle issues.

Growing demand for electricity, energy diversification, and climate change mitigation motivate the construction of new nuclear reactors.

[6] A better metric would be based on energy supply, not installed capacity, especially because of the relatively low capacity factors of some RE sources. Energy supply statistics for power plants constructed in 2012, however, are not available.

[7] REN21 (2013) estimates that biomass power capacity increased by 9 GW in 2012, CSP by 1 GW, and geothermal power by 0.3 GW.

The electricity from nuclear power does not contribute to direct GHG emissions. There are 69 reactors, representing 67 GWe of capacity, currently under construction in 14 countries (IAEA, 2013a). The bulk of the new builds are in China, Russia, India, Korea (Rep. of), and the United States—with 28, 10, 7, 5, and 3 reactors under construction, respectively (IAEA, 2013a). New reactors consist of 57 PWR, 5 PHWR, 4 BWR, 2 FBR, and one high-temperature gas-cooled reactor (HTGR) (IAEA, 2013a).

Commercial reactors currently under construction—such as the Advanced Passive-1000 (AP-1000, USA-Japan), Advanced Boiling Water Reactor (ABWR, USA-Japan), European Pressurized Reactor (EPR, France), Water-Water Energetic Reactor-1200 (VVER-1200, Russia), and Advanced Power Reactor-1400 (APR-1400, Rep. of Korea)—are Gen III and Gen III+ reactors that have evolutionary designs with improved active and passive safety features over the previous generation of reactors (Cummins et al., 2003; IAEA, 2006; Kim, 2009; Goldberg and Rosner, 2011).

Other more revolutionary small modular reactors (SMR) with additional passive safety features are under development (Rosner and Goldberg, 2011; IAEA, 2012a; Vujic et al., 2012; World Nuclear Association, 2013). The size of these reactors is typically less than 300 MWe, much smaller than the 1000 MWe or larger size of current LWRs. The idea of a smaller reactor is not new, but recent SMR designs with low power density, large heat capacity, and heat removal through natural means have the potential for enhanced safety (IAEA, 2005a, 2012a). Additional motivations for the interest in SMRs are economies of manufacturing from modular construction techniques, shorter construction periods, incremental power capacity additions, and potential for improved financing (Rosner and Goldberg, 2011; Vujic et al., 2012; World Nuclear Association, 2013). Several SMR designs are under consideration. Light-water SMRs are intended to rely on the substantial experience with current LWRs and utilize existing fuel-cycle infrastructure. Gas-cooled SMRs that operate at higher temperatures have the potential for increased electricity generation efficiencies relative to LWRs and industrial applications as a source of high-temperature process heat (EPRI, 2003; Zhang et al., 2009). A 210 MWe demonstration high-temperature pebble-bed reactor (HTR-PM) is under construction in China (Zhang et al., 2009). While several countries have interest in the development of SMRs, their widespread adoption remains uncertain.

The choice of the nuclear fuel cycle has a direct impact on uranium resource utilization, nuclear proliferation, and waste management. The use of enriched uranium fuels for LWRs in a once-through fuel cycle dominates the current nuclear energy system. In this fuel cycle, only a small portion of the uranium in the fuel is utilized for energy production, while most of the uranium remains unused. The composition of spent or used LWR fuel is approximately 94 % uranium, 1 % plutonium, and 5 % waste products (ORNL, 2012). The uranium and converted plutonium in the spent fuel can be used as new fuel through reprocessing. While the ultimate availability of natural uranium resources is uncertain (see Section 7.4.3), dependence on LWRs and the once-through fuel cycle implies greater demand for natural uranium. Transition to ore grades of lower uranium concentration for increasing uranium supply could result in higher extraction costs (Schneider and Sailor, 2008). Uranium ore costs are a small component of nuclear electricity costs, however, so higher uranium extraction cost may not have a significant impact on the competitiveness of nuclear power (IAEA, 2012b).

The necessity for uranium enrichment for LWRs and the presence of plutonium in the spent fuel are the primary proliferation concerns. There are differing national policies for the use or storage of fissile plutonium in the spent fuel, with some nations electing to recycle plutonium for use in new fuels and others electing to leave it intact within the spent fuel (IAEA, 2008a). The presence of plutonium and minor actinides in the spent fuel leads to greater waste-disposal challenges as well. Heavy isotopes such as plutonium and minor actinides have very long half-lives, as high as tens to hundreds of thousands of years (NRC, 1996), which require final waste-disposal strategies to address safety of waste disposal on such great timescales. Alternative strategies to isolate and dispose of fission products and their components apart from actinides could have significant beneficial impact on waste-disposal requirements (Wigeland et al., 2006). Others have argued that separation and transmutation of actinides would have little or no practical benefit for waste disposal (NRC, 1996; Bunn et al., 2003).

Alternative nuclear fuel cycles, beyond the once-through uranium cycle, and related reactor technologies are under investigation. Partial recycling of used fuels, such as the use of mixed-oxide (MOX) fuels where U-235 in enriched uranium fuel is replaced with recycled or excess plutonium, is utilized in some nations to improve uranium resource utilization and waste-minimization efforts (OECD and NEA, 2007; World Nuclear Association, 2013). The thorium fuel cycle is an alternative to the uranium fuel cycle, and the abundance of thorium resources motivates its potential use (see Section 7.4.3). Unlike natural uranium, however, thorium does not contain any fissile isotopes. An external source of fissile material is necessary to initiate the thorium fuel cycle, and breeding of fissile U-233 from fertile Th-232 is necessary to sustain the fuel cycle (IAEA, 2005b).

Ultimately, full recycling options based on either uranium or thorium fuel cycles that are combined with advanced reactor designs—including fast and thermal neutron spectrum reactors—where only fission products are relegated as waste can significantly extend nuclear resources and reduce high-level wastes (GIF, 2002, 2009; IAEA, 2005b). Current drawbacks include higher economic costs, as well as increased complexities and the associated risks of advanced fuel cycles and reactor technologies. Potential access to fissile materials from widespread application of reprocessing technologies further raises proliferation concerns. The advantages and disadvantages of alternative reprocessing technologies are under investigation.

There is not a commonly accepted, single worldwide approach to dealing with the long-term storage and permanent disposal of high-level waste. Regional differences in the availability of uranium ore and land resources, technical infrastructure and capability, nuclear fuel cost, and societal acceptance of waste disposal have resulted in alternative approaches to waste storage and disposal. Regardless of these differences and the fuel cycle ultimately chosen, some form of long-term storage and permanent disposal, whether surface or geologic (subsurface), is required.

There is no final geologic disposal of high-level waste from commercial nuclear power plants currently in operation, but Finland and Sweden are the furthest along in the development of geologic disposal facilities for the direct disposal of spent fuel (Posiva Oy, 2011, 2012; SKB, 2011). In Finland, construction of the geologic disposal facility is in progress and final disposal of spent fuel is to begin in early 2020 (Posiva Oy, 2012). Other countries, such as France and Japan, have chosen to reprocess spent fuel to use the recovered uranium and plutonium for fresh fuel and to dispose of fission products and other actinides in a geologic repository (OECD and NEA, 2007; Butler, 2010). Yet others, such as Korea (Rep. of), are pursuing a synergistic application of light and heavy water reactors to reduce the total waste by extracting more energy from used fuels (Myung et al., 2006). In the United States, waste-disposal options are currently under review with the termination of the Yucca Mountain nuclear waste repository in Nevada (CRS, 2012). Indefinite dry cask storage of high-level waste at reactor sites and interim storage facilities are to be pursued until decisions on waste disposal are resolved.

The implementation of climate change mitigation policies increases the competiveness of nuclear energy technologies relative to other technology options that emit GHG emissions (See 7.11, Nicholson et al., 2011). The choice of nuclear reactor technologies and fuel cycles will affect the potential risks associated with an expanded global response of nuclear energy in addressing climate change.

Nuclear power has been in use for several decades. With low levels of lifecycle GHG emissions (see Section 7.8.1), nuclear power contributes to emissions reduction today and potentially in the future. Continued use and expansion of nuclear energy worldwide as a response to climate change mitigation require greater efforts to address the safety, economics, uranium utilization, waste management, and proliferation concerns of nuclear energy use (IPCC, 2007, Chapter 4; GEA, 2012).

Research and development of the next-generation nuclear energy system, beyond the evolutionary LWRs, is being undertaken through national and international efforts (GIF, 2009). New fuel cycles and reactor technologies are under investigation in an effort to address the concerns of nuclear energy use. Further information concerning resources, costs, risks and co-benefits, deployment barriers, and policy aspects can be found in Sections 7.4.3, 7.8.2, 7.9, 7.10, and 7.12.

7.5.5 Carbon dioxide capture and storage (CCS)

As of mid-2013, CCS has not yet been applied at scale to a large, commercial fossil-fired power generation facility. However, all of the components of integrated CCS systems exist and are in use today by the hydrocarbon exploration, production, and transport, as well as the petrochemical refining sectors.

A 'complete end-to-end CCS system' captures CO_2 from large (e.g., typically larger than 0.1 $MtCO_2$/year) stationary point sources (e.g., hydrocarbon-fuelled power plants, refineries, cement plants, and steel mills), transports and injects the compressed CO_2 into a suitable deep (typically more than 800 m below the surface) geologic structure, and then applies a suite of measurement, monitoring, and verification (MMV) technologies to ensure the safety, efficacy, and permanence of the captured CO_2's isolation from the atmosphere (IPCC, 2005; Herzog, 2011). As of mid 2013, five large end-to-end commercial CCS facilities were in operation around the world. Collectively, they have stored more than 30 $MtCO_2$ over their lifetimes (Eiken et al., 2011; Whittaker et al., 2011; MIT, 2013). All of them capture a high-purity CO_2 stream from industrial (i.e., non-electricity-generating) facilities such as natural gas processing plants. The near-term deployment of CCS is likely to arise in just these kinds of industrial facilities that produce high-purity (which connotes relatively inexpensive to capture) CO_2 waste streams that would otherwise be vented to the atmosphere and/or in situations where the captured CO_2 can be used in a value-added manner as is the case with CO_2-driven tertiary hydrocarbon recovery (IPCC, 2005; Bakker et al., 2010; Vergragt et al., 2011).

In the long term, the largest market for CCS systems is most likely found in the electric power sector, where the cost of deploying CCS (measured on a USD/tCO_2 basis) will be much higher and, as a result, will be done solely for the purpose of isolating anthropogenic CO_2 from the atmosphere. However, this is unlikely to occur without sufficiently stringent limits on GHG emissions to make it economic to incur these additional costs, regulatory mandates that would require the use of CCS (for example, on new facilities), or sufficient direct or indirect financial support (IPCC, 2005; Herzog, 2011).

Research aimed at improving the performance and cost of CO_2 capture systems for the electric power sector is significant across three broad classes of CO_2 capture technologies: pre-combustion (Rubin et al., 2007; Figueroa et al., 2008), post-combustion (Lin and Chen, 2011; Padurean et al., 2011; Versteeg and Rubin, 2011), and oxyfuel capture (Scheffknecht et al., 2011; Wall et al., 2011).

The risks associated with a large-scale deployment of CCS technologies include concerns about the lifecycle toxicity of some capture solvents (IEAGHG, 2010; Korre et al., 2010; Corsten et al., 2013), the operational safety and long-term integrity of CO_2 storage sites (Birkholzer et al., 2009; Oruganti and Bryant, 2009; Juanes et al., 2010, 2012; Morris et al., 2011; Mazzoldi et al., 2012), as well as risks associated with CO_2 transport via dedicated pipelines (Aines et al., 2009; Mazzoldi et al., 2012).

There is, however, a growing body of literature on how to minimize capture risks and to ensure the integrity of CO_2 wells (Carey et al., 2007, 2010; Jordan and Benson, 2009; Crow et al., 2010; Zhang and Bachu, 2011; Matteo and Scherer, 2012), as well as on using detailed measurement, monitoring, and verification data to lower the threshold for detecting any leakage out of the intended injection zone (Hovorka et al., 2006; Gilfillan et al., 2009; Jordan and Benson, 2009; Eiken et al., 2011). The literature is also quantifying potential consequences of a pressure buildup within a formation caused by CO_2 storage such as induced seismicity (Juanes et al., 2012; Mazzoldi et al., 2012; NAS, 2013a), the potential human health impacts (Roberts et al., 2011; de Lary et al., 2012; Atchley et al., 2013), and environmental consequences from CO_2 that might migrate out of the primary injection zone (Gaus, 2010; Romanak et al., 2012; Zheng et al., 2012) as well as mechanisms for actively managing the storage formation such as withdrawing formation waters to reduce pressure buildup (Esposito and Benson, 2012; Réveillère et al., 2012; Sullivan et al., 2013).

The deployment of CCS at a scale of 100s of $GtCO_2$ over the course of this century (which is consistent with the stabilization scenarios described in Chapter 6 and in Section 7.11) would imply that large, regional, deep-geologic basins would have to accommodate multiple large-scale CO_2 injection projects (Bachu, 2008; Nicot, 2008; Birkholzer and Zhou, 2009; Juanes et al., 2010) while taking into account other industrial activities in the region that could impact the integrity of CO_2 storage reservoirs (Elliot and Celia, 2012). The peer-reviewed literature that has looked at these large CCS deployment scenarios stress the need for good CO_2 storage site selection that would explicitly address the cumulative far-field pressure effects from multiple injection projects in a given basin.

A considerable body of practical engineering and scientific knowledge has been generated from the first five large-scale, complete CCS deployments as well as from numerous smaller-scale CCS field experiments and technology demonstrations (Cavanagh et al., 2010; IEAGHG, 2011; NETL, 2012). In particular, a key advance has been the field testing of MMV technologies to monitor injected CO_2 in a variety of settings. These real-world MMV deployments are the beginnings of a broader portfolio of MMV technologies that can be matched to site-specific geology and project- and jurisdiction-specific MMV needs (Mathieson et al., 2010; Vasco et al., 2010; Sato et al., 2011). The value of high-quality MMV data is becoming clearer as these data allow for the active management of a geologic CO_2 storage formation and can provide operators and regulators with the ability to detect possible leakage out of the target formation at low levels, which, in turn, can reduce the probability and magnitude of adverse events (Dooley et al., 2010; Torvanger et al., 2012; Buscheck et al., 2012; Schloemer et al., 2013).

As noted by Bachu (2008), Krevor et al., (2012), and IPCC (2005), there are a number of key physical and chemical processes that work in concert to help ensure the efficacy of deep-geologic CO_2 storage over time. The accumulated knowledge from the five commercial CCS facilities mentioned above, from many smaller field experiments and technology demonstrations, and from laboratory-based research suggests a declining long-term risk profile for CO_2 stored in deep-geologic reservoirs once active CO_2 injection into the reservoir has ceased (Hovorka et al., 2006; Gilfillan et al., 2009; Jordan and Benson, 2009). Torvanger et al. (2012) builds upon this accumulated knowledge and concludes, "only in the most unfortunate conditions could such CO_2 escape [from deep-geologic CO_2 storage reservoirs and] compromise [humanity's ability to not exceed a] maximum 2.5 °C warming."

Further information concerning transport risks, costs, deployment barriers, and policy aspects can be found in Sections 7.6.4, 7.8.2, 7.10, and 7.12, respectively. The use of CCS in the industrial sector is described in Section 10.4.

The direct CO_2 emissions from biogenic feedstock combustion broadly correspond to the amount of atmospheric CO_2 sequestered through the growth cycle of bioenergy production.[8] A net removal of atmospheric CO_2 therefore would result, once the direct emissions are captured and stored using CCS technologies (see Section 11.13, Figure 11.22). As a consequence, a combination of bio-energy and CCS (BECCS) generally will result in net negative emissions (see IEA, 2011c, 2012c; IEAGHG, 2011). Currently, two small-scale examples of commercial precursors to BECCS are capturing CO_2 emissions from ethanol production facilities for enhanced oil recovery in close-proximity facilities (DiPietro and Balash, 2012).

BECCS is one of the few technologies that is capable of removing past CO_2 emissions remaining in the atmosphere. As this enhances the 'when' (i.e., temporal) flexibility during the design of mitigation scenarios considerably, BECCS plays a prominent role in many of the low-stabilization pathways discussed in Chapter 6 and Section 7.11. Potential risks associated with BECCS technologies are related to those associated with the upstream provision of the used biomass[9] (see Section 11.13) as well as those originating from the capture, transport, and long-term underground storage of CO_2 that would be emitted otherwise (see above).

[8] Non-vanishing life-cycle emissions originate from fossil fuels used during the planting, regrowth, and harvesting cycle and potential emissions from land-use and management change, among others. The lifecycle emissions depend on the type of feedstock, specific location, scale and practices of biomass production, and on the dynamics and management of land use. In some cases, if biomass growth accumulates carbon in the soil until reaching equilibrium, additional carbon sequestration can occur, but these may be short-term effects. Indirect emissions relate more directly to the use of food crops for energy than to the use of lignocellulosic biomass (see Section 11.13). Short rotation species (herbaceous plants) wastes have near-zero net emissions cycles.

[9] BECCS costs can be reduced by using large-scale biomass conversion facilities, which, in turn, require the development of cost-effective and low-emitting large-scale feedstock and supply logistics (Section 11.13.3).

7

7.6 Infrastructure and systemic perspectives

7.6.1 Electrical power systems

Reducing GHG emissions from the electric power sector will require infrastructure investments and changes in the operations of power systems—these will both depend on the mitigation technologies employed. The fundamental reliability constraints that underpin this process are the requirements that power supply and electricity demand remain in balance at all times (system balancing), that adequate generation capacity is installed to meet (peak) residual demand (capacity adequacy)[10], and that transmission and distribution network infrastructure is sufficient to deliver generation to end users (transmission and distribution). Studies of high variable RE penetration (Mason et al., 2010; Delucchi and Jacobson, 2011; Denholm and Hand, 2011; Huva et al., 2012; Elliston et al., 2012; Haller et al., 2012; Rasmussen et al., 2012; Budischak et al., 2013) and the broader literature (summarized in Sims et al., 2011) suggest that integrating significant RE generation technology is technically feasible, though economic and institutional barriers may hinder uptake. Integrating high penetrations of RE resources, particularly those that are intrinsically time variable, alongside operationally inflexible generation is expected to result in higher system-balancing costs. Compared to other mitigation options variable renewable generation will contribute less to capacity adequacy, and, if remote from loads, will also increase transmission costs. The determination of least-cost portfolios of those options that facilitate the integration of fluctuating power sources is a field of active and ongoing research (Haller et al., 2012; Steinke et al., 2013).

7.6.1.1 System balancing—flexible generation and loads

Variable RE resources may increase the need for system balancing beyond that required to meet variations in demand. Existing generating resources can contribute to this additional flexibility. An IEA assessment shows the amount of variable RE electricity that can be accommodated using *'existing'* balancing resources exceeds 20 % of total annual electricity supply in seven regions and is above 40 % in two regions and one country (IEA, 2011d). Higher RE penetrations will require additional flexible resources (De Vos et al., 2013). Surplus renewable supply can be curtailed by switching off unwanted plants or through regulation of the power output, but with corresponding economic consequences (Brandstätt et al., 2011; Jacobsen and Schröder, 2012).

Some low-carbon power technologies (such as nuclear) have relatively high up-front and low operating costs, making them attractive for baseload operation rather than providing flexible generation to assist in system balancing. Depending on the pattern of electricity demand, a relatively high share of energy can be provided by these baseload technologies but at some point, further increases in their penetration will require part-loaded operation,[11] load following, time shifting of demand (via load management or demand response), and/or deployment of storage where it is cost-effective (Knapp, 1969; Johnson and Keith, 2004; Chalmers et al., 2009; Pouret et al., 2009).

Part-load operation of nuclear plants is possible as in France, though in other regions it may be restricted by institutional barriers (Perez-Arriaga and Batlle, 2012). Load following by nuclear power plants is more challenging and must be considered at the design stage (NEA, 2011a, 2012; Greenblatt et al., 2012). Flexible operation of a CCS-fitted generation plant is also an active area of research (Chalmers and Gibbins, 2007; Nord et al., 2009; Cohen et al., 2011). Operational flexibility of combined heat and power (CHP) plants may be constrained by heat loads, though thermal storages and complementary heat sources can mitigate this effect (e.g., Lund and Andersen, 2005; Christidis et al., 2012; Blarke, 2012; Nuytten et al., 2013), however, the capital intensity of CHP will favor high load factors. Reservoir hydropower can be useful in balancing due to its flexibility.

Certain combinations may present further challenges (Ludig et al., 2011): high shares of variable RE power, for example, may not be ideally complemented by nuclear, CCS, and CHP plants (without heat storage). If those plants cannot be operated in a flexible manner, additional flexibility is required and can be obtained from a number of sources including investment in new flexible generation, improvements in the flexibility of existing power plants, demand response, and storage as summarized in the SRREN (Sims et al., 2011). Obtaining flexibility from fossil generation has a cost (see Section 7.8.2) and can affect the overall GHG reduction potential of variable RE (Pehnt et al., 2008; Fripp, 2011; Wiser et al., 2011; Perez-Arriaga and Batlle, 2012). Demand response[12] is of increasing interest due to its potentially low cost (see chapter 9 and 10; IEA, 2003b; Depuru et al., 2011; Cook et al., 2012; Joung and Kim, 2013; Procter, 2013), albeit some emphasize its limitation compared to flexible conventional supply technologies (Cutter et al., 2012). Smart meters and remote controls are key components of the so-called smart grid where information technology is used to improve the operation of power systems, especially with resources located at the distribution level (IEA, 2011e).

Energy storage might play an increasing role in the field of system balancing (Zafirakis et al., 2013). Today pumped hydro storage is the only widely deployed storage technology (Kanakasabapathy, 2013). Other storage technologies including compressed air energy storage (CAES) and batteries may be deployed at greater scale within centralized power systems in the future (Pickard et al., 2009a; b; Roberts and Sand-

10 Sometimes called resource adequacy.

11 In the field of RE this is called "curtailment".

12 Demand response is load management triggered by power price signals derived from the spot market prices or other control signals (IEA, 2003b).

berg, 2011), and the latter can be decentralized. These short-term storage resources can be used to compensate the day-night cycle of solar and short-term fluctuation of wind power (Denholm and Sioshansi, 2009; Chen et al., 2009; Loisel et al., 2010; Beaudin et al., 2010). With the exception of pumped hydro storage, full (levelized) storage costs are still high, but storage costs are expected to decline with technology development (IEA, 2009b; Deane et al., 2010; Dunn et al., 2011; EIA, 2012). 'Power to heat' and 'power to gas' (H_2 or methane) technologies might allow for translating surplus renewable electricity into other useful final energy forms (see Sections 7.6.2 and 7.6.3).

7.6.1.2 Capacity adequacy

One measure of reliability in a power system is the probability that demand will exceed available generation. The contribution of different generation technologies to ensuring the availability of sufficient generation is called the capacity credit or capacity value (Keane et al., 2011). The capacity credit of nuclear, thermal plants with CCS, geothermal, and large hydro is expected to be higher than 90 % (i.e., within 10 % of the plant nameplate capacity) as long as fuel supply and cooling water is sufficient and maintenance is scheduled outside critical periods. Variable RE will generally have a lower capacity credit that depends on the correlation between generation availability and periods of high demand. The capacity credit of wind power, for instance, ranges from 5 % to 40 % of the nameplate capacity (Mason et al., 2010; Holttinen et al., 2011); ranges of capacity credits for other RE resources are summarized in Sims et al. (2011).

The addition of significant plants with low capacity credit can lead to the need for a higher planning-reserve margin (defined as the ratio of the sum of the nameplate capacity of all generation to peak demand) to ensure the same degree of system reliability. If specifically tied to RE generation, energy storage can increase the capacity credit of that source; for example, the capacity credit of CSP with thermal storage is greater than without thermal storage (Madaeni et al., 2011).

7.6.1.3 Transmission and distribution

Due to the geographical diversity of RE resources, connecting RE sources to the existing transmission system may require the installation of additional transmission capacity and strengthening the existing system if significantly greater power flows are required across the system (Sims et al., 2011). Increased interconnection and strengthened transmission systems provide power system operators the capability to move surplus generation in one region to meet otherwise unmet demand in another, exploiting the geographical diversity of both loads and generation (Rasmussen et al., 2012). Although there will be a need for additional transmission capacity, its installation often faces institutional challenges, and it can be visually intrusive and unpopular in the affected areas. Infrastructure challenges are particularly acute for RE deployment in developing countries, which is why stand-alone decentralized generation, such as with solar home systems, is often favored.

Transmission considerations applied to CCS plants have to reflect the tradeoff between the cost of electrical transmission and the cost of pipeline transport of CO_2 to final depositories (Svensson et al., 2004; Benson et al., 2005; Herzog et al., 2005; Spiecker et al., 2011). Transmission investments may also be needed for future nuclear plants if these are located at some distance from load centers due to public perceptions of health and safety, access to cooling water, or other factors.

Distributed generation (DG), where small generating units (often renewable technologies, cogeneration units, or fuel cells) are connected directly to the electricity distribution system and near loads, may not have the same need for expansion of the transmission system. The net impact of DG on distribution networks depends on the local penetration level, the location of DG relative to loads, and temporal coincidence of DG generation and loads (Cossent et al., 2011). As DG grows, system operators would like to have increased visibility and controllability of DG to ensure overall system reliability. Smart grids might include components to facilitate the integration of various DG technologies, allow for more active control of the distribution network, and improve the market value of DG through aggregation into virtual power plants (Pudjianto et al., 2007; Clastres, 2011; IEA, 2011e; Wissner, 2011; Ardito et al., 2013; Hashmi et al., 2013).

7.6.2 Heating and cooling networks

Globally, 15.8 EJ were used in 2010 (2.6 % of global TPES) to produce nearly 14.3 EJ[13] of district heat for sale at CHP (44 %) and heat-only boilers (56 %) (Table 7.1). After a long decline in the 1990s, district heat returned to a growing trajectory in the last decade, rising by about 21 % above the year-2000 level (IEA, 2012a). This market is dominated by the Russian Federation with a 42 % share in the global heat generation, followed by Ukraine, United States, Germany, Kazakhstan, and Poland. Natural gas dominates in the fuel balance of heat generation (46 %), followed by coal (40 %), oil (5 %), biofuels and waste (5 %), geothermal and other renewables (2.4 %), and a small contribution from nuclear. Development of intelligent district heating and cooling networks in combination with (seasonal) heat storage allows for more flexibility and diversity (combination of wind and CHP production in Denmark) and facilitates additional opportunities for low-carbon technologies (CHP, waste heat use, heat pumps, and solar heating and cooling) (IEA, 2012a). In addition, excess renewable electricity can be converted into heat to replace what otherwise would have been produced by fossil fuels (Meibom et al., 2007).

Statistically reported average global efficiency of heat generation by heat-only boilers is 83 %, while it is possible to improve it to 90–95 %

13 UNES reports lower number. For 2008 this sources assess the total production of district heat equal to 10.7 EJ (UNES, 2011).

depending on fuel used. About 6.9 % of globally generated heat for sale is lost in heating networks (Table 7.1). In some Russian and Ukrainian municipal heating systems, such losses amount to 20–25 % as a result of excessive centralization of many district heating systems and of worn and poorly maintained heat supply systems (Bashmakov, 2009).

The promotion of district heating and cooling system should also account for future technology developments that impact the district heating sector (building heat demand reduction, high-efficiency single-housing boilers, heat-pump technology, cogeneration reciprocating engines, or fuel cells, etc.), which may allow switching to more-efficient decentralized systems (GEA, 2012). District heating and cooling systems could be more energy and economically efficient when heat or coldness load density is high through the development of tri-generation, the utilization of waste heat by communities or industrial sites, if heat (cooling) and power loads show similar patterns, and if heat-loss control systems are well-designed and managed (see 9.4.1.1).

7.6.3 Fuel supply systems

As noted in Section 7.5.1, fossil fuel extraction and distribution contributes around 5–10 % of total fossil fuel related GHG emissions. It has also been noted that specific emissions from this sector will increase due to increased energy requirements of extraction and processing of oil and gas from mature fields and unconventional sources, and the mining of coal from deeper mines. The fuel supply system supporting this sector does, however, provide opportunities to reduce GHG emissions by enabling the delivery of low-carbon fuels (such as biofuels, biogas, renewable H_2,or renewable methane).

Opportunities for delivery of liquid fuels are likely limited to fuels such as biodiesel and ethanol at points in the system that enable either storage or blending before transport to distribution nodes, which is discussed in Section 8.3.3; for gaseous fuels, supply of low-carbon fuels could occur across much of the gas delivery network.

More than 50 countries transport high-pressure natural gas through pipe networks greater than 1,000 km in length (Central Intelligence Agency, 2011). Although individual layout varies, connected to these are the lower-pressure networks that distribute gas for power generation, industry, and domestic use. Because of their ability to carry natural gas substitutes, these networks provide an opportunity to expand production of these gases; depending on the availability of resources, estimates suggest substitutes could replace 17.4 EJ of natural gas used in Europe by 2020 (IPCC, 2011a). Low CO_2-emitting natural gas substitutes can be produced from surplus fluctuating renewable electricity generation, e.g., 'power to methane' (Sterner, 2009; Arvizu et al., 2011), from other renewable sources such as biomass and waste, or via coal when combined with CCS; CCS can be added to gas production from biomass to further enhance the CO_2-mitigation potential (Carbo et al., 2011). Provided the substitute natural gas meets the relevant gas quality standard (IEA Bioenergy, 2006, 2009; IPCC, 2011a), and gas cleanup may be required to achieve this, there are no technical barriers to the injection of gas substitutes into the existing gas networks (Hagen et al., 2001). Biomethane produced from a variety of sources is already being injected into a number of natural gas networks (IEA Bioenergy, 2011; IPCC, 2011a).

The existing natural gas network also has the potential to transport and distribute hydrogen provided the injected fraction remains below 20 % by volume, although estimates vary (Naturalhy 2004). Limiting factors are gas quality standard and equipment compliance, pipeline integrity (failure, fire, and explosion) and end-user safety (Naturalhy, 2004; Tabkhi et al., 2008). Where the pipelines are suitable and more-frequent inspections can be undertaken, a higher fraction of hydrogen can be carried, although the lower volumetric energy density of hydrogen will reduce energy flow, unless gas pressure can be increased. If required, hydrogen separation is possible via a range of existing technologies.

For dedicated hydrogen delivery, transport distance is an important consideration; pipelines are favoured over shorter delivery distances and at high flow rates, while batch delivery of liquid hydrogen is favoured by long distances (Yang and Ogden, 2007). Hydrogen can be produced from renewable sources such as wind and solar (IEA, 2006; Moriarty and Honnery, 2007; Gahleitner, 2013) as well as biomass. Its production from intermittent renewable sources can provide greater system flexibility; drawbacks are the additional cost and reduced overall efficiency in energy delivery (Mason and Zweibel, 2007; Honnery and Moriarty, 2009; IPCC, 2011a).

7.6.4 CO_2 transport

There are more than 6,300 km of existing CO_2 pipeline in the U.S and much has been learned from the decades of operational experience obtained from these existing CO_2 pipeline systems (Dooley et al., 2011). There is a growing body of research that describes the magnitude and region-specific nature of future CO_2 transport systems. Specifically, there are a growing number of bottom-up studies that examine spatial relationships between where CO_2 capture units might be located and the very heterogeneous distribution, capacity, and quality of candidate geologic storage reservoirs. For example, the work of Dahowski et al., (2005, 2012) suggests that more than 90 % of the large stationary CO_2 point sources in the United States are within 160 km of at least one candidate geologic storage reservoir and 80 % of China's large stationary point sources are within 80 km of at least one candidate storage reservoir. For regions like these, the proximity of most large stationary CO_2 point sources to large and geographically distributed geologic CO_2 storage reservoirs suggests that—at least early on in the commercial deployment of CCS technologies—facilities might rely on dedicated pipelines linking the CO_2 source to an appropriate sink. The work of Johnson and Ogden (2011) suggests that once there is a critical density of CO_2 capture and storage projects in a region, a more-integrated national pipeline network may evolve. For other regions, especially Western/Northern

Europe, Japan, and Korea, where onshore storage options are not widely distributed, more care is needed in planning pipeline networks given the geographical (and political) challenges of linking distributed CO_2 sources to the available/usable predominantly offshore geologic storage options. This requires longer-term planning as well as political/legal agreements between countries in those regions as more coordination and cross-boundary transport will be necessary/desired (Huh et al., 2011; Ogawa et al., 2011; Strachan et al., 2011; ZEP, 2011a). While pipelines are likely to be the transport mode of choice for onshore and most offshore storage projects (IPCC, 2005), in certain circumstances, transporting CO_2 by large ocean going vessels could be a technically feasible and cost-effective option (Aspelund et al., 2006; Decarre et al., 2010; Ozaki and Ohsumi, 2011; Yoo et al., 2011).

The United States oil and gas industry has more than 40 years of experience associated with transporting large volumes of CO_2 via dedicated commercial pipelines (IPCC, 2005; Meyer, 2007). Available data suggests that these CO_2 pipelines have safety records that are as good or better than large interstate natural gas pipelines, their closest industrial analogue (Gale and Davison, 2004; IPCC, 2005; Cole et al., 2011). There is also a growing body of work combining pipeline fluid flow, pipeline engineering models, and atmospheric dispersion models suggesting that the hazard associated with potential ruptures in CO_2 pipelines is likely to be small for most plausible releases to the atmosphere (Aines et al., 2009; Koornneef et al., 2010; Mazzoldi et al., 2011). Although much can be learned from existing CO_2 pipeline systems, knowledge gaps exist for systems that integrate multiple CO_2 source points. Because of their impact on pipeline integrity, gas stream properties and flow management, impurity control is emerging as a major design feature of these systems (Oosterkamp and Ramsen, 2008; Cole et al., 2011) with particular importance given to limiting the amount of water in the gas stream at its source to avoid corrosion.

Estimates for the cost of transporting, injecting into a suitable formation, site closure, and long-term post-injection monitoring are summarized at the end of Section 7.8.2. Options for CO_2 geologic storage are presented in Section 7.5.5 and a discussion of the cost of CO_2 capture is presented in Section 7.8.2.

7.7 Climate change feedback and interaction with adaptation

Climate change will affect heating and cooling energy demands (see also Chapter 9.5; Arent et al., 2014), thereby also influencing energy supply needs. The effect on overall energy demand will vary geographically (Mideksa and Kallbekken, 2010; Pilli-Sihvola et al., 2010; Wan et al., 2011). Many studies indicate that demand for electricity will increase because of greater need for space cooling, while demand for natural gas and oil will decline because of less need for space heating (Isaac and van Vuuren, 2009; Akpinar-Ferrand and Singh, 2010; Arent et al., 2014). Peak electricity demand could also increase, especially as a result of extreme events, requiring a disproportionate increase in energy infrastructure (US EPA, 2008). Although impacts on energy demands outside of heating and cooling are less clear, possible effects include increased energy use for climate-sensitive processes, such as pumping water for irrigated agriculture and municipal uses (US EPA, 2008; Aromar and Sattherhwaite, 2014). As another example, reductions or changes to surface water flows could increase energy demand for desalination (Boyé, 2008; Scholes and Settele, 2014).

In addition to impacting energy supply through changes in energy demand, climate change will have various impacts on the potential future role of mitigation technologies in the energy supply sector. Though these impacts are summarized here, further details on potential impacts, as well as a summary of how conventional higher-carbon energy supplies might be affected, are available in the WGII AR5 report, especially but not limited to Chapter 10 (Arent et al., 2014).

Though the impact of climate change on the primary resource base for fossil fuels is likely to be small (World Bank, 2011a), RE sources can be particularly sensitive to climate change impacts. In general, any impacts are expected to increase with the level of climate change, but the nature and magnitude of these effects are technology-dependent and somewhat uncertain, and they may vary substantially on regional and local levels (IPCC, 2011a; Schaeffer et al., 2012; Arent et al., 2014). The SRREN SPM (IPCC, 2011a, p. 12), summarizes the available literature as follows:

> *"The future technical potential for bioenergy could be influenced by climate change through impacts on biomass production such as altered soil conditions, precipitation, crop productivity, and other factors. The overall impact of a global mean temperature change of less than 2 °C on the technical potential of bioenergy is expected to be relatively small on a global basis. However, considerable regional differences could be expected and uncertainties are larger and more difficult to assess compared to other RE options due to the large number of feedback mechanisms involved. For solar energy, though climate change is expected to influence the distribution and variability of cloud cover, the impact of these changes on overall technical potential is expected to be small. For hydropower the overall impacts on the global technical potential is expected to be slightly positive. However, results also indicate the possibility of substantial variations across regions and even within countries. Research to date suggests that climate change is not expected to greatly impact the global technical potential for wind energy development but changes in the regional distribution of the wind energy resource may be expected. Climate change is not anticipated to have significant impacts on the size or geographic distribution of geothermal or ocean energy resources."*

A decline in renewable resource potential in one area could lead to a shift in the location of electricity-generation technologies over time to areas where the resource has not degraded. Long-lived transmission and other infrastructure built to accommodate these technologies, however, may be stranded. The longer lifetimes of hydropower dams may mean that these facilities are also less adaptable to climate changes such as changes in local precipitation; nonetheless, dams also offer the opportunity for energy and water storage that may provide climate-adaptation benefits (Kumar et al., 2011; Schaeffer et al., 2012).

Climate change may also impact the design and operation of energy sourcing and delivery facilities (e.g., US DOE, 2013b). Offshore infrastructure, including gas and oil wells but also certain RE facilities such as offshore wind power plants, are vulnerable to extreme weather events (Karl et al., 2009; Wiser et al., 2011; World Bank, 2011a; Rose et al., 2012; Arent et al., 2014). Production losses from thermal power plants (whether low- or high-carbon facilities) and efficiency losses from energy-delivery infrastructures increase when temperatures exceed standard design criteria (Schaeffer et al., 2012; Sathaye et al., 2013). Some power-generation facilities will also be impacted by changes in access to and the temperature of cooling water, while both power-generation facilities and energy-delivery infrastructures can be impacted by sea-level rise and extreme weather events (Kopytko and Perkins, 2011; Schaeffer et al., 2012; Arent et al., 2014). Adaptation strategies include infrastructure relocation and reinforcement, cooling-facility retrofit, and proactive water-resource management (Rübbelke and Vögele, 2011; Arent et al., 2014).

Finally, interdependencies between the energy supply sector and other sectors of the economy are important to consider (de Lucena et al., 2009). For example, if climate change detrimentally impacts crop yields, bioenergy potential may decline and costs may rise because more land is demanded for food crop production (Porter and Xie 2014; 11.13). Climate change may also exacerbate water and energy tensions across sectors and regions, potentially impacting hydropower (either positively or negatively, depending on whether the potential climate-adaptation benefits of hydropower facilities are realized) and other technologies that require water (Kumar et al., 2011; Arent et al., 2014; Cisneros and Oki, 2014).

7.8 Costs and potentials

7.8.1 Potential emission reduction from mitigation measures

When assessing the potential of different mitigation opportunities, it is important to evaluate the options from a lifecycle perspective to take into account the emissions in the fuel chain and the manufacturing of the energy conversion technology (Annex II.6.3). This section contains a review of life-cycle GHG emissions associated with different energy supply technologies per unit of final energy delivered, with a focus on electricity generation (Figure 7.6).

The largest lifecycle GHG emissions are associated with the combustion of coal. Lifecycle assessments reviewed in SRREN (IPCC, 2011a), showed a range of 675–1689 gCO_2eq/kWh electricity. Corresponding ranges for oil and gas were 510–1170 gCO_2eq/kWh and 290–930 gCO_2eq/kWh[14]. For the AR5, the performance of prospective new fossil fuel power plants was assessed, taking into account a revised assessment of fugitive methane emission from coal mining and natural gas supply (Section 7.5.1). According to this assessment, modern-to-advanced hard coal power plants show a range of 710–950 gCO_2eq/kWh, while natural gas combined-cycle plants have emissions in the range of 410–650 gCO_2eq/kWh, with high uncertainty and variability associated with methane emissions from gas production (Section 7.5.1; Annex II.6). Compared to a separate provision of heat, cooling, and power from stand-alone fossil fuel-based facilities, combined heat and power plants reduce emissions by one quarter (Pehnt, 2008). The transformation pathways that achieve a stabilization of the global temperature consistent with the Cancun Agreement (Chapter 6, Section 7.11, Figure 7.9), however, are based on emissions intensities approaching zero in the second half of the 21st century, so that the employment of technologies with even lower emissions (than the one mentioned for gas-fired power and combined heat and power plants) is called for if these goals are to be achieved.

A number of power supply technologies offer very low lifecycle GHG emissions (Figure 7.6). The use of CCS is expected to reduce GHG emissions to 70–290 gCO_2eq/kWh for coal (98–396 gCO_2eq/kWh in SRREN). For gas power, the literature specifies 120–170 gCO_2eq/kWh assuming a leakage of 1 % of natural gas (Koornneef et al., 2008; Singh et al., 2011; Corsten et al., 2013), while SRREN specified 65–245 gCO_2eq/kWh. According to the literature, natural gas leakage is between 0.8 %–5.5 % (Burnham et al., 2012) (see Section 7.5.1 for a discussion and more references), resulting in emissions between 90 and 370 gCO_2eq/kWh (Figure 7.6). Most of these assessments assume that 90 % of the CO_2 in the flue gas is captured, while the remaining emissions are mainly connected to the fuel chain. The upper range of emissions for CCS-based power plants is flexible since plants can be designed to capture less, something that results in lower cost and less equipment required. (Figure 7.6).

Renewable heat and power generation and nuclear energy can bring more significant reductions in GHG emissions. The information provided here has been updated from the data provided in SRREN, taking into account new findings and reviews, where available. The ranges of harmonized lifecycle greenhouse gas emissions reported in the literature are 18–180 gCO_2eq/kWh for PV (Kim et al., 2012; Hsu et al., 2012), 9–63 gCO_2eq/kWh for CSP (Burkhardt et al.,

[14] All reported SRREN numbers are from Table A.II.4 in Moomaw et al.(2011)

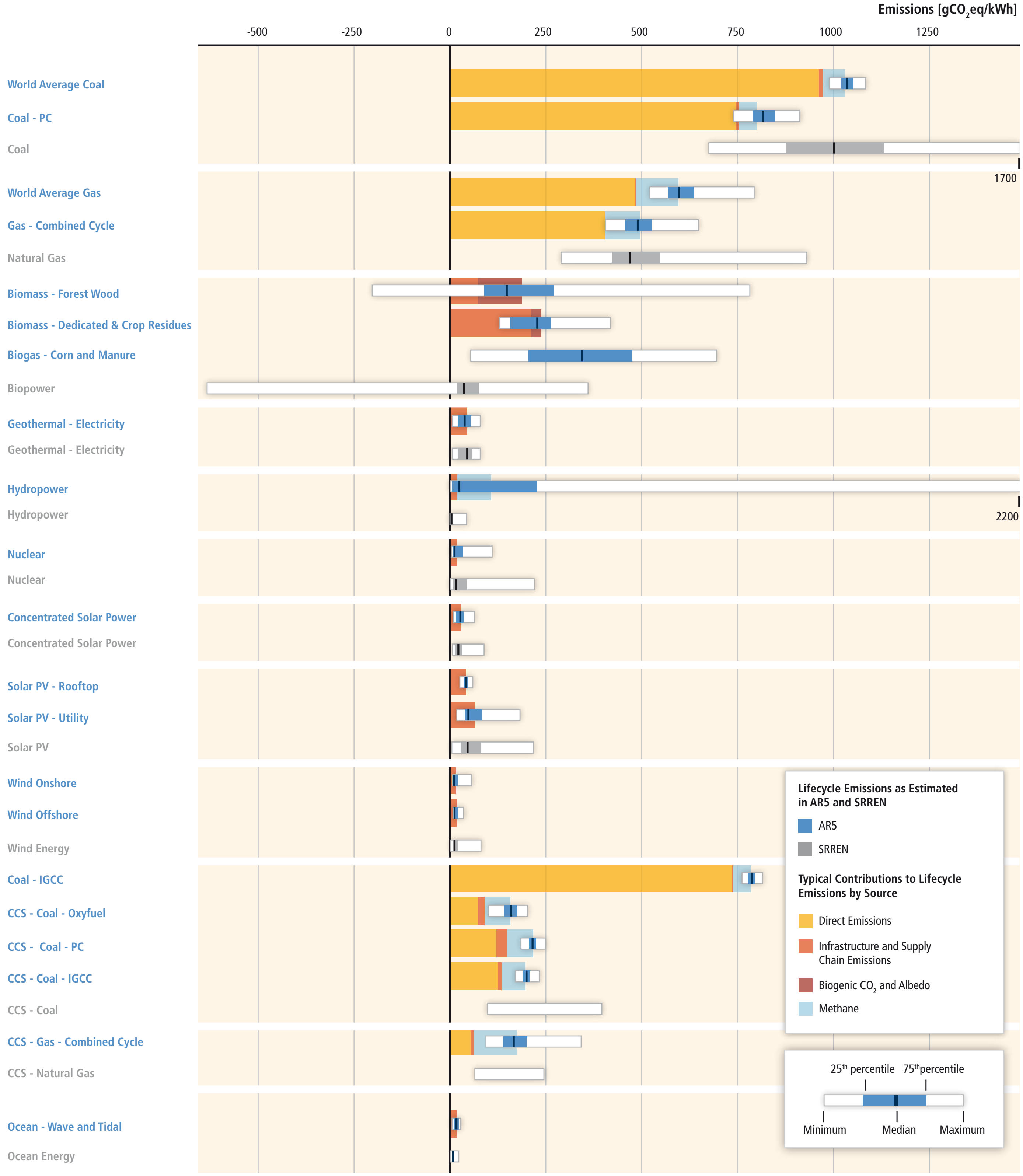


Figure 7.6 | Comparative lifecycle greenhouse gas emissions from electricity supplied by commercially available technologies (fossil fuels, renewable, and nuclear power) and projected emissions of future commercial plants of currently pre-commercial technologies (advanced fossil systems with CCS and ocean energy). The figure shows distributions of lifecycle emissions (harmonization of literature values for WGIII AR5 and the full range of published values for SRREN for comparison) and typical contributions to lifecycle emissions by source (cf. the notes below). Note that percentiles were displayed for RE and traditional coal and gas in the SRREN, but not for coal CCS and gas CCS. In the latter cases, the entire range is therefore shown. For fossil technologies, fugitive emissions of methane from the fuel chain are the largest indirect contribution and hence shown separately. For hydropower, the variation in biogenic methane emissions from project to project are the main cause of the large range. See also Annex II and Annex III.

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Abbreviations: AR5—IPCC WG III Fifth Assessment Report, CCS—CO_2 capture and storage, IGCC—integrated coal gasification combined cycle, PC—pulverized hard coal, PV—photovoltaic, SRREN—IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Sources: SRREN (IPCC, 2011a), Wind (Arvesen and Hertwich, 2012), PV (Kim et al., 2012; Hsu et al., 2012), CSP (Burkhardt et al., 2012), ocean and wave (Walker and Howell, 2011; Kelly et al., 2012), geothermal power (Sathaye et al., 2011), hydropower (Sathaye et al., 2011; Hertwich, 2013), nuclear power (Warner and Heath, 2012), bioenergy (Cherubini et al., 2012).

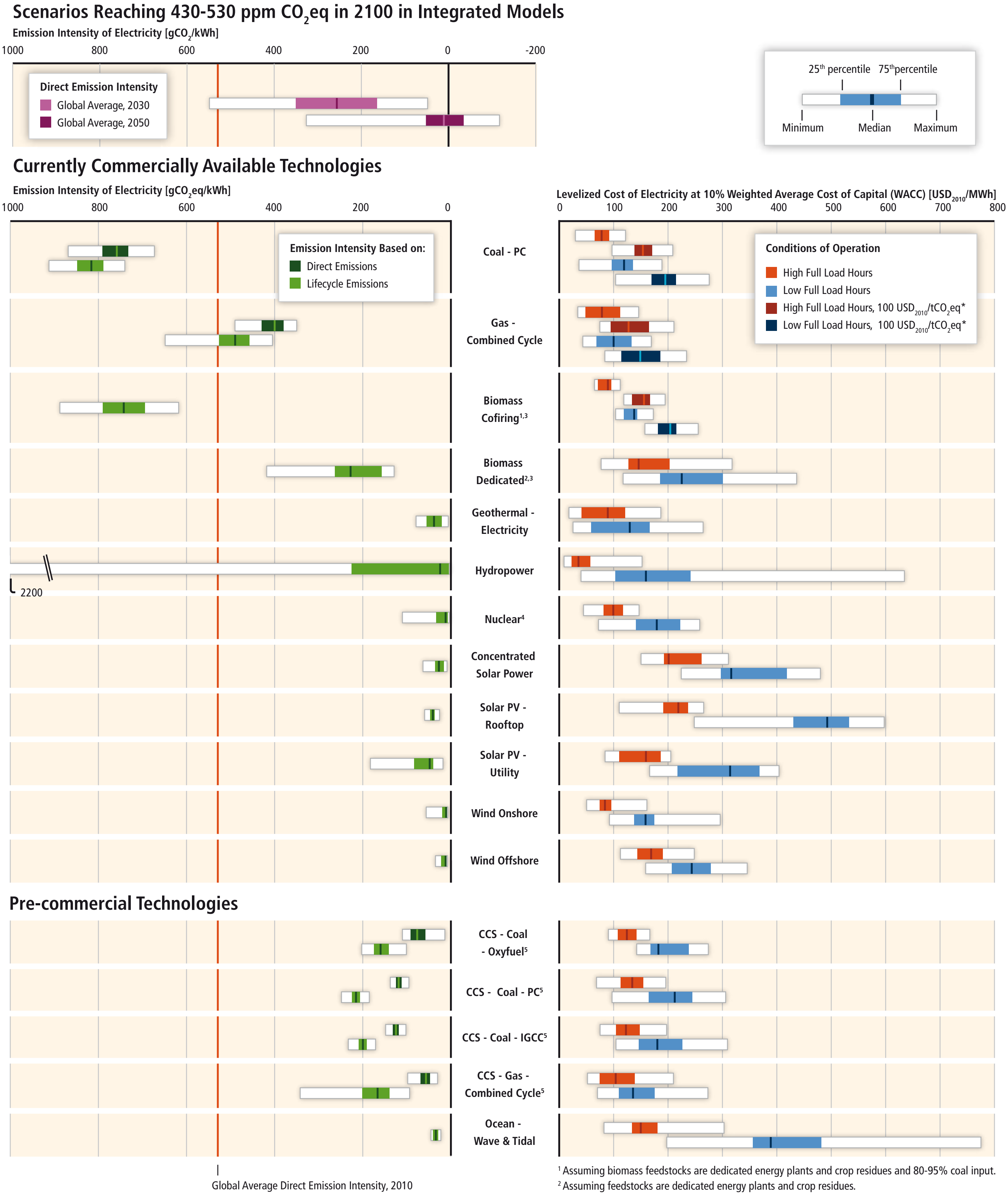
Notes: Harmonized values have been used where available and the mean values of the typical contributions are shown for the set of those cases where the data base allowed the separation. For world average coal and gas, the uncertainty range represents the uncertainty in the mean; the range of the uncerlying distribution is much larger. For the fossil fuel technologies, all fugitive methane emissions were calculated based on the range provided by (Burnham et al., 2012), infrastructure and supplies are based on (Singh et al., 2011), and direct emissions are based on (Singh et al., 2011; Corsten et al., 2013). For bioenergy, ranges include global climate impacts of CO_2 emissions from combustion of regenerative biomass (i.e., biogenic CO_2) and the associated changes in surface albedo following ecosystem disturbances, quantified according to the IPCC framework for emission metrics (see the 4th IPCC Assessment Report, (Forster et al., 2007)) and using global warming potentials (GWP) with TH = 100 years as characterization factors (Cherubini et al., 2012; Section 11.13.4). These impacts are site-specific and generally more significant for long rotation species. The category 'Biogas' includes cases where manure, dedicated crops (e.g., maize), or a mixture of both are used as feedstocks. In addition to the variability in the substrates, the large range in the results reflects different degrees of CH_4 emissions from leakage and digestate storage, with the latter that can be reduced in closed storage systems (Boulamanti et al., 2013). No contribution analysis was available for this category. For methodological issues, see Annex II.6 and Section 11.13.4, for a discussion of the data sources see Annex II.9.3. The numbers are presented in Table A.III.2.

2012), and 4–110 gCO_2eq/kWh for nuclear power (Warner and Heath, 2012). The harmonization has narrowed the ranges down from 5–217 gCO_2eq/kWh for PV, 7–89 gCO_2eq/kWh for CSP, and 1–220 gCO_2eq/kWh for nuclear energy. A new literature review for wind power published since 2002 reports 7–56 gCO_2eq/kWh, where the upper part of the range is associated with smaller turbines (< 100 kW) (Arvesen and Hertwich, 2012), compared to 2–81 gCO_2eq/kWh reported in SRREN. For all of these technologies, at least five studies are reviewed. The empirical basis for estimating the emissions associated with geothermal and ocean energy is much weaker. SRREN reported 6–79 gCO_2eq/kWh for geothermal power and 2–23 gCO_2eq/kWh for ocean energy (IPCC, 2011a). For ocean power, Figure 7.6 shows only the results of newer assessments, which range between 10–30 gCO_2eq/kWh for tidal barrages, marine current turbines, and wave power (Walker and Howell, 2011; Kelly et al., 2012). For RE, emissions are mainly associated with the manufacturing and installation of the power plants, but for nuclear power, uranium enrichment can be significant (Warner and Heath, 2012). Generally, the ranges are quite wide reflecting differences in local resource conditions, technology, and methodological choices of the assessment. The lower end of estimates often reflects incomplete systems while the higher end reflects poor local conditions or outdated technology.

Lifecycle direct global climate impacts of bioenergy in Figure 7.6 come from the peer-reviewed literature from 2010 to 2012 (reviewed in Section 11.13.4) and are based on a range of electric conversion efficiencies of 30%–50%. The category 'Biomass-dedicated and crop residues' includes perennial grasses like switchgrass and miscanthus, short-rotation species like willow and eucalyptus, and agricultural byproducts like wheat straw and corn stover. 'Biomass-forest wood' refers to sustainably harvested forest biomass from long-rotation species in various climate regions. The range in 'Biomass-forest wood' is representative of various forests and climates, e.g., aspen forest in Wisconsin (US), mixed forest in Pacific Northwest (US), pine forest in Saskatchewan (Canada), and spruce forest in Southeast Norway. Impacts from biogenic CO_2 and albedo are included in the same manner as the other GHGs, i.e., converted to gCO_2eq after characterization of emissions from combustion with case-specific GWPs (Cherubini et al., 2012). In areas affected by seasonal snow cover, the cooling contribution from the temporary change in surface albedo can be larger than the warming associated with biogenic CO_2 fluxes and the bioenergy system can have a net negative impact (i.e., cooling). Change in soil organic carbon can have a substantial influence on the overall GHG balance of bioenergy systems, especially for the case 'Biomass–dedicated and crop residues', but are not covered here due to their high dependence on local soil conditions and previous land use (Don et al., 2012; Gelfand et al., 2013).

The climate effect of hydropower is very project-specific. Lifecycle emissions from fossil fuel combustion and cement production related to the construction and operation of hydropower stations reported in the literature fall in the range of up to 40 gCO_2eq/kWh for the studies reviewed in the SRREN (Kumar et al, 2011) and 3–7 gCO_2eq/kWh for studies reviewed in (Dones et al., 2007). Emissions of biogenic CH_4 result from the degradation of organic carbon primarily in hydropower reservoirs (Tremblay et al., 2005; Barros et al., 2011; Demarty and Bastien, 2011), although some reservoirs act as sinks (Chanudet et. al 2011). Few studies appraise net emissions from freshwater reservoirs, i.e., adjusting for pre-existing natural sources and sinks and unrelated anthropogenic sources (Kumar et al, 2011, Section 5.6.3.2). A recent meta-analysis of 80 reservoirs indicates that CH_4 emission factors are log-normally distributed, with the majority of measurements being below 20 gCO_2eq/kWh (Hertwich, 2013), but emissions of approximately 2 $kgCO_2eq/kWh$ coming from a few reservoirs with a large area in relation to electricity production and thus low power intensity (W/m^2) (Abril et al., 2005; Kemenes et al., 2007, 2011). The global average emission rate was estimated to be 70 gCO_2eq/kWh (Maeck et al., 2013; Hertwich, 2013). Due to the high variability among power stations, the average emissions rate is not suitable for the estimation of emissions of individual countries or projects. Ideas for mitigating existing methane emissions have been presented (Ramos et al., 2009; Stolaroff et al., 2012).

The literature reviewed in this section shows that a range of technologies can provide electricity with less than 5% of the lifecycle GHG emissions of coal power: wind, solar, nuclear, and hydropower in suitable locations. In the future, further reductions of lifecycle emissions on these technologies could be attained through performance improvements (Caduff et al., 2012; Dale and Benson, 2013) and as a result of a cleaner energy supply in the manufacturing of the technologies (Arvesen and Hertwich, 2011).



[1] Assuming biomass feedstocks are dedicated energy plants and crop residues and 80-95% coal input.
[2] Assuming feedstocks are dedicated energy plants and crop residues.
[3] Direct emissions of biomass power plants are not shown explicitly, but included in the lifecycle emissions. Lifecycle emissions include albedo effect.
[4] LCOE of nuclear include front and back-end fuel costs as well as decommissioning costs.
[5] Transport and storage costs of CCS are set to 10 USD_{2010}/tCO_2.
* Carbon price levied on direct emissions. Effects shown where significant.

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Figure 7.7 | Specific direct and lifecycle emissions (gCO_2eq/kWh) and levelized cost of electricity (LCOE in USD_{2010}/MWh) for various power-generating technologies (cf. Figure 7.6 for lifecycle; Annex III, Section A.III.2 for data and assumptions and Annex II, Section A.II.3.1 and Section A.II.9.3 for methodological issues). The upper left graph shows global averages of specific direct CO_2 emissions (gCO_2/kWh) of power generation in 2030 and 2050 for the set of 430–530 ppm scenarios that are contained in the AR5 database (cf. Annex II, Section A.II.10). The global average of specific direct CO_2 emissions (gCO_2/kWh) of power generation in 2010 is shown as a vertical line (IEA, 2013a).

Note: The inter-comparability of LCOE is limited. For details on general methodological issues and interpretation see Annexes as mentioned above.

7.8.2 Cost assessment of mitigation measures

Though there are limits to its use as a tool for comparing the competitiveness of energy supply technologies, the concept of 'levelized costs of energy' (LCOE, also called levelized unit costs or levelized generation costs)[15] is frequently applied (IEA, 2005, 2010b, 2011a; GEA, 2012).

Figure 7.7 shows a current assessment of the private cost[16] of various low-carbon power supply technologies in comparison to their conventional counterparts.

The LCOE ranges are broad as values vary across the globe depending on the site-specific (renewable) energy resource base, on local fuel and feedstock prices as well as on country and site-specific projected costs of investment, and operation and maintenance. Investment decisions therefore should not be based on the LCOE data provided here; instead, site-, project-, and investor-specific conditions are to be considered. Integration costs, time-dependent revenue opportunities (especially in the case of intermittent renewables), and relative environmental impacts (e.g., external costs) play an important role as well (Heptonstall, 2007; Fischedick et al., 2011; Joskow, 2011; Borenstein, 2012; Edenhofer et al., 2013; Hirth, 2013).

The LCOE of many low-carbon technologies changed considerably since the release of the AR4. Even compared to the numbers published in the SRREN (IPCC, 2011a), the decline of LCOE of some RE technologies have been significant.[17] The LCOE of (crystalline silicon) photovoltaic systems, for instance, fell by 57 % since 2009. Compared to PV, a similar, albeit less-extreme trend towards lower LCOE (from the second quarter of 2009 to the first quarter of 2013) has been observed for onshore wind (–15 %), land-fill gas (–16 %), municipal solid waste (–15 %), and biomass gasification (–26 %) (BNEF and Frankfurt School-UNEP Centre, 2013).

Due to their rapid cost decline, some RE sources have become an economical solution for energy supply in an increasing number of countries (IRENA, 2013). Under favourable conditions (see Figure 7.7), large-scale hydropower (IEA, 2008b), larger geothermal projects (> 30 MWe) (IEA, 2007), and wind onshore power plants (IEA, 2010c) are already competitive. The same is true for selected off-grid PV applications (IEA, 2010d, 2011b). As emphasized by the SRREN (2011a) and IEA (IEA, 2008b, 2011b, 2012h) support policies, however, are still necessary in order to promote the deployment of many RE in most regions of the world.

Continuous cost reductions are not always a given (see BNEF and Frankfurt School-UNEP Centre, 2013), as illustrated by the recent increase in costs of offshore wind (+44 %) and technologies in an early stage of their development (marine wave and tidal, binary plant geothermal systems). This however, does not necessarily imply that technological learning has stopped. As observed for PV and wind onshore (see SRREN, IPCC, 2011a), phases characterized by an increase of the price might be followed by a subsequent decline, if, for instance, a shortage of input material is eliminated or a 'shake out' due to increasing supplier competition is happening (Junginger et al., 2005, 2010). In contrast, a production overcapacity as currently observed in the PV market might result in system prices that are temporarily below production costs (IEA, 2013a). A critical discussion of the solar photovoltaic grid-parity issue can be found in IEA (2013b).

While nuclear power plants, which are capable of delivering baseload electrical energy with low lifecycle emissions, have low operating costs (NEA, 2011b), investments in nuclear power are characterized by very large up-front investment costs, and significant technical, market, and regulatory risks (IEA, 2011a). Potential project and financial risks are illustrated by the significant time and cost over-runs of the two novel European Pressurized Reactors (EPR) in Finland and France (Kessides, 2012). Without support from governments, investments in new nuclear power plants are currently generally not economically attractive within liberalized markets, which have access to relatively cheap coal and/or gas (IEA, 2012b). Carbon pricing could improve the competitiveness of nuclear power plants (NEA, 2011b). The post Fukushima assessment of the economics and future fate of nuclear power is mixed. According to the IEA, the economic performance and future prospects of nuclear power might be significantly affected (IEA, 2011a, 2012b). Joskow and Parsons (2012) assesses that the effect will be quite modest at the global level, albeit based on a pre-Fukushima baseline evolution, which is a moderate one itself.

[15] A basic description of this concept, including its merits and shortcomings, can be found in Annex II of this report.

[16] Beyond variations in carbon prices, additional external costs are not considered in the following. Although the term 'private' will be omitted in the remainder of this section, the reader should be aware that all costs discussed here are private costs. An extended discussion of external costs is given in Fischedick et al., (2011).

[17] The subsequent percent values in LCOE data refer to changes between the second quarter (Q2) of 2009 and the first quarter (Q1) of 2013 (BNEF and Frankfurt School-UNEP Centre, 2013). Although the SRREN was published in 2011, the cost data base used there refers to 2009.

As there is still no commercial large-scale CCS power plant in operation today, the estimation of their projected costs has to be carried on the basis of design studies and few existing pilot projects. The associated problems are described in (Yeh and Rubin, 2010; Global CCS Institute, 2011; Rubin, 2012). The CCS technologies applied in the power sector will only become competitive with unabated technologies if the additional equipment attached to the power plant and their decreased efficiency as well as the additional cost for CO_2 transport and storage is compensated by sufficiently high carbon prices or direct financial support (Lohwasser and Madlener, 2011; IEA, 2013c). BECCS faces large challenges in financing and currently no such plants have been built and tested at scale (see Section 7.5.5).

The deployment of CCS requires infrastructure for long-term storage of waste products, which includes direct CO_2 transport and storage costs, along with costs associated with long-term measurement, monitoring, and verification. The related cost of transport and storage (excluding capture costs) are unlikely to exceed USD 15/tCO_2 for the majority of CCS deployment scenarios (Herzog et al., 2005; Herzog, 2011; ZEP, 2011b) and some estimates are below USD 5/tCO_2 (McCoy and Rubin, 2008; Dahowski et al., 2011). Figure 7.7 relies on an assumed cost of USD 10/tCO_2.

System integration costs (cf. Section 7.6.1, and not included in Figure 7.7) typically increase with the level of deployment and are dependent on the mitigation technology and the state of the background energy system. From the available evidence, these costs appear to be greater for variable renewable technologies than they are for dispatchable power plants (Hirth, 2013). The costs comprise (1) balancing costs (originating from the required flexibility to maintain a balance between supply and demand), (2) capacity adequacy costs (due to the need to ensure operation even at peak times of the residual load), and (3) transmission and distribution costs.

(1) Based on assessments carried out for OECD countries, the provision of additional balancing reserves increases the system costs of wind energy by approximately USD 1 to 7/MWh for wind energy market shares of up to approximately 30 % of annual electricity demand (IEA, 2010e, 2011d; Wiser et al., 2011; Holttinen et al., 2011). Balancing costs for PV are in a similar range (Hoke and Komor, 2012).

(2) As described in Section 7.6.1, the contribution of variable renewables like wind, solar, and tidal energy to meeting peak demand is less than the resources' nameplate capacity. Still, determining the cost of additional conventional capacity needed to ensure that peak demands are met is contentious (Sims et al., 2011). Estimates of this cost for wind power range from USD 0 to 10/MWh (IEA, 2010e, 2011d; Wiser et al., 2011). Because of the coincidence of solar generation with air-conditioning loads, solar at low-penetration levels can in some regions displace a larger amount of capacity, per unit of energy generated, than other supply options, yielding estimates of infrastructure savings as high as USD 23/MWh greater than the savings from baseload supply options (Mills et al., 2011).

(3) Estimates of the additional cost of transmission infrastructure for wind energy in OECD countries are often in the range of USD 0 to 15/MWh, depending on the amount of wind energy supply, region, and study assumptions (IEA, 2010e, 2011d; Wiser et al., 2011; Holttinen et al., 2011). Infrastructure costs are generally higher for time-variable and location-dependent RE, at least when developed as large centralized plants, than for other sources of energy supply (e.g., Sims et al., 2007; Hoogwijk et al., 2007; Delucchi and Jacobson, 2011). If mitigation technologies can be deployed near demand centres within the distribution network, or used to serve isolated autonomous systems (e.g., in less developed countries), such deployments may defer or avoid the need for additional transmission and distribution, potentially reducing infrastructure costs relative to a BAU scenario.[18]

7.8.3 Economic potentials of mitigation measures

Quantifying the economic potential of major GHG-mitigation options is problematic due to the definition of welfare metrics, broader impacts throughout the energy-economic system, and the background energy system carbon intensity, and energy prices (see Sections 3.4.3 and 3.7.1 for a general discussion). Three major approaches to reveal the economic potentials of mitigation measures are discussed in the literature:

One approach is to use energy supply cost curves, which summarize energy resource estimates (GEA, 2012) into a production cost curve on an annual or cumulative basis. Uncertainties associated with energy cost curves include the relationship between confirmed reserves and speculative resources, the impact of unconventional sources of fuels, future technological change and energy market structures, discounting, physical conditions (e.g., wind speeds), scenarios (e.g., land-use tradeoffs in energy vs. food production) and the uneven data availability on global energy resources. Illustrative renewable resource cost curves are discussed in Section 10.4 and Figure 10.29 of Fischedick et al., (2011).

A second and broader approach are marginal abatement cost (MAC) curves. The MAC curves (discussed in Section 3.9.3) discretely rank mitigation measures according to their GHG emission abatement cost (in USD/tCO_2) for a given amount of emission reduction (in million tCO_2). The MAC curves have become a standard policy communication tool in assessing cost-effective emissions reductions (Kesicki and Ekins, 2011). There is wide heterogeneity (discussed in detail in Section 3.9.3) in the method of construction, the use of experts vs. models, and the year/region to which the MAC is applied. Recent global

[18] The ability for distributed resources to defer distribution investments depends on the correlation of the generation profile and load, as well as on location-specific factors (Mendez et al., 2006; Thomson and Infield, 2007; Hernández et al., 2008; Wang et al., 2010; Agah and Abyaneh, 2011). At higher penetrations of distributed generation, additional distribution infrastructure may be required (e.g., Cossent et al., 2011).

MAC curve studies (van Vuuren et al., 2004; IEA, 2008c; Clapp et al., 2009; Nauclér and Enkvist, 2009) give overall mitigation potentials ranging from 20–100 % of the baseline for costs up to USD 100/tCO_2. These MACs can be a useful summary mechanism but improved treatment of interactions between mitigation measures and the path-dependency of potential cost reductions due to technological learning (e.g., Luderer et al., 2012), as well as more sophisticated modelling of interactions throughout the energy systems and wider economy are required.

A third approach—utilized in the AR5—overcomes these shortcomings through integrated modelling exercises in order to calculate the economic potential of specific supply-side mitigation options. These models are able to determine the economic potential of single options within the context of (other) competing supply-side and demand-side mitigation options by taking their interaction and potential endogenous learning effects into account. The results obtained in this way are discussed in Chapter 6; the different deployment paths of various supply-side mitigation options as part of least-cost climate protection strategies are shown in Section 7.11.

7.9 Co-benefits, risks and spillovers

Besides economic cost aspects, the final deployment of mitigation measures will depend on a variety of additional factors, including synergies and tradeoffs across mitigation and other policy objectives. The implementation of mitigation policies and measures can have positive or negative effects on these other objectives–and vice versa. To the extent these side-effects are positive, they can be deemed 'co-benefits'; if adverse and uncertain, they imply risks.[19]

Co-benefits, adverse side effects, technical risks and uncertainties associated with alternative mitigation measures and their reliability (Sections 7.9.1–7.9.3) as well as public perception thereof (Section 7.9.4) can affect investment decisions, individual behaviour as well as priority setting of policymakers. Table 7.3 provides an overview of the potential co-benefits and adverse side effects of the main mitigation measures that are assessed in this chapter. In accordance with the three sustainable development pillars described in Chapter 4, the table presents effects on objectives that may be economic, social, environmental, and health-related.

7.9.1 Socio-economic effects

There is an increasing body of work showing that the implementation of energy mitigation options can lead to a range of socio-economic co-benefits for, e.g., employment, energy security, and better access to energy services in rural areas (Shrestha and Pradhan, 2010; IPCC, 2011a; UNEP, 2011).

Employment. Analysis by Cai et al. (2011) shows that as a result of the increased share of renewable energy in China, the power sector registered 472,000 net job gains in 2010. For the same amount of power generated, solar PV requires as many as 18 and 7 times more jobs than nuclear and wind, respectively. Using conservative assumptions on local content of manufacturing activities, van der Zwaan et al. (2013) show that renewable sources of power generation could account for about 155,000 direct and 115,000 indirect jobs in the Middle East by 2050. Examples of Germany and Spain are also noteworthy where 500 to 600 thousand people could be employed in the renewable energy supply sector in each country by 2030 (Lehr et al., 2012; Ruiz-Romero et al., 2012) while the net effect is less clear. Wei et al. (2010) also found that over 4 million full-time jobs could be created by 2030 from the combined effect of implementing aggressive energy-efficiency measures coupled with meeting a 30 % renewable energy target. An additional 500,000 jobs could be generated by increasing the share of nuclear power to 25 % and CCS to 10 % of overall total generation capacity. In line with these trends, Kenley et al. (2009) show that adding 50,000 megawatts by 2020 of new nuclear generating capacity in the United States would lead to 117,000 new jobs, 250,000 indirect jobs, and an additional 242,000 non-nuclear induced jobs. Relating to CCS, although development in this sector could deliver additional employment (Yuan and Lyon, 2012; Bezdek and Wendling, 2013), safeguarding jobs in the fossil-based industry is expected to be the main employment co-benefit (Frankhauser et al., 2008). Whilst recognizing the growing contribution of mitigation options for employment, some sobering studies have highlighted that this potentially carries a high cost. In the PV sector in Germany, for example, the cost per job created can be as high as USD_{2010} 236,000 (€175,000 in 2008) (Frondel et al., 2010), underlining that continued employment and welfare gains will remain dependent on the level and availability of support and financing mechanisms (Alvarez et al., 2010; Furchtgott-Roth, 2012; Böhringer et al., 2013). Furthermore, given the higher cost of electricity generation from RE and CCS-based fossil fuels, at least in the short-term, jobs in energy-intensive economic sectors are expected to be affected (Delina and Diesendorf, 2013). The structure of the economy and wage levels will nonetheless influence the extent of industry restructuring and its impact of labour redeployment.

Energy security. As discussed in Section 6.6.2.2, energy security can generally be understood as "low vulnerability of vital energy systems"

[19] Co-benefits and adverse side-effects describe effects in non-monetary units without yet evaluating the net effect on overall social welfare. Please refer to the respective Sections in the framing chapters as well as to the glossary in Annex I for concepts and definitions–particularly Sections 2.4, 3.6.3, and 4.8. The extent to which co-benefits and adverse side-effects will materialize in practice as well as their net effect on social welfare will differ greatly across regions, and depend on local circumstances, implementation practices, as well as the scale and pace of the deployment of the different measures.

Table 7.3 | Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the energy supply sector. Arrows pointing up/down denote positive/negative effect on the respective objective/concern; a question mark (**?**) denotes an uncertain net effect. Please refer to Sections 11.7 and 11.13.6 for possible upstream effects of biomass supply on additional objectives. Co-benefits and adverse side-effects depend on local circumstances as well as on the implementation practice, pace, and scale (see Section 6.6). For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see Sections 3.9, 6.3.6, 13.2.2.3, and 14.4.2. Numbers correspond to references listed below the table.

Mitigation measures	Effect on additional objectives/concerns			
	Economic	**Social (including health)**	**Environmental**	**Other**
Nuclear replacing coal power	↑ Energy security (reduced exposure to fuel price volatility)[1] ↑ Local employment impact (but uncertain net effect)[2] ↑ Legacy cost of waste and abandoned reactors[3]	Health impact via ↓ Air pollution[4] and coal-mining accidents[5] ↑ Nuclear accidents[6] and waste treatment, uranium mining and milling[7] ↑ Safety and waste concerns[8]	Ecosystem impact via ↓ Air pollution[9] and coal mining[10] ↑ Nuclear accidents[11]	Proliferation risk[12]
RE (wind, PV, CSP, hydro, geothermal, bioenergy) replacing coal	↑ Energy security (resource sufficiency, diversity in the near/medium term)[13] ↑ Local employment impact (but uncertain net effect)[14] ↑ Irrigation, flood control, navigation, water availability (for multipurpose use of reservoirs and regulated rivers)[15] ↑ Extra measures to match demand (for PV, wind, and some CSP)[16]	Health impact via ↓ Air pollution (except bioenergy)[17] ↓ Coal-mining accidents[18] ↑ Contribution to (off-grid) energy access[19] ? Project-specific public acceptance concerns (e.g., visibility of wind)[20] ↑ Threat of displacement (for large hydro)[21]	Ecosystem impact via ↓ Air pollution (except bioenergy)[22] ↓ Coal mining[23] ↑ Habitat impacts (for some hydro)[24] ↑ Landscape and wildlife impact (for wind)[25] ↓ Water use (for wind and PV)[26] ↑ Water use (for bioenergy, CSP, geothermal, and reservoir hydro)[27]	Higher use of critical metals for PV and direct drive wind turbines[28]
Fossil CCS replacing coal	↑↑ Preservation vs. lock-in of human and physical capital in the fossil industry[29]	Health impact via ↑ Risk of CO_2 leakage[30] ↑ Upstream supply-chain activities[31] ↑ Safety concerns (CO_2 storage and transport)[32]	↑ Ecosystem impact via upstream supply-chain activities[33] ↑ Water use[34]	Long-term monitoring of CO_2 storage[35]
BECCS replacing coal	*See fossil CCS where applicable. For possible upstream effect of biomass supply, see Sections 11.7 and 11.13.6*			
Methane leakage prevention, capture, or treatment	↑ Energy security (potential to use gas in some cases)[36]	↑ Occupational safety at coal mines[37] ↓ Health impact via reduced air pollution[38]	↓ Ecosystem impact via reduced air pollution[39]	

References: [1]Adamantiades and Kessides (2009); Rogner (2010, 2012a; b). For the low share of fuel expenditures in LCOE, see IAEA (2008b) and Annex III. For the energy security effects of a general increase in nuclear power, see NEA (2010) and Jewell (2011a). [2]Cai et al. (2011); Wei et al. (2010); Kenley et al. (2009); McMillen et al. (2011). [3]Marra and Palmer (2011); Greenberg, (2013a); Schwenk-Ferrero (2013a); Skipperud et al. (2013); Tyler et al. (2013a). [4]Smith and Haigler (2008); Smith et al. (2012b); Smith et al. (2013); Gohlke et al. (2011); Rückerl et al. (2011), and WGII Section 11.9 on health impacts from air pollution attributable to coal; Solli et al. (2006); Dones et al. (2007); Dones et al. (2005); Simons and Bauer (2012) on air pollution attributable to nuclear; see Section 7.9.2 for comparison.[5]See Section 7.9.3 and references cited therein: Epstein et al. (2010); Burgherr et al. (2012); Chen et al. (2012); Chan and Griffiths (2010); Asfaw et al. (2013). [6]See Section 7.9.3, in particular Cardis et al. (2006); Balonov et al. (2011); Moomaw et al. (2011a); WHO (2013). [7]Abdelouas (2006); Al-Zoughool and Kewski (2009) cited in Sathaye et al. (2011a); Smith et al. (2013); Schnelzer et al. (2010); Tirmarche (2012); Brugge and Buchner (2011). [8]Visschers and Siegrist (2012); Greenberg (2013a); Kim et al. (2013); Visschers and Siegrist (2012); see Section 7.9.4 and references cited therein: Bickerstaff et al. (2008); Sjoberg and Drottz-Sjoberg (2009); Corner et al. (2011); Ahearne (2011). [9]Simons and Bauer (2012) for comparison of nuclear and coal. See Section 7.9.2 and references cited therein for ecological impacts of coal: Galloway et al. (2008); Doney (2010); Hertwich et al. (2010); Rockstrom et al. (2009); van Grinsven et al. (2013) for eutrophication and acidification; Emberson et al. (2012); van Geothem et al. (2013) for photooxidants; IEA (2011a); Pacyna et al. (2007) for increased metal emissions; and Nagajyoti et al. (2010); Sevcikova et al. (2011); Mahboob (2013) for the ecosystem effects of those emissions. [10]Adibee et al. (2013); Cormier et al. (2013); Smith et al. (2013), and reference cited therein: Palmer et al. (2010). [11]Møller et al. (2012); Hiyama et al. (2013); Mousseau and Møller (2013); Møller and Mousseau (2011); Møller et al. (2011). [12]von Hippel et al. (2011, 2012); Sagan (2011); Yim and Li (2013); Adamantiades and Kessides (2009); Rogner (2010). [13]Sathaye et al. (2011); McCollum et al. (2013b); Jewell et al. (2014); Cherp et al. (2013). [14]van der Zwaan et al. (2013); Cai et al. (2011); Lehr et al. (2012); Ruiz-Romero et al. (2012); Böhringer et al. (2013); Sathaye et al. (2011), and references cited therein, e.g., Frondel et al. (2010) and Barbier (2009). [15]Kumar et al. (2011); Schaeffer et al. (2012); Smith et al. (2013); WCD (2000) and Moore et al. (2010), cited in Sathaye et al. (2011a). [16]IEA (2011d); Williams et al. (2012); Sims et al. (2011); Holttinen et al. (2011); Rasmussen et al. (2012). [17]Sathaye et al. (2011); Smith, GEA (2012); Smith et al. (2013); Figure 7.8, Annex II and references cited therein. [18]Section 7.9.3, especially Moomaw et al. (2011a); Chen et al. (2012); Burgherr et al. (2012). [19]Pachauri et al. (2012); Sathaye et al. (2011); Kanagawa and Nakata (2008); Bazilian et al. (2012); Sokona et al. (2012); Byrne et al. (2007); D'Agostino et al. (2011); Pachauri et al. (2012); Díaz et al. (2013); van der Vleuten et al. (2013); Nguyen, (2007); Narula et al. (2012); Sudhakara-Reddy et al. (2009). [20]Lovich and Ennen (2013); Sathaye et al. (2011); Wiser et al. (2011). [21]Bao (2010); Scudder (2005); Kumar et al. (2011); Sathaye et al. (2011a) and references cited therein: Richter et al. (2010); Smith et al. (2013) and references cited therein: Hwang et al. (2011); McDonald-Wilmsen and Webber (2010); Finley-Brook and Thomas (2010). [22]See Section 7.9.2 and references cited therein for ecological impacts of coal: Galloway et al., (2008); Doney, (2010); Hertwich et al., (2010); Rockstrom et al. (2009); van Grinsven (2013) for eutrophication

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and acidification; Emberson et al. (2012) and van Geothem et al. (2013) for photooxidants. See Arversen and Hertwich (2011, 2012) for wind, Fthenakis et al. (2008) and Laleman et al. (2011) for PV, Becerralopez and Golding (2007) and Moomaw et al. (2011a) for CSP, and Moomaw et al. (2011b) for a general comparison. [23]See footnote 10 on ecosystem impact from coal mining. [24]Kumar et al. (2011); Alho (2011); Kunz et al. (2011); Smith et al. (2013); Ziv et al. (2012). [25]Wiser et al. (2011); Lovich and Ennen (2013); Garvin et al. (2011); Grodsky et al. (2011); Dahl et al. (2012); de Lucas et al. (2012); Dahl et al. (Dahl et al., 2012); Jain et al. (2011). [26]Pachauri et al. (2012); Fthenakis and Kim (2010); Sathaye et al. (2011); Moomaw et al. (2011a); Meldrum et al. (2013). [27]Pachauri et al. (2012); Fthenakis and Kim (2010); Sathaye et al. (2011); Moomaw et al. (2011a); Meldrum et al. (2013); Berndes (2008); Pfister et al. (2011); Fingerman et al. (2011); Mekonnen and Hoekstra (2012); Bayer et al. (2013a). [28]Section 7.9.2, Kleijn and van der Voet (2010); Graedel (2011); Zuser and Rechberger (2011); Fthenakis and Anctil (2013); Ravikumar and Malghan (2013); Pihl et al. (2012); Hoenderdaal et al. (2013). [29]Vergragt et al. (2011); Markusson et al. (2012); IPCC (2005); Benson et al. (2005); Fankhauser et al. (2008); Shackley and Thompson (2012). [30]Atchley et al. (2013)–simarly applicable to animal health; Apps et al. (2010); Siirila et al. (2012); Wang and Jaffe (2004). [31]Koorneef et al. (2011); Singh et al. (2011); Hertwich et al. (2008); Veltman et al. (2010); Corsten et al.(2013). [32]Ashworth et al. (2012); Einsiedel et al. (2013); IPCC (2005); Miller et al. (2007); de Best-Waldhober et al. (2009); Shackley et al. (2009); Wong-Parodi and Ray (2009); Waööquist et al. (2009, 2010); Reiner and Nuttall (2011). [33]Koorneef et al. (2011); Singh et al. (2011); Hertwich et al. (2008); Veltman et al. (2010); Corsten et al.(2013). [34]Zhai et al. (2011); Koorneef et al. (2011); Sathaye et al. (2011); Moomaw et al. (2011a). [35]Haszeldine et al. (2009); Sauer et al. (2013); Kudryavtsev et al. (2012); Held and Edenhofer (2009). [36]Wilkinson (2011); Song and Liu (2012). [37]Karacan et al. (2011); Deng et al. (2013); Wang et al. (2012); Zhang et al. (2013); Cheng et al. (2011). [38]IEA, (2009c); Jerrett et al. (2009); Shindell et al. (2012); Smith et al. (2013), and references cited therein: Kim et al. (2013); Ito et al. (2005); Ji et al. (2011). [39]Van Dingenen et al. (2009); Shindell et al. (2012); van Goethem et al. (2013).

(Cherp et al., 2012). Energy security concerns can be grouped as (1) the sufficiency of resources to meet national energy demand at competitive and stable prices, and (2) the resilience of the energy supply.[20] Since vital energy systems and their vulnerabilities differ from one country to another, the concept of energy security also differs between countries (Chester, 2009; Cherp and Jewell, 2011; Winzer, 2012). Countries with a high share of energy imports in total imports (or export earnings) are relatively more vulnerable to price fluctuations and historically have focused on curtailing energy imports (GNESD, 2010; Jain, 2010; Sathaye et al., 2011), but more recently, also building the resilience of energy supply (IEA, 2011a; Jewell, 2011b). For energy importers, climate policies can increase the sufficiency of national energy demand by decreasing imports and energy intensity while at the same time increasing the domestic resource buffer and the diversity of energy supply (Turton and Barreto, 2006; Costantini et al., 2007; Kruyt et al., 2009; McCollum et al., 2013a; Jewell et al., 2014). Energy-exporting countries are similarly interested in stable and competitive global prices, but they have the opposite interest of maintaining or increasing energy export revenues (Sathaye et al., 2011; Cherp and Jewell, 2011). There is uncertainty over how climate policies would impact energy export revenues and volumes as discussed in Section 6.3.6.6. One of the biggest energy security issues facing developing countries is the necessity to dramatically expand energy systems to support economic growth and development (Kuik et al., 2011; Cherp et al., 2012), which makes energy security in low- and middle-income countries closely related to the energy-access challenge, discussed in the next paragraphs and in Section 6.6.2.3.

Rural development. In various developing countries such as India, Nepal, Brazil, and parts of Africa, especially in remote and rural areas, some renewables are already cost-competitive options for increasing energy access (Nguyen, 2007; Goldemberg et al., 2008; Cherian, 2009; Sudhakara Reddy et al., 2009; Walter et al., 2011; Narula et al., 2012). Educational benefits as a function of rural electrification (Kanagawa and Nakata, 2008), and enhanced support for the productive sector and income generation opportunities (Bazilian et al., 2012; Sokona, Y. et al., 2012; Pachauri et al., 2013) are some of the important co-benefits of some mitigation options. However, the co-benefits may not be evenly distributed within countries and local jurisdictions. While there is a regressive impact of higher energy prices in developed countries (Grainger and Kolstad, 2010), the empirical evidence is more mixed for developing countries (Jakob and Steckel, 2013). The impact depends on the type of fuel used by different income groups, the redistribution of the revenues through, e.g., a carbon tax, and in what way pro-poor measures are able to mitigate adverse effects (Casillas and Kammen, 2010) (see Section 15.5.2.3 for a discussion of the distributional incidence of fuel taxes). Hence, regulators need to pay attention that the distributive impacts of higher prices for low-carbon electricity (fuel) do not become a burden on low-income rural households (Rao, 2013). The success of energy access programmes will be measured against affordability and reliability criteria for the poor.

Other positive spillover effects from implementation of renewable energy options include technology trade and knowledge transfer (see Chapter 13), reduction in the exposure of a regional economy to the volatility of the price of fossil fuels (Magnani and Vaona, 2013; see Chapter 14), and enhanced livelihoods conditions at the household level (Cooke et al., 2008; Oparoacha and Dutta, 2011).

7.9.2 Environmental and health effects

Energy supply options differ with regard to their overall environmental and health impacts, not only their GHG emissions (Table 7.3). Renewable energies are often seen as environmentally benign by nature; however, no technology—particularly in large scale application—comes without environmental impacts. To evaluate the relative burden of energy systems within the environment, full energy supply chains need to be considered on a lifecycle basis, including all system components, and across all impact categories.

To avoid creating new environmental and health problems, assessments of mitigation technologies need to address a wide range of issues, such as land and water use, as well as air, water, and soil pollution, which are often location-specific. Whilst information is scarce

[20] These dimensions are roughly in line with the treatment of energy security in the SRREN albeit with terminology based on recent literature–along the lines of the *sovereignty* and *robustness* perspectives on the one hand and *resilience* on the other described by Cherp and Jewell (2011). It is also very similar to the IEA's distinction between energy system *risks* and *resilience capacities* (IEA, 2011a; Jewell, 2011b).

Box 7.1 | Energy systems of LDCs: Opportunities & challenges for low-carbon development

One of the critical indicators of progress towards achieving development goals in the Least Developed Countries (LDCs) is the level of access to modern energy services. It is estimated that 79 % of the LDC population lacked access to electricity in 2009, compared to a 28 % average in the developing countries (WHO and UNDP, 2009). About 71 % of people in LDCs relied exclusively on biomass burning for cooking in 2009. The dominance of subsistence agriculture in LDCs as the mainstay of livelihoods, combined with a high degree of population dispersal, and widespread income poverty have shaped the nature of energy systems in this category of countries (Banuri, 2009; Sokona, Y. et al., 2012). The LDCs from sub-Saharan Africa and parts of Asia, with limited access to fossil-based electricity (and heat), would need to explore a variety of appropriate sustainable technologies to fuel their development goals (Guruswamy, 2011). In addition to deploying fossil-based and renewable technologies, improved biomass cooking from biogas and sustainably produced wood for charcoal will remain essential in LDCs (Guruswamy, 2011).

Bioenergy production from unsustainable biomass harvesting, for direct combustion and charcoal production is commonly practiced in most LDCs. The net GHG emissions from these practices is significant (FAO, 2011), and rapid urbanization trends is likely to intensify harvesting for wood, contributing further to rises in GHG emissions, along with other localized environmental impacts. However, important initiatives from multilateral organizations and from the private sector with innovative business models are improving agricultural productivity for food and creating bioenergy development opportunities. One example produces liquid biofuels for stove cooking while creating, near cities, agroforestry zones with rows of fast-growing leguminous trees/shrubs and alleys planted with annual crop rotations, surrounded by a forestry shelterbelt zone that contains indigenous trees and oilseed trees and provides business opportunities across the value chain including for women (WWF-UK, 2011). The mixture of crops and trees produces food with higher nutritive values, enables clean biofuels production for stove cooking, develops businesses, and simultaneously avoids GHG emissions from deforestation to produce charcoal for cooking (Zvinavashe et al., 2011). A dearth of documented information and a lack of integration of outcomes of the many successful specific projects that show improved management practices of so-called traditional forest biomass resource into sustainably managed forest propagate the impression that all traditional biomass is unsustainable. As more data emerge, the record will be clarified. Holistic biomass programmes that address the full value chain, from sustainable production of wood-based fuels to their processing, conversion, distribution, and marketing, and use with the potential to reduce future GHG emissions are currently being promoted (see Box 11.6). Other co-benefits associated with these programmes include reduced burden of fuel collection, employment, and improved health conditions of the end users (Reddy et al., 2000; Lambrou and Piana, 2006; Hutton et al., 2007; Anenberg et al., 2013; Owen et al., 2013). The LDC contribution to climate stabilization requires minimizing future GHG emissions while meeting unmet (or suppressed) energy demand, which is likely to rise. For example, though emissions levels remain low, the rate of growth in emissions in Africa is currently above the world average, and the continent's share of global emissions is likely to increase in the coming decades (Canadell et al., 2009). Whilst growth in GHG emissions is expected as countries build their industrial base and consumption moves beyond meeting basic needs, minimizing this trend will involve exploring new opportunities for scaling up modern energy access where possible by embracing cleaner and more-efficient energy options that are consistent with regional and global sustainability goals. One such opportunity is the avoidance of associated natural gas flaring in oil- and gas-producing developing countries where venting and flaring amounts to 69 % of world total of 150 billion cubic metres—representing 1.2 % of global CO_2 emissions (Farina, 2011; GGFR and World Bank, 2011). For a country such as Nigeria, which flares about 15 billion m^3 of gas—sufficient to meet its energy needs along with the current needs of many neighbouring countries (Dung et al., 2008), this represents an opportunity towards a low-carbon pathway (Hassan and Kouhy, 2013). Collier and Venables (2012) argue that while abundant natural endowments in renewable and fossil resources in Africa and other LDCs should create opportunities for green energy development, energy sourcing, conversion, distribution, and usage are economic activities that require the fulfilment of factors such as capital, governance capacity, and skills (see Box 1.1).

and often difficult to generalize, tradeoffs among the different types of impacts, affecting different species, and at different times, become important in carrying out the assessments (Sathaye et al., 2011). Also, the analysis has to go beyond marginal changes (see Section 3.6.3) in the existing system to address alternative futures. Environmental and health implications of different low-carbon technologies as they are understood today are briefly discussed below.

Combustion-related emissions cause substantial human health and ecological impacts. Exposure to outdoor particulate matter emitted directly or formed from products of incomplete combustion, i. e., sulphur, nitrogen oxides, and ammonia, lead to cardiovascular disease, chronic and acute respiratory illness, lung cancer, and other health damages, causing in the order of 3.2 million premature deaths per year (Pope et al., 2009; Lim et al., 2012; Smith et al., 2012a). Despite air pollution policies,

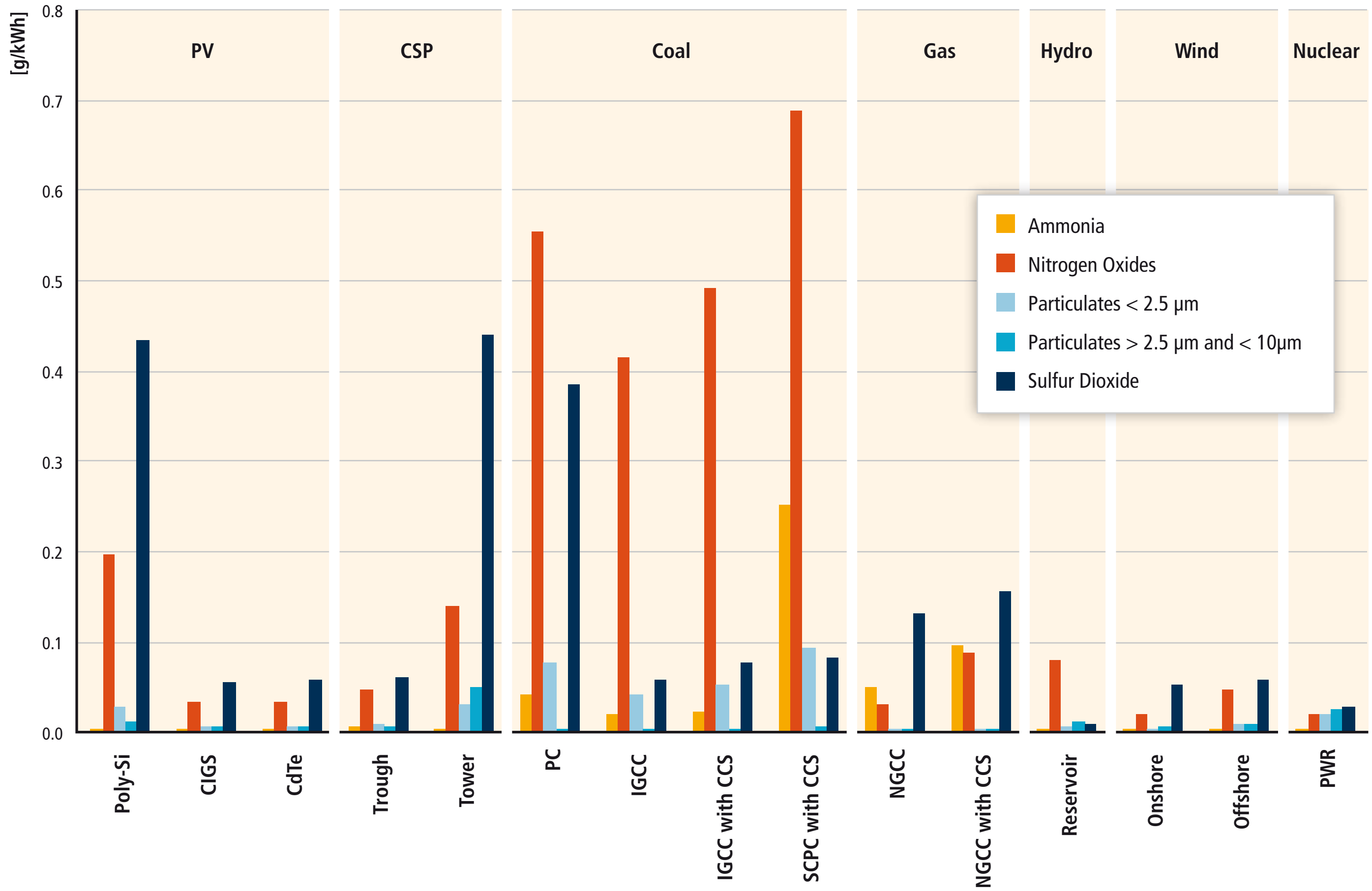


Figure 7.8 | Life-cycle inventory results of the production of 1 kWh of electricity for important air pollutants contributing to particulate matter (PM) exposure, the leading cause of health impact from air pollution. The technology modelling considers state-of-the-art pollution control equipment for fossil power plants. Data sources: Arvesen and Hertwich (2011); Burkhardt et al. (2011); Whitaker (2013), Dones et al. (2005); Singh et al. (2011). Abbreviations: PC = pulverized coal, PV = photovoltaic, CSP = concentrating solar power, Poly-Si = polycrystalline silicon, CIGS = copper indium gallium selenide thin film, CdTe = cadmium telluride thin film, IGCC = integrated gasification combined cycle, CCS = CO_2 capture and storage, SCPC = supercritical pulverized coal, NGCC = natural gas combined cycle, PWR = pressurized water reactor.

the exposure to ambient air pollution of 80 % of the world's population is estimated to exceed the World Health Organization (WHO) recommendation of 10 µg/m^3 for PM2.5 (Brauer et al., 2012; Rao et al., 2013).[21] Sulphur and nitrogen oxides are involved in the acidification of fresh water and soils; and nitrogen oxides in the eutrophication of water bodies (Galloway et al., 2008; Doney, 2010), both threatening biodiversity (Rockstrom et al., 2009; Hertwich et al., 2010; van Grinsven et al., 2013). Volatile organic compounds and nitrogen oxides cause the formation of photochemical oxidants (summer smog), which impact human health (Lim et al., 2012) and ecosystems (Emberson et al., 2012; van Goethem et al., 2013).[22] Coal is an important source of mercury (IEA, 2011a) and other toxic metals (Pacyna et al., 2007), harming ecosystems (Nagajyoti et al., 2010; Sevcikova et al., 2011; Mahboob, 2013), and potentially also human health (van der Voet et al., 2012; Tchounwou et al., 2012). Many of these pollutants can be significantly reduced through various types of pollution control equipment, but even with this equipment in place, some amount of pollution remains. In addition, surface mining of coal and tar sand causes substantial land use and mining waste (Yeh et al., 2010; Elliott Campbell et al., 2012; Jordaan, 2012).

Reducing fossil fuel combustion, especially coal combustion, can reduce many forms of pollution and may thus yield co-benefits for health and ecosystems. Figure 7.8 indicates that most renewable power projects offer a reduction of emissions contributing to particulate matter exposure even compared to modern fossil fuel-fired power plants with state-of-the-art pollution control equipment.

Ecological and health impacts of renewable energy have been comprehensively assessed in the SRREN, which also provides a review of life-cycle assessments of nuclear and fossil-based power generation (Sathaye et al., 2011). Renewable energy sources depend on large areas to harvest energy, so these technologies have a range of eco-

[21] See WGII 11.9 (Smith et al., 2014) and Chapter 4 of the Global Energy Assessment "Energy and Health" (Smith et al., 2012) for a recent overview of human health effects associated with air pollution.

[22] See Chapter 3 of the Global Energy Assessment "Energy and Environment" (Emberson et al., 2012) for a recent overview of environmental effects associated with air pollution.

logical impacts related to habitat change, which—depending on site characteristics and the implementation of the technology—may be higher than that of fossil fuel-based systems (Sathaye et al., 2011). For wind power plants, collisions with raptors and bats, as well as site disturbance during construction cause ecological concerns (Garvin et al., 2011; Grodsky et al., 2011; Dahl et al., 2012). Adjustments in the location, design and operation of facilities can mitigate some of these damages (Arnett et al., 2011; de Lucas et al., 2012). For hydropower plants, dams present an obstacle to migratory species (Alho, 2011; Ziv et al., 2012). The large-scale modification of river flow regimes affects the amount and timing of water release, reduces seasonal flooding, and sediment and nutrient transport to flood plains (Kunz et al., 2011). These modifications result in a change of habitat of species adapted to seasonal flooding or living on flood plains (Young et al., 2011). Geothermal (Bayer et al., 2013b) and concentrating solar power (CSP) (Damerau et al., 2011) can cause potential concerns about water use/pollution, depending on design and technological choices.

Wind, ocean, and CSP need more iron and cement than fossil fuel fired power plants, while photovoltaic power relies on a range of scarce materials (Burkhardt et al., 2011; Graedel, 2011; Kleijn et al., 2011; Arvesen and Hertwich, 2011). Furthermore, mining and material processing is associated with environmental impacts (Norgate et al., 2007), which make a substantial contribution to the total life-cycle impacts of renewable power systems. There has been a significant concern about the availability of critical metals and the environmental impacts associated with their production. Silver, tellurium, indium, and gallium have been identified as metals potentially constraining the choice of PV technology, but not presenting a fundamental obstacle to PV deployment (Graedel, 2011; Zuser and Rechberger, 2011; Fthenakis and Anctil, 2013; Ravikumar and Malghan, 2013). Silver is also a concern for CSP (Pihl et al., 2012). The limited availability of rare earth elements used to construct powerful permanent magnets, especially dysprosium and neodymium, may limit the application of efficient direct-drive wind turbines (Hoenderdaal et al., 2013). Recycling is necessary to ensure the long-term supply of critical metals and may also reduce environmental impacts compared to virgin materials (Anctil and Fthenakis, 2013; Binnemans et al., 2013). With improvements in the performance of renewable energy systems in recent years, their specific material demand and environmental impacts have also declined (Arvesen and Hertwich, 2011; Caduff et al., 2012).

While reducing atmospheric GHG emissions from power generation, CCS will increase environmental burdens associated with the fuel supply chains due to the energy, water, chemicals, and additional equipment required to capture and store CO_2. This is likely to increase the pressure on human health and ecosystems through chemical mechanisms by 0–60 % compared to the best available fossil fuel power plants (Singh, et al., 2011). However, these impacts are considered to be lower than the ecological and human health impacts avoided through reduced climate change (Singh et al., 2012). Uncertainties and risks associated with long-term storage also have to be considered (Sections 7.5.5 and 7.9.3; Ketzer et al., 2011; Koornneef et al., 2011). For an overview of mitigation options and their unresolved challenges, see Section 7.5.

The handling of radioactive material[23] poses a continuous challenge to the operation of the nuclear fuel chain and leads to releases of radionuclides. The most significant routine emissions of radionuclides occurs during fuel processing and mining (Simons and Bauer, 2012). The legacy of abandoned mines, sites, and waste storage causes some concerns (Marra and Palmer, 2011; Greenberg, 2013b; Schwenk-Ferrero, 2013; Skipperud et al., 2013; Tyler et al., 2013).

Epidemiological studies indicate an increase in childhood leukemia of populations living within 5 km of a nuclear power plant in a minority of sites studied (Kaatsch et al., 2008; Raaschou-Nielsen et al., 2008; Laurier et al., 2008; Heinävaara et al., 2010; Spycher et al., 2011; Koerblein and Fairlie, 2012; Sermage-Faure et al., 2012), so that the significance of a potential effect is not resolved (Fairlie and Körblein, 2010; Laurier et al., 2010).

Thermal power plants with high cooling loads and hydropower reservoirs lead to reduced surface water flows through increased evaporation (IPCC, 2008; Dai, 2011), which can adversely affect the biodiversity of rivers (Hanafiah et al., 2011) and wetlands (Amores et al., 2013; Verones et al., 2013).

While any low-carbon energy system should be subject to scrutiny to assure environmental integrity, the outcome must be compared against the performance of the current energy system as a baseline, and well-designed low-carbon electricity supply outperforms fossil-based systems on most indicators. In this context, it should be noted that the environmental performance of fossil-based technologies is expected to decline with increasing use of unconventional resources with their associated adverse environmental impacts of extraction (Jordaan et al., 2009; Yeh et al., 2010).

7.9.3 Technical risks

Within the context of sustainable development, a comprehensive assessment of energy supply and mitigation options needs to take into account technical risks, especially those related to accidents risks. In the event of accidents, fatality and injury may occur among workers and residents. Evacuation and resettlements of residents may also take place. This section, therefore, updates the risk assessment presented in Chapter 9 of the SRREN (IPCC, 2011a): "Accidental events can be triggered by natural hazards (e.g., Steinberg et al., 2008; Kaiser et al., 2009; Cozzani et al., 2010), technological failures (e.g., Hirschberg et al., 2004; Burgherr et al., 2008), purposefully malicious action (e.g., Giroux, 2008), and human errors (e.g., Meshakti, 2007; Ale et al., 2008)", (IPCC, 2011a, p. 745). An analysis of the fatalities caused by

[23] Accidents are addressed in Section 7.9.3.

large accidents (≥ 5 fatalities or ≥ 10 injured or ≥ 200 evacuated) recorded in the Energy-Related Severe Accident Database (ENSAD) (Burgherr et al., 2011), as presented in SRREN, allows for a comparison of the potential impacts. The analysis in SRREN included accidents in the fuel chain, such as coal mining and oil shipping, 1970–2008.

SRREN indicates high fatality rates (> 20 fatalities per PWh)[24] associated with coal, oil, and hydropower in non-OECD countries and low fatalities (< 2 fatalities per PWh) associated with renewable and nuclear power in OECD countries (Figure 9.12 in Sathaye et al., 2011). Coal and oil power in OECD countries and gas power everywhere were associated with impacts on the order of 10 fatalities per PWh.

Coal mining accidents in China were identified to have contributed to 25,000 of the historical total of 33,000 fatalities in severe accidents from 1970–2008 (Epstein et al., 2010; Burgherr et al., 2012). New analysis indicates that the accident rate in Chinese coal mining has been reduced substantially, from 5670 deaths in 2001 to 1400 in 2010, or from 5.1 to 0.76 fatalities per Mt coal produced (Chen et al., 2012). The majority of these fatalities is apparently associated with smaller accidents not covered in the ENSAD database. In China, accident rates in smaller coal mines are higher than those in larger mines (Chan and Griffiths, 2010), and in the United States, less profitable mines have higher rates than more profitable ones (Asfaw et al., 2013). A wide range of research into underlying causes of accidents and measures to prevent future accidents is currently under way.

For oil and gas, fatalities related to severe accidents at the transport and distribution stage are a major component of the accident related external costs. Over 22,000 fatalities in severe accidents for the oil chain were reported, 4000 for LPG, and 2800 for the natural gas chain (Burgherr et al., 2011, 2012). Shipping and road transport of fuels are associated with the highest number of fatalities, and accident rates in non-OECD countries are higher than those in OECD countries (Eckle and Burgherr, 2013).

For hydropower, a single event, the 1975 Banqiao/Shimantan dam failure in China, accounted for 26,000 immediate fatalities. Remaining fatalities from large hydropower accidents amount to nearly 4000, but only 14 were recorded in OECD countries (Moomaw et al., 2011a; Sathaye et al., 2011).

Severe nuclear accidents have occurred at Three-Mile Island in 1979, Chernobyl in 1986, and Fukushima in 2011. For Three-Mile Island, no fatalities or injuries were reported. For Chernobyl, 31 immediate fatalities occurred and 370 persons were injured (Moomaw et al., 2011a). Chernobyl resulted in high emissions of iodine-131, which has caused measureable increases of thyroid cancer in the surrounding areas (Cardis et al., 2006). The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) identified 6000 thyroid cases in individuals who were below the age of 18 at the time of the accident, 15 of which had resulted in mortalities (Balonov et al., 2011). A significant fraction of these are above the background rate. Epidemiological evidence for other cancer effects does not exist; published risk estimates often assume a linear no-threshold dose-response relationship, which is controversial (Tubiana et al., 2009). Between 14,000 and 130,000 cancer cases may potentially result (Cardis et al., 2006), and up to 9,000 potential fatalities in the Ukraine, Belarus, and Russia in the 70 years after the accident (Hirschberg et al., 1998). The potential radiation-induced increase in cancer incidence in a population of 500 million would be too low to be detected by an epidemiological study and such estimates are neither endorsed nor disputed by UNSCEAR (Balonov et al., 2011). Adverse effects on other species have been reported within the 30-km exclusion zone (Alexakhin et al., 2007; Møller et al., 2012; Geras'kin et al., 2013; Mousseau and Møller, 2013).

The Fukushima accident resulted in much lower radiation exposure. Some 30 workers received radiation exposure above 100 mSv, and population exposure has been low (Boice, 2012). Following the linear, no-threshold assumption, 130 (15–1100) cancer-related mortalities, and 180 (24–1800) cancer-related morbidities have been estimated (Ten Hoeve and Jacobson, 2012). The WHO does not estimate cancer incidence from low-dose population exposure, but identifies the highest lifetime attributable risk to be thyroid cancer in girls exposed during infancy in the Fukushima prefecture, with an increase of a maximum of 70 % above relatively low background rates. In the highest exposed locations, leukemia in boys may increase by 5 % above background, and breast cancer in girls by 4 % (WHO, 2013).

Design improvements for nuclear reactors have resulted in so-called Generation III+ designs with simplified and standardized instrumentation, strengthened containments, and 'passive' safety designs seeking to provide emergency cooling even when power is lost for days. Nuclear power reactor designs incorporating a 'defence-in-depth' approach possess multiple safety systems including both physical barriers with various layers and institutional controls, redundancy, and diversification—all targeted at minimizing the probability of accidents and avoiding major human consequences from radiation when they occur (NEA, 2008).

The fatality rates of non-hydro RE technologies are lower than those of fossil chains, and are comparable to hydro and nuclear power in developed countries. Their decentralized nature limits their capacity to have catastrophic impacts.

As indicated by the SRREN, accidents can result in the contamination of large land and water areas with radionuclides or hydrocarbons. The accidental releases of crude oil and its refined products into the maritime environment have been substantially reduced since the 1970s through technical measures, international conventions, national legislations, and increased financial liabilities (see e.g. Kontovas et al., 2010; IPCC, 2011a; Sathaye et al., 2011). Still, oil spills are common and can affect both marine and freshwater resources (Jernelöv, 2010;

[24] The global electricity production in 2008 was 17 PWh.

Rogowska and Namiesnik, 2010). Furthermore, increased drilling in deep offshore waters (e.g., Gulf of Mexico, Brazil) and extreme environments (e.g., the Arctic) poses a risk of potentially high environmental and economic impacts (Peterson et al., 2012; Moreno et al., 2013; Paul et al., 2013). Leakage of chemicals used in hydraulic fracturing during shale gas and geothermal operations can potentially contaminate local water flows and reservoirs (Aksoy et al., 2009; Kargbo et al., 2010; Jackson et al., 2013). Further research is needed to investigate a range of yet poorly understood risks and risk factors related to CCS storage (see Sections 7.5.5 and 7.9.4). Risks of CO_2 transport are discussed in Section 7.6.4.

7.9.4 Public perception[25]

Although public concerns are often directed at higher-GHG-emitting energy sources, concerns also exist for lower-emitting sources, and opposition can impede their deployment. Although RE sources often receive relatively wide public support, public concerns do exist, which, because of the diversity of RE sources and applications, vary by technology (Sathaye et al., 2011). For bioenergy, concerns focus on direct and indirect land use and related GHG emissions, deforestation, and possible competition with food supplies (e.g., Chum et al., 2011; and Bioenergy Annex of chapter 11). For hydropower, concerns include the possibility of the displacement of human populations, negative environmental impacts, and altered recreational opportunities (e.g., Kumar et al., 2011). For wind energy, concerns primarily relate to visibility and landscape impacts as well as potential nuisance effects, such as noise (e.g., Wiser et al., 2011). For solar energy, land area requirements can be a concern for large, utility-scale plants (e.g., Arvizu et al., 2011). For ocean energy, sea area requirements are a concern (e.g., Lewis et al., 2011). Concerns for geothermal energy include the possibility of induced local seismicity and impacts on natural—especially recreational—areas (e.g., Goldstein et al., 2011).

For nuclear energy, anxieties often focus on health and safety (e.g., accidents, disposal of wastes, decommissioning) and proliferation (e.g., terrorism, civil unrest). Further, perceptions are dependent on how the debate around nuclear is framed relative to other sources of energy supply (e.g., Bickerstaff et al., 2008; Sjoberg and Drottz-Sjoberg, 2009; Corner et al., 2011; Ahearne, 2011; Visschers and Siegrist, 2012; Greenberg, 2013b; Kim et al., 2013).

Among CCS technologies, early[26] misgivings include the ecological impacts associated with different storage media, the potential for accidental release and related storage effectiveness of stored CO_2, and the perception that CCS technologies do not prevent all of the non-GHG social and environmental impacts of fossil energy sources (e.g., IPCC, 2005; Miller et al., 2007; de Best-Waldhober et al., 2009; Shackley et al., 2009; Wong-Parodi and Ray, 2009; Wallquist et al., 2009, 2010; Reiner and Nuttall, 2011; Ashworth et al., 2012; Einsiedel et al., 2013). For natural gas, the recent increase in the use of unconventional extraction methods, such as hydraulic fracturing, has created concerns about potential risks to local water quality and public health (e.g., US EPA, 2011; IEA, 2012i).

Though impacts, and related public concerns, cannot be entirely eliminated, assessing, minimizing and mitigating impacts and concerns are elements of many jurisdictions' planning, siting, and permitting processes. Technical mitigation options show promise, as do procedural techniques, such as ensuring the availability of accurate and unbiased information about the technology, its impacts and benefits; aligning the expectations and interests of different stakeholders; adjusting to the local societal context; adopting benefit-sharing mechanisms; obtaining explicit support at local and national levels prior to development; building collaborative networks; and developing mechanisms for articulating conflict and engaging in negotiation (e.g., Ashworth et al., 2010; Fleishman, De Bruin, and Morgan, 2010; Mitchell et al., 2011; Terwel et al., 2010).

7.10 Barriers and opportunities

7.10.1 Technical aspects

From a global perspective, the large number of different technologies that are available to mitigate climate change (Section 7.5.) facilitates the achievement of prescribed climate protection goals. Given that many different combinations of the mitigation technologies are often feasible, least-cost portfolios can be determined that select those options that interact in the best possible way (Chapter 6, Section 7.11). On a local scale and/or concerning specific technologies, however, technological barriers might constrain their mitigation potential. These limits are discussed in Sections 7.4, 7.5, 7.6, and 7.9.

25 Other portions of this chapter and AR5 contain discussions of actual ecological and environmental impacts of various energy sources. Although not addressed here, energy transmission infrastructure can also be the focus of public concern. See also Chapters 2, 6, and 10, which cover issues of public acceptance through complementary lenses.

26 Knowledge about the social acceptability of CCS is limited due to the early state of the technologies' deployment, though early research has deepened our understanding of the issues related to CCS significantly (de Best-Waldhober et al., 2009; Malone et al., 2010; Ter Mors et al., 2010; Corry and Reiner, 2011. See also Section 2.6.6.2)

7.10.2 Financial and investment barriers and opportunities

The total global investment in the energy supply sector in 2010 is estimated to be USD 1,076 to 1,350 billion per year, of which 43–48 % is invested in the power sector and 37–50 % is invested in fossil extraction. In the power sector, 49–55 % of the investments is used for power generation and 45–51 % is used for transmission and distribution (see Section 16.2.2).

The total investment in renewables excluding hydropower in 2012 was USD 244 billion, which was six times the level in 2004. Out of this total, USD 140 billion was for solar and USD 80 billion for wind power. The total was down 12 % from a record USD 279 billion in 2011 in part due to changes in support policies and also due to sharp reductions in renewable energy technology costs. Total investment in developed countries fell 29 % in 2012 to USD 132 billion, while investment in developing countries rose 19 % to USD 112 billion. The investment in renewables is smaller than gross investment on fossil-fuel plants (including replacement plant) at USD 262 billion, but much larger than net investment in fossil-fuel technologies, at USD 148 billion. The amount of installed capacity of renewables excluding hydropower was 85 GW, up from 2011's 80 GW (BNEF and Frankfurt School-UNEP Centre, 2013; REN21, 2013).

Additional investments required in the energy supply sector by 2050 are estimated to be USD 190 billion to USD 900 billion/year to limit the temperature increase below 2 °C (about 0.30 % to 1.4 % of world GDP in 2010) (GEA, 2012; IEA, 2012h; Kainuma et al., 2013). The additional investment costs from both supply and demand sides are estimated to about USD 800 billion/year according to McCollum et al. (2014). With a greater anticipated increase in energy demands, developing countries are expected to require more investments than the developed countries (see also Chapter 6 and Chapter 16).

Investment needs in the energy supply sector increase under low-GHG scenarios. However, this should be set in the context of the total value of the world's financial stock, which (including global stock market capitalization) stood at more than USD 210 trillion at the end of 2010 (Roxburgh et al., 2011). Moreover, the investment needs described above would be offset, to a degree, by the lower operating costs of many low-GHG energy supply sources, as well as those due to energy-efficiency improvements in the end-use sectors (IEA, 2012h).

Though only a fraction of the available private-sector capital stock would be needed to cover the costs of low-GHG energy supply even in aggressive GHG-reduction scenarios, private capital will not be mobilized automatically for such purposes. For this reason, various measures—such as climate investment funds, carbon pricing, feed-in tariffs, RE quotas and RE-tendering/bidding schemes, carbon offset markets, removal of fossil fuel subsidies and private/public initiatives aimed at lowering barriers for investors—are currently being implemented (see Section 7.12, chapters 13, 14, and Section 15.2), and still more measures may be needed to achieve low-GHG stabilization scenarios. Uncertainty in policies is also a barrier to investment in low-GHG energy supply sources (United Nations, 2010; World Bank, 2011b; IEA, 2012h; IRENA, 2012a; BNEF and Frankfurt School-UNEP Centre, 2013).

Investment in LDCs may be a particular challenge given their less-developed capital markets. Multilateral development banks and institutions for bilateral developmental cooperation will have an important role towards increasing levels of confidence for private investors. Innovative insurance schemes to address regulatory and policy barriers could encourage participation of more diverse types of institutional investors (Patel, 2011). Building capacity in local governments in developing countries for designing and implementing appropriate policies and regulations, including those for efficient and transparent procurement for infrastructure investment, is also important (World Economic Forum, 2011; IRENA, 2012a; Sudo, 2013).

Rural areas in LDCs are often characterized by very low population densities and income levels. Even with the significant decline in the price of PV systems, investment cost barriers are often substantial in these areas (IPCC, 2011b). Micro-finance mechanisms (grants, concessional loans) adapted to the pattern of rural activities (for instance, installments correlated with income from agriculture) may be necessary to lift rural populations out of the energy poverty trap and increase the deployment of low-carbon energy technologies in these areas (Rao et al., 2009; Bazilian et al., 2012; IRENA, 2012c).

7.10.3 Cultural, institutional, and legal barriers and opportunities

Managing the transition from fossil fuels to energy systems with a large penetration of low-carbon technologies and improved energy efficiency will pose a series of challenges and opportunities, particularly in the case of poor countries. Depending on the regions and the development, barriers and opportunities may differ dramatically.

Taking the example in the United States, Sovacool (Sovacool, 2009) points to significant social and cultural barriers facing renewable power systems as policymakers continue to frame electricity generation as a mere technical challenge. He argues that in the absence of a wider public discourse around energy systems and challenging entrenched values about perceived entitlements to cheap and abundant forms of electricity, RE and energy-efficiency programmes will continue to face public acceptability problems. Indeed, attitudes towards RE in addition to rationality are driven by emotions and psychological issues. To be successful, RE deployment, as well as information and awareness efforts and strategies need to take this explicitly into account (Sathaye et al., 2011). Legal regulations and procedures are also impacting on the deployment of nuclear energy, CCS, shale gas, and renewable energy. However, the fundamental reasons (environment, health, and safety) may differ according to the different types of energy. The underlying risks are discussed in Sections 7.5 and 7.9, and enabling policies to address them are in Section 7.12.

A huge barrier in the case of poor, developing countries is the cultural, economic, and social gap between rural and urban areas (Khennas, 2012). For instance, cooking fuels, particularly firewood, is widely used in rural areas because it is a suitable fuel for these communities in addition to its access without payment apart from the time devoted to its collection. Indeed, values such as time have different perceptions and opportunity costs depending on the social and geographical context. Furthermore, legal barriers are often hindering the penetration of modern energy services and distorting the economics of energy systems. For instance, informal settlements in poor peripheral urban areas mean legal barriers to get access to electricity. Land tenancy issues and illegal settlements are major constraints to energy access, which are often overcome by illegal power connections with an impact on the safety of the end users and economic loss for the utility due to meter tampering. In addition, in many slums, there is a culture of non-payment of the bills (UN Habitat and GENUS, 2009). Orthodox electrification approaches appear to be inefficient in the context of urban slums, particularly in sub-Saharan Africa. Adopting a holistic approach encompassing cultural, institutional, and legal issues in the formulation and implementation of energy policies and strategies is increasingly perceived particularly in sub-Saharan Africa as essential to addressing access to modern energy services. In South Africa, the Electricity Supply Commission (ESKOM), the large utility in Africa, implemented a holistic Energy Losses Management Program (UN Habitat and GENUS, 2009), with strong community involvement to deal with the problem of energy loss management and theft. As a result prepayment was successfully implemented as it gives poor customers a daily visibility of consumption and a different culture and understanding of access to modern energy services.

7.10.4 Human capital capacity building

Lack of human capital is widely recognized as one of the barriers to development, acquisition, deployment, and diffusion of technologies required for meeting energy-related CO_2 emissions reduction targets (IRENA, 2012d). Human capacity is critical in providing a sustainable enabling environment for technology transfer in both the host and recipient countries (Barker et al., 2007; Halsnæs et al., 2007). Human workforce development has thus been identified as an important near-term priority (IEA, 2010c).

There is increasing concern in the energy supply sector in many countries that the current educational system is not producing sufficient qualified workers to fill current and future jobs, which increasingly require science, technology, engineering, and mathematics (STEM) skills. This is true not only in the booming oil and gas and traditional power industries, but also in the rapidly expanding RE supply sector (NAS, 2013b). Skilled workforce in the areas of RE and decentralized energy systems, which form an important part of 'green jobs' (Strietska-Ilina et al., 2011), requires different skill sets for different technologies and local context, and hence requires specific training (Moomaw et al., 2011b). Developing the skills to install, operate, and maintain the RE equipment is exceedingly important for a successful RE project, particularly in developing countries (UNEP, 2011), where shortages of teachers and trainers in subjects related to the fast-growing RE supply sector have been reported (Strietska-Ilina et al., 2011) (ILO and EU, 2011). Well-qualified workers will also be required on other low-carbon energy technologies, particularly nuclear and CCS—should there be large-scale implementation (Creutzig and Kammen, 2011; NAS, 2013b).

Apart from technology-oriented skills, capacity for decision support and policymaking in the design and enactment stages is also essential, particularly on assessing and choosing technology and policy options, and designing holistic policies that effectively integrate renewable energy with other low-carbon options, other policy goals, and across different but interconnected sectors (Mitchell et al., 2011; Jagger et al., 2013).

To avoid future skill shortages, countries will need to formulate short- and long-term capacity development strategies based on well-informed policy decisions, and adequate information on labour market and skill needs in the context of low-carbon transition and green jobs (Strietska-Ilina et al., 2011; Jagger et al., 2013). But producing a skilled workforce with the right skills at the right time requires additional or alternatives to conventional approaches. These include, but are not limited to, increased industry-education-government partnership, particularly with industry organizations, in job demand forecasting, designing education and training curricula, augmenting available skills with specific skills, and adding energy supply sector experience in education and training (Strietska-Ilina et al., 2011; NAS, 2013b).

7.10.5 Inertia in energy systems physical capital stock turnover

The long life of capital stock in energy supply systems (discussed in detail in Section 5.6.3) gives the possibility of path-dependant carbon lock-in (Unruh, 2002). The largest contribution to GHG emissions from existing high-carbon energy capital stock is in the global electricity sector, which is also characterized by long-lived facilities—with historical plant lifetimes for coal, natural gas, and oil plant of 38.6, 35.8, and 33.8 years, respectively (Davis et al., 2010). Of the 1549 GW investments (from 2000–2010) in the global electricity sector (EIA, 2011), 516 GW (33.3 %) were coal and 482 GW (31.1 %) were natural gas. Only 34 GW (2.2 %) were nuclear investments, with combined renewable source power plants at 317 GW (20.5 %). The investment share for RE power plants accelerated toward the end of the decade. The transport, industrial, commercial, and residential sectors generally have smaller technology sizes, shorter lifetimes, and limited plant level data for directly emitting GHG facilities; however, in combination, contribute over half of the GHG emissions from existing primary energy capital stock (Davis et al., 2010).

Long-lived fossil energy system investments represent an *effective* (high-carbon) lock-in. Typical lifetime of central fossil-fuelled power plants are between 30 and 40 years; those of electricity and gas infrastructures between 25–50 years (Philibert and Pershing, 2002). Although such capital stock is not an irreversible investment, premature retirement (or retrofitting with CCS if feasible) is generally expensive. Examples include low natural gas prices in the United States due to shale gas production making existing coal plants uneconomic to run, or merit order consequences of new renewable plants, which endanger the economic viability of dispatchable fossil fuel power plants in some European countries under current market conditions (IEA, 2013b). Furthermore, removal of existing fossil plants must overcome inertia from existing providers, and consider wider physical, financial, human capital, and institutional barriers.

Explicit analysis of path dependency from existing energy fossil technologies (450 ppm scenario, IEA, 2011a) illustrates that if current trends continue, by 2015 at least 90 % of the available 'carbon budget' will be allocated to existing energy and industrial infrastructure, and in a small number of subsequent years there will be extremely little room for manoeuvre at all (IEA, 2011a, Figure 6.12).

Effective lock-in from long-lived energy technologies is particularly relevant for future investments by developing economies, which are projected to account for over 90 % of the increase in primary energy demand by 2035 (IEA, 2011a). The relative lack of existing energy capital in many developing countries bolsters the potential opportunities to develop a low-carbon energy system, and hence reduce the effective carbon lock-in from broader energy infrastructures (e. g., oil refineries, industrial heat provision, transport networks) (Guivarch and Hallegatte, 2011), or the very long-lived capital stock embodied in buildings and urban patterns (Jaccard and Rivers, 2007).

7.11 Sectoral implication of transformation pathways and sustainable development

This section reviews long-term integrated scenarios and transformation pathways with regard to their implication for the global energy system. Focus is given to energy-related CO_2 emissions and the required changes to the energy system to achieve emissions reductions compatible with a range of long-term climate targets. Aggregated *energy-related emissions*, as primarily discussed in this section, comprise the *full energy system*, including energy sourcing, conversion, transmission, as well as the supply of energy carriers to the end-use sectors *and* their use in the end-use sectors. Aggregated energy-related emissions are further split into emissions from electricity generation and the rest of the energy system.[27,28] This section builds upon about 1200 emissions scenarios, which were collated by Chapter 6 in the WGIII AR5 Scenario Database (Section 6.2.2 and Annex II.10). The scenarios were grouped into baseline and mitigation scenarios. As described in more detail in Section 6.3.2, the scenarios are further categorized into bins based on 2100 concentrations: between 430–480 ppm CO_2eq, 480–530 ppm CO_2eq, 530–580 ppm CO_2eq, 580–650 ppm CO_2eq, 650–720 ppm CO_2eq, 720–1000 ppm CO_2eq, and > 1000 ppm CO_2eq by 2100. An assessment of geophysical climate uncertainties consistent with the dynamics of Earth System Models assessed in WG I found that the most stringent of these scenarios—leading to 2100 concentrations between 430 and 480 ppm CO_2eq—would lead to an end-of-century median temperature change between 1.5 to 1.7 °C compared to pre-industrial times, although uncertainties in understanding of the climate system mean that the possible temperature range is much wider than this. These scenarios were found to maintain temperature change below 2 °C over the course of the century with a *likely* chance. Scenarios in the concentration category of 650–720 ppm CO_2eq correspond to comparatively modest mitigation efforts, and were found to lead to median temperature rise of approximately 2.6–2.9 °C in 2100 (see Section 6.3.2 for details).

7.11.1 Energy-related greenhouse gas emissions

In the baseline scenarios assessed in AR5, direct CO_2 emissions of the *energy supply sector* increase from 14.4 $GtCO_2$/yr in 2010 to 24–33 $GtCO_2$/yr in 2050 (25–75th percentile; full range 15–42 $GtCO_2$/yr), with most of the baseline scenarios assessed in AR5 showing a significant increase. The lower end of the full range is dominated by scenarios with a focus on energy intensity improvements that go well beyond the observed improvements over the past 40 years [Figure TS 15].

In absence of climate change mitigation policies,[29] *energy-related* CO_2 emissions (i. e. those taking into account the emissions of the energy

[27] Note that the other Sections in Chapter 7 are focusing on the *energy supply sector*, which comprises only energy extraction, conversion, transmission, and distribution. As noted in Section 7.3, CO_2 emissions from the energy supply sector are the most important source of climate forcing. Climate forcing associated with emissions from non-CO_2 greenhouse gases (e. g., CH_4 and N_2O) of the energy supply sector is smaller than for CO_2. For the most part, non-CO_2 greenhouse gases are emitted by other non-energy sectors, though CH_4 is released in primary energy sourcing and supply as a bi-product of oil, gas, and coal production as well as in the transmission and distribution of methane to markets. While its share in total GHG emissions is relatively small, the energy supply sector is, however, a major source of sulphur and other aerosol emissions. (See also Section 6.6)

[28] The mitigation scenarios in the WGIII AR5 Scenario Database do not provide information on energy-related emissions of non-CO_2 gases. The assessment in this section thus focuses on CO_2 emissions only.

[29] Beyond those already in effect.

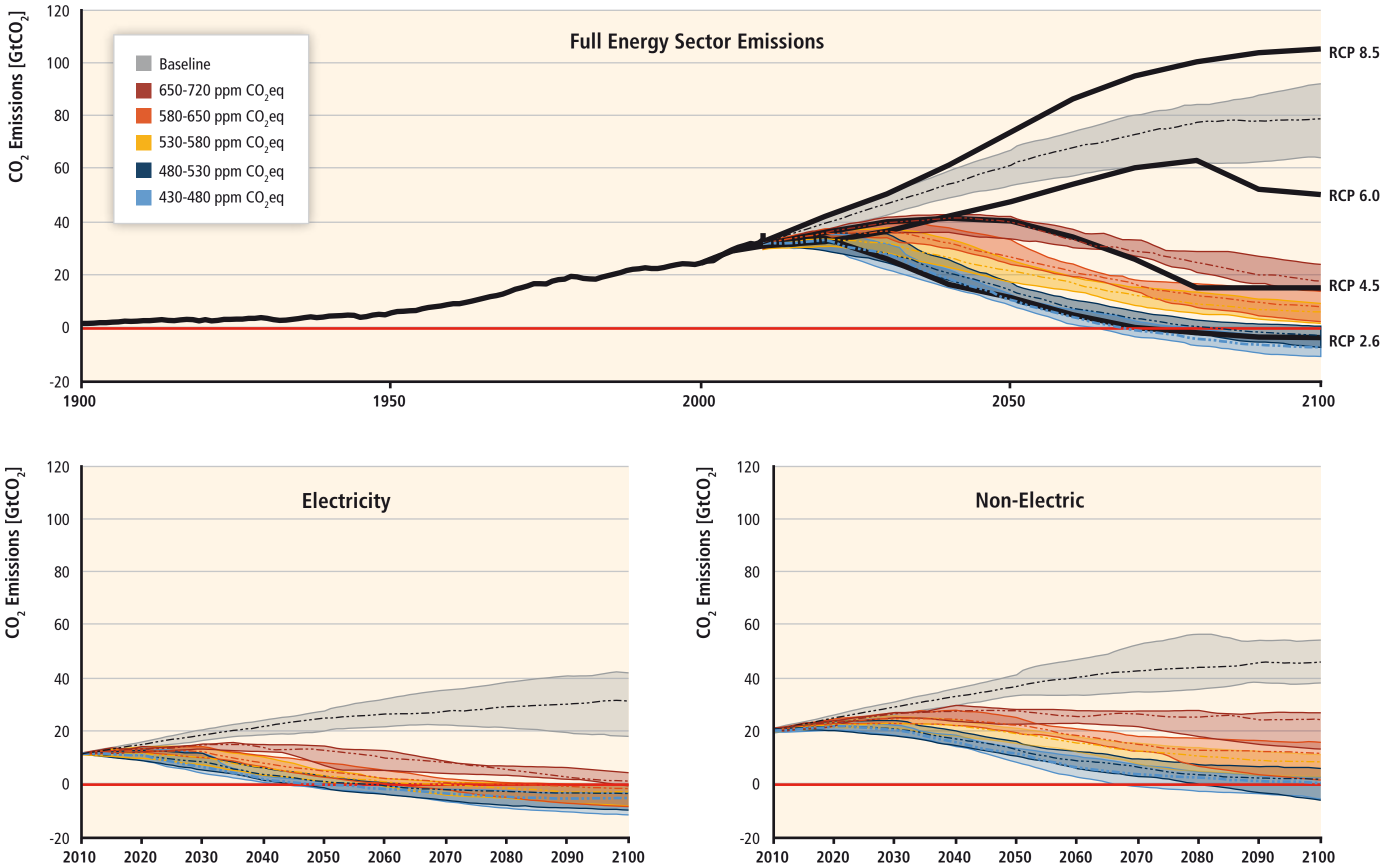


Figure 7.9 | Global development of annual CO_2 emissions for the full energy system including energy supply, and end uses (upper panel), and the split between electricity and non-electric emissions (lower panels). The baseline emissions range (grey) is compared to the range of emissions from mitigation scenarios grouped according to their long-term CO_2eq concentration level by 2100. Shaded areas correspond to the 25th–75th percentile and dashed lines to the median across the scenarios. 'Non-electric' comprises emissions from the full chain of non-electric conversion processes as well as emissions from fossil fuels supplied to the end-use sectors. The upper panel includes in addition also the representative concentration pathways (RCPs) (black lines, see Chapter 6, Table 6.2). Source: WGIII AR5 Scenario Database (See Section 6.2.2 and Annex II.10). Note: Some scenarios report industrial process emissions (e.g., CO_2 released from cement manufacture beyond energy-related emissions) as part of the energy system.

supply sector *and those in the* end-use sectors) are expected to continue to increase from current levels to about 55–70 $GtCO_2$ by 2050 (25th–75th percentile of the scenarios in the WGIII AR5 Scenario Database, see Figure 7.9).[30] This corresponds to an increase of between 80 % and 130 % compared to emissions of about 30 $GtCO_2$ in the year 2010. By the end of the 21st century, emissions could grow further, the 75th percentile of scenarios reaching about 90 $GtCO_2$.[31,32]

The stabilization of GHG concentrations requires fundamental changes in the global energy system relative to a baseline scenario. For example, in mitigation scenarios reaching 450 ppm CO_2eq concentrations in 2100, CO_2 emissions from the energy supply sector decline over the next decades, reach 90 % below 2010 levels between 2040 and 2070 and in many scenarios decline to below zero thereafter. As discussed in Section 7.11.4, unlike traditional pollutants, CO_2 concentrations can only be stabilized if global emissions peak and in the long term, decline toward zero. The lower the concentration at which CO_2 is to be stabilized, the sooner and lower is the peak. For example, in the majority of the scenarios compatible with a long-term concentration goal of below 480 ppm CO_2eq, energy-related emissions peak between 2020 and 2030, and decline to about 10–15 $GtCO_2$ by 2050 (Figure 7.9). This corresponds to emissions reductions by 2050 of 50–70 % compared to the year 2010, and 75–90 % compared to the business-as-usual (25th–75th percentile).

7.11.2 Energy supply in low-stabilization scenarios

While stabilizing CO_2eq concentrations requires fundamental changes to the global energy supply systems, a portfolio of measures is available that includes the reduction of final energy demand through

30 Note that the total energy-related emissions include in some scenarios also fossil fuel emissions from industrial processes, such as the use of fossil fuel feedstocks for lubricants, asphalt, or cement production. A split between energy and industrial process emissions is not available from the WGIII AR5 Scenario Database.

31 The full uncertainty range of the WGIII AR5 Scenario Database includes high-emissions scenarios approaching 80 $GtCO_2$ by 2050, and almost 120 $GtCO_2$ by 2100.

32 If not otherwise mentioned, ranges refer to the 25th—75th percentile of the WGIII AR5 Scenario Database.

7

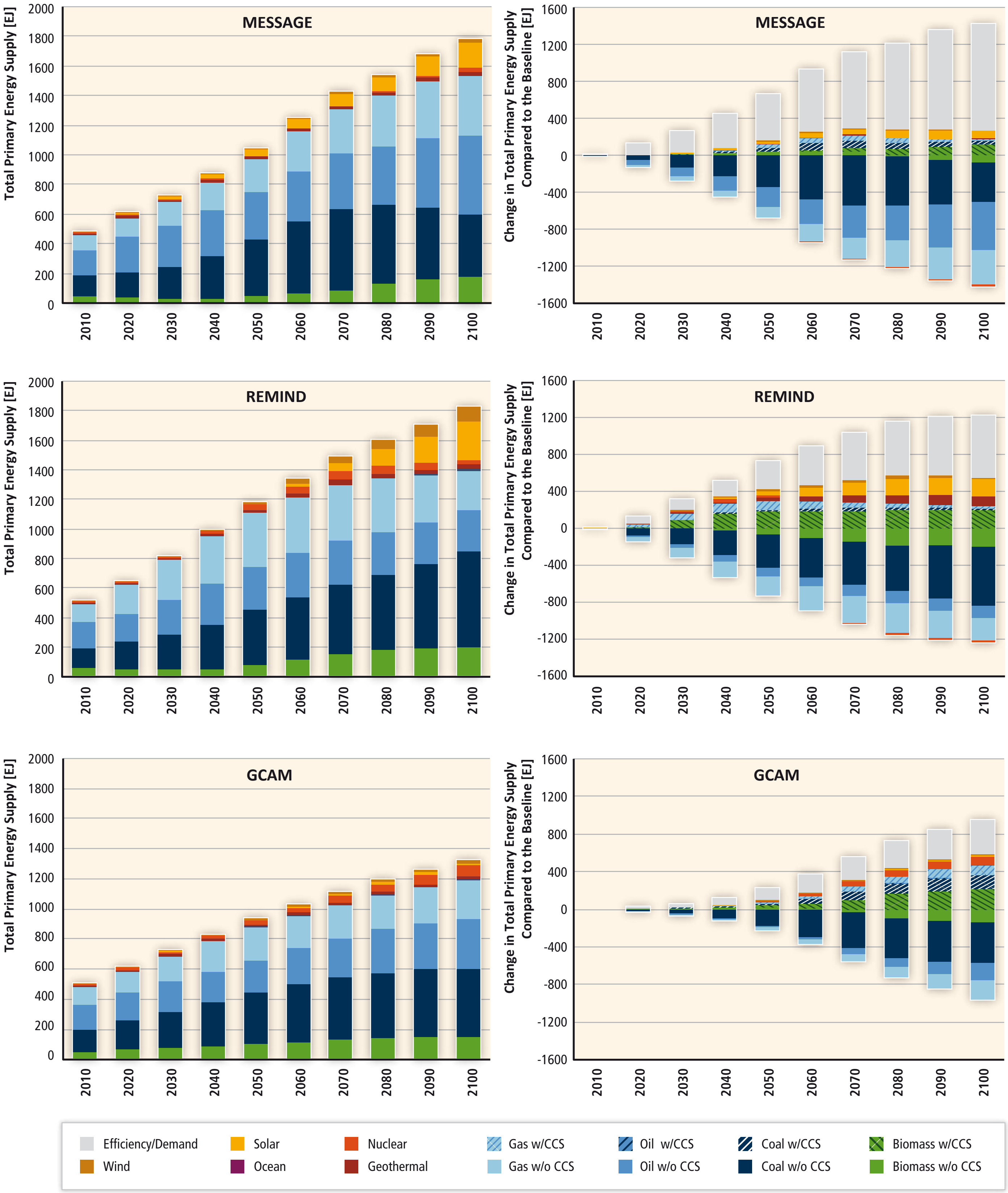
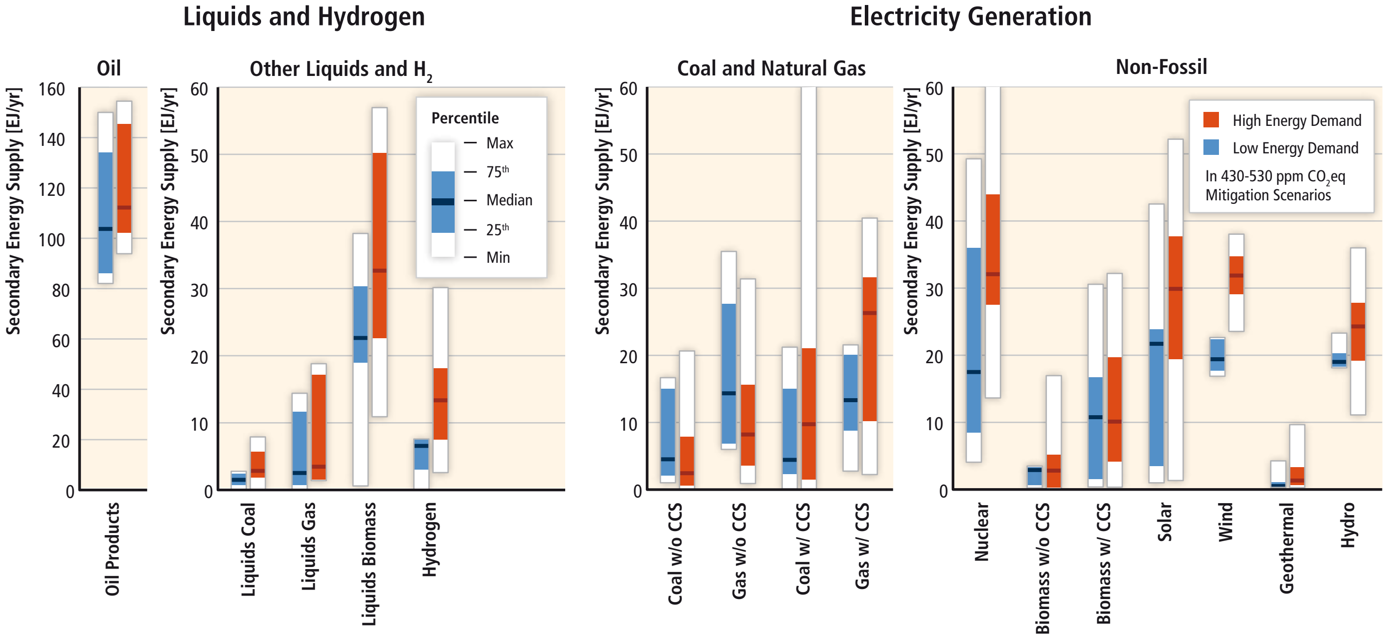


Figure 7.10 | Development of annual primary energy supply (EJ) in three illustrative baseline scenarios (left-hand panel); and the change in primary energy compared to the baseline to meet a long-term concentration target between 430 and 530 ppm CO_2eq. Source: ReMIND (RoSE: Bauer et al., 2013); GCAM (AME: Calvin et al., 2012); MESSAGE (GEA: Riahi et al., 2012).*

* Note that 'Savings' is calculated as the residual reduction in total primary energy.



1	2	3	4
High energy demand scenarios show higher levels of oil supply.	In high energy demand scenarios, alternative liquid and hydrogen technologies are scaled up more rapidly.	High energy demand scenarios show a more rapid up-scaling of CCS technologies but a more rapid phase-out of unabated fossil fuel conversion technologies.	In high energy demand scenarios non-fossil electricity generation technologies are scaled up more rapidly.

Figure 7.11 | Influence of energy demand on the deployment of energy supply technologies for stringent mitigation scenarios (430–530 ppm CO_2eq) in 2050. Blue bars for 'low energy demand' show the deployment range of scenarios with limited growth of final energy of < 20 % in 2050 compared to 2010. Red bars show the deployment range of technologies in case of 'high energy demand' (> 20 % growth in 2050 compared to 2010). For each technology, the median-, interquartile-, and full-deployment range is displayed. (Source: WGIII AR5 Scenario Database; see Annex II.10).

Notes: Scenarios assuming technology restrictions and scenarios with final energy in the base-year outside ±5 % of 2010 inventories are excluded. Ranges include results from many different integrated models. Multiple scenario results from the same model were averaged to avoid sampling biases. For further details see Chapter 6.

enhanced efficiency or behavioural changes as well as fuel switching (e.g., from coal to gas) and the introduction of low-carbon supply options such as renewables, nuclear, CCS, in combination with fossil or biomass energy conversion processes, and finally, improvements in the efficiency of fossil fuel use. These are discussed in Section 7.5 as well as in Chapters 8–10.

Figure 7.10 shows three examples of alternative energy system transformation pathways that are consistent with limiting CO_2eq concentrations to about 480 ppm CO_2eq by 2100. The scenarios from the three selected models are broadly representative of different strategies for how to transform the energy system. In absence of new policies to reduce GHG emissions, the energy supply portfolio of the scenarios continues to be dominated by fossil fuels. Global energy supply in the three baseline scenarios increases from present levels to 900–1200 EJ/yr by 2050 (left-hand panels of Figure 7.10). Limiting concentrations to low levels requires the rapid and pervasive replacement of fossil fuel without CCS (see the negative numbers at the right-hand panels of Figure 7.10). Between 60 and 300 EJ of fossil fuels are replaced across the three scenarios over the next two decades (by 2030). By 2050 fossil energy use is 230–670 EJ lower than in non-climate-policy baseline scenarios.[33]

The three scenarios achieve their concentration goals using different portfolios. These differences reflect the wide range in assumptions about technology availability and the policy environment.[34] While the pace of the transformation differs across the scenarios (and depends also on the carbon-intensity and energy-demand development in the baseline), all three illustrative scenarios show the importance of measures to reduce energy demand over the short term. For instance, by

33 The numbers refer to the replacement of freely emitting (unabated) fossil fuels without CCS. The contribution of fossil fuels with CCS is increasing in the mitigation scenarios.

34 For example, the MESSAGE scenario corresponds to the so-called "efficiency" case of the Global Energy Assessment, which depicts low energy demand to test the possibility of meeting the concentration goal even if nuclear power were phased out. GCAM on the other hand imposed no energy supply technology availability constraints and assumed advances across a broad suite of technologies.

2030, between 40–90 % of the emissions reductions are achieved through energy-demand savings, thus reducing the need for fossil fuels. The long-term contribution of energy-demand savings differs, however, significantly across the three scenarios. For instance, in MESSAGE about 1200 EJ of fossil fuels are replaced through efficiency and demand-side improvements by 2100, compared to about 400 EJ in the GCAM scenario.

Achieving concentrations at low levels (430–530 ppm CO_2eq) requires significant up-scaling of low-carbon energy supply options. The up-scaling of low-carbon options depends greatly on the development of energy demand, which determines the overall 'size' of the system. Hence, scenarios with greater emphasis on efficiency and other measures to limit energy demand, generally show less pervasive and rapid up-scaling of supply-side options (see right-side panels of Figure 7.11). Figure 7.11 compares stringent mitigation scenarios with low and comparatively high global energy demands by 2050. The higher energy-demand scenarios are generally accompanied by higher deployment rates for low-carbon options and more rapid phaseout of freely emitting fossil fuels without CCS. Moreover, and as also shown by Figure 7.11, high energy demand leads to a further 'lock-in' into fossil-intensive oil-supply infrastructures, which puts additional pressure on the supply system of other sectors that need to decarbonize more rapidly to compensate for the increased emissions from oil products. The results confirm the importance of measures to limit energy demand (Wilson et al, 2013) to increase the flexibility of energy supply systems, thus reducing the risk that stringent mitigation stabilization scenarios might get out of reach (Riahi et al., 2013). Note also that even at very low concentration levels, a significant fraction of energy supply in 2050 may be provided by freely emitting fossil energy (without CCS).

The projected deployment of renewable energy technologies in the mitigation scenarios (Figure 7.12), with the exception of biomass, is well within the estimated global technical potentials assessed by the IPCC (2011a). As illustrated in Figure 7.12, global technical potentials of, for instance, wind, solar, geothermal, and ocean energy are often more than an order of magnitude larger than the projected deployment of these technologies by 2050. Also for hydropower the technical potentials are larger than the projected deployment, whereas for biomass, projected global deployment is within the wide range of global technical potential estimates. Considering the large up-scaling in the mitigation scenarios, global technical potentials of biomass and hydropower seem to be more limiting than for other renewables (Figure 7.12). That said, considering not only global potentials, but also regional potentials, other renewable energy sources may also be limited by technical potentials under mitigation scenarios (Fischedick et al., 2011).

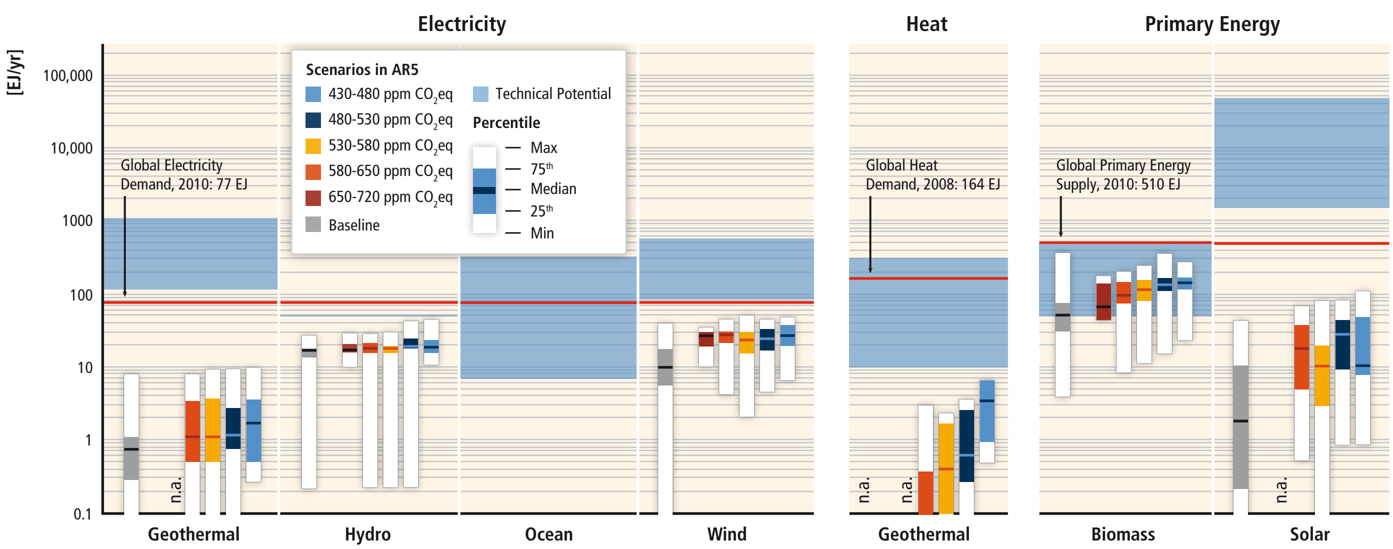


Figure 7.12 | Comparison of global technical potentials of renewable energy sources (Moomaw et al., 2011b) and deployment of renewable energy technologies in integrated model scenarios in 2050 (WGIII AR5 Scenario Database, see Annex II.10). Solar energy and biomass are displayed as primary energy as they can serve multiple uses. Note that the figure is presented in logarithmic scale due to the wide range of assessed data. Integrated model mitigation scenarios are presented for different ranges of CO_2eq concentration levels (see Chapter 6).

Notes: The reported technical potentials refer to the total worldwide annual RE supply. Any potential that is already in use is not deducted. Renewable energy power sources could also supply heating applications, whereas solar and biomass resources are represented in terms of primary energy because they could be used for multiple (e.g., power, heat, and transport) services. The ranges were derived by using various methodologies and the given values refer to different years in the future. As a result, the displayed ranges cannot be strictly compared across different technologies. Additional information concerning data sources and additional notes that should be taken into account in interpreting the figure, see Moomaw et al. (2011b). Contribution of ocean energy in the integrated model scenarios is less than 0.1 EJ and thus outside the logarithmic scale of the figure. Note that not all scenarios report deployment for all RE sources. The number of assessed scenarios differs thus across RE sources and scenario categories. The abbreviation 'n.a.' indicates lack of data for a specific concentration category and RE. Scenarios assuming technology restrictions are excluded.

Additionally, reaching the global deployment levels as projected by the mitigation scenarios requires addressing potential environmental concerns, public acceptance, the infrastructure requirements to manage system integration and deliver renewable energy to load centres, and other barriers (see Section 7.4.2, 7.6, 7.8, 7.9, 7.10; IPCC, 2011a). Competition for land and other resources among different renewables may also impact aggregate technical potentials as well as deployment levels, as might concerns about the carbon footprint and sustainability of the resource (e.g., biomass) as well as materials demands (cf. Annex Bioenergy in Chapter 11; de Vries et al., 2007; Kleijn and van der Voet, 2010; Graedel, 2011). In many mitigation scenarios with low demand, nuclear energy supply is projected to increase in 2050 by about a factor of two compared to today, and even a factor of 3 or more in case of relatively high energy demand (Figure 7.11). Resource endowments will not be a major constraint for such an expansion, however, greater efforts will be necessary to improve the safety, uranium utilization, waste management, and proliferation concerns of nuclear energy use (see also Sections 7.5.4, 7.4.3, 7.8, 7.9, and 7.10).

Integrated models (see Section 6.2) tend to agree that at about USD 100–150/tCO_2 the electricity sector is largely decarbonized with a significant fraction being from CCS deployment (Krey and Riahi, 2009; Luckow et al., 2010; Wise et al., 2010). Many scenarios in the WGIII AR5 Scenario Database achieve this decarbonization at a carbon tax of approximately USD 100/tCO_2. This price is sufficient, in most scenarios, to produce large-scale utilization of bioenergy with CCS (BECCS) (Krey and Riahi, 2009; Azar et al., 2010; Luckow et al., 2010; Edmonds et al., 2013). BECCS in turn allows net removal of CO_2 from the atmosphere while simultaneously producing electricity (Sections 7.5.5 and 11.13). In terms of large-scale deployment of CCS in the power sector, Herzog (2011, p. 597), and many others have noted that "Significant challenges remain in growing CCS from the megatonne level where it is today to the gigatonne level where it needs to be to help mitigate global climate change. These challenges, none of which are showstoppers, include lowering costs, developing needed infrastructure, reducing subsurface uncertainty, and addressing legal and regulatory issues". In addition, the up-scaling of BECCS, which plays a prominent role in many of the stringent mitigation scenarios in the literature, will require overcoming potential technical barriers to increase the size of biomass plants. Potential adverse side effects related to the biomass feedstock usage remain the same as for biomass technologies without CCS (Sections 7.5.5, 11.13, particularly 11.7, 11.13.6, and 11.13.7).

Over the past decade, a standardized geologic CO_2 storage-capacity methodology for different types of deep geologic formations (Bachu et al., 2007; Bradshaw et al., 2007; Kopp et al., 2009; Orr, 2009; Goodman et al., 2011; De Silva et al., 2012) has been developed and applied in many regions of the world. The resulting literature has been surveyed by Dooley (2013), who reports that, depending on the quality of the underlying data used to calculate a region's geologic CO_2 storage capacity, and on the type and stringency of various engineering and economic constraints, global theoretical CO_2 storage could be as much as 35,000 GtCO_2, global effective storage capacity is 13,500 GtCO_2, global practical storage capacity is 3,900 GtCO_2, and matched geologic CO_2 storage capacity for those regions of the globe where this has been computed is 300 GtCO_2. Dooley (2013) compared these estimates of geologic storage capacity to the potential demand for storage capacity in the 21st century by looking across more than 100 peer-reviewed scenarios of CCS deployment. He concludes that a lack of geologic storage space is unlikely to be the primary impediment to CCS deployment as the average demand for geologic CO_2 storage for scenarios that have end-of-century CO_2 concentrations of 400–500 ppm ranges from 448 GtCO_2 to 1,000 GtCO_2.

Energy system response to a prescribed climate policy varies across models and regions. There are multiple alternative transition pathways, for both the global energy system as a whole, and for individual regional energy systems. In fact the special circumstances encountered by individual regions imply greater regional variety in energy mitigation portfolios than in the global portfolio (Calvin et al., 2012; Bauer et al., 2013).

7.11.3 Role of the electricity sector in climate change mitigation

Electrification of the energy system has been a major driver of the historical energy transformation from an originally biomass-dominated energy system in the 19th century to a modern system with high reliance on coal and gas (two of the major sources of electricity generation today). Many mitigation scenario studies (Edmonds et al., 2006; as well as the AR5 database; cf. Sections 6.3.4 and 6.8) have three generic components: (1) decarbonize power generation; (2) substitute electricity for direct use of fossil fuels in buildings and industry (see Sections 9.3 and 10.4), and in part for transportation fuels (Chapter 8); and (3) reduce aggregate energy demands through technology and other substitutions.

Most scenarios in the WGIII AR5 Scenario Database report a continuation of the global electrification trend in the future (Figure 7.13). In the baseline scenarios (assuming no new climate policies) most of the demand for electricity continues to be in the residential, commercial, and industry sectors (see Chapters 9 and 10), while transport sectors rely predominantly on liquid fuels (Section 8.9). Biofuels and electricity both have the potential to provide transport services without fossil fuel emissions. The relative contribution of each depends at least in part on the character of technologies that evolve to provide transport services with each fuel.

Electricity production is the largest single sector emitting fossil fuel CO_2 at present and in baseline scenarios of the future. A variety of mitigation options exist in the electricity sector, including renewables (wind, solar energy, biomass, hydro, geothermal), nuclear, and the possibility of fossil or biomass with CCS. The electricity sector plays a major role in mitigation scenarios with deep cuts of GHG emissions. Many mitiga-

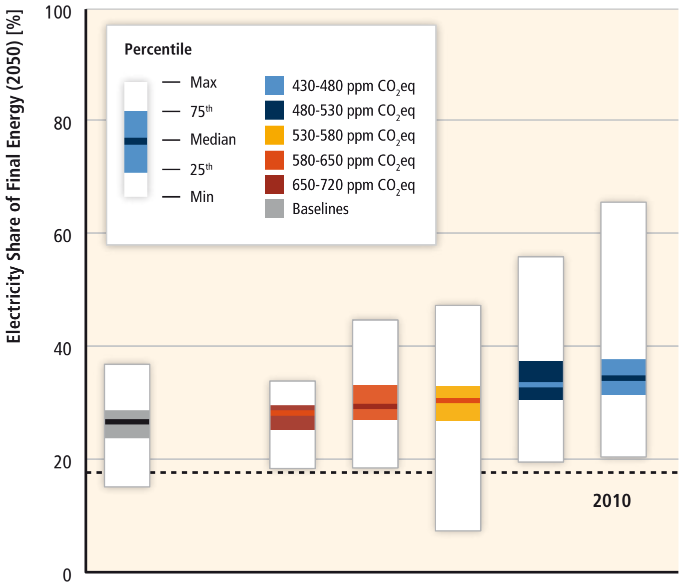


Figure 7.13 | Share of electricity in total final energy for the year 2050 in baseline scenarios and five different levels of mitigation stringency (long-term concentration levels in ppm CO_2eq by 2100). Colored bars show the interquartile range and white bars indicate the full range across the baseline and mitigation scenarios (See Section 6.3.2). Dashed horizontal line shows the electricity share for the year 2010. Source: WGIII AR5 Scenario Database (see Annex II.10). Scenarios assuming technology restrictions are excluded.

tion scenario studies report an acceleration of the electrification trend in mitigation scenarios (Figure 7.13).

Mitigation scenario studies indicate that the decarbonization of the electricity sector may be achieved at a much higher pace than in the rest of the energy system (Figure 7.14). In the majority of stringent mitigation scenarios (430–480 ppm and 480–530 ppm), the share of low-carbon energy increases from presently about 30 % to more than 80 % by 2050. In the long term (2100), fossil-based electricity generation without CCS is phased out entirely in these scenarios.

Figure 7.15 shows the evolution over time of transformation pathways for primary energy supply, electricity supply, and liquid fuels supply for reference scenarios and low-concentration scenarios (430–530 ppm CO_2eq). The development of the full scenario ensemble is further compared to the three illustrative mitigation scenarios by the ReMIND, MESSAGE, and GCAM models discussed in Section 7.11.2 (see Figure 7.10). The effect of climate policy plays out differently in each of the three supply domains. In aggregate, mitigation leads to a reduction in primary energy demands. However, two distinctly different mitigation portfolios emerge—one in which hydro-carbon fuels, including biomass, BECCS, and fossil CCS play a prominent role; and the other where, taken together, non-biomass renewables and nuclear power take center stage. In both instances, the share of fossil energy without CCS declines to less than 20 % of the total by 2100. Note that in the scenarios examined here, the major branch point occurs around the 2050 period, while the foundations are laid in the 2030 to 2050 period.

Electricity generation is a somewhat different story. While as previously noted, electricity generation decarbonizes rapidly and completely (in many scenarios emissions actually become negative), taken together, non-biomass renewables and nuclear power always play an important role. The role of CCS varies greatly, but even when CCS becomes extremely important to the overall mitigation strategy, it never exceeds half of power generation. By 2050, the contribution of fossil CCS technologies is in most scenarios larger than BECCS (see Figure 7.11). In contrast to the overall scale of primary energy supply, which falls in climate policy scenarios relative to baseline scenarios, the scale of power generation can be higher in the presence of climate policy depending on whether the pace of electrification proceeds more or less rapidly than the rate of end-use energy demand reductions. With regards to the deployment of individual non-biomass renewables or different CCS technologies, see also Figure 7.11 and Figure 7.12.

Liquid fuels are presently supplied by refining petroleum. Many scenarios report increasing shares for liquids derived from other primary

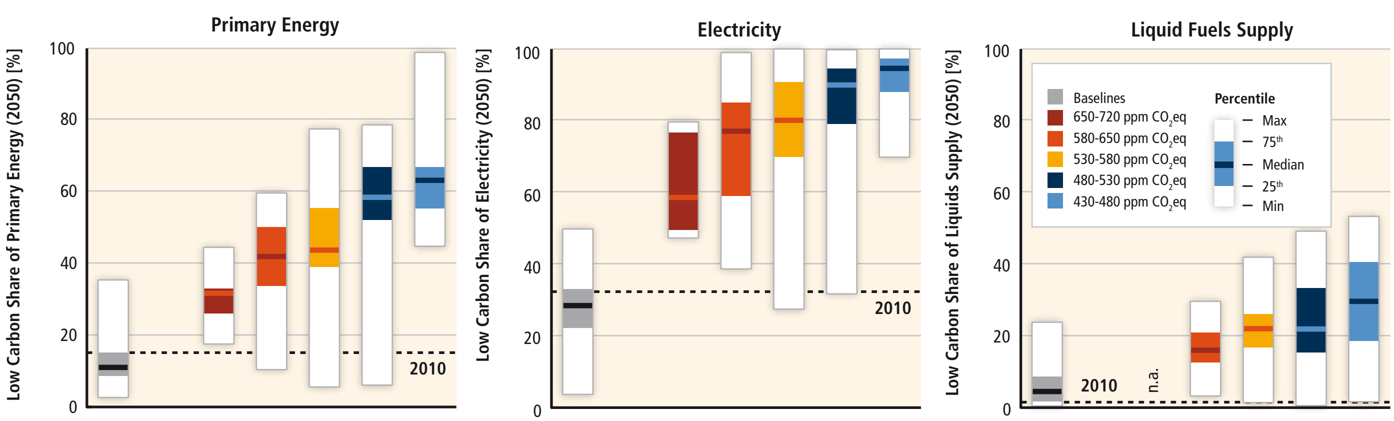
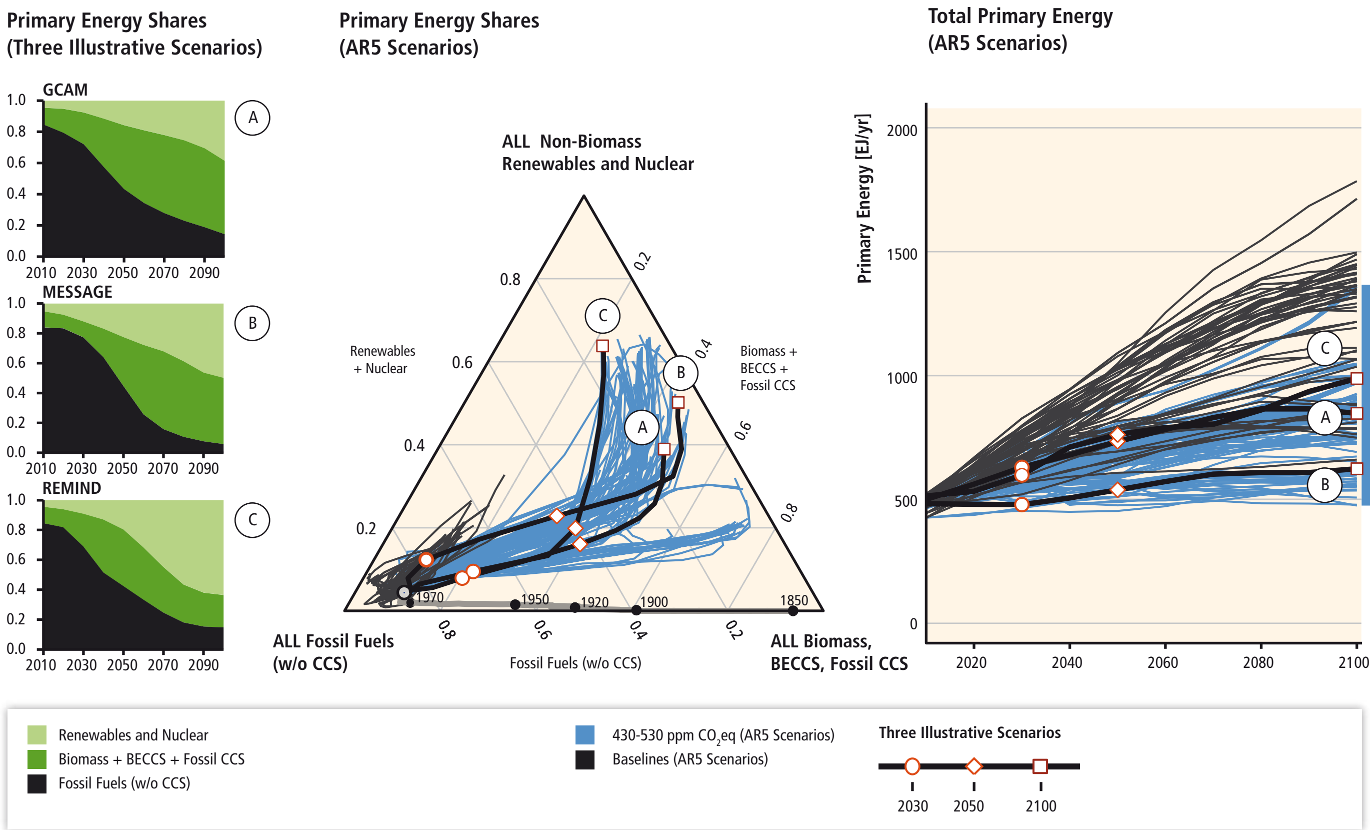
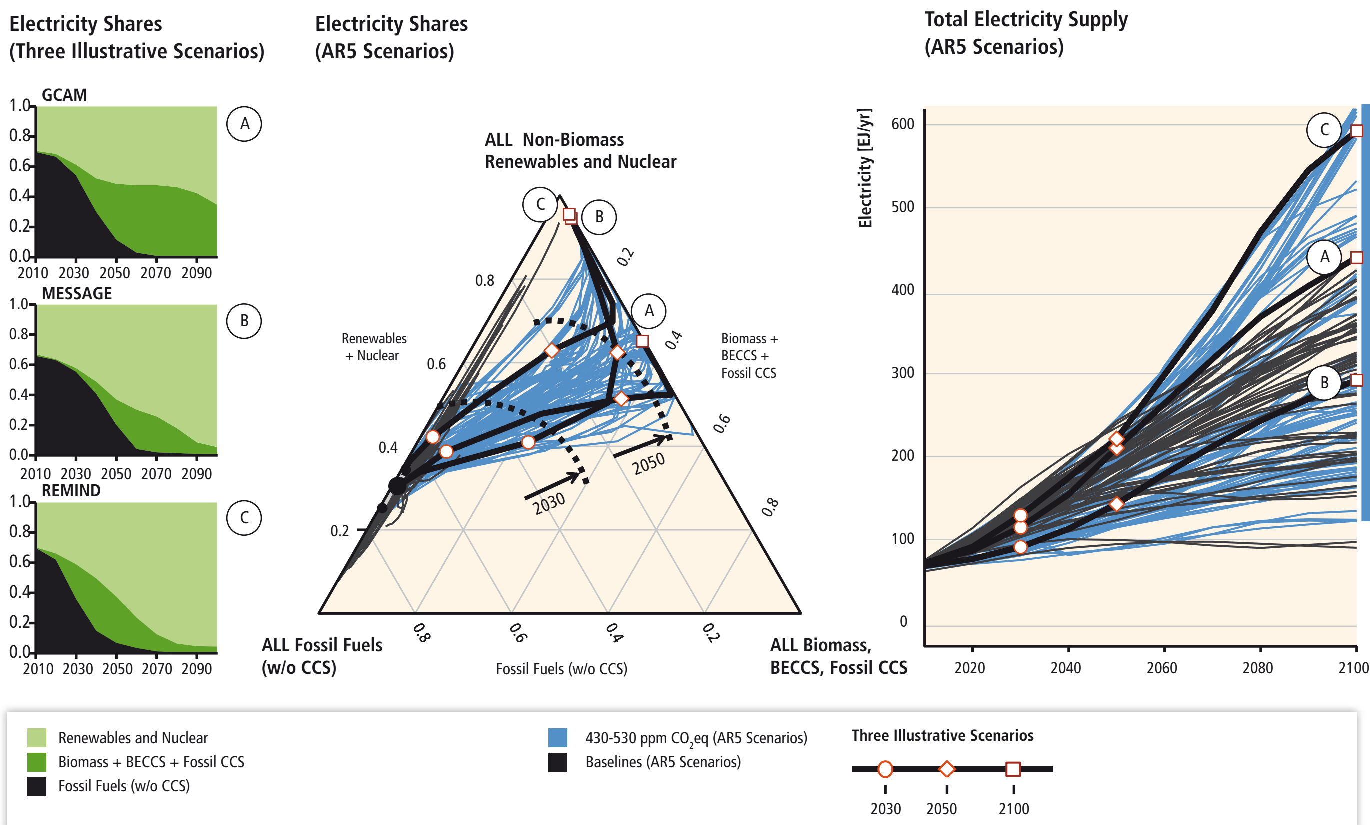


Figure 7.14 | Share of low-carbon energy in total primary energy, electricity and liquid supply sectors for the year 2050. Colored bars show the interquartile range and white bars indicate the full range across the baseline and mitigation scenarios for different CO_2eq ppm concentration levels in 2100 (Section 6.3.2). Dashed horizontal lines show the low-carbon share for the year 2010. Low-carbon energy includes nuclear, renewables, fossil fuels with CCS and bioenergy with CCS: WGIII AR5 Scenario Database (see Annex II.10). Scenarios assuming technology restrictions are excluded.

a) Primary Energy



b) Electricity Generation



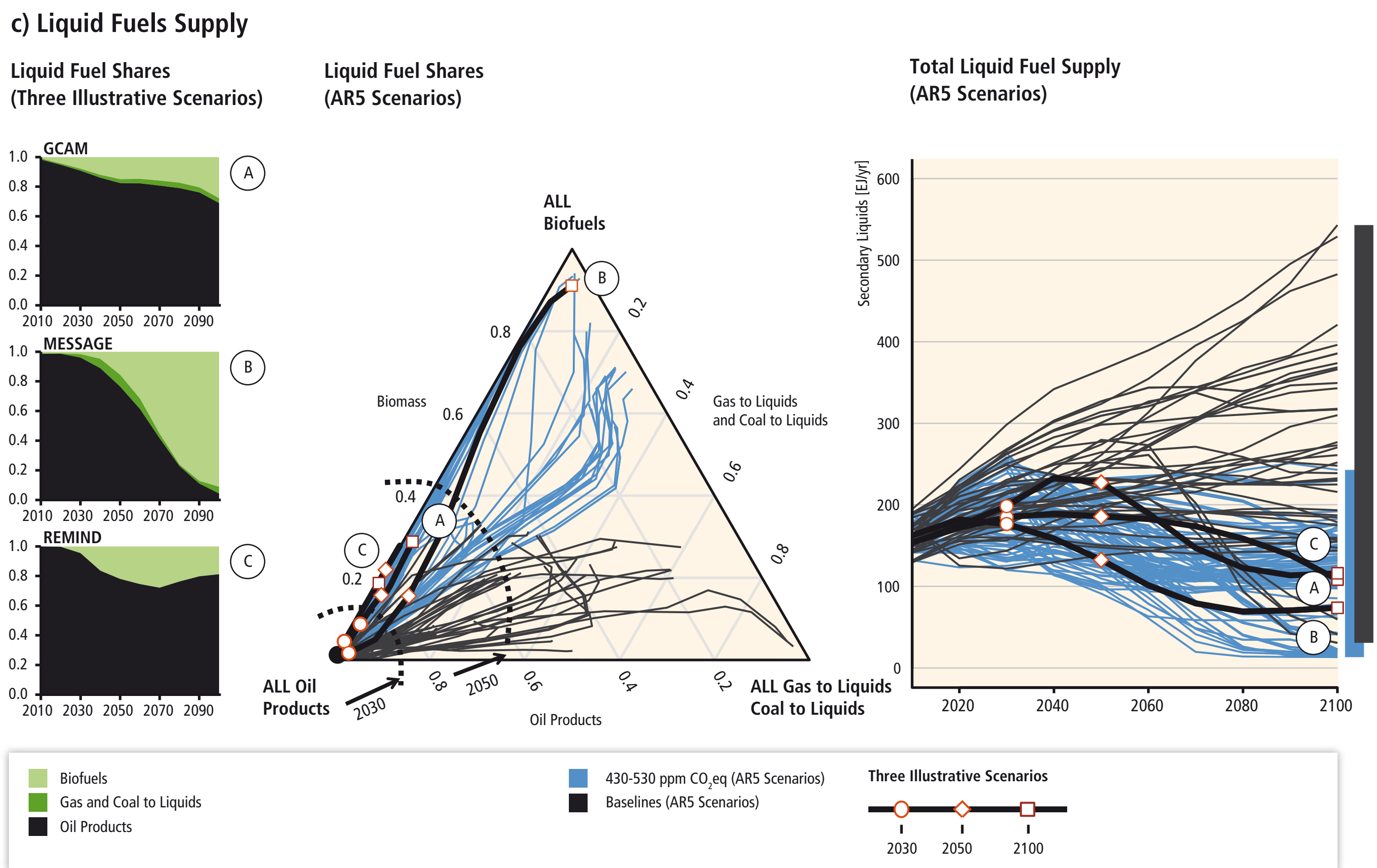


Figure 7.15 | Transition Pathways for the Aggregate Energy Supply Transformation System (a), Electricity Supply (b), and the Supply of Liquid Fuels (c): 2010 to 2100 for baseline and stringent mitigation scenarios (430–530 ppm CO_2eq). The pathways of three illustrative scenarios (cases A, B, and C) are highlighted for comparison. The illustrative pathways correspond to the same scenarios as shown in Figure 7.10. Dashed lines in the middle panels show the development to 2030 and 2050, and are indicative only for central trends across the majority of the scenarios. Source: WGIII AR5 Scenario Database (see Section 6.2.2 and Annex II.10) and three illustrative scenarios from ReMIND (Rose: Bauer et al., 2013); GCAM (AME: Calvin et al., 2012); and the MESSAGE model (GEA: Riahi et al., 2012).

Note: Scenarios assuming technology restrictions and scenarios with significant deviations for the base-year (2010) are excluded.

energy feedstocks such as bioenergy, coal, and natural gas. This transition is gradual, and becomes more pronounced in the second half of the century. Like aggregate primary energy supply, the supply of liquid fuels is reduced in climate policy scenarios compared with baseline scenarios. In addition, the primary feedstock shifts from petroleum and other fossil fuels to bioenergy.

7.11.4 Relationship between short-term action and long-term targets

The relationship between near-term actions and long-term goals is complex and has received a great deal of attention in the research literature. Unlike short-lived species (e.g., CH_4, CO, NO_x, and SO_2) for which stable concentrations are associated with stable emissions, stable concentrations of CO_2 ultimately in the long term require net emissions to decline to zero (Kheshgi et al., 2005).[35] Two important implications follow from this observation.

First, it is cumulative emissions over the entire century that to a first approximation determines the CO_2 concentration at the end of the century, and therefore no individual year's emissions are critical (for cumulative CO_2 emissions consistent with different concentration goals see Section 6.3.2, and Meinshausen et al, 2009). For any stable concentration of CO_2, emissions must peak and then decline toward zero, and for low concentrations, some period of negative emissions may prove necessary.

35 The precise relationship is subject to uncertainty surrounding processes in both the oceans and on land that govern the carbon cycle. Processes to augment ocean uptake are constrained by international agreements.

Second, minimization of global social cost implies an immediate initiation of global emissions mitigation, relative to a reference, no-climate-policy scenario, with a marginal value of carbon that rises exponentially (Hotelling, 1931; Peck and Wan, 1996). The consequence of this latter feature is that emissions abatement and the deployment of mitigation technologies grows over time. When only a long-term state, e.g., a fixed level of radiative forcing in a specific year such as 2.6 Wm^{-2} in 2100, is prescribed, the interim path can theoretically take on any value before the target year. 'Overshoot scenarios' are scenarios for which target values are exceeded during the period before the target date. They are possible because carbon is removed from the atmosphere by the oceans over an extended period of time, and can be further extended by the ability of society to create negative emissions through sequestration in terrestrial systems (Section 7.5, Chapter 11), production of bioenergy in conjunction with CCS technology (Section 7.5.5), and/or direct air capture (DAC). See for example, Edmonds, et al. (2013).

Even so, the bounded nature of the cumulative emissions associated with any long-term CO_2 concentration limit creates a derived limit on near-term emissions. Beyond some point, the system cannot adjust sufficiently to achieve the goal. Early work linking near-term actions with long-term goals was undertaken by researchers such as Swart, et al. (1998), the 'safe landing' concept, and Bruckner, et al., (1999), the 'tolerable windows' concept. O'Neill, et al., (2010) and Rogelj et al., (2013) assessed the relationship between emissions levels in 2020 and 2050 to meet a range of long-term targets (in 2100). They identified 'emissions windows' through which global energy systems would need to pass to achieve various concentration goals.

Recent intermodel comparison projects AMPERE, LIMITS and RoSE (Bauer et al., 2013; Eom et al., 2013; Kriegler et al., 2013; Luderer et al., 2013; Riahi et al., 2013; Tavoni et al., 2014) have explored the implications of different near-term emissions targets for the attainability and costs of reaching low-concentrations levels of 430–530 ppm CO_2eq. The studies illustrate that the pace of the energy transformation will strongly depend on the attainable level of emissions in the near term (Figure 7.16). Scenarios that achieve comparatively lower global emissions levels by 2030 (< 50 $GtCO_2$eq) show a more gradual transformation to 2050 corresponding to about a doubling of the low-carbon energy share every 20 years. Scenarios with higher 2030 emissions levels (> 55 $GtCO_2$eq) lead to a further 'lock-in' into GHG-intensive energy infrastructures without any significant change in terms of the low-carbon energy share by 2030. This poses a significant challenge for the time period between 2030 and 2050, where the low-carbon share in these scenarios would need to be rapidly scaled by nearly a factor of four (from about 15 % to about 60 % in 20 years).

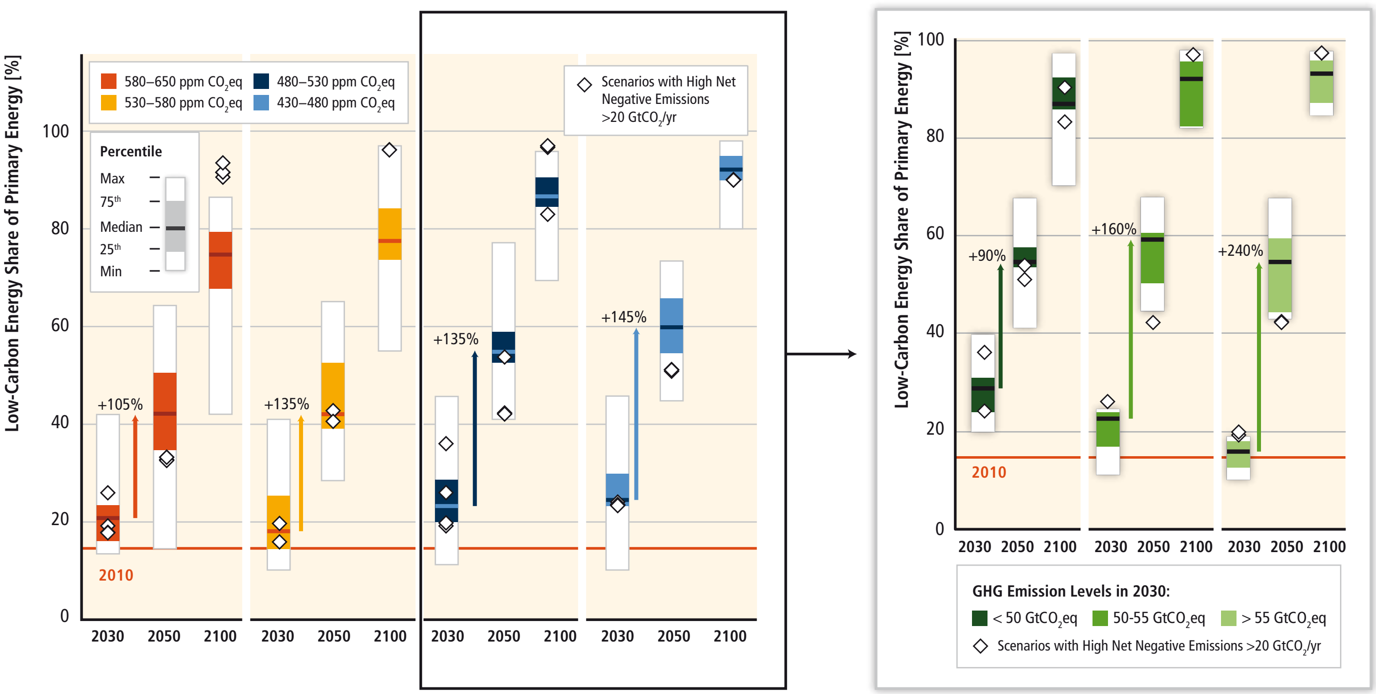


Figure 7.16 | The up-scaling of low-carbon energy in scenarios meeting different 2100 CO_2eq concentration levels (left panel). The right panel shows the rate of up-scaling for different levels of emissions in 2030 in mitigation scenarios reaching 450 to 500 (430–530) ppm CO_2eq concentrations by 2100. Colored bars show the interquartile range and white bars indicate the full range across the scenarios, excluding those with large net negative global emissions (> 20 $GtCO_2$/yr) (see Section 6.3.2 for more details). Scenarios with large net negative global emissions are shown as individual points. The arrows indicate the magnitude of zero- and low-carbon energy supply up-scaling from 2030 to 2050. Zero- and low-carbon energy supply includes renewables, nuclear energy, fossil energy with CCS, and bioenergy with CCS (BECCS). Note: Only scenarios that apply the full, unconstrained mitigation technology portfolio of the underlying models (default technology assumption) are shown. Scenarios with exogenous carbon price assumptions are excluded in both panels. In the right panel, scenarios with policies affecting the timing of mitigation other than 2030 interim targets are also excluded. Sources: WGIII AR5 Scenario Database (see Annex II.10). The right panel builds strongly upon scenarios from multimodel comparisons with explicit 2030 emissions targets: AMPERE: Riahi et al. (2013), Eom et al. (2013); LIMITS: Kriegler et al. (2013), ROSE: Luderer et al. (2013).

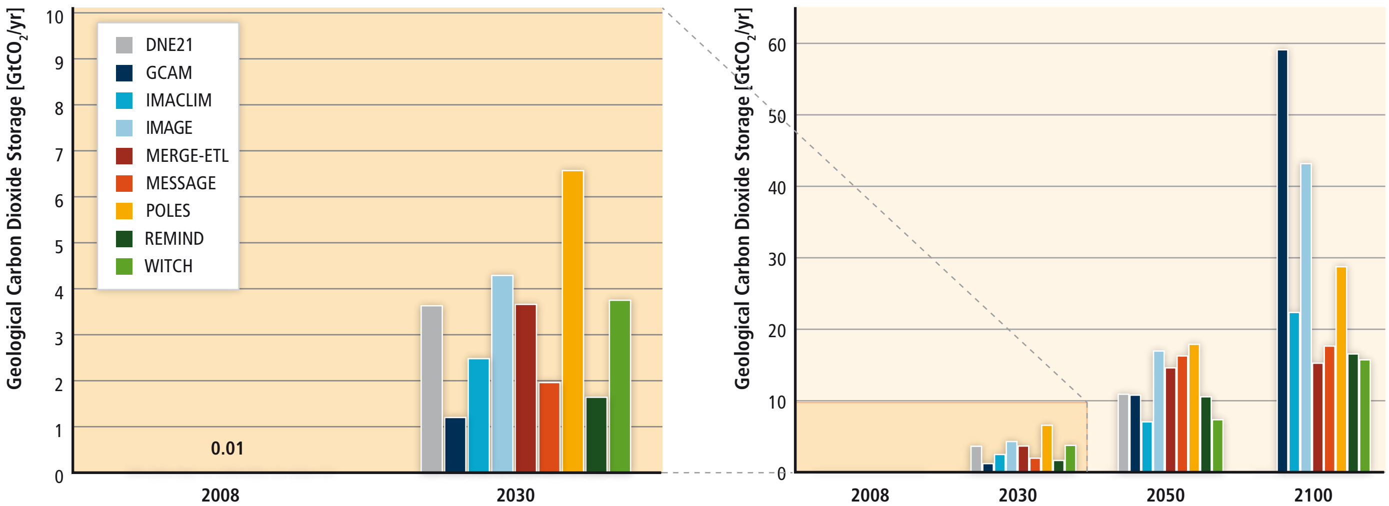


Figure 7.17 | Annual Levels of Geological Carbon Dioxide Storage in cost-effective mitigation scenarios reaching 430–530 ppm CO_2eq. Source: AMPERE intermodelling comparison; Eom et al. (2013), Riahi et al. (2013). Source: Reprinted from *Technological Forecasting and Social Change*, Eom J. et al., "The impact of near-term climate policy choices on technology and emission transition pathways", 2013, with permission from Elsevier.

Eom et al. (2013) indicates that such rapid transformations due to delays in near-term emissions reductions would pose enormous challenges with respect to the up-scaling of individual technologies. The study shows that depending on the assumptions about the technology portfolio, a quadrupling of the low-carbon share over 20 years (2030–2050) would lead on average to the construction of 29 to 107 new nuclear plants per year. While the lower-bound estimate corresponds to about the observed rate of nuclear power installations in the 1980s (Wilson et al., 2013), the high estimate is historically unprecedented. The study further indicates an enormous requirement for the future up-scaling of RE technologies. For instance, solar power is projected in the models to increase by 50–360 times of the year-2011 global solar capacity between 2030 and 2050. With respect to the attainability of such high deployment rates, the recent study by Wilson et al. (2013) indicates that the diffusion of successful technologies in the past has been generally more rapid than the projected technology diffusion by integrated models.

As shown in Figure 7.17, cost-effective pathways (without delay) show a remarkable near-term up-scaling (between 2008 and 2030) of CCS technologies by about three orders of magnitude from the current CCS facilities that store a total of 5 $MtCO_2$ per year (see also, Sathre et al., 2012). The deployment of CCS in these scenarios is projected to accelerate even further reaching CO_2 storage rates of about half to double current global CO_2 emissions from fossil fuel and industry by 2100. The majority of the models indicate that in absence of this CCS potential, the transformation to low-GHG concentrations (about 480 ppm CO_2eq) might not be attainable if mitigation is delayed to 2030 (Riahi et al., 2013). Delays in mitigation thus reduce technology choices, and as a result some of the currently optional technologies might become 'a must' in the future (Riahi et al., 2012, 2013; Rogelj et al., 2013). It should be noted that even at the level of CCS deployment as depicted by the cost-effective scenarios, CO_2 storage capacity is unlikely to be a major limiting factor for CCS (see 7.11.2.), however, various concerns related to potential ecological impacts, accidental release of CO_2, and related storage effectiveness of CCS technologies might pose barriers to deployment. (See Section 7.9)

7.12 Sectoral policies

The stabilization of GHG concentrations at a level consistent with the Cancun agreement requires a fundamental transformation of the energy supply system, and the long-term substitution of freely emitting (i.e., unabated)[36] fossil fuel conversion technologies by low-carbon alternatives (Chapter 6, Section 7.11). Studies that have analyzed current policies plus the emission reduction pledges under the Cancun agreement have found that global GHG emissions are expected to grow (den Elzen et al., 2011; IEA, 2011a; e.g., Carraro and Massetti, 2012). As a consequence, additional policies must be enacted and/or the coverage and stringency of the existing ones must be increased if the Cancun agreement is to be fulfilled.

Currently, most countries combine instruments from three domains: economic instruments to guide investments of profit-maximizing firms, information and regulation approaches to guide choices where economic instruments are politically not feasible or not fully reflected in satisficing behaviour of private actors, and innovation and infrastructure policies reflecting public investment in long-term transformation needs (Grubb et al., 2013). This section discusses the outcome of *existing climate policies* that address the energy supply sector in terms of

[36] These are those not using carbon dioxide capture and storage technologies.

their GHG-emission reduction, their influence on the *operation,* and (via changed investments) on the *structure* of the energy system, as well as the associated side effects. The policy categories considered in the following are those introduced in Section 3.8. The motivation behind the policies (e.g., their economic justification) and problems arising from enacting multiple policies simultaneously are discussed in Sections 3.8.6, 3.8.7, 15.3, and 15.7. A general evaluation of the performance of the policies is carried out in Section 15.5.

7.12.1 Economic instruments

GHG pricing policies, such as GHG-emission trading schemes (ETS) and GHG-emission taxes, have been frequently proposed to address the market externalities associated with GHG emissions (see Sections 3.8 and 15.5). In the power sector, GHG pricing has primarily been pursued through emission trading mechanisms and, to a lower extent, by carbon taxes (Sumner et al., 2009; IEA, 2010f; Lin and Li, 2011). Economic instruments associated with the provision of transport fuels and heat are discussed in chapters 8–10.

The existence of GHG (allowance or tax) prices increases the cost of electricity from fossil-fuelled power plants and, as a consequence, average electricity prices. The short-term economic impacts of power price increases for industrial and private consumers have been widely discussed (Parry, 2004; Hourcade et al., 2007). To address the associated distributional impacts, various compensation schemes have been proposed (IEA, 2010f; Burtraw et al., 2012; EU Commission, 2012). The impact of an emission trading scheme on the profitability of power generation can vary. Allowances that are allocated for free lead to windfall gains (Keats and Neuhoff, 2005; IEA, 2010f). With full auctioning, the impact on profitability can vary between different power stations (Keppler and Cruciani, 2010).

From an *operational* point of view, what counts is the *fuel- and technology-dependent* mark up in the marginal costs of fossil fuel power plants due to GHG prices. Power plants with low specific GHG emissions (e.g., combined cycle gas turbines) will see a smaller increase of their marginal costs compared to those with higher specific emissions (e.g., coal power plants). The resulting influence on the relative competiveness of different power plants and the associated effect on the generation mix depends, in part, on fuel prices (which help set the marginal cost reference levels) and the stringency of the GHG-emission cap or tax (defining the GHG price) (IEA, 2010f).

Although GHG taxes are expected to have a high economic efficiency (see Section 15.5.2), explicit GHG taxes that must be obeyed by the power sector (e.g., as part of an economy-wide system) have only been enacted in a couple of countries (WEC, 2008; Tanaka, 2011). In contrast, taxes on fuels are common (Section 15.5.2). Concerning *operational decisions,* GHG taxes, taxes or charges on input fuels and emission permit schemes are equal as long as the resulting (explicit or implicit) GHG price is the same. Concerning *investment decisions (especially those made under uncertainty)*, there are differences that are discussed as part of the 'prices versus quantities' debate (see Weitzman, 1974, 2007; OECD, 2009). Due to some weaknesses of existing ETSs and associated uncertainties, there is a renewed interest in hybrid systems, which combine the merits of both approaches by introducing price caps (serving as 'safety valves') and price floors into emission trading schemes to increase their flexibility in the context of uncertain costs (Pizer, 2002; Philibert, 2008). Concerning the issue of potential intertemporal and spatial leakages, as discussed in the Green Paradox literature (Section 15.5.2.4), differences between tax and GHG ETSs exist as well. Options to address these issues are discussed in Section 15.5.3.8 and Kalkuhl and Edenhofer (2013).

The EU ETS[37] is perhaps the world's most-prominent example of a GHG trading scheme, and the GHG prices observed in that market, in combination with other policies that have been enacted simultaneously, have been effective in changing *operating and investment choices* in a way that has allowed the *short-term* fulfilment of the sector-specific GHG reduction goals (Ellerman et al., 2010; IEA, 2010f). The significant associated emission reductions compared to the baseline are discussed in Section 14.4.2.1. Shortcomings of emissions trading in general, and the EU ETS in particular (e.g., the high GHG price volatility and the resulting lack of stable price signals), are addressed by (Grubb et al., 2006; Neuhoff et al., 2006; Åhman et al., 2007; Kettner et al., 2008; Ellerman et al., 2010; IEA, 2010f; Pahle et al., 2011). According to the IEA (2010f), these shortcomings can be mitigated by setting long-term emission caps that are consistent with given GHG concentration stabilization goals and by avoiding a free allocation of allowances to power producers. A general discussion of the performance of GHG trading schemes is given in Section 15.5.3, including programs outside Europe. The main factors that have contributed to the low EU ETS carbon prices currently observed include caps that are modest in comparison to the Cancun agreement, relatively low electricity demand due to the economic crisis in the EU, increasing shares of RE, as well as an unexpected high inflow of certificates from CDM projects (IEA, 2013c).

In the longer term and provided that sufficiently stringent emissions caps are set, GHG pricing (potentially supplemented by technology support, see Section 15.6) can support low-emitting technologies (e.g., RE, nuclear power, and CCS) due to the fuel- and technology-dependent mark-up in the marginal costs of fossil fuel power plants:

(a) The economic performance of nuclear power plants, for instance, can be improved by the establishment of GHG pricing schemes (NEA, 2011b; Linares and Conchado, 2013).

(b) CCS technologies applied in the power sector will only become competitive with their freely emitting (i.e., unabated) counterparts if the additional investment and operational costs associated with the CCS technology are compensated for by sufficiently high carbon prices

[37] For additional information on the history and general success of this policy see Sections 14.4.2.1, and 15.5.3.

or direct financial support (Herzog, 2011; IEA, 2013c). In terms of the price volatility seen in the ETS, Oda and Akimoto (2011) analyzed the influence of carbon price volatility on CCS investments and concluded that carbon prices need to be higher to compensate for the associated uncertainty. The provision of capital grants, investment tax credits, credit guarantees, and/or insurance are considered to be suitable means to support CCS technologies as long as they are in their early stages of development (IEA, 2013c).

(c) Many RE technologies still need direct (e.g., price-based or quantity-based deployment policies) or indirect (e.g., sufficiently high carbon prices and the internalization of other externalities) support if their market shares are to be increased (see Section 7.8.2; IPCC, 2011a; IRENA, 2012a). To achieve this goal, specific RE deployment policies have been enacted in a large number of countries (Halsnæs et al., 2012; Zhang et al., 2012; REN21, 2013). These policies are designed to facilitate the process of bringing RE technologies down the learning curve (IEA, 2011f; IRENA, 2012a). Taken together, RE policies have been successful in driving an escalated growth in the deployment of RE (IPCC, 2011a). Price-based mechanisms (such as feed-in tariffs (FITs)) and quantity-based systems (such as quotas or renewable portfolio standards, RPS, and tendering/bidding) are the most common RE deployment policies in the power sector (Section 15.6, Halsnæs et al., 2012; REN21, 2013). With respect to their success and efficiency, the SRREN SPM (IPCC, 2011a, p.25) notes "that some feed in tariffs have been effective and efficient at promoting RE electricity, mainly due to the combination of long-term fixed price or premium payments, network connections, and guaranteed purchase of all RE electricity generated. Quota policies can be effective and efficient if designed to reduce risk; for example, with long-term contracts". Supported by Klessmann et al. (2013), a new study confirms: "Generally, it can be concluded that support schemes, which are technology specific, and those that avoid unnecessary risks in project revenues, are more effective and efficient than technology-neutral support schemes, or schemes with higher revenue risk" (Ragwitz and Steinhilber, 2013).

Especially in systems with increasing and substantial shares of RE and "despite the historic success of FITs, there is a tendency to shift to tender-based systems because guaranteed tariffs without a limit on the total subsidy are difficult to handle in government budgets. Conversely a system with competitive bidding for a specified amount of electricity limits the total amount of subsidy required" (Halsnæs et al., 2012, p.6). A renewed tendency to shift to tender-based systems with public competitive bidding to deploy renewables is observed by REN21 (2013) as well. Assessing the economic efficiency of RE policies requires a clear distinction between whether a complete macroeconomic assessment is intended (i.e., one where competing mitigation options are taken into account as well) or whether prescribed and time-dependent RE shares are to be achieved in a cost-effective manner. In addition, the planning horizon must be clearly stated. RE policies might be considered to be inefficient in a short-term (myopic) perspective, while they could be potentially justified in an intertemporal setting where a dynamic optimization over a couple of decades is carried out (see Section 15.6, IEA, 2011f; SRREN Sections 11.1.1 and 11.5.7.3 in IPCC, 2011a; Kalkuhl et al., 2012, 2013).

Issues related to synergetic as well as adverse interactions of RE policies with GHG policies (Halsnæs et al., 2012) are discussed in detail in Section 15.7 and SRREN Sections 11.1.1 and 11.5.7.3. A new line of reasoning shows that delayed emission-pricing policies can be partially compensated by near-term support of RE (Bauer et al., 2012). The macroeconomic burden associated with the promotion of RE is emphasized by Frondel et al. (2010). The relationship between RE policy support and larger power markets is also an area of focus. Due to the 'merit order effect', RE can, in the short term, reduce wholesale electricity prices by displacing power plants with higher marginal costs (Bode, 2006; Sensfuß et al., 2008; Woo et al., 2011; Würzburg et al., 2013), though in the long term, the impact may be more on the temporal profile of wholesale prices and less on overall average prices. The promotion of low-carbon technologies can have an impact on the economics of backup power plants needed for supply security. The associated challenges and options to address them are discussed in Lamont, (2008); Sáenz de Miera et al., (2008); Green and Vasilakos, (2011); Hood, (2011); Traber and Kemfert, (2011); IEA, (2012b, 2013b; c); and Hirth, (2013).

According to Michaelowa et al., (2006); Purohit and Michaelowa, (2007); Restuti and Michaelowa, (2007); Bodas Freitas et al., (2012); Hultman et al., (2012); Zhang et al., (2012); and Spalding-Fecher et al., (2012), the emissions credits generated by the Clean Development Mechanism (CDM) have been a significant incentive for the expansion of renewable energy in developing countries.

Zavodov (2012), however, has questioned this view and argues that CDM in its current form is not a reliable policy tool for long-term RE development plans. In addition, CCS has been accepted as an eligible measure under the CDM by the UN (IEA, 2010g).

The phaseout of inefficient fossil fuel subsidies as discussed during the G-20 summit meetings in 2009, 2010, 2011, and 2012 will have a visible influence on global energy-related carbon emissions (Bruvoll et al., 2011; IEA, 2011g, 2013c). Removing these subsidies could lead to a 13% decline in CO_2 emissions and generate positive spillover effects by reducing global energy demand (IMF, 2013). In addition, inefficiently low pricing of externalities (e.g., environmental and social costs of electricity production) in the energy supply sector introduces a bias against the development of many forms of low-carbon technologies (IRENA, 2012a).

A mitigation of GHG emissions in *absolute terms* is only possible through policies/measures that either reduce the amount of fossil fuel carbon oxidized and/or that capture and permanently remove GHGs from fossil fuel extraction, processing, and use from the atmosphere (Sections 7.5, 7.11). The deployment of renewable or nuclear energy or energy efficiency as such does not guarantee that fossil fuels will not be burned (in an unabated manner). The interplay between growth in energy demand, energy-efficient improvements, the usage of low-carbon energy, and fossil fuel is discussed in detail in SRREN Chapter 1 (Figure 1.14), and Chapter 10 (IPCC, 2011a).

The question whether or not the deployment of low-carbon technologies *substitutes fossil fuels that otherwise would have emitted GHG* have to take into account the complexity of economic systems and human behaviour (York, 2012). A central aspect in this context is the rebound effect, which is extensively discussed in Sections 3.9.5 and 5.6.2. Spillover effects that are highly related to this issue are discussed in Section 6.3.6. To constrain the related adverse effects, carefully drafted packages combining GHG pricing schemes with technology policies in a way that avoids negative interactions have been proposed (see SRREN Chapter 11 in IPCC, 2011a).

7.12.2 Regulatory approaches

The formulation of low-carbon technologies targets can help technology companies to anticipate the scale of the market and to identify opportunities for their products and services (Lester and Neuhoff, 2009), thus, motivating investments in innovation and production facilities while reducing costs for low-carbon technologies. Currently, for instance, about 138 countries have renewable targets in place. More than half of them are developing countries (REN21, 2013).

The success of energy policies heavily depends on the development of an underlying solid legal framework as well as a sufficient regulatory stability (Reiche et al., 2006; IPCC, 2011a). Property rights, contract enforcement, appropriate liability schemes, and emissions accounting are essential for a successful implementation of climate policies. For example, well-defined responsibilities for the long-term reliability of geologic storages are an important pre-requisite for successful CCS applications (IEA, 2013c), while non-discriminatory access to the grid is of similar importance for RE.

Concerning the promotion of RE, the specific challenges that are faced by developing countries and countries with regulated markets are addressed by IRENA (2012a); IRENA, (2012b); Kahrl (2011); and Zhang et al. (2012). Renewable portfolio standards (or quota obligations, see Section 15.5.4.1) are usually combined with the trading of green certificates and therefore have been discussed under the topic of economic instruments (see Section 7.12.1). Efficiency and environmental performance standards are usual regulatory instruments applied to fossil fuel power plants.

In the field of nuclear energy, a stable policy environment comprising a regulatory and institutional framework that addresses operational safety and the appropriate management of nuclear waste as well as long-term commitments to the use of nuclear energy are requested to minimize investment risks for new nuclear power plants (NEA, 2013).

To regain public acceptance after the Fukushima accident, comprehensive safety reviews have been carried out in many countries. Some of them included 'stress tests', which investigated the capability of existing and projected reactors to cope with extreme natural and man-made events, especially those lying outside the reactor design assumptions. As a result of the accident and the subsequent investigations, a "radical revision of the worst-case assumptions for safety planning" is expected to occur (Rogner, 2013, p. 291).

7.12.3 Information programmes

Though information programs play a minor role in the field of power plant-related energy efficiency improvements and fossil fuel switching, awareness creation, capacity building, and information dissemination to stakeholders outside of the traditional power plant sector plays an important role especially in the use of decentralized RE in LDCs (IRENA, 2012c). Other low-carbon technologies like CCS and nuclear would require specifically trained personnel (see Section 7.10.4). Furthermore, enhanced transparency of information improves public and private decisions and can enhance public perception (see Section 7.9.4).

7.12.4 Government provision of public goods or services

Public energy-related R&D expenditures in the IEA countries peaked in 2009 as a result of economic stimulus packages, but soon after suffered a substantial decline. Although R&D spending is now again rising, energy-related expenditures still account for less than 5 % of total government R&D—compared to 11 % that was observed in 1980 (IEA, 2012j). Nuclear has received significant support in many countries and the share of research, development, and demonstration (RD&D) for RE has increased, but public R&D for CSS is lower, and does not reflect its potential importance (see Section 7.11) for the achievement of negative emissions (von Stechow et al., 2011; Scott et al., 2013) IEA, 2012j).

Although private R&D expenditures are seldom disclosed,[38] they are estimated to represent a large share of the overall spending for RD&D activities (IEA, 2012j). Private R&D investments are not only stimulated by R&D policies. Additional policies (e.g., deployment policies, see 7.12.1 and Section 15.6) addressing other parts of the innovation chain as well as broad GHG pricing policies might assist in triggering private investments in R&D (IPCC, 2011a; Rogge et al., 2011; Battelle, 2012).

The integration of variable RE poses additional challenges, as discussed earlier in Section 7.6, with a variety of possible technical and institutional responses. Many of these technical and institutional measures require an enabling regulatory framework facilitating their application. Infrastructure challenges, e.g., grid extension, are particularly acute

[38] A rare exception is the annual forecast of Battelle (2012).

for RE deployment in developing countries, sometimes preventing deployment (IRENA, 2012a). Governments can play a prominent role in providing the infrastructure (e.g., transmissions grids or the provision of district heating and cooling systems) that is needed to allow for a transformation of energy systems towards lower GHG emissions (IEA, 2012b; Grubb et al., 2013).

7.12.5 Voluntary actions

Voluntary agreements (see Section 15.5.7.4) have been frequently applied in various sectors around the globe, though they often have been replaced by mandatory schemes in the long-term (Halsnæs et al., 2012). According to Chapter 15, their success is mixed. "Voluntary agreements had a positive effect on energy efficiency improvements, but results in terms of GHG emissions reductions have been modest, with the exception of Japan, where the status of these voluntary agreements has also been much more 'binding' than in other countries in line with Japanese cultural traditions" (Halsnæs et al., 2012, p. 13; IPCC, 2007; Yamaguchi, 2012).

7.13 Gaps in knowledge and data

Gaps in knowledge and data are addressed to identify those that can be closed through additional research and others that are inherent to the problems discussed and are therefore expected to persist. Chapter 7 is confronted by various gaps in knowledge, especially those related to methodological issues and availability of data:

- The diversity of energy statistic and GHG emission accounting methodologies as well as several years delay in the availability of energy statistics data limit reliable descriptions of current and historic energy use and emission data on a global scale (Section 7.2, 7.3).

- Although fundamental problems in identifying fossil fuel and nuclear resource deposits, the extent of potential carbon storage sites, and technical potentials of RE are acknowledged, the development of unified and consistent reporting schemes, the collection of additional field data, and further geological modelling activities could reduce the currently existing uncertainties (Section 7.4).

- There is a gap in our knowledge concerning fugitive CH_4 emissions as well as adverse environmental side effects associated with the increasing exploitation of unconventional fossil fuels. As novel technologies are applied in these fields, research could help reduce the gap. Operational and supply chain risks of nuclear power plants, the safety of CCS storage sites and adverse side effects of some RE, especially biomass and hydropower, are often highly dependent on the selected technologies and the locational and regulatory context in which they are applied. The associated risks are therefore hard to quantify, although further research could, in part, reduce the associated knowledge gaps (Section 7.5).

- There is limited research on the integration issues associated with high levels of low-carbon technology utilization (Section7.6).

- Knowledge gaps pertain to the regional and local impacts of climate change on the technical potential for renewable energy and appropriate adaptation, design, and operational strategies to minimize the impact of climate change on energy infrastructure (Section 7.7).

- The current literature provides a limited number of comprehensive studies on the economic, environmental, social, and cultural implications that are associated with low-carbon emission paths. Especially, there is a lack of consistent and comprehensive global surveys concerning the current cost of sourcing and using unconventional fossil fuels, RE, nuclear power, and the expected ones for CCS and BECCS. In addition, there is a lack of globally comprehensive assessments of the external cost of energy supply and GHG-related mitigation options (Sections 7.8, 7.9, 7.10).

- Integrated decision making requires further development of energy market models as well as integrated assessment modelling frameworks, accounting for the range of possible cobenefits and tradeoff between different policies in the energy sector that tackle energy access, energy security, and/or environmental concerns (Section 7.11).

- Research on the effectiveness and cost-efficiency of climate-related energy policies and especially concerning their interaction with other policies in the energy sector is limited (Section 7.12).

7.14 Frequently Asked Questions

FAQ 7.1 How much does the energy supply sector contribute to the GHG emissions?

The energy supply sector comprises all energy extraction, conversion, storage, transmission, and distribution processes with the exception of those that use final energy in the demand sectors (industry, transport, and building). In 2010, the energy supply sector was responsible for 46 % of all energy-related GHG emissions (IEA, 2012b) and 35 % of anthropogenic GHG emissions, up from 22 % in 1970 (Section 7.3).

In the last 10 years, the growth of GHG emissions from the energy supply sector has outpaced the growth of all anthropogenic GHG emissions by nearly 1 % per year. Most of the primary energy delivered to the sector is transformed into a diverse range of final energy products including electricity, heat, refined oil products, coke, enriched coal, and natural gas. A significant amount of energy is used for transformation, making the sector the largest consumer of energy. Energy use in the sector results from end-user demand for higher-quality energy carriers such as electricity, but also the relatively low average global efficiency of energy conversion and delivery processes (Sections 7.2, 7.3).

Increasing demand for high-quality energy carriers by end users in many developing countries has resulted in significant growth in the sectors' GHG emission, particularly as much of this growth has been fuelled by the increased use of coal in Asia, mitigated to some extent by increased use of gas in other regions and the continued uptake of low-carbon technologies. While total output from low-carbon technologies, such as hydro, wind, solar, biomass, geothermal, and nuclear power, has continued to grow, their share of global primary energy supply has remained relatively constant; fossil fuels have maintained their dominance and carbon dioxide capture and storage (CCS) has yet to be applied to electricity production at scale (Sections 7.2, 7.5).

Biomass and hydropower dominate renewable energy, particularly in developing countries where biomass remains an important source of energy for heating and cooking; per capita emissions from many developing countries remain lower than the global average. Renewable energy accounts for one-fifth of global electricity production, with hydroelectricity taking the largest share. Importantly, the last 10 years have seen significant growth in both wind and solar, which combine to deliver around one-tenth of all renewable electricity. Nuclear energy's share of electricity production declined from maximum peak of 17 % in 1993 to 11 % in 2012 (Sections 7.2, 7.5).

FAQ 7.2 What are the main mitigation options in the energy supply sector?

The main mitigation options in the energy supply sector are energy efficiency improvements, the reduction of fugitive non-CO_2 GHG emissions, switching from (unabated) fossil fuels with high specific GHG emissions (e. g., coal) to those with lower ones (e. g., natural gas), use of renewable energy, use of nuclear energy, and carbon dioxide capture and storage (CCS). (Section 7.5).

No single mitigation option in the energy supply sector will be sufficient to hold the increase in global average temperature change below 2 °C above pre-industrial levels. A combination of some, but not necessarily all, of the options is needed. Significant emission reductions can be achieved by energy-efficiency improvements and fossil fuel switching, but they are not sufficient by themselves to provide the deep cuts needed. Achieving deep cuts will require more intensive use of low-GHG technologies such as renewable energy, nuclear energy, and CCS.

Using electricity to substitute for other fuels in end-use sectors plays an important role in deep emission cuts, since the cost of decarbonizing power generation is expected to be lower than that in other parts of the energy supply sector (Chapter 6, Section 7.11).

While the combined global technical potential of low-carbon technologies is sufficient to enable deep cuts in emissions, there are local and regional constraints on individual technologies (Sections 7.4, 7.11). The contribution of mitigation technologies depends on site- and context-specific factors such as resource availability, mitigation and integration costs, co-benefits/adverse side effects, and public perception (Sections 7.8, 7.9, 7.10). Infrastructure and integration challenges vary by mitigation technology and region. While these challenges are not in general technically insurmountable, they must be carefully considered in energy supply planning and operations to ensure reliable and affordable energy supply (Section 7.6).

FAQ 7.3 What barriers need to be overcome in the energy supply sector to enable a transformation to low-GHG emissions?

The principal barriers to transforming the energy supply sector are mobilizing capital investment; lock-in to long-lived high-carbon systems; cultural, institutional, and legal aspects; human capital; and lack of perceived clarity about climate policy (Section 7.10).

Though only a fraction of available private-sector capital investment would be needed to cover the costs of future low-GHG energy supply, a range of mechanisms—including climate investment funds, carbon pricing, removal of fossil fuel subsidies and private/public initiatives aimed at lowering barriers for investors—need to be utilized to direct investment towards energy supply (Section 7.10.2).

Long-lived fossil energy system investments represent an effective (high-carbon) lock-in. The relative lack of existing energy capital in many developing countries therefore provides opportunities to develop a low-carbon energy system (Section 7.10.5).

A holistic approach encompassing cultural, institutional, and legal issues in the formulation and implementation of energy supply strategies is essential, especially in areas of urban and rural poverty where conventional market approaches are insufficient. Human capital capacity building—encompassing technological, project planning, and institutional and public engagement elements—is required to develop a skilled workforce and to facilitate wide-spread adoption of renewable, nuclear, CCS, and other low-GHG energy supply options (Sections 7.10.3, 7.10.4).

Elements of an effective policy aimed at achieving deep cuts in CO_2 emissions would include a global carbon-pricing scheme supplemented by technology support, regulation, and institutional development tailored to the needs to individual countries (notably less-developed countries) (Section 7.12, Chapters 13–15).

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8 Transport

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Dedication to Lee Schipper

This Transport chapter is dedicated to the memory of Leon Jay (Lee) Schipper. A leading scientist in the field of energy research with emphasis on transport, Lee died on 16 August 2011 at the age of 64. He was a friend and colleague of many of the Chapter authors who were looking forward to working with him in his appointed role as Review Editor. Lee's passing is a great loss to the research field of transport, energy, and the environment and his expertise and guidance in the course of writing this chapter was sorely missed by the author team, as were his musical talents.

Executive Summary

Reducing global transport greenhouse gas (GHG) emissions will be challenging since the continuing growth in passenger and freight activity could outweigh all mitigation measures unless transport emissions can be strongly decoupled from GDP growth (*high confidence*).

The transport sector produced 7.0 $GtCO_2eq$ of direct GHG emissions (including non-CO_2 gases) in 2010 and hence was responsible for approximately 23 % of total energy-related CO_2 emissions (6.7 $GtCO_2$) [8.1]. Growth in GHG emissions has continued since the Fourth Assessment Report (AR4) in spite of more efficient vehicles (road, rail, water craft, and aircraft) and policies being adopted. (*robust evidence, high agreement*) [Section 8.1, 8.3]

Without aggressive and sustained mitigation policies being implemented, transport emissions could increase at a faster rate than emissions from the other energy end-use sectors and reach around 12 Gt CO_2eq/yr by 2050. Transport demand per capita in developing and emerging economies is far lower than in Organisation for Economic Co-operation and Development (OECD) countries but is expected to increase at a much faster rate in the next decades due to rising incomes and development of infrastructure. Analyses of both sectoral and integrated model scenarios suggest a higher emission reduction potential in the transport sector than the levels found possible in AR4 and at lower costs. Since many integrated models do not contain a detailed representation of infrastructural and behavioural changes, their results for transport can possibly be interpreted as conservative. If pricing and other stringent policy options are implemented in all regions, substantial decoupling of transport GHG emissions from gross domestic product (GDP) growth seems possible. A strong slowing of light-duty vehicle (LDV) travel growth per capita has already been observed in several OECD cities suggesting possible saturation. (*medium evidence, medium agreement*) [8.6, 8.9, 8.10]

Avoided journeys and modal shifts due to behavioural change, uptake of improved vehicle and engine performance technologies, low-carbon fuels, investments in related infrastructure, and changes in the built environment, together offer high mitigation potential (*high confidence*).

Direct (tank-to-wheel) GHG emissions from passenger and freight transport can be reduced by:

- *avoiding journeys* where possible—by, for example, densifying urban landscapes, sourcing localized products, internet shopping, restructuring freight logistics systems, and utilizing advanced information and communication technologies (ICT);
- *modal shift* to lower-carbon transport systems—encouraged by increasing investment in public transport, walking and cycling infrastructure, and modifying roads, airports, ports, and railways to become more attractive for users and minimize travel time and distance;
- *lowering energy intensity* (MJ/passenger km or MJ/tonne km)—by enhancing vehicle and engine performance, using lightweight materials, increasing freight load factors and passenger occupancy rates, deploying new technologies such as electric 3-wheelers;
- *reducing carbon intensity of fuels* (CO_2eq/MJ)—by substituting oil-based products with natural gas, bio-methane, or biofuels, electricity or hydrogen produced from low GHG sources.

In addition, indirect GHG emissions arise during the construction of infrastructure, manufacture of vehicles, and provision of fuels (well-to-tank). (*robust evidence, high agreement*) [8.3, 8.4, 8.6 and Chapters 10, 11, 12]

Both short- and long-term transport mitigation strategies are essential if deep GHG reduction ambitions are to be achieved (*high confidence*).

Short-term mitigation measures could overcome barriers to low-carbon transport options and help avoid future lock-in effects resulting, for example, from the slow turnover of vehicle stock and infrastructure and expanding urban sprawl. Changing behaviour of consumers and businesses will likely play an important role but is challenging and the possible outcomes, including modal shift, are difficult to quantify. Business initiatives to decarbonize freight transport have begun, but need support from policies that encourage shifting to low-carbon modes such as rail or waterborne options where feasible, and improving logistics. The impact of projected growth in world trade on freight transport emissions may be partly offset in the near term by more efficient vehicles, operational changes, 'slow steaming' of ships, eco-driving and fuel switching. Other short-term mitigation strategies include reducing aviation contrails and emissions of particulate matter (including black carbon), tropospheric ozone and aerosol precursors (including NO_x) that can have human health and mitigation co-benefits in the short term. (*medium evidence, medium agreement*) [8.2, 8.3, 8.6, 8.10]

Methane-based fuels are already increasing their share for road vehicles and waterborne craft. Electricity produced from low-carbon sources has near-term potential for electric rail and short- to medium-term potential as electric buses, light-duty and 2-wheel road vehicles are deployed. Hydrogen fuels from low-carbon sources constitute longer-term options. Gaseous and liquid-biofuels can provide co-benefits. Their mitigation potential depends on technology advances (particularly advanced 'drop-in' fuels for aircraft and other vehicles) and sustainable feedstocks. (*medium evidence, medium agreement*) [8.2, 8.3]

The technical potential exists to substantially reduce the current CO_2eq emissions per passenger or tonne kilometre for all modes by 2030 and beyond. Energy efficiency and vehicle performance improvements range from 30–50 % relative to 2010 depending on mode and vehicle type. Realizing this efficiency potential will depend on large investments by vehicle manufacturers, which may require strong incentives and regulatory policies in order to achieve GHG emissions reduction goals. (*medium evidence, medium agreement*) [8.3, 8.6, 8.10]

Over the medium-term (up to 2030) to long-term (to 2050 and beyond), urban (re)development and investments in new infrastructure, linked with integrated urban planning, transit-oriented development and more compact urban form that supports cycling and walking can all lead to modal shifts. Such mitigation measures could evolve to possibly reduce GHG intensity by 20–50 % below 2010 baseline by 2050. Although high potential improvements for aircraft efficiency are projected, improvement rates are expected to be slow due to long aircraft life, and fuel switching options being limited, apart from biofuels. Widespread construction of high-speed rail systems could partially reduce short-to-medium-haul air travel demand. For the transport sector, a reduction in total CO_2eq emissions of 15–40 % could be plausible compared to baseline activity growth in 2050. (*medium evidence, medium agreement*) [8.3, 8.4, 8.6, 8.9, 12.3, 12.5]

Barriers to decarbonizing transport for all modes differ across regions, but can be overcome in part by reducing the marginal mitigation costs (*medium evidence, medium agreement*).

Financial, institutional, cultural, and legal barriers constrain low-carbon technology uptake and behavioural change. All of these barriers include the high investment costs needed to build low-emissions transport systems, the slow turnover of stock and infrastructure, and the limited impact of a carbon price on petroleum fuels already heavily taxed. Other barriers can be overcome by communities, cities, and national governments which can implement a mix of behavioural measures, technological advances, and infrastructural changes. Infrastructure investments (USD/tCO_2 avoided) may appear expensive at the margin, but sustainable urban planning and related policies can gain support when co-benefits, such as improved health and accessibility, can be shown to offset some or all of the mitigation costs. (*medium evidence, medium agreement*) [8.4, 8.7, 8.8]

Oil price trends, price instruments on emissions, and other measures such as road pricing and airport charges can provide strong economic incentives for consumers to adopt mitigation measures. Regional differences, however, will likely occur due to cost and policy constraints. Some near term mitigation measures are available at low marginal costs but several longer-term options may prove more expensive. Full societal mitigation costs (USD/tCO_2eq) of deep reductions by 2030 remain uncertain but range from very low or negative (such as efficiency improvements for LDVs, long-haul heavy-duty vehicles (HDVs) and ships) to more than 100 USD/tCO_2eq for some electric vehicles, aircraft, and possibly high-speed rail. Such costs may be significantly reduced in the future but the magnitude of mitigation cost reductions is uncertain. (*limited evidence, low agreement*) [8.6, 8.9]

There are regional differences in transport mitigation pathways with major opportunities to shape transport systems and infrastructure around low-carbon options, particularly in developing and emerging countries where most future urban growth will occur (*robust evidence, high agreement*).

Transport can be an agent of sustained urban development that prioritizes goals for equity and emphasizes accessibility, traffic safety, and time-savings for the poor while reducing emissions, with minimal detriment to the environment and human health. Transformative trajectories vary with region and country due to differences in the dynamics of motorization, age and type of vehicle fleets, existing infrastructure, and urban development processes. Prioritizing access to pedestrians and integrating non-motorized and public transit services can result in higher levels of economic and social prosperity in all regions. Good opportunities exist for both structural and technological change around low-carbon transport systems in most countries but particularly in fast growing emerging economies where investments in mass transit and other low-carbon transport infrastructure can help avoid future lock-in to carbon intensive modes. Mechanisms to accelerate the transfer and adoption of improved vehicle efficiency and low-carbon fuels to all economies, and reducing the carbon intensity of freight particularly in emerging markets, could offset much of the growth in non-OECD emissions by 2030. It appears possible for LDV travel per capita in OECD countries to peak around 2035, whereas in non-OECD countries it will likely continue to increase dramatically from a very low average today. However, growth will eventually need to be slowed in all countries. (*limited evidence, medium agreement*) [8.7, 8.9]

A range of strong and mutually-supportive policies will be needed for the transport sector to decarbonize and for the co-benefits to be exploited (*robust evidence, high agreement*).

Decarbonizing the transport sector is likely to be more challenging than for other sectors, given the continuing growth in global demand, the rapid increase in demand for faster transport modes in developing and emerging economies, and the lack of progress to date in slowing growth of global transport emissions in many OECD countries. Transport strategies associated with broader non-climate policies at all government levels can usually target several objectives simultaneously to give lower travel costs, improved mobility, better health, greater energy security, improved safety, and time savings. Realizing the co-benefits depends on the regional context in terms of economic, social, and political feasibility as well as having access to appropriate and cost-effective advanced technologies. (*medium evidence, high agreement*) [8.4, 8.7]

In rapidly growing developing economies, good opportunities exist for both structural and technological change around low-carbon transport. Established infrastructure may limit the options for modal shift and lead to a greater reliance on advanced vehicle technologies. Policy changes can maximize the mitigation potential by overcoming the barriers to achieving deep carbon reductions and optimizing the synergies. Pricing strategies, when supported by education policies to help create social acceptance, can help reduce travel demand and increase the demand for more efficient vehicles (for example, where fuel economy standards exist) and induce a shift to low-carbon modes (where good modal choice is available). For freight, a range of fiscal, regulatory, and advisory policies can be used to incentivize businesses to reduce the carbon intensity of their logistical systems. Since rebound effects can reduce the CO_2 benefits of efficiency improvements and undermine a particular policy, a balanced package of policies, including pricing initiatives, could help to achieve stable price signals, avoid unintended outcomes, and improve access, mobility, productivity, safety, and health. (*medium evidence*, *medium agreement*) [8.7, 8.9, 8.10]

Knowledge gaps in the transport sector

There is a lack of comprehensive and consistent assessments of the worldwide potential for GHG emission reduction and especially costs of mitigation from the transport sector. Within this context, the potential reduction is much less certain for freight than for passenger modes. For LDVs, the long-term costs and high energy density potential for on-board energy storage is not well understood. Also requiring evaluation is how best to manage the tradeoffs for electric vehicles between performance, driving range and recharging time, and how to create successful business models.

Another area that requires additional research is in the behavioural economic analysis of the implications of norms, biases, and social learning in decision making, and of the relationship between transport and lifestyle. For example, how and when people will choose to use new types of low-carbon transport and avoid making unnecessary journeys is unknown. Consequently, the outcomes of both positive and negative climate change impacts on transport services and scheduled timetables have not been determined, nor have the cost-effectiveness of carbon-reducing measures in the freight sector and their possible rebound effects. Changes in the transport of materials as a result of the decarbonization of other sectors and adaptation of the built environment are unknown. [8.11]

8.1 Freight and passenger transport (land, air, sea and water)

Greenhouse gas (GHG) emissions from the transport sector have more than doubled since 1970, and have increased at a faster rate than any other energy end-use sector to reach 7.0 Gt CO_2eq in 2010[1] (IEA, 2012a; JRC/PBL, 2013; see Annex II.8). Around 80 % of this increase has come from road vehicles (see Figure 8.1). The final energy consumption for transport reached 28 % of total end-use energy in 2010 (IEA, 2012b), of which around 40 % was used in urban transport (IEA, 2013). The global transport industry (including the manufacturers of vehicles, providers of transport services, and constructors of infrastructure) undertakes research and development (R&D) activities to become more carbon and energy efficient. Reducing transport emissions will be a daunting task given the inevitable increases in demand and the slow turnover and sunk costs of stock (particularly aircraft, trains, and large ships) and infrastructure. In spite of a lack of progress to date, the transition required to reduce GHG emissions could arise from new technologies, implementation of stringent policies, and behavioural change.

Key developments in the transport sector since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC, 2007) include:

- continued increase in annual average passenger km per capita, but signs that LDV[2] ownership and use may have peaked in some OECD countries (8.2);
- deployment of technologies to reduce particulate matter and black carbon, particularly in OECD countries (8.2);
- renewed interest in natural gas as a fuel, compressed for road vehicles and liquefied for ships (8.3);
- increased number of electric vehicles (including 2-wheelers) and bus rapid transit systems, but from a low base (8.3);
- increased use of sustainably produced biofuels including for aviation (8.3, 8.10);
- greater access to mobility services in developing countries (8.3, 8.9);
- reduced carbon intensity of operations by freight logistics companies, the slow-steaming of ships, and the maritime industry imposing GHG emission mandates (8.3, 8.10);
- improved comprehension that urban planning and developing infrastructure for pedestrians, bicycles, buses and light-rail can impact on modal choice while also addressing broader sustainability concerns such as health, accessibility and safety (8.4, 8.7);
- better analysis of comparative passenger and freight transport costs between modes (8.6);
- emerging policies that slow the rapid growth of LDVs especially in Asia, including investing in non-motorized transport systems (8.10);
- more fuel economy standards (MJ/km) and GHG emission vehicle performance standards implemented for light and heavy duty vehicles (LDVs and HDVs) (8.10); and
- widely implemented local transport management policies to reduce air pollution and traffic congestion (8.10).

1 CO_2eq units are used throughout this chapter for direct emissions wherever feasible, although this is not always the case in some literature that reports CO_2 emissions only. For most transport modes, non-CO_2 gases are usually less than 5 % of total vehicle emissions.

2 LDVs are motorized vehicles (passenger cars and commercial vans) below approximately 2.5 – 3.0 t net weight with HDVs (heavy duty vehicles or "trucks" or "lorries") usually heavier.

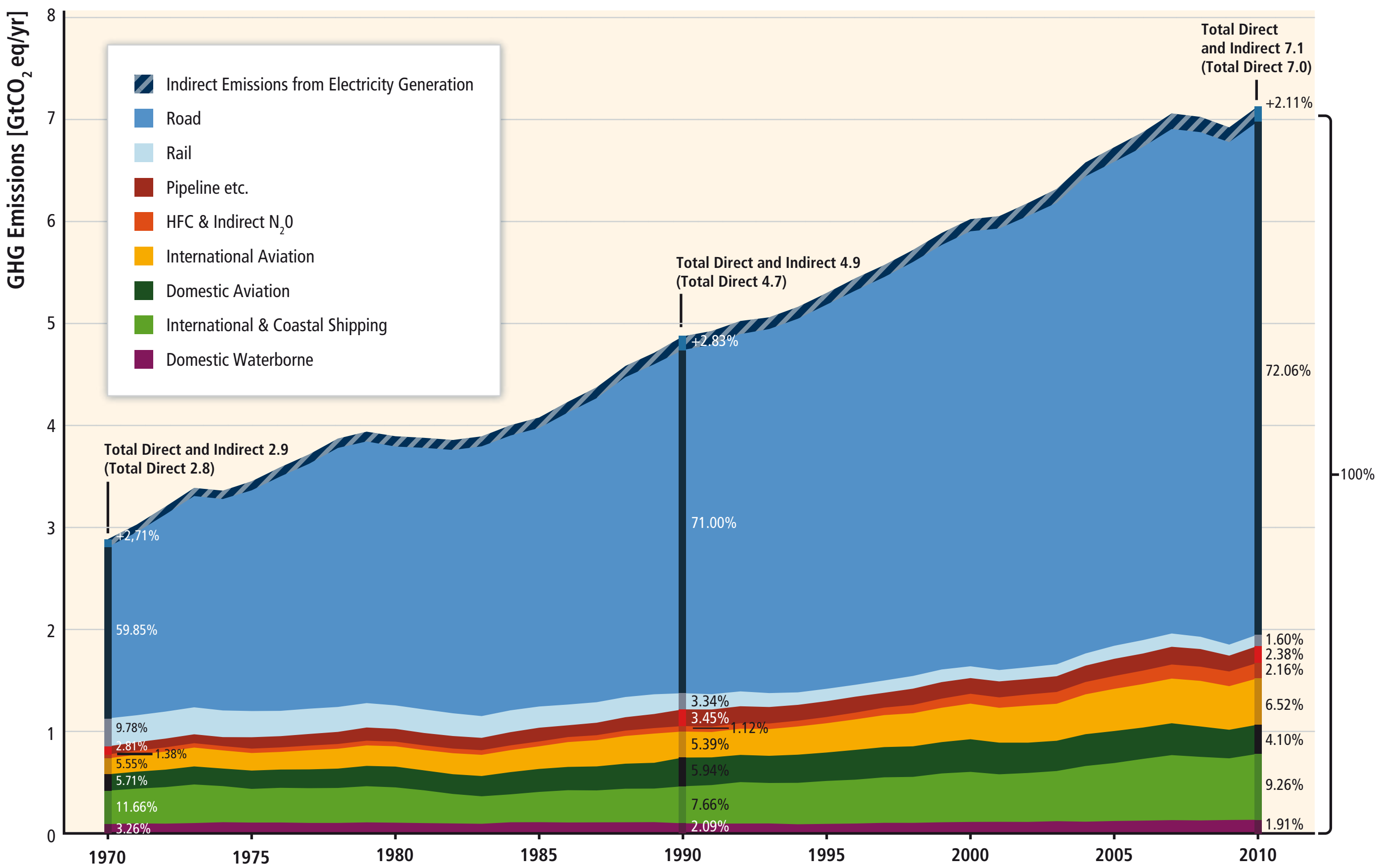


Figure 8.1 | Direct GHG emissions of the transport sector (shown here by transport mode) rose 250 % from 2.8 Gt CO_2eq worldwide in 1970 to 7.0 Gt CO_2eq in 2010 (IEA, 2012a; JRC/PBL, 2013; see Annex II.8).

Note: Indirect emissions from production of fuels, vehicle manufacturing, infrastructure construction etc. are not included.

For each mode of transport, direct GHG emissions can be decomposed[3] into:

- **activity**—total passenger-km/yr or freight tonne-km/yr having a positive feedback loop to the state of the economy but, in part, influenced by behavioural issues such as journey avoidance and restructuring freight logistics systems;
- **system infrastructure and modal choice** *(*NRC, 2009*)*;
- **energy intensity**—directly related to vehicle and engine design efficiency, driver behaviour during operation *(*Davies, 2012*)*, and usage patterns; and
- **fuel carbon intensity**—varies for different transport fuels including electricity and hydrogen.

Each of these components has good potential for mitigation through technological developments, behavioural change, or interactions between them, such as the deployment of electric vehicles impacting on average journey distance and urban infrastructure (see Figure 8.2).

Deep long-term emission reductions also require pricing signals and interactions between the emission factors. Regional differences exist such as the limited modal choice available in some developing countries and the varying densities and scales of cities (Banister, 2011a). Indirect GHG emissions that arise during the construction of transport infrastructure, manufacture of vehicles, and provision of fuels, are covered in Chapters 12, 10, and 7 respectively.

8.1.1 The context for transport of passengers and freight

Around 10 % of the global population account for 80 % of total motorized passenger-kilometres (p-km) with much of the world's population hardly travelling at all. OECD countries dominate GHG transport emissions (see Figure 8.3) although most recent growth has taken place in Asia, including passenger kilometres travelled by low GHG emitting 2- to 3-wheelers that have more than doubled since 2000 (see Figure 8.4). The link between GDP and transport has

[3] Based on the breakdown into A (total Activity), S (modal Structure), I (modal energy Intensity), and F (carbon content of Fuels) using the 'ASIF approach'. Details of how this decomposition works and the science involved can be found in Schipper et al. (2000); Kamakaté and Schipper (2009).

been a major reason for increased GHG emissions (Schafer and Victor, 2000) though the first signs that decoupling may be happening are now apparent (Newman and Kenworthy, 2011a; Schipper, 2011). Slower rates of growth, or even reductions in the use of LDVs, have been observed in some OECD cities (Metz, 2010, 2013; Meyer et al., 2012; Goodwin and van Dender, 2013; Headicar, 2013) along with a simultaneous increase in the use of mass transit systems (Kenworthy, 2013). The multiple factors causing this decoupling, and how it can be facilitated more widely, are not well understood (ITF, 2011; Goodwin and Van Dender, 2013). However, 'peak' travel trends are not expected to occur in most developing countries in the foreseeable future, although transport activity levels may eventually plateau at lower GDP levels than for OECD countries due to higher urban densities and greater infrastructure constraints (ADB, 2010; Figueroa and Ribeiro, 2013).

As shown in Figure 8.3, the share of transport emissions tended to increase due to structural changes as GDP per capita increased, i.e., countries became richer. The variance between North America and other OECD countries (Western Europe and Pacific OECD) shows that the development path of infrastructure and settlements taken by developing countries and economies in transition (EITs) will have a significant impact on the future share of transport related emissions and, consequently, total GHG emissions (see Section 12.4).

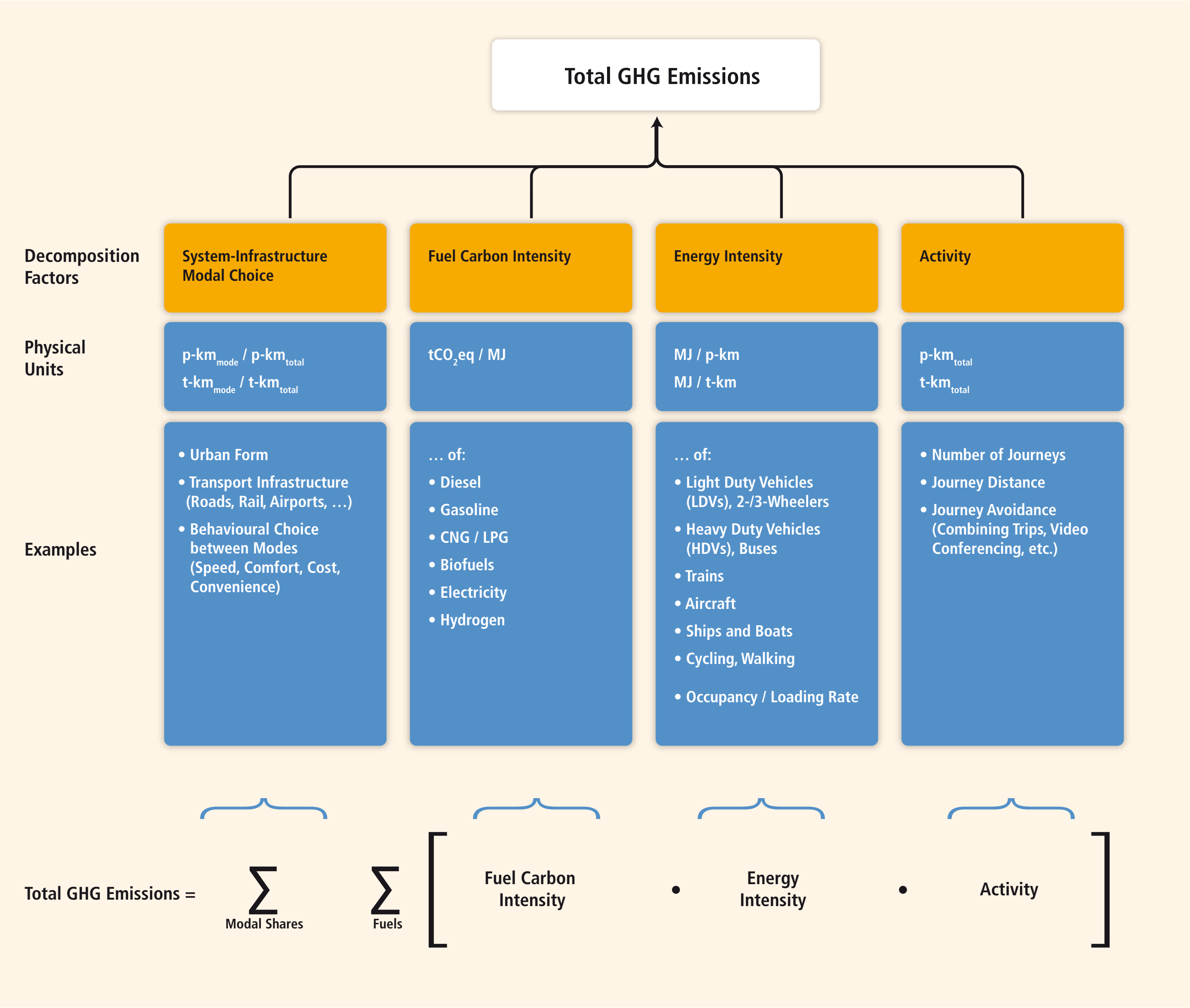


Figure 8.2 | Direct transport GHG emission reductions for each mode and fuel type option decomposed into activity (passenger or freight movements); energy intensity (specific energy inputs linked with occupancy rate); fuel carbon intensity (including non-CO_2 GHG emissions); and system infrastructure and modal choice. These can be summated for each modal option into total direct GHG emissions. Notes: p-km = passenger-km; t-km = tonne-km; CNG = compressed natural gas; LPG = liquid petroleum gas (Creutzig et al., 2011; Bongardt et al., 2013).

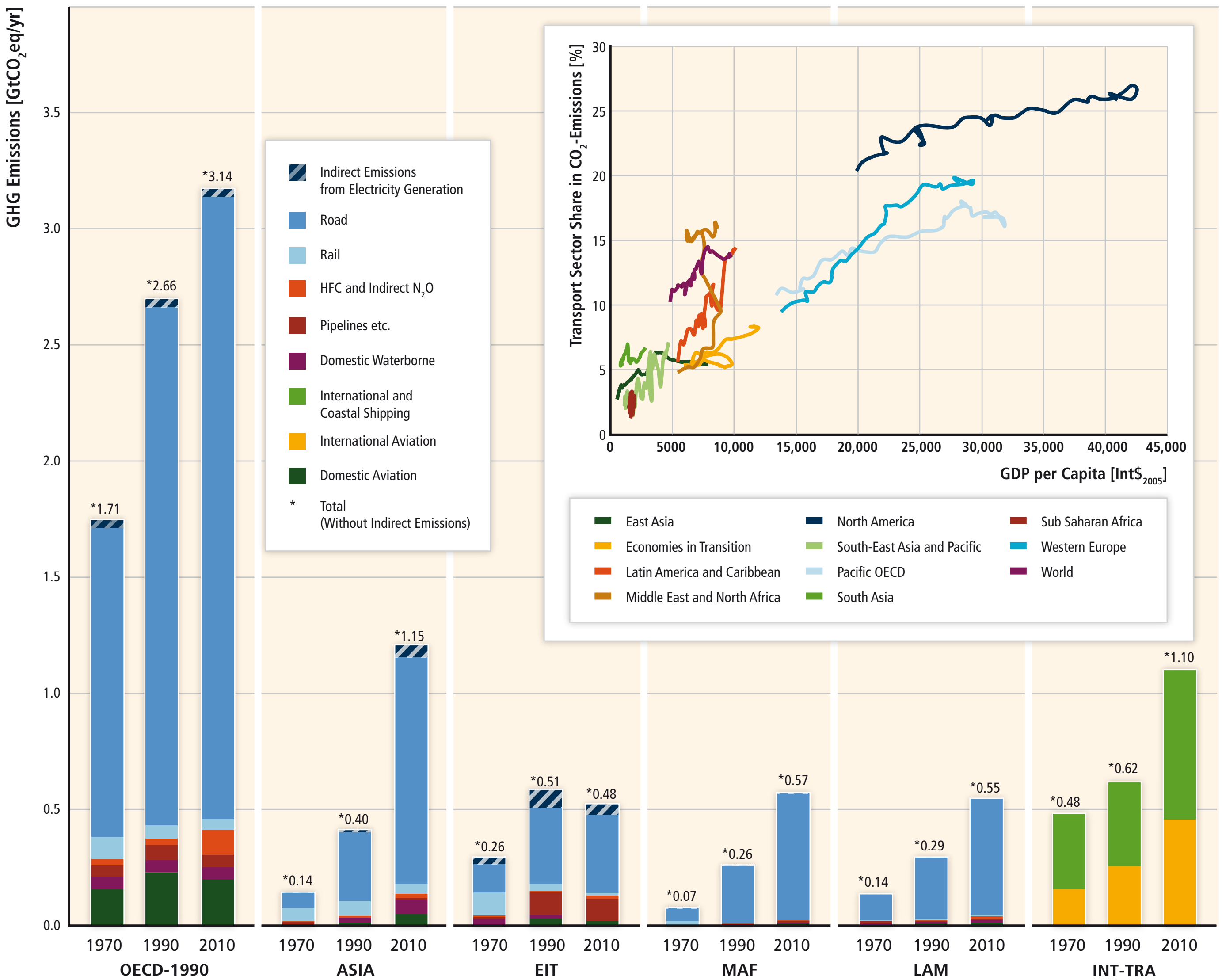


Figure 8.3 | GHG emissions from transport sub-sectors by regions in 1970, 1990 and 2010 with international shipping and aviation shown separately (IEA, 2012a; JRC/PBL, 2013; see Annex II.8). Inset shows the relative share of total GHG emissions for transport relative to GDP per capita from 1970 to 2010 for each region and the world. Adapted from Schäfer et al. (2009), Bongardt et al. (2013) using data from IEA (2012a) and JRC/PBL (2013); see Annex II.8.

8.1.2 Energy demands and direct/indirect emissions

Over 53 % of global primary oil consumption in 2010 was used to meet 94 % of the total transport energy demand, with biofuels supplying approximately 2 %, electricity 1 %, and natural gas and other fuels 3 % (IEA, 2012b). LDVs consumed around half of total transport energy (IEA, 2012c). Aviation accounted for 51 % of all international passenger arrivals in 2011 (UNWTO, 2012) and 17 % of all tourist travel in 2005 (ICAO, 2007a; UNWTO and UNEP, 2008). This gave 43 % of all tourism transport CO_2eq emissions, a share forecast to increase to over 50 % by 2035 (Pratt et al., 2011). Buses and trains carried about 34 % of world tourists, private cars around 48 %, and waterborne craft only a very small portion (Peeters and Dubois, 2010).

Freight transport consumed almost 45 % of total transport energy in 2009 with HDVs using over half of that (Figure 8.5). Ships carried around 80 % (8.7 Gt) of internationally traded goods in 2011 (UNCTAD, 2013) and produced about 2.7 % of global CO_2 emissions (Buhaug and et. al, 2009).

Direct vehicle CO_2 emissions per kilometre vary widely for each mode (see Figure 8.6). The particularly wide range of boat types and sizes gives higher variance for waterborne than for other modes of transport (Walsh and Bows, 2012). Typical variations for freight movement range from ~2 gCO_2/t-km for bulk shipping to ~1,700 gCO_2/t-km for short-haul aircraft, whereas passenger transport typically ranges from ~20–300 gCO_2/p-km. GHG emissions arising from the use of liquid and gaseous fuels produced from unconventional reserves, such as

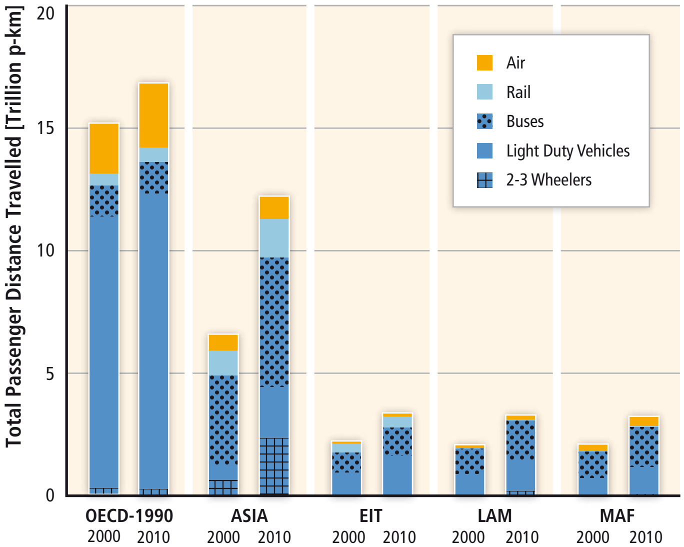


Figure 8.4 | Total passenger distance travelled by mode and region in 2000 and 2010 (IEA, 2012c)

Note: Non-motorized modal shares are not included, but can be relatively high in Asia and Africa. For RC5 region definitions see Annex II.2.

from oil sands and shale deposits, vary with the feedstock source and refining process. Although some uncertainty remains, GHG emissions from unconventional reserves are generally higher per vehicle kilometre compared with using conventional petroleum products (Brandt, 2009, 2011, 2012; Charpentier et al., 2009; ETSAP, 2010; IEA, 2010a; Howarth et al., 2011, 2012; Cathles et al., 2012).

'Sustainable transport', arising from the concept of sustainable development, aims to provide accessibility for all to help meet the basic daily mobility needs consistent with human and ecosystem health, but to constrain GHG emissions by, for example, decoupling mobility from oil dependence and LDV use. Annual transport emissions per capita correlate strongly with annual income, both within and between countries (Chapter 5) but can differ widely even for regions with similar income per capita. For example, the United States has around 2.8 times the transport emissions per capita than those of Japan (IEA, 2012a). In least developed countries (LDCs), increased motorized mobility will produce large increases in GHG emissions but give significant social benefits such as better access to markets and opportunities to improve education and health (Africa Union, 2009; Pendakur, 2011; Sietchiping et al., 2012). Systemic goals for mobility, climate, and energy security can help develop the more general sustainable transport principles. Affordable, safe, equitable, and efficient travel services can be provided with fairness of mobility access across and within generations (CST, 2002; ECMT, 2004; Bongardt et al., 2011; E C Environment, 2011; Zegras, 2011; Figueroa and Kahn Ribeiro, 2013).

The following sections of this chapter outline how changes to the transport sector could reduce direct GHG emissions over the next decades to help offset the significant global increase in demand projected for movement of both passengers and freight.

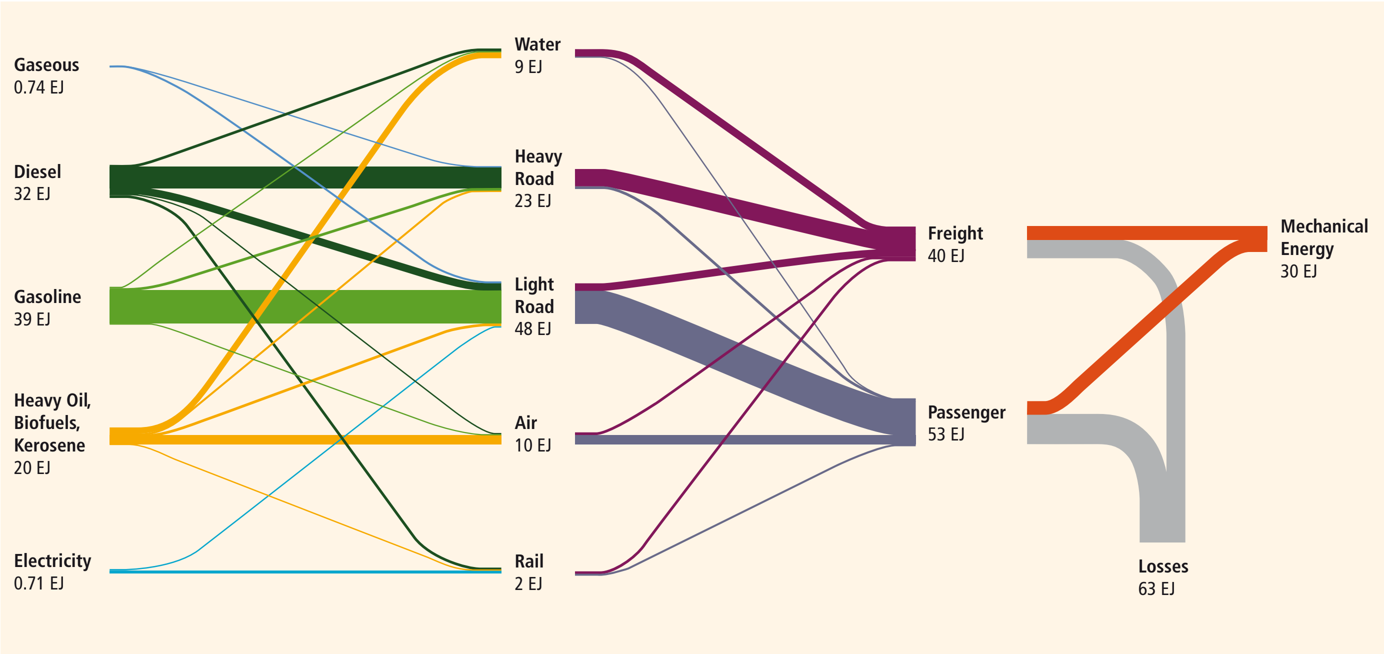


Figure 8.5 | Final energy consumption of fuels by transport sub-sectors in 2009 for freight and passengers, with heat losses at around two thirds of total fuel energy giving an average conversion efficiency of fuel to kinetic energy of around 32 %. Note: Width of lines depicts total energy flows. (IEA, 2012d).

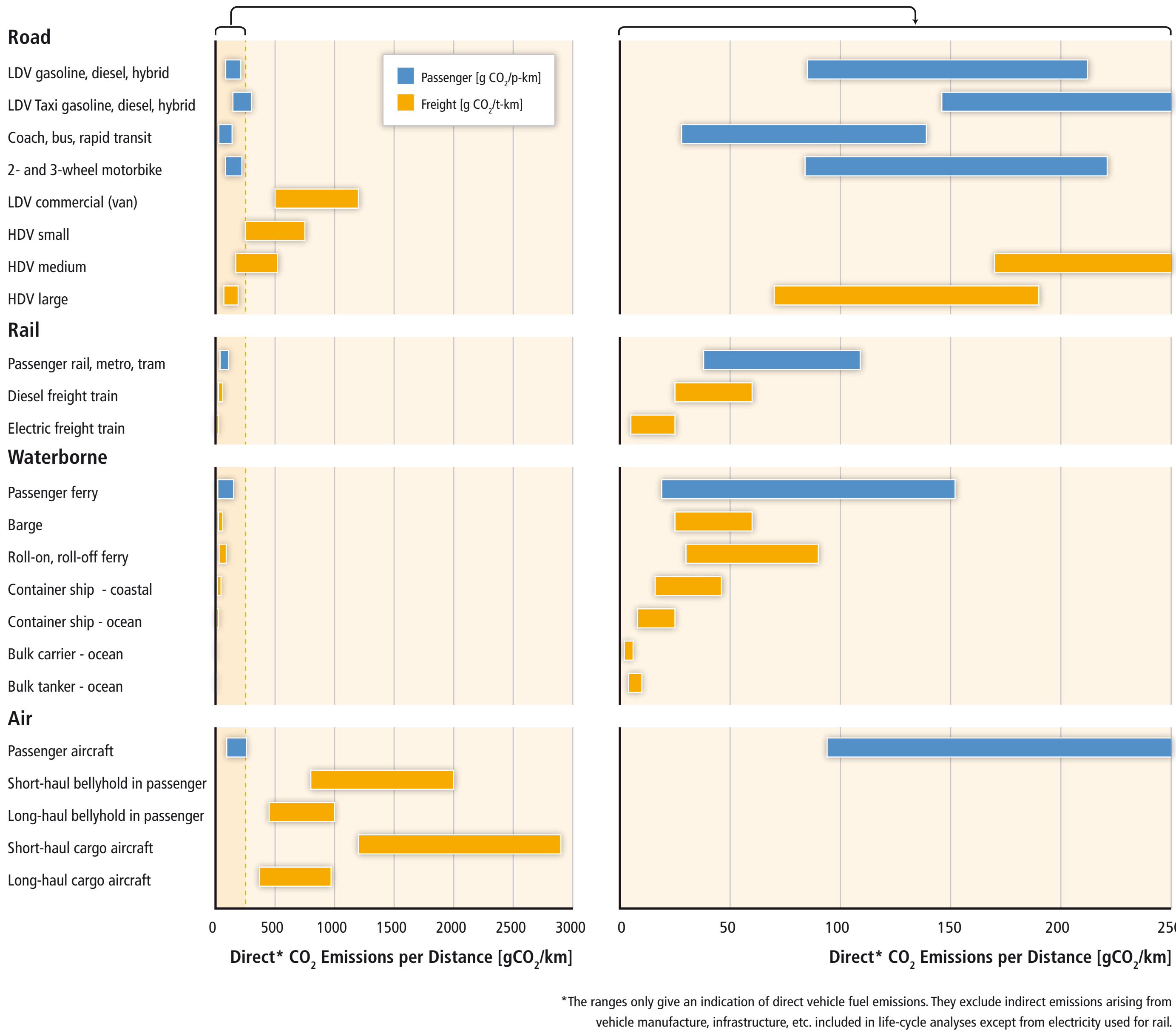


Figure 8.6 | Typical ranges of direct CO_2 emissions per passenger kilometre and per tonne-kilometre for freight, for the main transport modes when fuelled by fossil fuels including thermal electricity generation for rail. (ADEME, 2007; US DoT, 2010; Der Boer et al., 2011; NTM, 2012; WBCSD, 2012).

8.2 New developments in emission trends and drivers

Assessments of transport GHG emissions require a comprehensive and differential understanding of trends and drivers that impact on the movement of goods and people. Transport's share of total national GHG emissions range from up to 30 % in high income economies to less than 3 % in LDCs, mirroring the status of their industry and service sectors (Schäfer et al., 2009; Bongardt et al., 2011) (IEA, 2012a; JRC/PBL, 2013; see Annex II.8) (see inset Figure 8.3). Travel patterns vary with regional locations and the modes available, and guide the development of specific emission reduction pathways.

Indicators such as travel activity, vehicle occupancy rates, and fuel consumption per capita can be used to assess trends towards reducing emissions and reaching sustainability goals (WBCSD, 2004; Dalkmann and Brannigan, 2007; Joumard and Gudmundsson, 2010; Kane, 2010; Litman, 2007; Ramani et al., 2011). For example, petroleum product consumption to meet all transport demands in 2009 ranged from 52 GJ/capita in North America to less than 4 GJ/capita in Africa and India where mobility for many people is limited to walking and cycling. Likewise, residents and businesses of several cities in the United States consume over 100 GJ/capita each year on transport whereas those in many Indian and Chinese cities use less than 2 GJ/capita (Newman and Kenworthy, 2011a). For freight, companies are starting to adopt green initiatives as a means of cost savings and sustainability initiatives (Fürst and Oberhofer, 2012). Such programmes are also likely to reduce GHG emissions, although the long-term impact is difficult to assess.

8.2.1 Trends

As economies have shifted from agriculture to industry to service, the absolute GHG emissions from transport (Figure 8.1) and the share of total GHG emissions by the transport sector (Chapter 5.2.1) have risen considerably. Total LDV ownership is expected to double in the next few decades (IEA, 2009) from the current level of around 1 billion vehicles (Sousanis, 2011). Two-thirds of this growth is expected in non-OECD countries where increased demand for mobility is also being met by motorized two-wheelers and expansion of bus and rail public transport systems. However, passenger kilometres travelled and per capita ownership of LDVs will likely remain much lower than in OECD countries (Cuenot et al., 2012; Figueroa et al., 2013).

Air transport demand is projected to continue to increase in most OECD countries (see Section 8.9). Investments in high-speed rail systems could moderate growth rates over short- to medium-haul distances in Europe, Japan, China, and elsewhere (Park and Ha, 2006; Gilbert and Perl, 2010; Åkerman, 2011; Salter et al., 2011).

There is limited evidence that reductions to date in carbon intensity, energy intensity, and activity, as demonstrated in China, Japan, and Europe, have adequately constrained transport GHG emissions growth in the context of mitigation targets. Recent trends suggest that economic, lifestyle, and cultural changes will be insufficient to mitigate global increases in transport emissions without stringent policy instruments, incentives, or other interventions being needed (see Section 8.10).

8.2.1.1 Non-CO_2 greenhouse gas emissions, black carbon, and aerosols

The transport sector emits non-CO_2 pollutants that are also climate forcers. These include methane, volatile organic compounds (VOCs), nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), F-gases, black carbon, and non-absorbing aerosols (Ubbels et al., 2002; Sections 5.2.2 and 6.6.2.1). Methane emissions are largely associated with leakage from the production of natural gas and the filling of compressed natural gas vehicles; VOCs, NO_x and CO are emitted by internal combustion engines; and F-gas emissions generally from air conditioners (including those in vehicles) and refrigerators. Contrails from aircraft and emissions from ships also impact on the troposphere and the marine boundary layer, respectively (Fuglestvedt et al., 2009; Lee et al., 2010). Aviation emissions can also impact on cloud formation and therefore have an indirect effect on climate forcing (Burkhardt and Kärcher, 2011).

Black carbon and non-absorbing aerosols, emitted mainly during diesel engine operation, have short lifetimes in the atmosphere of only days to weeks, but can have significant direct and indirect radiative forcing effects and large regional impacts (Boucher et al., 2013). In North and South America and Europe, over half the black carbon emissions result from combusting diesel and other heavy distillate fuels (including marine oil), in vehicle engines (Bond et al., 2013). Black carbon emissions are also significant in parts of Asia, Africa, and elsewhere from biomass and coal combustion, but the relative contribution from transport is expected to grow in the future. There is strong evidence that reducing black carbon emissions from HDVs, off-road vehicles, and ships could provide an important short term strategy to mitigate atmospheric concentrations of positive radiative forcing pollutants (USEPA, 2012; Shindell et al., 2013; Chapter 6.6; WG I Chapter 7).

Conversely, transport is also a significant emitter of primary aerosols that scatter light and gases that undergo chemical reactions to produce secondary aerosols. Primary and secondary organic aerosols, secondary sulphate aerosols formed from sulphur dioxide emissions, and secondary nitrate aerosols from nitrogen oxide emissions from ships, aircraft, and road vehicles, can have strong, local, and regional cooling impacts (Boucher et al., 2013).

The relative contributions of different short-term pollutants to radiative forcing in 2020 have been equated by Unger et al. (2010) to having continuous constant GHG emissions since 2000. Although this study did not provide a projection for future emissions scenarios, it did offer a qualitative comparison of short- and long-term impacts of different pollutants. Relative to CO_2, major short-term impacts stem from black carbon, indirect effects of aerosols and ozone from land vehicles, and aerosols and methane emissions associated with ships and aircraft. Their relative impacts due to the longer atmospheric lifetime of CO_2 will be greatly reduced when integrated from the present time to 2100.

Although emissions of non-CO_2 GHGs and aerosols can be mitigated by reducing carbon intensity, improving energy intensity, changing to lower-carbon modes, and reducing transport activity, they can also be significantly reduced by technologies that prevent their formation or lead to their destruction using after-treatments. Emission control devices such as diesel particulate filters and selective catalytic reduction have fuel efficiency penalties that can lead to an increase in transport CO_2 emissions.

Non-CO_2 emissions from road transport and aviation and shipping activities in ports have historically been constrained by local air quality regulations that are directed at near-surface pollution and seek to protect human health and welfare by reducing ozone, particulate matter, sulphur dioxide, and toxic components or aerosols, including vanadium, nickel, and polycyclic aromatic hydrocarbons (Verma et al. 2011). The importance of regional climate change in the context of mitigation has prompted a growing awareness of the climate impact of these emissions. Policies are already in place for reducing emissions of F-gases, which are expected to continue to decrease with time (Prinn et al., 2000). More efforts are being directed at potential programmes to accelerate control measures to reduce emissions of black carbon, ozone precursors, aerosols, and aerosol precursors (Lin and Lin, 2006). Emissions from road vehicles continue to decrease per unit of travel in many regions due to efforts made to protect human health from air pollution. The implementation of these controls could potentially be accelerated as a driver to mitigate climate change (Oxley et al., 2012). Short-term mitigation strategies that focus on black carbon and contrails from aircraft, together with national and international programmes to reduce aerosol and sulphate emissions from shipping, are being implemented (Buhaug and et. al, 2009; Lack, 2012). However, the human health benefits from GHG emissions reductions and the co-benefits of climate change mitigation through black carbon reductions need to be better assessed (Woodcock et al., 2009).

8.2.2 Drivers

The major drivers that affect transport trends are travel time budgets, costs and prices, increased personal income, and social and cultural factors (Schäfer, 2011). For a detailed discussion of effects of urban form and structure on elasticities of vehicle kilometres travelled see Section 12.4.2.

Travel time budget. Transport helps determine the economy of a city or region based on the time taken to move people and goods around. Travel time budgets are usually fixed and tied to both travel costs and time costs (Noland, 2001; Cervero, 2001; Noland and Lem, 2002). Because cities vary in the proportion of people using different transport modes, urban planners tend to try to adapt land use planning to fit these modes in order to enable speeds of around 5 km/hr for walking, 20–30 km/hr for mass transit, and 40–50 km/hr for LDVs, though subject to great variability. Infrastructure and urban areas are usually planned for walking, mass transit, or LDVs so that destinations can be reached in half an hour on average (Newman and Kenworthy, 1999).

Urban travel time budgets for a typical commute between work and home average around 1.1–1.3 hours per traveller per day in both developed and developing economies (Zahavi and Talvitie, 1980; van Wee et al., 2006). Higher residential density can save fuel for LDVs, but leads to more congested commutes (Small and Verhoef, 2007; Downs, 2004). While new road construction can reduce LDV travel time in the short run, it also encourages increased LDV demand, which typically leads to increases in travel time to a similar level as before (Maat and Arentze, 2012). Moreover, land uses quickly adapt to any new road transport infrastructure so that a similar travel time eventually resumes (Mokhtarian and Chen, 2004).

Regional freight movements do not have the same fixed time demands, but rather are based more on the need to remain competitive by limiting transport costs to a small proportion of the total costs of the goods (Schiller et al. 2010). See also Section 12.4.2.4 on accessibility aspects of urban form.

Costs and prices. The relative decline of transport costs as a share of increasing personal expenditure has been the major driver of increased transport demand in OECD countries throughout the last century and more recently in non-OECD countries (Mulalic et al., 2013). The price of fuel, together with the development of mass transit systems and non-motorized transport infrastructure, are major factors in determining the level of LDV use versus choosing public transport, cycling, or walking (Hughes et al., 2006). Transport fuel prices, heavily influenced by taxes, also impact on the competition between road and rail freight. The costs of operating HDVs, aircraft, and boats increase dramatically when fuel costs go up given that fuel costs are a relatively high share of total costs (Dinwoodie, 2006). This has promulgated the designs of more fuel efficient engines and vehicle designs (Section 8.3) (IEA, 2009). Although the average life of aircraft and marine engines is two to three decades and fleet turnover is slower than for road vehicles and small boats, improving their fuel efficiency still makes good economic sense (IEA, 2009).

The high cost of developing new infrastructure requires significant capital investment that, together with urban planning, can be managed and used as a tool to reduce transport demand and also encourage modal shift (Waddell et al., 2007). Changing urban form through planning and development can therefore play a significant role in the mitigation of transport GHG emissions (see Section 8.4) (Kennedy et al., 2009). See also Section 12.5.2 on urban policy instruments.

Social and cultural factors. Population growth and changes in demographics are major drivers for increased transport demand. Economic structural change, particularly in non-OECD countries, can lead to increased specialization of jobs and a more gender-diversified workforce, which can result in more and longer commutes (McQuaid and Chen, 2012). At the household level, once a motorized vehicle becomes affordable, even in relatively poor households, then it becomes a major item of expenditure; however, ownership has still proven to be increasingly popular with each new generation (Giuliano and Dargay, 2006; Lescaroux, 2010; Zhu et al., 2012). Thus, there is a high growth rate in ownership of motorized two-wheel vehicles and LDVs evident in developing countries, resulting in increasing safety risks for pedestrians and non-motorized modes (Nantulya and Reich 2002; Pendakur, 2011). The development of large shopping centres and malls usually located outside the city centre allows many products to be purchased by a consumer following a single journey but the travel distance to these large shopping complexes has tended to increase (Weltevreden, 2007). For freight transport, economic globalization has increased the volume and distance of movement of goods and materials (Henstra et al., 2007).

Modal choice can be driven by social factors that are above and beyond the usual time, cost, and price drivers. For example, some urban dwellers avoid using mass transit or walking due to safety and security issues. However, there is evidence that over the past decade younger people in some OECD cities are choosing walking, cycling, and mass transit over LDVs (Parkany et al., 2004; Newman and Kenworthy, 2011b; Delbosc and Currie, 2013; Kuhnimhof et al., 2013) although this trend could change as people age (Goodwin and van Dender, 2013).

Another example is that in some societies, owning and driving a LDV can provide a symbolic function of status and a basis for sociability and networking through various sign-values such as speed, safety, success, career achievement, freedom, masculinity, and emancipation of women (Mokhtarian and Salomon, 2001; Steg, 2005; Bamberg et al., 2011; Carrabine and Longhurst, 2002; Miller, 2001; Sheller, 2004; Urry, 2007). In such cases, the feeling of power and superiority associated with owning and using a LDV may influence driver behaviour, for example, speeding without a concern for safety, or without a concern about fuel consumption, noise, or emissions (Brozović and Ando, 2009; Tiwari and Jain, 2012). The possible effects on travel patterns from declining incomes are unclear.

Lifestyle and behavioural factors are important for any assessment of potential change to low-carbon transport options and additional research is needed to assess the willingness of people to change (Ashton-Graham, 2008; Ashton-Graham and Newman, 2013). Disruptive technologies such as driverless cars and consumer-based manufacturing (e.g. 3-D printing) could impact on future transport demands but these are difficult to predict. Likewise, the impact of new information technology (IT) applications and telecommuting could potentially change travel patterns, reduce trips, or facilitate interactions with the mode of choice (ITF, 2011). Conversely, increased demand for tourism is expected to continue to be a driver for all transport modes (Sections 8.1 and 10.4; Gössling et al., 2009).

8.3 Mitigation technology options, practices and behavioural aspects

Technological improvements and new technology-related practices can make substantial contributions to climate change mitigation in the transport sector. This section focuses on energy intensity reduction technology options for LDVs, HDVs, ships, trains and aircraft and fuel carbon intensity reduction options related to the use of natural gas, electricity, hydrogen and biofuels. It also addresses some technology-related behavioural aspects concerning the uptake and use of new technologies, behaviour of firms, and rebound effects. Urban form and modal shift options are discussed in Section 8.4.

8.3.1 Energy intensity reduction—incremental vehicle technologies

Recent advances in LDVs in response to strong regulatory efforts in Japan, Europe, and the United States have demonstrated that there is substantial potential for improving internal combustion engines (ICEs) with both conventional and hybrid drive-trains. Recent estimates suggest substantial additional, unrealized potentials exist compared to similar-sized, typical 2007–2010 vehicles, with up to 50 % improvements in vehicle fuel economy (in MJ/km or litres/100km units, or equal to 100 % when measured as km/MJ, km/l, or miles per gallon) (Bandivadekar et al., 2008; Greene and Plotkin, 2011). Similar or slightly lower potentials exist for HDVs, waterborne craft, and aircraft.

8.3.1.1 Light duty vehicles

As of 2011, leading-edge LDVs had drive-trains with direct injection gasoline or diesel engines (many with turbochargers), coupled with automated manual or automatic transmissions with six or more gears (SAE International, 2011). Drive-train redesigns of average vehicles to bring them up to similar levels could yield reductions in fuel consumption and GHG emissions of 25 % or more (NRC, 2013). In European Union 27 (EU27), the average tested emissions of 2011 model LDVs was 136 gCO_2/km, with some models achieving below 100 gCO_2/km (EEA, 2012). In developing countries, vehicle technology levels are typically lower, although average fuel economy can be similar since vehicle size, weight, and power levels are also typically lower (IEA, 2012d).

Hybrid drive-trains (ICE plus electric motor with battery storage) can provide reductions up to 35 % compared to similar non-hybridized vehicles (IEA, 2012e) and have become mainstream in many countries, but with only a small share of annual sales over the last decade except in Japan, where over two million had been sold by 2012 (IEA, 2012e). There is substantial potential for further advances in drive-train design and operation, and for incremental technologies (NRC, 2013). There is often a time lag between when new technologies first appear in OECD countries and when they reach developing countries, which import mostly second-hand vehicles (IEA, 2009).

Lower fuel consumption can be achieved by reducing the loads that the engine must overcome, such as aerodynamic forces, auxiliary components (including lighting and air conditioners), and rolling resistance. Changes that reduce energy loads include improved aerodynamics, more efficient auxiliaries, lower rolling-resistance tyres, and weight reduction. With vehicle performance held constant, reducing vehicle weight by 10 % gives a fuel economy improvement of about 7 % (EEA, 2006). Together, these non-drive-train changes offer potential fuel consumption reductions of around 25 % (ICCT, 2012a; NRC, 2013). Combined with improved engines and drive-train systems, overall LDV fuel consumption for new ICE-powered vehicles could be reduced by at least half by 2035 compared to 2005 (Bandivadekar et al., 2008; NRC, 2013). This predicted reduction is consistent with the *Global Fuel Economy Initiative* target for new LDVs of a 50 % reduction in average fuel use per kilometre in 2030 compared to 2005 (Eads, 2010).

8.3.1.2 Heavy-duty vehicles

Most modern medium and HDVs already have efficient diesel engines (up to 45 % thermal efficiency), and long-haul trucks often have streamlined spoilers on their cabs to reduce drag, particularly in OECD countries. Aerodynamic drag can also be reduced using other modifications offering up to 10 % reduction in fuel consumption (TIAX, 2009; NRC, 2010; AEA, 2011). In non-OECD countries, many older trucks with relatively inefficient (and highly polluting) engines are common. Truck modernization, along with better engine, tyre, and vehicle maintenance, can significantly improve fuel economy in many cases.

Medium and HDVs in the United States can achieve a reduction in energy intensity of 30–50 % by 2020 by using a range of technology and operational improvements (NRC, 2010a). Few similar estimates are available in non-OECD countries, but most technologies eventually will be applicable for HDVs around the world.

Expanding the carrying capacity of HDVs in terms of both volume and weight can yield significant net reductions in the energy intensity of trucks so long as the additional capacity is well utilized. A comparison of the performance of 18 longer and heavier HDVs in nine countries (ITF/OECD, 2010) concluded that higher capacity vehicles can significantly reduce CO_2 emissions per t-km. The use of long combination vehicles rather than single trailer vehicles has been shown to cut direct GHG emissions by up to 32 % (Woodrooffe and Ash, 2001).

Trucks and buses that operate largely in urban areas with a lot of stop-and-go travel can achieve substantial benefits from using electric hybrid or hydraulic hybrid drive-trains. Typically a 20–30 % reduction in fuel consumption can be achieved via hybridization (Chandler et al., 2006; AEA, 2011).

8.3.1.3 Rail, waterborne craft, and aircraft

Rail is generally energy efficient, but improvements can be gained from multiple drive-trains and load-reduction measures. For example, the high-speed 'Shinkansen' train in Japan gained a 40 % reduction of energy consumption by optimizing the length and shape of the lead nose, reducing weight, and by using efficient power electronics (UIC, 2011); Amtrack in the United States employed regenerative braking systems to reduce energy consumption by 8 % (UIC, 2011); and in China, electrification and other measures from 1975 to 2007 contributed to a 87 % reduction in CO_2 emission intensity of the rail system (He et al., 2010).

Shipping is a comparatively efficient mode of freight and passenger transport, although size and load factor are important determinants for specific motorized craft, large and small. Efficiency of new-built vessels can be improved by 5–30 % through changes in engine and transmission technologies, waste heat recovery, auxiliary power systems, propeller and rotor systems, aerodynamics and hydrodynamics of the hull structure, air lubrication systems, electronically controlled engine systems to give fuel efficient speeds, and weight reduction (IMO, 2009; Notteboom and Vernimmen, 2009; AEA, 2007; IEA, 2009; IMO, 2009; ICCT, 2011). Retrofit and maintenance measures can provide additional efficiency gains of 4–20 % (Buhaug and et. al, 2009) and operational changes, such as anti-fouling coatings to cut water resistance, along with operation at optimal speeds, can provide 5–30 % improvement (Pianoforte, 2008; Corbett et al., 2009; WSC, 2011).

Several methods for improving waterborne craft efficiency are already in use. For example, wind propulsion systems such as kites and parafoils can provide lift and propulsion to reduce fuel consumption by up to 30 %, though average savings may be much less (Kleiner, 2007). Photovoltaics and small wind turbines can provide on-board electricity and be part of 'cold ironing' electric systems in ports. For international shipping, combined technical and operational measures have been estimated to potentially reduce energy use and CO_2 emissions by up to 43 % per t-km between 2007 and 2020 and by up to 60 % by 2050 (Crist, 2009; IMO, 2009).

Aircraft designs have received substantial, on-going technology efficiency improvements over past decades (ITF, 2009) typically offering a 20–30 % reduction in energy intensity compared to older aircraft models (IEA, 2009). Further fuel efficiency gains of 40–50 % in the 2030–2050 timeframe (compared to 2005) could come from weight reduction, aerodynamic and engine performance improvements, and aircraft systems design (IEA, 2009). However, the rate of introduction of major aircraft design concepts could be slow without significant policy incentives, regulations at the regional or global level, or further increases in fuel prices (Lee, 2010). Retrofit opportunities, such as engine replacement and adding 'winglets', can also provide significant reductions (Gohardani et al., 2011; Marks, 2009). Improving air traffic management can reduce CO_2 emissions through more direct routings and flying at optimum altitudes and speeds (Dell'Olmo and Lulli, 2003; Pyrialakou et al., 2012). Efficiency improvements of ground service equipment and electric auxiliary power units can provide some additional GHG reductions (Pyrialakou et al., 2012).

8.3.2 Energy intensity reduction—advanced propulsion systems

At present, most vehicles and equipment across all transport modes are powered by ICEs, with gasoline and diesel as the main fuels for LDVs; gasoline for 2- and 3-wheelers and small water craft; diesel for HDVs; diesel or heavy fuel oil for ships and trains (other than those using grid electricity); and kerosene for aircraft turbine engines. New propulsion systems include electric motors powered by batteries or fuel cells, turbines (particularly for rail), and various hybridized concepts. All offer significant potential reductions in GHG, but will require considerable time to penetrate the vehicle fleet due to slow stock turnover rates.

8.3.2.1 Road vehicles—battery and fuel cell electric-drives

Battery electric vehicles (BEVs) emit no tailpipe emissions and have potentially very low fuel-production emissions (when using low-carbon electricity generation) (Kromer and Heywood, 2007). BEVs operate at a drive-train efficiency of around 80 % compared with about 20–35 % for conventional ICE LDVs. At present, commercially available BEVs typically have a limited driving range of about 100–160km, long recharge times of four hours or more (except with fast-charging or battery switching systems), and high battery costs that lead to relatively high vehicle retail prices (Greene and Plotkin, 2011). Lithium ion (Li-ion) batteries will likely improve but new battery technologies (e.g., Li-air, Li-metal, Li-sulphur) and ultra-capacitors may be required to achieve much higher energy and power densities (IEA, 2009; NRC, 2013). Compressed air as an energy storage medium for LDVs is thermo-dynamically inefficient and would require high storage volume (Creutzig et al., 2009).

Plug-in hybrid electric vehicles (PHEVs) capable of grid recharging typically can operate on battery electricity for 20 to 50 km, but emit CO_2 when their ICE is operating. The electric range of PHEVs is heavily dependent on the size of battery, design architectures, and control strategies for the operation of each mode (Plotkin et al., 2001).

For HDVs, the use of BEVs is most applicable to light-medium duty urban vehicles such as delivery vans or garbage collection trucks whose drive cycles involve frequent stops and starts and do not need a long range (TIAX, 2009; AEA, 2011). Transit buses are also good candidates for electrification either with batteries or more commonly using overhead wire systems (IEA, 2009). Electric 2-wheelers with lower requirements for battery and motor capacities are a mature technology with widespread acceptance, especially in developing countries (Weinert, 2008). For example, there were over 120 million electric 2-wheelers in China by the end of 2010 (Wu et al., 2011).

Fuel cell vehicles (FCVs) can be configured with conventional, hybrid, or plug-in hybrid drive-trains. The fuel cells generate electricity from hydrogen that may be generated on-board (by reforming natural gas, methanol, ammonia, or other hydrogen-containing fuel), or produced externally and stored on-board after refuelling. FCVs produce no tailpipe emissions except water and can offer a driving range similar to today's gasoline/diesel LDVs, but with a high cost increment. Fuel cells typically operate with a conversion efficiency of 54–61 % (significantly better than ICEs can achieve), giving an overall fuel-cycle efficiency of about 35–49 % for an LDV (JHFC, 2011).

Although a number of FCV LDVs, HDVs, and buses have been demonstrated and some are expected to become commercially available within five years, overall it could take 10 years or longer for FCVs to achieve commercial success based on current oil and vehicle purchase prices (IEA, 2012e).

8.3.2.2 Rail, waterborne craft, and aircraft

Diesel-hybrid locomotives demonstrated in the UK and advanced types of hybrid drive-trains under development in the United States and Japan, could save 10–20 % of diesel fuel plus around a 60 % reduction of NO_x and particulate matter compared to conventional locomotives (JR East, 2011). A shift to full electrification may enable many rail systems to reach very low CO_2 emissions per kilometre where electricity generation has been deeply decarbonized. Fuel cell systems for rail may be attractive in areas lacking existing electricity infrastructure (IEA, 2012e).

Most ocean-going ships will probably continue to use marine diesel engines for the foreseeable future, given their high reliability and low cost. However, new propulsion systems are in development. Full electrification appears unlikely given the energy storage requirements for long-range operations, although on-board solar power generation systems could be used to provide auxiliary power and is already used for small craft (Crist, 2009). Fuel cell systems (commonly solid-oxide) with electric motors could be used for propulsion, either with hydrogen fuel directly loaded and stored on board or with on-board reforming. However, the cost of such systems appears relatively high, as are nuclear power systems as used in some navy vessels.

For large commercial aircraft, no serious alternative to jet engines for propulsion has been identified, though fuel-switching options are possible, including 'drop-in' biofuels (that are fungible with petroleum products, can be blended from 0 to 100 %, and are compatible with all existing engines) or hydrogen. Hydrogen aircraft are considered only a very long run option due to hydrogen's low energy density and the difficulty of storing it on board, which requires completely new aircraft designs and likely significant compromises in performance (Cryoplane, 2003). For small, light aircraft, advanced battery electric/motor systems could be deployed but would have limited range (Luongo et al., 2009).

8.3.3 Fuel carbon intensity reduction

In principle, low-carbon fuels from natural gas, electricity, hydrogen, and biofuels (including biomethane) could all enable transport systems to be operated with low direct fuel-cycle CO_2eq emissions, but this would depend heavily on their feedstocks and conversion processes.

Natural gas (primarily methane) can be compressed (CNG) to replace gasoline in Otto-cycle (spark ignition) vehicle engines after minor modifications to fuel and control systems. CNG can also be used to replace diesel in compression ignition engines but significant modifications are needed. Denser storage can be achieved by liquefaction of natural gas (LNG), which is successfully being used for long-haul HDVs and ships (Buhaug and et. al, 2009; Arteconi et al., 2010). The energy efficiency of driving on CNG is typically similar to that for gasoline or diesel but with a reduction of up to 25 % in tailpipe emissions (CO_2/km) because of differences in fuel carbon intensity. Lifecycle GHG analysis suggests lower net reductions, in the range of 10–15 % for natural gas fuel systems. They may also provide a bridge to lower carbon biomethane systems from biogas (IEA, 2009).

Electricity can be supplied to BEVs and PHEVS via home or public rechargers. The varying GHG emissions intensity of power grids directly affects lifecycle CO_2eq emissions (IEA, 2012e). Since the GHG intensity of a typical coal-based power plant is about 1000 gCO_2eq/kWh at the outlet (Wang, 2012a), for a BEV with efficiency of 200 Wh/km, this would equate to about 200 gCO_2eq/km, which is higher than for an efficient ICE or hybrid LDV. Using electricity generated from nuclear or renewable energy power plants, or from fossil fuel plants with carbon dioxide capture and storage (CCS), near-zero fuel-cycle emissions could result for BEVs. The numbers of EVs in any country are unlikely to reach levels that significantly affect national electricity demand for at least one to two decades, during which time electricity systems could be at least partially decarbonized and modified to accommodate many EVs (IEA, 2012e).

Hydrogen used in FCVs, or directly in modified ICEs, can be produced by the reforming of biomass, coal or natural gas (steam methane reforming is well-established in commercial plants); via commercial but relatively expensive electrolysis using electricity from a range of sources including renewable; or from biological processes (IEA, 2009). The mix of feedstocks largely determines the well-to-wheel GHG emissions of FCVs. Advanced, high-temperature and photo-electrochemical technologies at the R&D stage could eventually become viable pathways (Arvizu et al., 2011). Deployment of FCVs (8.3.2.1) needs to be accompanied by large, geographically focused, investments into hydrogen production and distribution and vehicle refuelling infrastructure. Costs can be reduced by strategic placement of stations (Ogden and Nicholas, 2011) starting with specific locations ('lighthouse cities') and a high degree of coordination between fuel suppliers, vehicle manufacturers and policy makers is needed to overcome 'chicken-or-egg' vehicle/fuel supply problems (ITS-UC Davis, 2011).

A variety of liquid and gaseous biofuels can be produced from various biomass feedstocks using a range of conversion pathways (Chapter 11.A.3). The ability to produce and integrate large volumes of biofuels cost-effectively and sustainably are primary concerns of which policy makers should be aware (Sims et al., 2011). In contrast to electricity and hydrogen, liquid biofuels are relatively energy-dense and are, at least in certain forms and blend quantities, compatible with the existing petroleum fuel infrastructure and with all types of ICEs installed in LDVs, HDVs, waterborne craft, and aircraft. Ethanol and biodiesel (fatty-acid-methyl-ester, FAME) can be blended at low levels (10–15 %) with petroleum fuels for use in unmodified ICEs. New ICEs can be cheaply modified during manufacture to accommodate much higher blends as exemplified by 'flex-fuel' gasoline engines where ethanol can reach 85 % of the fuel blend (ANFAVEA, 2012). However, ethanol has about a 35 % lower energy density than gasoline, which reduces vehicle range—particularly at high blend levels— that can be a problem especially for aircraft. Synthetic 'drop-in' biofuels have similar properties to diesel and kerosene fuels. They can be derived from a number of possible feedstocks and conversion processes, such as the hydro-treatment of vegetable oils or the Fischer-Tropsch conversion of biomass (Shah, 2013). Bio-jet fuels suitable for aircraft have been demonstrated to meet the very strict fuel specifications required (Takeshita and Yamaji, 2008; Caldecott and Tooze, 2009). Technologies to produce ligno-cellulosic, Fisher-Tropsch, algae-based, and other advanced biofuels are in development, but may need another decade or more to achieve widespread commercial use (IEA, 2011a). Bio-methane from suitably purified biogas or landfill gas can also be used in natural gas vehicles (REN21, 2012).

Biofuels have direct, fuel-cycle GHG emissions that are typically 30–90 % lower per kilometre travelled than those for gasoline or diesel fuels. However, since for some biofuels, indirect emissions—including from land use change—can lead to greater total emissions than when using petroleum products, policy support needs to be considered on a case by case basis (see Chapter 11.13 and, for example, Lapola et al., 2010; Plevin et al., 2010; Wang et al., 2011; Creutzig et al., 2012a).

8.3.4 Comparative analysis

The vehicle and power-train technologies described above for reducing fuel consumption and related CO_2 emissions span a wide range and are not necessarily additive. When combined, and including different propulsion and fuel systems, their overall mitigation potential can be evaluated as an integrated fuel/vehicle system (see Section 8.6). However, to produce an overall mitigation evaluation of the optimal design of a transport system, non-CO_2 emissions, passenger or freight occupancy factors, and indirect GHG emissions from vehicle manufacture and infrastructure should also be integrated to gain a full comparison of the relative GHG emissions across modes (see Section 8.4; Hawkins et al., 2012; Borken-Kleefeld et al., 2013).

Taking LDVs as an example, a comparative assessment of current and future fuel consumption reduction potentials per kilometre has been made (Figure 8.7), starting from a 2010 baseline gasoline vehicle at about 8 lge[4] /100km and 195 g/km CO_2. Using a range of technologies, average new LDV fuel economy can be doubled (in units of distance per energy, i.e., energy intensity cut by 50 %). Further improvements can be expected for hybrids, PHEVs, BEVs, and FCVs, but several hurdles must be overcome to achieve wide market penetration (see Section 8.8). Vehicle cost increases due to new technologies could affect customers' willingness to pay, and thus affect market penetration, although cost increases would be at least partly offset by fuel cost savings (see Section 8.6).

8.3.5 Behavioural aspects

The successful uptake of more efficient vehicles, advanced technologies, new fuels, and the use of these fuels and vehicles in 'real life' conditions, involves behavioural aspects.

[4] "Litre per gasoline equivalent" allows for a comparison between fuels with different energy contents.

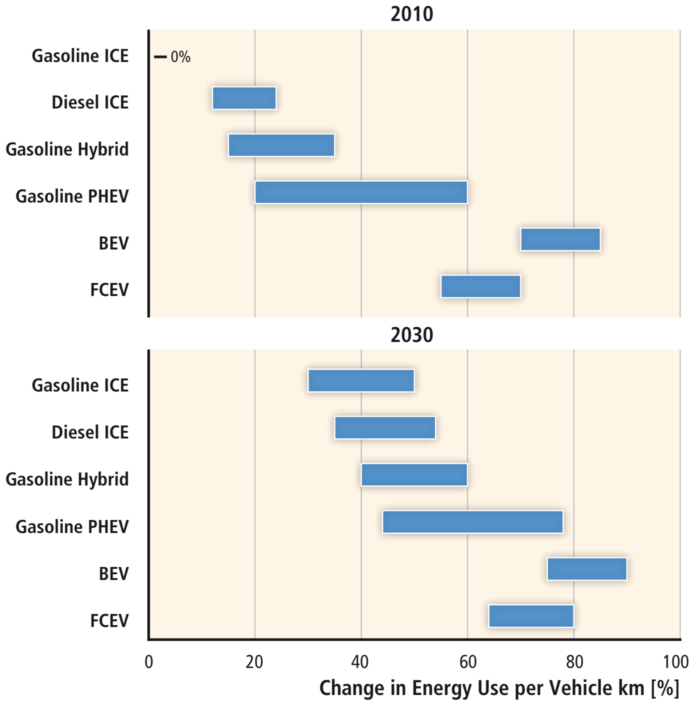


Figure 8.7 | Indicative fuel consumption reduction potential ranges for a number of LDV technology drive-train and fuel options in 2010 and 2030, compared with a baseline gasoline internal combustion engine (ICE) vehicle consuming 8 l/100km in 2010. (Based on Kobayashi et al., 2009; Plotkin et al., 2009; IEA, 2012b; NRC, 2013).

- **Purchase behaviour:** Few consumers attempt to minimize the lifecycle costs of vehicle ownership (Greene, 2010a), which leads to a considerable imbalance of individual costs versus society-wide benefits. There is often a lack of interest in purchasing more fuel efficient vehicles (Wozny and Allcott, 2010) due to imperfect information, information overload in decision making, and consumer uncertainty about future fuel prices and vehicle life (Anderson et al., 2011; Small, 2012). This suggests that in order to promote the most efficient vehicles, strong policies such as fuel economy standards, sliding-scale vehicle tax systems, or 'feebate' systems with a variable tax based on fuel economy or CO_2 emissions may be needed (Section 8.10) (Gallagher and Muehlegger, 2011). Vehicle characteristics are largely determined by the desires of new-car buyers in wealthier countries, so there may be a five-year or longer lag before new technologies reach second-hand vehicle markets in large quantities, particularly through imports to many developing countries (though this situation will likely change in the coming decades as new car sales rise across non-OECD countries) (IEA, 2009).

- **New technologies/fuels:** Consumers' unwillingness to purchase new types of vehicles with significantly different attributes (such as smaller size, shorter range, longer refuelling or recharging time, higher cost) is a potential barrier to introducing innovative propulsion systems and fuels (Brozović and Ando, 2009). This may relate simply to the perceived quality of various attributes or to risk aversion from uncertainty (such as driving range anxiety for BEVs[5]) (Wenzel and Ross, 2005). The extent to which policies must compensate by providing incentives varies but may be substantial (Gallagher and Muehlegger, 2011).

- **On-road fuel economy:** The fuel economy of a vehicle as quoted from independent testing can be up to 30 % better than that actually achieved by an average driver on the road (IEA, 2009; TMO, 2010; ICCT, 2012). This gap reflects a combination of factors including inadequacies in the test procedure, real-world driving conditions (e.g., road surface quality, weather conditions), driver behaviour, and vehicle age and maintenance. Also congested traffic conditions in OECD cities differ from mixed-mode conditions in some developing countries (Tiwari et al., 2008; Gowri et al., 2009). Some countries have attempted to adjust for these differences in their public vehicle fuel economy information. A significant reduction in the gap may be achievable by an 'integrated approach' that includes better traffic management, intelligent transport systems, and improved vehicle and road maintenance (IEA, 2012e).

- **Eco-Driving:** A 5–10 % improvement in on-road fuel economy can be achieved for LDVs through efforts to promote 'eco-driving' (An et al., 2011; IEA, 2012d). Fuel efficiency improvements from eco-driving for HDVs are in the 5–20 % range (AEA, 2011).

- **Driving behaviour with new types of vehicles:** Taking electric vehicles (EVs) as an example, day/night recharging patterns and the location of public recharging systems could affect how much these vehicles are driven, when and where they are driven, and potentially their GHG emissions impacts (Axsen and Kurani, 2012).

- **Driving rebound effects:** Reactions to lowering the cost of travel (through fuel economy measures or using budget airline operators) can encourage more travel, commonly known as the (direct) rebound effect (Greene et al., 1999; for a general discussion of the rebound effect see Section 5.6.1). In North America, fuel cost elasticity is in the range of a −0.05 to −0.30 (e.g., a 50 % cut in the fuel cost would result in a 2.5 % to 15 % increase in driving). Several studies show it is declining (Hughes et al., 2006; Small and van Dender, 2007; EPA, 2012). The rebound effect is larger when the marginal cost of driving (mostly gasoline) is a high share of household income. The implication for non-OECD countries is that the price elasticity of demand for vehicle travel will be a function of household income. The rebound effect may be higher in countries with more modal choice options or where price sensitivity is higher, but research is poor for most countries and regions outside the OECD. Minimizing the rebound can be addressed by fuel taxes or road pricing that offset the lower travel costs created by efficiency improvements or reduced oil prices (see Section 8.10) (Hochman et al., 2010; Rajagopal et al., 2011; Chen and Khanna, 2012).

[5] Should a BEV run out of stored energy, it is less easy to refuel than is an ICE vehicle that runs out of gasoline. With typical ranges around 100–160 km, BEV drivers can become anxious about failing to complete their journey.

- **Vehicle choice-related rebounds:** Other types of rebound effect are apparent, such as shifts to purchasing larger cars concurrent with cheaper fuel or shifts from gasoline to diesel vehicles that give lower driving costs (Schipper and Fulton, 2012). Shifts to larger HDVs and otherwise less expensive systems can divert freight from lower carbon modes, mainly rail, and can also induce additional freight movements (Umweltbundesamt, 2007; TML, 2008; Leduc, 2009; Gillingham et al., 2013).

- **Company behaviour:** Behavioural change also has a business dimension. Company decision making can exert a strong influence on the level of transport emissions, particularly in the freight sector (Rao and Holt, 2005). Freight business operators have a strong incentive to reduce energy intensity, since fuel typically accounts for around one third of operating costs in the road freight sector, 40 % in shipping, and 55 % in aviation (Bretzke, 2011). The resulting reductions in transport costs can cause a rebound effect and generate some additional freight movement (Matos and Silva, 2011). For company managers to switch freight transport modes often requires a tradeoff of higher logistics costs for lower carbon emissions (Winebrake et al., 2008). Many large logistics service providers have set targets for reducing the carbon intensity of their operations by between 20 % and 45 % over the period from 2005/2007 to 2020, (McKinnon and Piecyk, 2012) whereas many smaller freight operators have yet to act (Oberhofer and Fürst, 2012).

8.4 Infrastructure and systemic perspectives

Transport modes, their infrastructures, and their associated urban fabric form a system that has evolved into the cities and regions with which we are most familiar. 'Walking cities' existed for 8000 years; some are being reclaimed around their walkability (Gehl, 2011). 'Transit cities' were built and developed around trams, trolley buses, and train systems since the mid 19th century (Cervero, 1998; Newman and Kenworthy, 1999). 'Automobile cities' evolved from the advent of cheap LDVs (Brueckner, 2000) and have become the dominant paradigm since the 1950s, leading to automobile dependence and automobility (Urry, 2007). A region can be defined and understood in terms of the transport links to ports and airports regardless of the number and types of cities located there. In all cases, the inter-linkages between transport infrastructure and the built environment establish path dependencies, which inform long-term transport-related mitigation options. For a general discussion of urban form and infrastructure see Chapter 12.4.

8.4.1 Path dependencies of infrastructure and GHG emission impacts

Systemic change tends to be slow and needs to address path dependencies embedded in sunk costs, high investment levels, and cultural patterns. Technological and behavioural change can either adapt to existing infrastructures, or develop from newly constructed infrastructures, which could provide an initial template for low carbon technologies and behaviour. Developments designed to improve infrastructure in rapidly urbanizing developing countries will decisively determine the future energy intensity of transport and concomitant emissions (Lefèvre, 2009), and will require policies and actions to avoid lock-in.

The construction, operation, maintenance, and eventual disposal of transport infrastructure (such as rail tracks, highways, ports, and airports), all result in GHG emissions. These infrastructure-related emissions are usually accounted for in the industry and building sectors. However, full accounting of life cycle assessment (LCA) emissions from a transport-perspective requires these infrastructure-related emissions to be included along with those from vehicles and fuels (see Section 8.3.5). GHG emissions per passenger-kilometre (p-km) or per tonne-kilometre (t-km) depend, *inter alia*, on the intensity of use of the infrastructure and the share of tunnels, bridges, runways, etc. (Åkerman, 2011; Chang and Kendall, 2011; UIC, 2012). In the United States, GHG emissions from infrastructure built for LDVs, buses, and

Table 8.1 | High-speed rail transport infrastructure GHG emissions based on LCA data.

Mode/component	Emissions (gCO_2eq/p-km)	Reference	Comment
Swedish high-speed rail plans for Europabanan infrastructure	2.7	Amos et al., 2010; Åkerman, 2011	At 25 million passengers per year
Vehicle construction and maintenance emissions; Swedish high-speed rail	1.0	Åkerman, 2011	Over full lifetime of high-speed rail vehicles
Inter-city express (ICE) system study (Germany and surrounds)	9.7	Von Rozycki et al., 2003	About half total emissions arise from infrastructure including non-high-speed stretches
High-speed rail infrastructure (Europe)	3.1–10.9	Tuchschmid, 2009	Low emission value for 90 trains per track per day, high emission value for 25. Current EU network is at 6.3 g/p-km
US high-speed rail plans	3.2 g/p-km	Chang and Kendall, 2011	This 725 km line will emit 2.4 $MtCO_2eq$/yr

Note: Since LCA assumptions vary, the data can only be taken as indicative and not compared directly.

air transport amount to 17–45 gCO_2eq/p-km, 3–17 gCO_2eq/p-km, and 5–9 gCO_2eq/p-km respectively (Chester and Horvath, 2009) with rail typically between 3–11 gCO_2eq/p-km (see Table 8.1). Other than for rail, relevant regional infrastructure-related GHG emissions research on this topic is very preliminary.

Opportunities exist to substantially reduce these infrastructure related emissions, for instance by up to 40 % in rail (Milford and Allwood, 2010), by the increased deployment of low-carbon materials and recycling of rail track materials at their end-of-life (Network Rail, 2009; Du and Karoumi, 2012). When rail systems achieve modal shift from road vehicles, emissions from the rail infrastructure may be partially offset by reduced emissions from road infrastructures (Åkerman, 2011). To be policy-relevant, LCA calculations that include infrastructure need to be contextualized with systemic effects such as modal shifts (see Sections 8.4.2.3 and 8.4.2.4).

Existing vehicle stock, road infrastructure, and fuel-supply infrastructure prescribe future use and can lock-in emission paths for decades while inducing similar investment because of economies of scale (Shalizi and Lecocq, 2009). The life span of these infrastructures ranges from 50 to more than 100 years. This range makes the current development of infrastructure critical to the mode shift opportunities of the future. For example, the successful development of the United States interstate highway system resulted in a lack of development of an extensive passenger rail system, and this determined a demand-side lock-in produced by the complementarity between infrastructure and vehicle stock (Chapter 12.3.2). The construction of the highway system accelerated the growth of road vehicle kilometres travelled (VKT) around 1970, and ex-urban development away from city centres created a second peak in road transport infrastructure investment post 1990 (Shalizi and Lecocq, 2009). Conversely, the current rapid development of high-speed rail infrastructure in China (Amos et al., 2010) may provide low emission alternatives to both road transport and aviation. Substantial additional rail traffic has been generated by constructing new lines (Chapter 12.4.2.5), although a net reduction of emissions will only occur after achieving a minimum of between 10 and 22 million passengers annually (Westin and Kågeson, 2012).

Aviation and shipping require less fixed infrastructures and hence tend to have a relative low infrastructure share of total lifecycle emissions. Rising income and partially declining airfares have led to increased air travel (Schäfer et al., 2009), and this correlates not only with new construction and expansion of airports, but also with shifting norms in travel behaviour (Randles and Mander, 2009).

8.4.2 Path dependencies of urban form and mobility

Transport demand and land use are closely inter-linked. In low-density developments with extensive road infrastructure, LDVs will likely dominate modal choice for most types of trips. Walking and cycling can be made easier and safer where high accessibility to a variety of activities are located within relative short distances (Ewing and Cervero, 2010) and when safe cycle infrastructure and pedestrian pathways are provided (Tiwari and Jain, 2012; Schepers et al., 2013). Conversely the stress and physical efforts of cycling and walking can be greater in cities that consistently prioritize suburban housing developments, which leads to distances that accommodate the high-speed movement and volume of LDVs (Naess, 2006). In developing countries, existing high-density urban patterns are conducive to walking and cycling, both with substantial shares. However, safe infrastructure for these modes is often lacking (Thynell et al., 2010; Gwilliam, 2013). Sustainable urban planning offers tremendous opportunities (reduced transport demand, improved public health from non-motorized transport (NMT), less air pollution, and less land use externalities) (Banister, 2008; Santos et al., 2010; Bongardt et al., 2013; Creutzig et al., 2012a). As an example, an additional 1.1 billion people will live in Asian cities in the next 20 years (ADB, 2012a) and the majority of this growth will take place in small-medium sized cities that are at an early stage of infrastructure development. This growth provides an opportunity to achieve the long-term benefits outlined above (Grubler et al., 2012) (see also 8.7 and Chapter 12.4.1).

Urban population density inversely correlates with GHG emissions from land transport (Kennedy et al., 2009; Rickwood et al., 2011) and enables non-motorized modes to be more viable (Newman and Kenworthy, 2006). Disaggregated studies that analyze individual transport use confirm the relationship between land use and travel (Echenique et al., 2012). Land use, employment density, street design and connectivity, and high transit accessibility also contribute to reducing car dependence and use (Handy et al., 2002; Ewing, 2008; Cervero and Murakami, 2009; Olaru et al., 2011). The built environment has a major impact on travel behaviour (Naess, 2006; Ewing and Cervero, 2010), but residential choice also plays a substantial role that is not easy to quantify (Cao et al., 2009; Ewing and Cervero, 2010). There exists a non-linear relationship between urban density and modal choice (Chapter 12.4.2.1). For example, suburban residents drive more and walk less than residents living in inner city neighbourhoods (Cao et al., 2009), but that is often true because public transit is more difficult to deploy successfully in suburbs with low densities (Frank and Pivo, 1994). Transport options that can be used in low density areas include para-transit[6] and car-sharing, both of which can complement individualized motorized transport more efficiently and with greater customer satisfaction than can public transit (Baumgartner and Schofer, 2011). Demand-responsive, flexible transit, and car sharing services can have lower GHG emissions per passenger kilometre with higher quality service than regional public transport (Diana et al., 2007; Mulley and Nelson, 2009; Velaga et al., 2012; Loose, 2010).

[6] Para-transit, also called "community-transit", is where flexible passenger transport minibuses (also termed matatus and marshrutkas), shared taxis, and jitneys operate in areas with low population density without following fixed routes or schedules.

The number of road intersections along the route of an urban journey, the number of destinations within walking distance, and land use diversity issues have been identified as key variables for determining the modal choice of walking (Ewing and Cervero, 2010). Public transport use in the United States is related to the variables of street network design and proximity to transit. Land use diversity is a secondary factor.

8.4.2.1 Modal shift opportunities for passengers

Small but significant modal shifts from LDVs to bus rapid transit (BRT) have been observed where BRT systems have been implemented. Approximately 150 cities worldwide have implemented BRT systems, serving around 25 million passengers daily (Deng and Nelson, 2011; BRT Centre of Excellence, EMBARQ, IEA and SIBRT, 2012). BRT systems can offer similar benefits and capacities as light rail and metro systems at much lower capital costs (Deng and Nelson, 2011), but usually with higher GHG emissions (depending on the local electricity grid GHG emission factor) (Table 8.2). High occupancy rates are an important requirement for the economic and environmental viability of public transport.

Public transit, walking, and cycling are closely related. A shift from non-motorized transport (NMT) to LDV transport occurred during the 20th century, initially in OECD countries and then globally. However, a reversion to cycling and walking now appears to be happening in many cities— mostly in OECD countries—though accurate data is scarce (Bassett et al., 2008; Pucher et al., 2011). Around 90 % of all public transit journeys in the United States are accompanied with a walk to reach the final destination and 70 % in Germany (Pucher and Buehler, 2010). In Germany, the Netherlands, Denmark, and elsewhere, the cycling modal share of total trips has increased since the 1970s and are now between 10–25 % (Pucher and Buehler, 2008). Some carbon emission reduction has resulted from cycle infrastructure deployment in some European cities (COP, 2010; Rojas-Rueda et al., 2011; Creutzig et al., 2012a) and in some cities in South and North America (USCMAQ, 2008; Schipper et al., 2009; Massink et al., 2011; USFHA, 2012). Walking and cycling trips vary substantially between countries, accounting for over 50 % of daily trips in the Netherlands and in many Asian and African cities (mostly walking); 25–35 % in most European countries; and approximately 5–10 % in the United States and Australia (Pucher and Buehler, 2010; Leather et al., 2011; Pendakur, 2011; Mees and Groenhart, 2012).

The causes for high modal share of NMT differ markedly between regions depending on their cultures and characteristics. For example, they tend to reflect low-carbon urban policies in OECD countries such as the Netherlands, while reflecting a lack of motorization in developing countries. Land use and transport policies can influence the bicycle modal share considerably (Pucher and Buehler, 2006), most notably by the provision of separate cycling facilities along heavily traveled roads and at intersections, and traffic-calming of residential neighbourhoods (Andrade et al., 2011; NRC, 2011b). Many Indian and Chinese cities with traditionally high levels of walking are now reporting dramatic decreases in this activity (Leather et al., 2011), with modal shifts to personal transport including motorbikes and LDVs. Such shifts are to some degree inevitable, and are in part desirable as they reflect economic growth. However, the maintenance of a healthy walking and cycling modal share could be a sign of a liveable and attractive city for residents and businesses (Bongardt et al., 2011; Gehl, 2011).

Deliberate policies based around urban design principles have increased modal shares of walking and cycling in Copenhagen, Melbourne, and Bogota (Gehl, 2011). Public bicycle share systems have created a new mode for cities (Shaheen et al., 2010), with many cities now implementing extensive public cycling infrastructure, which results in increased bicycle modal share (DeMaio, 2009). Revising electric bicycle standards to enable higher performance could increase the feasible commuting range and encourage this low emissions personal transport mode. Electric bicycles offer many of the benefits of LDVs in terms of independence, flexibility of routes, and scheduling freedom, but with much lower emissions and improved health benefits.

With rising income and urbanization, there will likely be a strong pull toward increasing LDV ownership and use in many developing countries. However, public transit mode shares have been preserved at fairly high levels in cities that have achieved high population densities and that have invested heavily in high quality transit systems (Cervero, 2004). Their efficiency is increased by diverse forms of constraints on LDVs, such as reduced number of lanes, parking restrictions, and limited access (La Branche, 2011). Investments in mass rapid transit, timed with income increases and population size/density increases,

Table 8.2 | Comparison of capital costs, direct CO_2 emissions, and capacities for BRT, light rail, and metro urban mass transit options (IEA, 2012e).

	Bus rapid transit	Light rail	Metro
Capital cost (million USD_{2010}/km)	5–27	13–40	27–330
Length of network that can be constructed for 1 USD_{2010} billion cost (km)	37–200	25–77	3–37
World network length in 2011 (km)	2,139	15,000	10,000
Direct CO_2 intensity (gCO_2/p-km)	14–22	4–22	3–21
Capacity (thousand passengers per hour per direction)	10–35	2–12	12–45

have been successful in some Asian megacities (Acharya and Morichi, 2007). As traffic congestion grows and freeway infrastructure reaches physical, political, and economic limits, the modal share of public transit has increased in some OECD countries (Newman and Kenworthy, 2011b).

High-speed rail can substitute for short-distance passenger air travel (normally up to around 800 km but also for the 1500 km in the case of Beijing to Shanghai), as well as for most road travel over those distances, and hence can mitigate GHG emissions (McCollum et al., 2010; IEA, 2008). With optimized operating speeds and long distances between stops, and high passenger load factors, energy use per passenger-km could be as much as 65 to 80 % less than air travel (IEA, 2008). A notable example is China, which has shown a fast development of its high-speed rail system. When combined with strong land-use and urban planning, a high-speed rail system has the potential to restructure urban development patterns, and may help to alleviate local air pollution, noise, road, and air congestion (McCollum et al., 2010).

8.4.2.2 Modal shift opportunities for freight

Over the past few decades, air and road have increased their global share of the freight market at the expense of rail and waterborne transport (European Environment Agency, 2011; Eom et al., 2012). This has been due to economic development and the related change in the industry and commodity mix, often reinforced by differential rates of infrastructure improvement and the deregulation of the freight sector, which typically favours road transport. Inducing a substantial reversal of recent freight modal split trends will be difficult, *inter alia* because of 'structural inelasticity' which confines shorter distance freight movements to the road network because of its much higher network density (Rich et al., 2011). If growth in global truck travel between 2010 and 2050 could be cut by half from the projected 70 % and shifted to expanded rail systems, about a 20 % reduction in fuel demand and CO_2 could be achieved, with only about a fifth of this savings being offset by increased rail energy use (IEA, 2009). The European Commission (EC) set an ambitious target of having all freight movements using rail or waterborne modes over distances greater than 300 km by 2030, leading to major changes in modal shares (Figure 8.8) (Tavasszy and Meijeren, 2011; EC, 2013).

The capacity of the European rail network would have to at least double to handle this increase in freight traffic and the forecast growth in rail passenger volumes, even if trains get longer and run empty less often (den Boer et al., 2011). Longer-term transformations need to take account of the differential rates at which low-carbon technologies could impact on the future carbon intensity of freight modes. Applying current average energy intensity values (Section 8.3.1) may result in over-estimates of the potential carbon benefits of the modal shift option. Although rail freight generates far lower GHG emissions per tonne-kilometre than road (Table 8.3), the rate of carbon-related technical innovation, including energy efficiency improvements, has been faster in HDV than rail freight and HDV replacement rate is typically much shorter, which ensures a more rapid uptake of innovation.

The potential for shifting freight to greener modes is difficult in urban areas. Improvements in intra-urban rail freight movements are possible (Maes and Vanelslander, 2011), but city logistical systems are almost totally reliant on road vehicles and are likely to remain so. The greater the distance of land haul for freight, the more competitive the lower carbon modes become. Within cities, the concept of modal split between passenger and freight movement can be related to the interaction. Currently, large amounts of freight on the so-called 'last mile' to a home or business are carried by shoppers in LDVs and public transport vehicles. With the rapid growth of on-line retailing, much private car-borne freight, which seldom appears in freight transport statistics, will be transferred to commercial delivery vans. Comparative analyses of conventional and on-line retailing suggest that substituting a van delivery for a personal shopping trip by private car can yield a significant carbon saving (Edwards et al., 2010).

At the international level, opportunities for switching freight from air to shipping services are limited. The two markets are relatively discrete and the products they handle have widely differing monetary values and time-sensitivity. The deceleration of deep-sea container vessels in recent years in accordance with the 'slow steaming' policies of the shipping lines has further widened the transit time gap between sea and air services. Future increases in the cost of fuel may, however, encourage businesses to economize on their use of air-freight, possibly switching to sea-air services in which products are air-freighted for only part of the way. This merger of sea and air transport offers substantial cost and CO_2 savings for companies whose global supply chains are less time-critical (Conway, 2007; Terry, 2007).

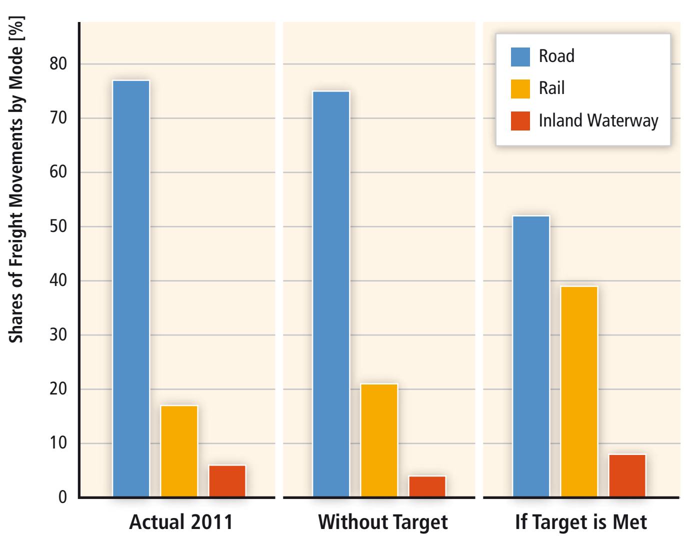


Figure 8.8 | Projected freight modal split in the EU-25 in 2030 comparing 2011 shares with future business-as-usual shares without target and with EU White Paper modal split target. Source: Based on Tavasszy and Meijeren, 2011.

8.5 Climate change feedback and interaction with adaptation

Transport is impacted by climate change both positively and negatively. These impacts are dependent on regional variations in the nature and degree of climate change and the nature of local transport infrastructure and systems. Adapting transport systems to the effects of climate in some cases complement mitigations efforts while in others they have a counteracting effect. Little research has so far been conducted on the inter-relationship between adaptation and mitigation strategies in the transport sector.

8.5.1 Accessibility and feasibility of transport routes

Decreases in the spatial and temporal extent of ice cover in the Arctic and Great Lakes region of North America regions are opening new and shorter shipping routes over longer periods of the year (Drobot et al., 2009; Stephenson et al., 2011). The expanded use of these routes could reduce GHG emissions due to a reduction in the distance travelled. For example, the Northern Sea Route (NSR) between Shanghai and Rotterdam is approximately 4,600 km shorter (about 40 %) than the route via the Suez Canal. The NSR passage takes 18–20 days compared to 28–30 days via the southern route (Verny and Grigentin, 2009). Climate change will not only affect ice coverage, but may also increase the frequency and severity of northern hemisphere blizzards and arctic cyclones, deterring use of these shorter routes (Wassmann, 2011; Liu et al., 2012). It is, nevertheless, estimated that the transport of oil and gas through the NSR could increase from 5.5 Mt in 2010 to 12.8 Mt by 2020 (Ho, 2010). The passage may also become a viable option for other bulk carriers and container shipping in the near future (Verny & Grigentin, 2009; Schøyen & Bråthen, 2011). The economic viability of the NSR is still uncertain without assessments of potentially profitable operation (Liu and Kronbak, 2010) and other more pessimistic prospects for the trans-Arctic corridors (Econ, 2007). One possible negative impact would be that the increase in shipping through these sensitive ecosystems could lead to an increase in local environmental and climate change impacts unless additional emissions controls are introduced along these shipping routes (Wassmann, 2011). Of specific concern are the precursors of photochemical smog in this polar region that could lead to additional local positive regional climate forcing (Corbett et al., 2010) and emissions of black carbon (see Section 8.2.2.1). Measurement methods of black carbon emissions from ships and additional work to evaluate their impact on the Arctic are needed before possible control measures can be investigated.

Changes in climate are also likely to affect northern inland waterways (Millerd, 2011). In summer, these effects are likely to adversely affect waterborne craft when reductions in water levels impair navigability and cut capacity (Jonkeren et al., 2007; Görgen et al. 2010; Nilson et al., 2012). On the other hand, reduced winter freezing can benefit inland waterway services by extending the season. The net annual effect of climate change on the potential for shifting freight to this low-carbon mode has yet to be assessed.

8.5.2 Relocation of production and reconfiguration of global supply chains

Climate change will induce changes to patterns of agricultural production and distribution (Ericksen et al., 2009; Hanjra and Qureshi, 2010; Tirado et al., 2010; Nielsen and Vigh, 2012; Teixeira et al., 2012). The effect of these changes on freight transport at different geographical scales are uncertain (Vermeulen et al., 2012). In some scenarios, food supply chains become longer, generating more freight movement (Nielsen and Vigh, 2012; Teixeira et al., 2012). These and other long supply lines created by globalization could become increasingly vulnerable to climate change. A desire to reduce climate risk may be one of several factors promoting a return to more localized sourcing in some sectors (World Economic Forum and Accentura, 2009), a trend that would support mitigation. Biofuel production may also be adversely affected by climate change inhibiting the switch to lower carbon fuels (de Lucena et al., 2009).

8.5.3 Fuel combustion and technologies

Increased ambient temperatures and humidity levels are likely to affect nitrogen oxide, carbon monoxide, methane, black carbon, and other particulate emissions from internal combustion engines and how these gases interact with the atmosphere (Stump et al., 1989; Rakopoulos, 1991; Cooper and Ekstrom, 2005; Motallebi et al., 2008; Lin and Jeng, 1996; McCormick et al., 1997; Pidolal, 2012). Higher temperatures also lead to higher evaporative emissions of volatile organic compound emissions (VOCs) (Roustan et al., 2011) and could lead to higher ozone levels (Bell et al., 2007). The overall effects are uncertain and could be positive or negative depending on regional conditions (Ramanathan & Carmichael, 2008).

As global average temperatures increase, the demand for on-board cooling in both private vehicles and on public transport will increase. The heating of vehicles could also grow as the frequency and severity of cold spells increase. Both reduce average vehicle fuel efficiencies. For example, in a passenger LDV, air-conditioning can increase fuel consumption by around 3–10 % (Farrington and Rugh, 2000; IEA, 2009). Extremes in temperature (both high and low) negatively impact on the driving range of electric vehicles due to greater use of on-board heating and air conditioning, and thus will require more frequent recharging. In the freight sector, energy consumption and emissions in the refrigeration of freight flows will also increase as the extent and degree of temperature-control increases across the supply chains of food and other perishable products (James and James, 2010).

8.5.4 Transport infrastructure

Climate proofing and adaptation will require substantial infrastructure investments (see Section 8.4 and the Working Group II (WGII) Contribution to the IPCC Fifth Assessment Report (AR5), Chapter 15). This will generate additional freight transport if implemented outside of the normal infrastructure maintenance and upgrade cycle. Climate proofing of transport infrastructure can take many forms (ADB, 2011a; Highways Agency, 2011) varying in the amount of additional freight movement required. Resurfacing a road with more durable materials to withstand greater temperature extremes may require no additional freight movement, whereas re-routing a road or rail link, or installing flood protection, are likely to generate additional logistics demands, which have yet to be quantified.

Adaptation efforts are likely to increase transport infrastructure costs (Hamin & Gurran, 2009), and influence the selection of projects for investment. In addition to inflating maintenance costs (Jollands et al., 2007; Larsen et al., 2008), climate proofing would divert resources that could otherwise be invested in extending networks and expanding capacity. This is likely to affect all transport modes to varying degrees. If, for example, climate proofing were to constrain the development of a rail network more than road infrastructure, it might inhibit a modal shift to less carbon-intensive rail services.

The future choice of freight and passenger traffic between modes may also become more responsive to their relative sensitivity to extreme weather events (Koetse and Rietveld, 2009; Taylor and Philp, 2010). The exposure of modes to climate risks include aviation (Eurocontrol, 2008), shipping (Becker et al., 2012), and land transport (Hunt and Watkiss, 2011). Little attempt has been made to conduct a comparative analysis of their climate risk profiles, to assess the effects on the modal choice behaviour of individual travellers and businesses, or to take account of regional differences in the relative vulnerability of different transport modes to climate change (Koetse and Rietveld, 2009).

Overall, the transport sector will be highly exposed to climate change and will require extensive adaptation of infrastructure, operations, and service provision. It will also be indirectly affected by the adaptation and decarbonization of the other sectors that it serves. Within the transport sector there will be a complex interaction between adaptation and mitigation efforts. Some forms of adaptation, such as infrastructural climate proofing, will be likely to generate more freight and personal movement, while others, such as the NSR, could substantially cut transport distances and related emissions.

8.6 Costs and potentials

For transport, the potential for reducing GHG emissions, as well as the associated costs, varies widely across countries and regions. Appropriate policies and measures that can accomplish such reductions also vary (see Section 8.10) (Kahn Ribeiro et al., 2007; Li, 2011). Mitigation costs and potentials are a function of the stringency of climate goals and their respective GHG concentration stabilization levels (Fischedick et al., 2011; Rogelj et al., 2013). This section presents estimates of mitigation potentials and associated costs from the application of new vehicle and fuel technologies, performance efficiency gains, operational measures, logistical improvements, electrification of modes, and low-carbon fuels and activity reduction for different transport modes (aviation, rail, road, waterborne and cross-modal). Potential CO_2eq emissions reductions from passenger-km (p-km) and tonne-km (t-km) vary widely by region, technology, and mode according to how rapidly the measures and applications can be developed, manufactured, and sold to buyers replacing existing ones in vehicles an fuels or adding to the total fleet, and on the way they are used given travel behaviour choices (Kok et al., 2011). In general, there is a larger emission reduction potential in the transport sector, and at a lower cost, compared to the findings in AR4 (Kahn Ribeiro et al., 2007).

The efforts undertaken to reduce activity, to influence structure and modal shift, to lower energy intensity, and to increase the use of low-carbon fuels, will influence future costs and potentials. Ranges of mitigation potentials have an upper boundary based on what is currently understood to be technically achievable, but will most likely require strong policies to be achieved in the next few decades (see Section 8.10). Overall reductions are sensitive to per-unit transport costs (that could drop with improved vehicle efficiency); resulting rebound effects; and shifts in the type, level, and modal mix of activity. For instance, the deployment of more efficient, narrow-body jet aircraft could increase the number of commercially-attractive, direct city-to-city connections, which may result in an overall increase in fleet fuel use compared to hub-based operations.

This assessment follows a bottom-up approach to maintain consistency in assumptions. Table 8.3 outlines indicative direct mitigation costs using reference conditions as baselines, and illustrative examples of existing vehicles and situations for road, aviation, waterborne, and rail (as well as for some cross-mode options) available in the literature. The data presented on the cost-effectiveness of different carbon reduction measures is less detailed than data on the potential CO_2eq savings due to literature gaps. The number of studies assessing potential future GHG reductions from energy intensity gains and use of low-carbon fuels is larger than those assessing mitigation potentials and cost from transport activity, structural change and modal shift, since they are highly variable by location and background conditions.

Key assumptions made in this analysis were:

- cost estimates are based on societal costs and benefits of technologies, fuels, and other measures, and take into account initial costs as well as operating costs and fuel savings;
- existing transport options are compared to current base vehicles and activities, whereas future options are compared to estimates of baseline future technologies and other conditions;

- fuel price projections are based on the IEA World Energy Outlook (IEA, 2012b) and exclude taxes and subsidies where possible;
- discount rates of 5 % are used to bring future estimates back to present (2013) values, though the literature considered has examined these issues mostly in the developed-world context; and
- indirect responses that occur through complex relationships within sectors in the larger socioeconomic system are not included (Stepp et al., 2009).

Results in Table 8.3 indicate that, for LDVs, efficiency improvement potentials of 50 % in 2030 are technically possible compared to 2010, with some estimates in the literature even higher (NRC, 2010). Virtually all of these improvements appear to be available at very low, or even negative, societal costs. Electric vehicles have a CO_2eq reduction cost highly correlated with the carbon intensity of electricity generation: using relatively high-carbon intensity electricity systems (500–600 gCO_2eq/kWh), EVs save little CO_2eq compared to conventional LDVs and the mitigation cost can be many hundreds of dollars per tonne; for very low-carbon electricity (below 200 gCO_2eq/kWh) the mitigation cost drops below 200 USD_{2010}/tCO_2eq. In the future, with lower battery costs and low-carbon electricity, EVs could drop below 100 USD_{2010}/tCO_2eq and even approach zero net cost.

For long-haul HDVs, up to a 50 % reduction in energy intensity by 2030 appears possible at negative societal cost per tCO_2eq due to the very large volumes of fuel they use. HDVs used in urban areas where their duty cycle does not require as much annual travel (and fuel use), have a wider range of potentials and costs, reaching above 100 USD_{2010}/t CO_2eq. Similarly, inter-city buses use more fuel annually than urban buses, and as a result appear to have more low-cost opportunities for CO_2eq reduction (IEA, 2009; NRC, 2010; TIAX, 2011).

Recent designs of narrow and wide-body commercial aircraft are significantly more efficient than the models they replace, and provide CO_2eq reductions at net negative societal cost when accounting for fuel savings over 10–15 years of operation at 5 % discount rate. An additional 30–40 % CO_2eq reduction potential is expected from future new aircraft in the 2020–2030 time frame, but the mitigation costs are uncertain and some promising technologies, such as open rotor engines, appear expensive (IEA, 2009; TOSCA, 2011).

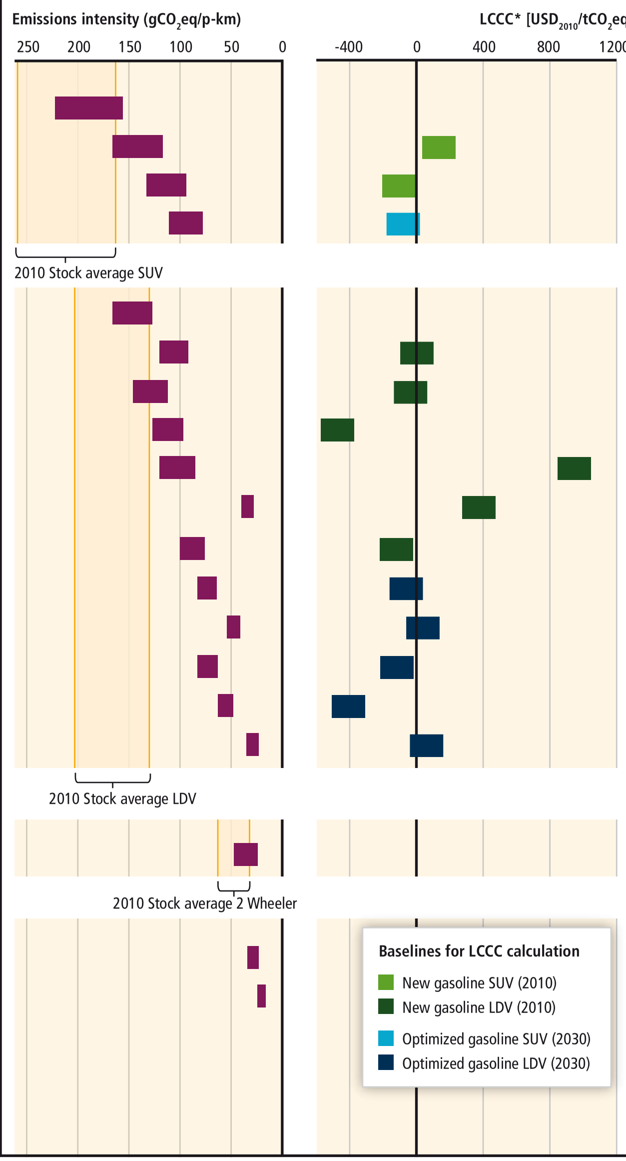
For virtually all types of ocean-going ships including container vessels, bulk carriers, and oil tankers, the potential reduction in CO_2eq emissions is estimated to be over 50 % taking into account a wide range of technology and operational changes. Due to the large volume of fuel used annually by these ships, the net cost of this reduction is likely to be negative (Buhaug and et. al, 2009; Crist, 2009).

Key factors in the long term decarbonization of rail transport will be the electrification of services and the switch to low-carbon electricity generation, both of which will vary widely by country. Potential improvements of 35 % energy efficiency for United States rail freight, 46 % for European Union rail freight and 56 % for EU passenger rail services have been forecast for 2050 (Anderson et al., 2011; Vyas et al., 2013). The EU improvements will yield a 10–12 % reduction in operating costs, though no information is available on the required capital investment in infrastructure and equipment.

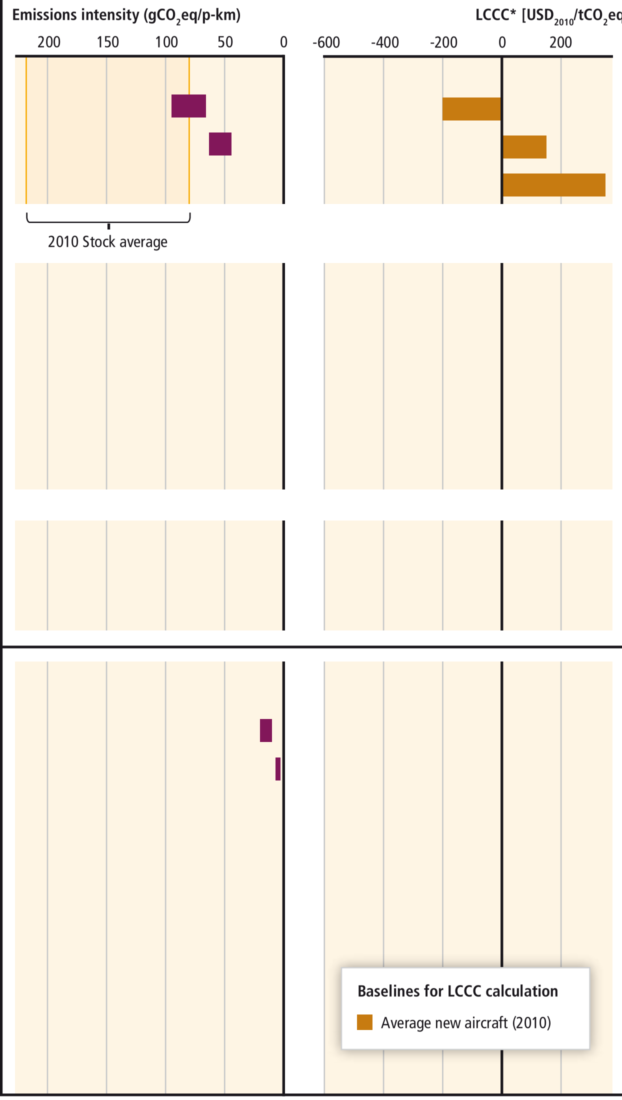
Regarding fuel substitution in all modes, some biofuels have the potential for large CO_2eq reduction, although net GHG impact assessments are complex (see Sections 8.3 and 11.13). The cost per tonne of CO_2eq avoided will be highly dependent on the net CO_2eq reduction and the relative cost of the biofuel compared to the base fuel (e.g., gasoline or diesel), and any technology changes required to the vehicles and fuel distribution network in order to accommodate new fuels and blends. The mitigation cost is so sensitive that, for example, while an energy unit of biofuel that cuts CO_2eq emissions by 80 % compared to gasoline and costs 20 % more has a mitigation cost of about 80 USD/t CO_2eq, if the biofuel's cost drops to parity with gasoline, the mitigation cost drops to 0 USD/t CO_2eq (IEA, 2009).

The mitigation potentials from reductions in transport activity consider, for example, that "walking and cycle track networks can provide 20 % (5–40 % in sensitivity analyses) *induced* walking and cycle journeys that would not have taken place without the new networks, and around 15 % (0–35 % in sensitivity analyses) of current journeys less than 5 km made by car or public transport can be *replaced* by walking or cycling" (Sælensminde, 2004). Urban journeys by car longer than 5 km can be replaced by combined use of non-motorized and intermodal public transport services (Tirachini and Hensher, 2012).

Table 8.3 | Selected CO_2eq mitigation potentials and costs for various modes in the transport sector with baselines of stock average fleet compared with 2010 new vehicles and 2030 projected vehicle based on available data. (See foot-notes at end of Table).

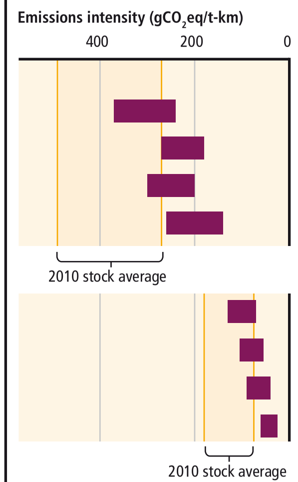
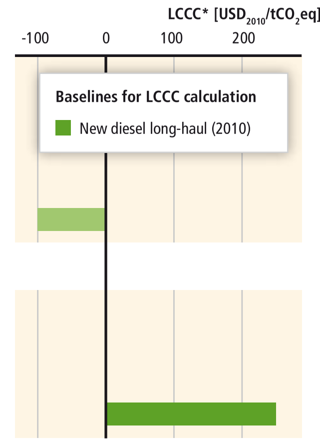
Mitigation options in passenger transport	Indicative 2010 stock average baseline CO_2eq emissions and reduction potential	Indicative direct mitigation cost in relation to the baseline (can be positive or negative)	Reference conditions and assumptions made	Illustrative examples
Road **New sport utility vehicles (SUV), mid-size** 2010 Gasoline 2010 Hybrid gasoline 2030 Gasoline 2030 Hybrid gasoline			**Baseline 2010 stock average vehicles** Industry average; 164 gCO_2/p-km (6). Drive-train redesigns may yield 25% improvement. Additional reductions from light-weighting, aerodynamics, more efficient accessories (6). Most current and many future LDV efficiency improvements are at negative cost of USD/tCO_2 (4, 47). Potential 40–60% fuel efficiency gains by 2030 compared to similar size 2010 LDVs (5). **2030 conventional/hybrid:** - mid-size; 70–120 gCO_2/p-km (25). **2010 EV:** - 80–125 gCO_2/p-km using high-carbon electricity grid at 600 gCO_2/kWh; - 28–40 gCO_2/p-km using low-carbon grid electricity at 200 gCO_2/kWh. Likely over 200 USD/tCO_2 in 2010 even with low-carbon grid electricity. **2030 EV:** - 55–235 USD/tCO_2 with high-carbon electricity. - 0–100 USD/tCO_2 with low-carbon electricity (5). EV efficiency 0.2–0.25 kWh/km on road (7). Battery cost: - 750 USD/kWh in 2010; - 200–300 USD /kWh in 2030 (11). Vehicle intensity (well-to-wheel) of 144–180 gCO_2/100km at 0.20–0.25 kWh/km. **PHEV:** 15–70% well-to-wheel more efficient than baseline ICEV (7); 28–50% more efficient by 2030 (5).	Average CO_2 emissions level of new cars in the EU decreased from 170 gCO_2/km in 2001 to 136 gCO_2/km in 2011 (43, 47) **New mid-size gasoline:** 2012 Toyota Yaris hybrid; 79 gCO_2/p-km (6). **New mid-size Diesel:** Volkswagen Golf Blue motion 1.6 TDI: 99 gCO_2/p-km (6) **EVs:** 2013 Nissan Leaf: 24 kWh has 175 km range on New European Driving Cycle, ranging from 76 to 222 km depending on driving conditions (6).
New light duty vehicles (LDV), mid-size 2010 Gasoline 2010 Hybrid gasoline 2010 Diesel 2010 Compressed natural gas 2010 Electric, 600 g CO_2eq/kWh_{el} 2010 Electric, 200 g CO_2eq/kWh_{el} 2030 Gasoline 2030 Hybrid gasoline 2030 Hybrid gasoline/biofuel* (50/50 share) 2030 Diesel 2030 Compressed natural gas 2030 Electric, 200 gCO_2eq/kWh_{el}				
New 2 wheeler **(Scooter up to 200 cm³ cylinder capacity)** 2010 Gasoline			**Baseline: 2010 stock average scooters** Up to 200 cc typical for Asia (48).	
New buses, large size 2010 Diesel 2010 Hybrid diesel			**Baseline: 2010 stock average medium haul bus** 40-passenger occupancy vehicle. Potential efficiency improvement 0–30%.	30% savings in fuel consumption for hybrid buses in Montreal (14).
Bus rapid transit (BRT)			**BRT** infrastructure cost: 1–27 million USD/km (13). Benefit-cost-ratios of selected BRT systems: Hamilton, Canada 0.37–1.34; Canberra, Australia 1.98–4.78 (12, 36)	**BRT** system, Bogota, Colombia has emission reductions of 250,000 tCO_2eq/yr (12).

*Levelized cost of conserved carbon (LCCC), here at 5% weighted average cost of capital (WACC)



Mitigation options in passenger transport	Indicative 2010 stock average baseline CO_2eq emissions and reduction potential	Indicative direct mitigation cost in relation to the baseline (can be positive or negative)	Reference conditions and assumptions made	Illustrative examples
Aviation (Commercial, medium to long haul) 2010 Narrow and wide body 2030 Narrow body 2030 Narrow body, open rotor engine			**Baseline: 2010 stock average commercial (25)** Medium haul aircraft; 150-passenger occupancy; average trip distance. **Aircraft efficiency:** Incremental changes to engines and materials up to 20% efficiency improvement. Most efficient present aircraft designs provide 15–30% CO_2 emissions reductions per revenue p-km compared to previous generation aircraft, at net negative costs since fuel savings typically greater than cost of improved technology. (5) **2030 next generation aircraft design:** Advanced engines up to 33% improvement; radical new designs such as 'flying wing', up to 50% improvement. Medium and long-haul (narrow and wide-body) aircraft compared to today's best aircraft design: - 20–35% CO_2 emissions reduction potential by 2025 for conventional aircraft - up to 50% with advanced designs (e.g., flying wing)(2) **Costs:** ~20% CO_2 reduction at <0–100 USD/tCO_2 (narrow body); ~33% reduction at <0–400 USD/tCO_2 (open rotor engine) (34).	New current long-haul wide body: Boeing 787 is 30% more fuel efficient than Boeing 767; Boeing 747-800 is 20% more efficient than Boeing 747-400 (1, 51). New 2010 medium-long-haul, narrow body: Airbus A320 and Boeing 737 (42).
Operational measures			**Taxiing and flight operations** including direct routing, optimum altitude and speed; circling, landing patterns. Improved ground equipment and auxiliary power units can yield 6–12% fuel efficiency gains (3).	
Rail (light rail car) 2010 Electric, 600 g CO_2eq/kWh$_{el}$ 2010 Electric, 200 g CO_2eq/kWh$_{el}$			**Baseline: 2010 electric medium haul train** - Based on electricity grid 600 gCO_2/kWh: 3–20 gCO_2/p-km (25). **2010 light rail**; 60 passenger occupancy car: - CO_2 reduction at 4–22 gCO_2/p-km; - Infrastructure cost 14–40 million USD/km (5). **2010 metro:** - CO_2 reduction 3–21 gCO_2/p-km; - Infrastructure cost 27–330 million USD/km (5). **2010 long-distance rail:** - 45–50% reduction in CO_2/p-km (augmented if switch to low-carbon electricity). - 14% reduction in operating costs (allowing for increase in speed and with energy costs excluded from cost calculation (38). - 8–40% efficiency gains (12–19 gCO_2/p-km). - Infrastructure cost 4–75 million USD/km (5). Potential GHG savings from eco-driving 15%; regenerative braking 13%; mass reduction 6% (38).	European rail operations: Passenger: 46% reduction in GHG/p-km by 2050 with 11% reduction in operating costs (43). 8% improvement via regenerative braking systems (Amtrak, US); 40% through design and engine improvements (Shinkansen, Japan) (18). 35% reduction in energy intensity - for US rail operations (17).

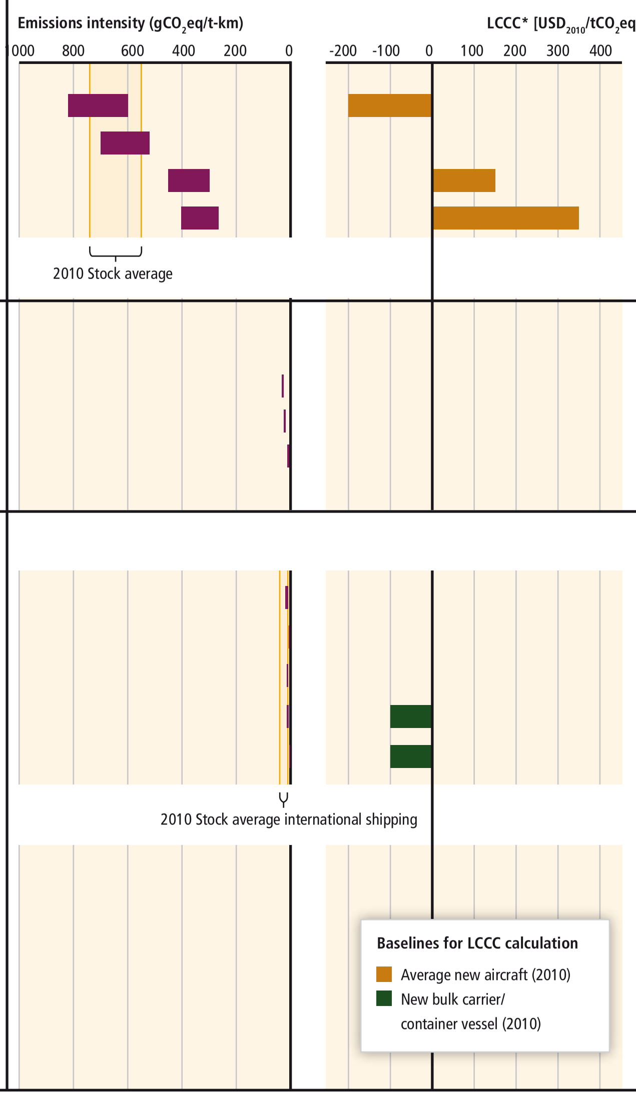
*Levelized cost of conserved carbon (LCCC), here at 5% weighted average cost of capital (WACC)

Mitigation options in freight transport	Indicative 2010 stock average baseline CO_2eq emissions and reduction potential	Indicative direct mitigation cost in relation to the baseline (can be positive or negative)	Reference conditions and assumptions made	Illustrative examples
Road **New medium duty trucks** 2010 Diesel 2010 Diesel hybrid 2010 Compressed natural gas 2030 Diesel **New heavy duty, long-haul trucks** 2010 Diesel 2010 Compressed natural gas 2030 Diesel 2030 Diesel/biofuel (50/50 share)**			**Baseline stock average medium haul HDV** Diesel fuelled HDVs: 76–178 gCO_2/t-km (25). 55% improvement in energy efficiency of tractor trailer HDV between 2010 and 2030 and 50% for other categories of HDV (9, 10). 30–62% improvement by 2030 compared to a similar size 2007–2010 HDV, including increasing load factor by up to 32% (5, 11). Urban HDVs 30–50% reductions at 0–200 USD/tCO_2. Long-haul HDV up to 50% potential CO_2 reduction at negative costs per tCO_2 saved.	New diesel example (47) New diesel hybrid example (47) 'Green Trucks Project' Guangzhou, China, could save 8.6 billion l/yr of fuel and reduce CO_2 emissions by 22.3 $MtCO_2$/yr if all HDVs in the province participated (12). UK 'Logistics Carbon Reduction Scheme' comprising 78 businesses set target for reducing the target intensity of road freight transport by 8% between 2010 and 2015, which is likely to be achieved by the end of 2013.

*Levelized cost of conserved carbon (LCCC), here at 5% weighted average cost of capital (WACC)
**Assuming 70% Less CO_2eq/MJ Biofuel than /MJ Dies

8

Mitigation options in freight transport	Indicative 2010 stock average baseline CO_2eq emissions and reduction potential	Indicative direct mitigation cost in relation to the baseline (can be positive or negative)	Reference conditions and assumptions made	Illustrative examples
Aviation (Commercial, medium to long haul) 2010 Dedicated airfreighter 2010 Belly-hold 2030 Improved aircraft 2030 Improved, open rotor engine			See Passenger "Aviation" assumptions above Freight factors for wide-bodied passenger aircraft are around 15-30% whilst narrow bodied planes are typically 0-10% (52),	See Passenger "Aviation" examples above
Rail (freight train) 2010 Diesel, light goods 2010 Diesel, heavy goods 2010 Electric , 200 gCO_2eq/kWh_{el}			**Baseline** based on electricity grid 600 gCO_2/kWh: 6–33 $gCO_2/t\text{-km}$ (25). - 40–45% reduction in $CO_2/t\text{-km}$ (augmented if switch to low-carbon electricity). - 14% reduction in operating costs (allowing for increase in speed and with energy costs excluded from cost calculation) (38). Also see passenger "Rail (Light Rail Car)" above.	See passenger "Rail (Light Rail Car)" above
Waterborne 2010 New large international container vessel 2010 Large bulk carrier/tanker 2010 LNG bulk carrier 2030 Optimized container vessel 2030 Optimized bulk carrier			**Baseline: Stock average international ships** 10–40 $gCO_2/t\text{-km}$ (25). **2010 water craft:** 5–30% $CO_2/t\text{-km}$ reduction potential; retrofit and maintenance measures 2–20%; total reduction 43% (2020) to 63% (2050) (19). Potential up to 60% CO_2 reduction by 2030 from optimized technology and operation (19). 30% or more reduction in $CO_2/t\text{-km}$ by 2030 at zero cost (30). **2030 water craft:** Business-as-usual reduction in carbon intensity of shipping of 20% between 2010 and 2030 but could rise to 37% with industry initiatives (39).	2010 new medium vessel:(46) Industry initiatives through the Energy Efficiency Design Index and Ship Energy Efficiency Management Programme of the International Maritime Organisation (IMO)(22)
Water craft operations and logistics Slow steaming of container vessel. Inland waterways			**Operations:** Potential CO_2 reductions 15–39%; Slow steaming at 3–9kts slower than 24kt baseline. **Cost savings** around 200 USD/tCO_2 at bunker fuel price of 700 USD/t and combining savings for carriers and shippers (37). CO_2 emissions reductions of 43% per t-km by 2020 (20); - 63% $CO_2/t\text{-km}$ by 2050 (21); - 25–75% GHG intensity by 2050 (22); - 39–57 % $CO_2/t\text{-km}$ 'attainable' by 2050; - 59–72 % $CO_2/t\text{-km}$ is 'optimistic' by 2050 (23)	Global average speed reduction of 15% would give benefits that outweigh costs by 178–617 billion USD by 2050 (31). 'Slow steaming' at 10% slower speed gives 15–19% CO_2 emissions reduction; 20% slower speed gives 36–39% (24, 31, 37). Inland waterways potential (46)



*Levelized cost of conserved carbon (LCCC), here at 5% weighted average cost of capital (WACC)

Cross-modal mitigation options	Indicative 2010 stock average baseline CO_2eq emissions and reduction potential	Indicative direct mitigation cost in relation to the baseline (can be positive or negative)	Reference conditions and assumptions made	Illustrative examples
Biofuels	Broad range	Broad range	0–100% excluding land use change effects (26, 33). GHG reduction potential by fuel type: - sugarcane ethanol: 0–80% - enzymatic hydrolysis ethanol: 0–100% - advanced biomass-to-liquid processes (direct gasoline/diesel replacements): 0–100% (33). 80 USD/tCO_2 for biofuels with 80% lower net GHG emissions and 20% higher cost per litre gasoline equivalent (lge) than base fuel (e.g., gasoline).	Brazilian sugarcane: 80% GHG emissions reduction compared with gasoline (excluding land use change effects) (33).
Logistics and freight operations			13–330 USD/tCO_2 (26, 28). ~18% reduction in CO_2/t-km possible from: - speed reduction (7 percentage points) - optimized networks (5 percentage points) - modal switch (4 percentage points) - increased home delivery (1 percentage point) - reduced congestion (1 percentage point) (27).	UK Government best practice programme for freight/logistics at –12 USD/tCO_2 (28). Low-carbon technologies for urban and long-haul road freight –67–110 USD/tCO_2; Route management : ~330 USD/tCO_2.
Eco-driving and driver education			Negative costs per tCO_2 saved even with on-board eco-drive assistance technologies and meters (32). 5–10% reduced fuel consumption (50) 5–25% reduced fuel consumption (15, 16).	Japan: 12% fuel consumption savings through eco-driving-schemes in freight (12).
Activity reduction in urban areas			GHG reduction of up to 30% (29, 40, 41)	Urban densification in the USA over about 50 years could reduce fuel use by 9–16% (35).

Selected CO_2eq mitigation potentials resulting from changes in transport modes with different emission intensities (tCO_2eq/p-km or /t-km) and associated levelized cost of conserved carbon (LCCC in USD_{2010}/tCO_2eq saved). Estimates are indicative. Variations in emission intensities stem from variation in vehicle efficiencies and occupancy/load rates. Estimated LCCC for passenger road transport options are point estimates ±100 USD_{2010}/tCO_2eq based on central estimates of input parameters that are very sensitive to assumptions (e.g., specific improvement in vehicle fuel economy to 2030, specific biofuel CO_2eq intensity, vehicle costs, fuel prices). They are derived relative to different baselines (see legend for colour coding) and need to be interpreted accordingly. Estimates for 2030 are based on projections from recent studies, but remain inherently uncertain. LCCC for aviation and for freight transport are taken directly from the literature. Additional context to these estimates is provided in the two right-most columns of the table (see Annex III, Section A.III.3 for data and assumptions on emission intensities and cost calculations and Annex II, Section A.II.3.1 for methodological issues on levelized cost metrics).

References: 1: IATA (2009), 2: TOSCA (2011), IEA (2009), 3: Dell'Olmo and Lulli (2003), Pyrialakou et al. (2012), 4: Bandivadekar (2008), ICCT (2010), Greene and Plotkin (2011), IEA (2012a), 5: IEA (2012), 6: NRC (2011a), 7: Sims et al. (2011), 8: Chandler et al. (2006), 9: ICCT (2010), NRC (2010), IEA (2012e), 10: ICCT. (2012), 11: NRC (2012), 12: UNEP (2011), 13: Chandler et al. (2006), IPCC (2007), AEA (2011), ITF (2011), IEA (2012d), 14: Hallmark et al. (2013), 15: Goodwin and Lyons (2010), Taylor and Philp (2010), Ashton-Graham et al. (2011), Höjer et al. (2011), Salter et al. (2011), Pandey (2006), 16: Behrendt et al. (2010), 17: Argonne National Lab. (2013), 18: UIC (2011), 19: IEA (2011a), 20: Crist (2009), IMO (2009), DNV (2010), ICCT (2011b), Lloyds Register and DNV (2011), Eide et al. (2011), 21: Crist (2009), 22: IMO (2009), 23: Lloyds Register and DNV (2011), 24: DNV (2010), 25: TIAX (2009), IEA (2012c), 26: Lawson et al. (2007), AEA (2011), 27: World Economic Forum/Accenture (2009), 28: Lawson et al. (2007), 29: TFL (2007), Eliasson (2008), Creutzig and He (2009), 30: IMO (2009), 31: Faber et al. (2012), 32: IEA (2009), IEA (2010b), 33: Bioenergy Annex, Chapter 11; 34: TOSCA (2011), 35: Marshall (2011), 36: ITDP (2009), 37: Maloni et al. (2013), 38: Andersson et al. (2011), 39: Wang (2012b), 40: Sælensminde (2004), 41: Tirachini and Hensher (2012), 42: DfT (2010), 43: Andersson et al. (2011), 44: Halzedine et al. (2009), 45: Sharpe (2010), 46: Skinner et al. (2010a), 47: Hill et al. (2012), 48: IEA (2012c), 49: Freight Transport Association (2013), 50: SAFED 2013; 51: NTM (2011), 52: Jardine (2009).

8.7 Co-benefits, risks and spillovers

Mitigation in the transport sector has the potential to generate synergies and co-benefits with other economic, social, and environmental objectives. In addition to mitigation costs (see Section 8.6), the deployment of mitigation measures will depend on a variety of other factors that relate to the broader objectives that drive policy choices. The implementation of policies and measures can have positive or negative effects on these other objectives—and vice versa. To the extent these effects are positive, they can be deemed as 'co-benefits'; if adverse and uncertain, they imply risks. Potential co-benefits and adverse side effects of alternative mitigation measures (Section 8.7.1), associated technical risks and uncertainties (Section 8.7.2), and public perceptions (Section 8.7.3) can significantly affect investment decisions and individual behaviour as well as influence the priority-setting of policymakers. Table 8.4 provides an overview of the potential co-benefits and adverse side-effects of the mitigation measures that are assessed in this chapter. In accordance with the three sustainable development pillars described in Sections 4.2 and 4.8, the table presents effects on objectives that may be economic, social, environmental, and health related. The extent to which co-benefits and adverse side effects will materialize in practice, and their net effect on social welfare, differ greatly across regions. Both are strongly dependent on local circumstances and implementation practices as well as on the scale and pace of the deployment of the different mitigation measures (see Section 6.6).

8.7.1 Socio-economic, environmental, and health effects

Transport relies almost entirely on oil with about 94 % of transport fuels being petroleum products (IEA, 2011b). This makes it a key area of energy security concern. Oil is also a major source of harmful emissions that affect air quality in urban areas (see Section 8.2) (Sathaye et al., 2011). In scenario studies of European cities, a combination of public transit and cycling infrastructures, pricing, and land-use measures is projected to lead to notable co-benefits. These include improved energy security, reduced fuel spending, less congestion, fewer accidents, and increased public health from more physical activity, less air pollution and less noise-related stress (Costantini et al., 2007; Greene, 2010b; Rojas-Rueda et al., 2011; Rojas-Rueda et al., 2012; Creutzig et al., 2012a). However, only a few studies have assessed the associated welfare effects comprehensively and these are hampered by data uncertainties. Even more fundamental is the epistemological uncertainty attributed to different social costs. As a result, the range of plausible social costs and benefits can be large. For example, the social costs of the co-dimensions congestion, air pollution, accidents, and noise in Beijing were assessed to equate to between 7.5 % to 15 % of GDP (Creutzig and He, 2009). Improving energy security, mobility access, traffic congestion, public health, and safety are all important policy objectives that can possibly be influenced by mitigation actions (Jacobsen, 2003; Goodwin, 2004; Hultkrantz et al., 2006; Rojas-Rueda et al., 2011).

Energy security. Transport stands out in comparison to other energy end-use sectors due to its almost complete dependence on petroleum products (Sorrell and Speirs, 2009; Cherp et al., 2012). Thus, the sector suffers from both low resilience of energy supply and, in many countries, low sufficiency of domestic resources. (For a broader discussion on these types of concerns see Section 6.6.2.2). The sector is likely to continue to be dominated by oil for one or more decades (Costantini et al., 2007). For oil-importing countries, the exposure to volatile and unpredictable oil prices affects the terms of trade and their economic stability. Measuring oil independence is possible by measuring the economic impact of energy imports (Greene, 2010b). Mitigation strategies for transport (such as electrifying the sector and switching to biofuels) would decrease the sector's dependence on oil and diversify the energy supply, thus increasing resilience (Leiby, 2007; Shakya and Shrestha, 2011; Jewell et al., 2013). However, a shift away from oil could have implications for energy exporters (see Chapter 14). Additionally, mitigation measures targeted at reducing the overall transport demand—such as more compact urban form with improved transport infrastructure and journey distance reduction and avoidance (see Sections 8.4 and 12.4.2.1)—may reduce exposure to oil price volatility and shocks (Sovacool and Brown, 2010; Leung, 2011; Cherp et al., 2012).

Access and mobility. Mitigation strategies that foster multi-modality are likely to foster improved access to transport services particularly for the poorest and most vulnerable members of society. Improved mobility usually helps provide access to jobs, markets, and facilities such as hospitals and schools (Banister, 2011b; Boschmann, 2011; Sietchiping et al., 2012). More efficient transport and modal choice not only increases access and mobility it also positively affects transport costs for businesses and individuals (Banister, 2011b). Transport systems that are affordable and accessible foster productivity and social inclusion (Banister, 2008; Miranda and Rodrigues da Silva, 2012).

Employment impact. In addition to improved access in developing countries, a substantial number of people are employed in the formal and informal public transport sector (UN-Habitat, 2013). A shift to public transport modes is likely to generate additional employment opportunities in this sector (Santos et al., 2010). However, the net effect on employment of a shift towards low-carbon transport remains unclear (UNEP, 2011).

Traffic congestion. Congestion is an important aspect for decision makers, in particular at the local level, as it negatively affects journey times and creates substantial economic cost (Goodwin, 2004; Duranton and Turner, 2011). For example, in the United States in 2000, time lost in traffic amounted to around 0.7 % of GDP (Federal Highway Administration, 2000) or approximately 85 billion USD_{2010}. This increased to

101 billion USD_{2010} in 2010, also being 0.7 % of GDP, but with more accurate data covering the cost per kilometre travelled of each major vehicle type for 500 urban centres (Schrank et al., 2011). Time lost was valued at 1.2 % of GDP in the UK (Goodwin, 2004); 3.4 % in Dakar, Senegal; 4 % in Manila, Philippines (Carisma and Lowder, 2007); 3.3 % to 5.3 % in Beijing, China (Creutzig and He, 2009); 1 % to 6 % in Bangkok, Thailand (World Bank, 2002) and up to 10 % in Lima, Peru where people on average spend around four hours in daily travel (JICA, 2005; Kunieda and Gauthier, 2007).

Modal shifts that reduce traffic congestion can simultaneously reduce GHG emissions and short-lived climate forcers. These include road congestion pricing, modal shifts from aviation to rail, and shifts from LDVs to public transport, walking, and cycling (Cuenot et al., 2012). However, some actions that seek to reduce congestion can induce additional travel demand, for example, expansions of airport infrastructure or construction of roads to increase capacity (Goodwin, 2004; ECMT, 2007; Small and van Dender, 2007).

Health*.* Exposure to vehicle exhaust emissions can cause cardiovascular, pulmonary, and respiratory diseases and several other negative health impacts (McCubbin, D.R., Delucchi, 1999; Medley et al., 2002; Chapters 7.9.2, 8.2, and WG II Chapter 11.9). In Beijing, for example, the social costs of air pollution were estimated to be as high as those for time delays from congestion (Creutzig and He, 2009). Various strategies to reduce fuel carbon intensity have varying implications for the many different air pollutants. For example, many studies indicate lower carbon monoxide and hydrocarbon emissions from the displacement of fossil-based transport fuels with biofuels, but NO_x emissions are often higher. Advanced biofuels are expected to improve performance, such as the low particulate matter emissions from ligno-cellulosic ethanol (see Hill et al., 2009, Sathaye et al., 2011 and Section 11.13.5). Strategies that target local air pollution, for example switching to electric vehicles, have the potential to also reduce CO2 emissions (Yedla et al., 2005) and black carbon emissions (UNEP and WMO, 2011) provided the electricity is sourced from low-carbon sources. Strategies to improve energy efficiency in the LDV fleet though fostering diesel-powered vehicles may affect air quality negatively (Kirchstetter et al., 2008; Schipper and Fulton, 2012) if not accompanied by regulatory measures to ensure emission standards remain stable. The structure and design of these strategies ultimately decides if this potential can be realized (see Section 8.2).

Transport also contributes to noise and vibration issues, which affect human health negatively (WHO, 2009; Oltean-Dumbrava et al., 2013; Velasco et al., 2013). Transport-related human inactivity has also been linked to several chronic diseases (WHO, 2008). An increase in walking and cycling activities could therefore lead to health benefits but conversely may also lead to an increase in traffic accidents and a larger lung intake of air pollutants (Kahn Ribeiro et al., 2012; Takeshita, 2012). Overall, the benefits of walking and cycling significantly outweigh the risks due to pollution inhalation (Rojas-Rueda et al., 2011; Rabl and de Nazelle, 2012).

Assessing the social cost of public health is a contested area when presented as disability-adjusted life years (DALYs). A reduction in CO_2 emissions through an increase in active travel and less use of ICE vehicles gave associated health benefits in London (7,332 DALYs per million population per year) and Delhi (12,516 (DALYs/million capita)/yr)—significantly more than from the increased use of lower-emission vehicles (160 (DALYs/million capita)/yr) in London, and 1,696 in Delhi) (Woodcock et al., 2009). More generally, it has been found consistently across studies and methods that public health benefits (induced by modal shift from LDVs to non-motorized transport) from physical activity outweighs those from improved air quality (Woodcock et al., 2009; de Hartog et al., 2010; Rojas-Rueda et al., 2011; Grabow et al., 2012; Maizlish et al., 2013). In a similar trend, reduced car use in Australian cities has been shown to reduce health costs and improve productivity due to an increase in walking (Trubka et al., 2010a).

Safety. The increase in motorized road traffic in most countries places an increasing incidence of accidents with 1.27 million people killed globally each year, of which 91 % occur in low and middle-income countries (WHO, 2011). A further 20 to 50 million people suffer serious injuries (WHO, 2011). By 2030, it is estimated that road traffic injuries will constitute the fifth biggest reason for premature deaths (WHO, 2008). Measures to increase the efficiency of the vehicle fleet can also positively affect the crash-worthiness of vehicles if more stringent safety standards are adopted along with improved efficiency standards (Santos et al., 2010). Lack of access to safe walking, cycling, and public transport infrastructure remains an important element affecting the success of modal shift strategies, in particular in developing countries (Sonkin et al., 2006; Tiwari and Jain, 2012).

Fossil fuel displacement. Economists have criticized the assumption that each unit of energy replaces an energy-equivalent quantity of fossil energy, leaving total fuel use unaffected (Drabik and de Gorter, 2011; Rajagopal et al., 2011; Thompson et al., 2011). As with other energy sources, increasing energy supply through the production of bioenergy affects energy prices and demand for energy services, and these changes in consumption also affect net global GHG emissions (Hochman et al., 2010; Rajagopal et al., 2011; Chen and Khanna, 2012). The magnitude of the effect of increased biofuel production on global fuel consumption is uncertain (Thompson et al., 2011) and depends on how the world responds in the long term to reduced petroleum demand in regions using increased quantities of biofuels. This in turn depends on the Organization of Petroleum Exporting Countries' (OPEC) supply response and with China's and India's demand response to a given reduction in the demand for petroleum in regions promoting biofuels, and the relative prices of biofuels and fossil fuels including from hydraulic fracturing (fracking) (Gehlhar et al., 2010; Hochman et al., 2010; Thompson et al., 2011). Notably, if the percentage difference in GHG emissions between an alternative fuel and the incumbent fossil fuel is less than the percentage rebound effect (the fraction not displaced, in terms of GHG emissions), a net increase in GHG emissions will result from promoting the alternative fuel, despite its nominally lower rating (Drabik and de Gorter, 2011).

Table 8.4 | Overview of potential co-benefits (green arrows) and adverse side effects (orange arrows) of the main mitigation measures in the transport sector. Arrows pointing up/down denote positive/negative effect on the respective objective/concern; a question mark (**?**) denotes an uncertain net effect. Co-benefits and adverse side-effects depend on local circumstances as well as on the implementation practice, pace, and scale (see Section 6.6). For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., energy prices, consumption, growth, and trade), see Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. For possible upstream effects of low-carbon electricity and biomass supply, see Sections 7.9 as well as 11.7 and 11.13.6. Numbers in brackets correspond to references below the table.

Mitigation measures	Effect on additional objectives/concerns		
	Economic	**Social (including health)**	**Environmental**
Reduction of fuel carbon intensity: electricity, hydrogen, CNG, biofuels, and other fuels	↑ Energy security (diversification, reduced oil dependence and exposure to oil price volatility) (1–3,32–34,94) ↑ Technological spillovers (e.g., battery technologies for consumer electronics) (17,18,44,55,90)	Health impact via urban air pollution (59,69) by ? CNG, biofuels: net effect unclear (13,14,19,20,36,50) ↓ Electricity, hydrogen: reducing most pollutants (13,20,21,36,58,63,92) ↑ Shift to diesel: potentially increasing pollution (11,23,25) ↓ Health impact via reduced noise (electricity and fuel cell LDVs) (10,61,64–66,82) ↓ Road safety (silent electric LDVs at low speed) (56)	Ecosystem impact of electricity and hydrogen via: ↓ Urban air pollution (13,20,69,91–93) ↑ Material use (unsustainable resource mining) (17,18) ? Ecosystem impact of biofuels (24,41,42,89)
Reduction of energy intensity	↑ Energy security (reduced oil dependence and exposure to oil price volatility) (1–3,32–34)	↓ Health impact via reduced urban air pollution (22,25,43,59,62,69,84) ↑ Road safety (crash-worthiness depending on the design of the standards) (38,39,52,60)	↓ Ecosystem and biodiversity impact via reduced urban air pollution (20,22,69,95)
Compact urban form and improved transport infrastructure **Modal shift**	↑ Energy security (reduced oil dependence and exposure to oil price volatility) (77–80,86) ↑ Productivity (reduced urban congestion and travel times, affordable and accessible transport) (6–8,26,35,45,46,48,49) ? Employment opportunities in the public transport sector vs. car manufacturing jobs (38,76,89)	Health impact for non-motorized modes via ↓ Increased physical activity (7,12,27,28,29,51,64,70,73,74) ↑ Potentially higher exposure to air pollution (19,27,59,69,70,74) ↓ Noise (modal shift and travel reduction) (58,61,64–66,81–83) ↑ Equitable mobility access to employment opportunities, particularly in developing countries (4,5,8,9,26,43,47,49) ↑ Road safety (via modal shift and/or infrastructure for pedestrians and cyclists) (12,27,37,39,40,87,88)	Ecosystem impact via ↓ Urban air pollution (20,54,58,60,69) ↓ Land-use competition (7,9,58,71,75)
Journey distance reduction and avoidance	↑ Energy security (reduced oil dependence and exposure to oil price volatility) (31,77–80,86) ↑ Productivity (reduced urban congestion, travel times, walking) (6–8,26,45,46,49)	↓ Health impact (for non-motorized transport modes) (7,12,22,27–30,67,68,72,75)	Ecosystem impact via ↓ Urban air pollution (20,53,54,60,69) ↑ New/shorter shipping routes (15,16,57) ↓ Land-use competition from transport infrastructure (7,9,58,71,75)

References: 1: Greene (2010b), 2: Costantini et al. (2007), 3: Bradley and Lefevre (2006), 4: Boschmann (2011), 5: Sietchiping et al. (2012), 6: Cuenot et al. (2012), 7: Creutzig et al. (2012a), 8: Banister (2008), 9: Geurs and Van Wee (2004), Banister (2008), 10: Creutzig and He (2009), 11: Leinert et al. (2013), 12: Rojas-Rueda et al. (2011), 13: Sathaye et al. (2011), 14: Hill et al. (2009), 15: Garneau et al. (2009), 16: Wassmann (2011), 17: Eliseeva and Bünzli (2011), 18: Massari and Ruberti (2013), 19: Takeshita (2012), 20: Kahn Ribeiro et al. (2012), 21: IEA (2011a), 22: Woodcock et al. (2009), 23: Schipper and Fulton (2012), 24: see Section 11.13.6, 25: Kirchstetter et al. (2008), 26: Banister (2008), Miranda and Rodrigues da Silva (2012), 27: Rojas-Rueda et al. (2011), Rabl and de Nazelle (2012), 28: Jacobsen (2003), 29: Hultkrantz et al. (2006), 30: Goodwin (2004), 31: Sorrell and Speirs (2009), 32: Jewell et al. (2013), 33: Shakya and Shrestha (2011), 34: Leiby (2007), 35: Duranton and Turner (2011), 36: Trubka et al. (2010a), 37: WHO (2011), 38: Santos et al. (2010), 39: Tiwari and Jain (2012), 40: Sonkin et al. (2006), 41: Chum et al. (2011), 42: Larsen et al. (2009), 43: Steg and Gifford (2005), 44: Christensen et al. (2012), 45: Schrank et al. (2011), 46: Carisma and Lowder (2007), 47: World Bank (2002), 48: JICA (2005), 49: Kunieda and Gauthier (2007), 50: see Section 11.13.5, 51: Maizlish et al. (2013), 52: WHO (2008), 53: ICCT (2012b), 54: Yedla et al. (2005), 55: Lu et al. (2013), 56: Schoon and Huijskens (2011), 57: see Section 8.5, 58: see Section 12.8, 59: Medey et al. (2002), 60: Machado-Filho (2009), 61: Milner et al. (2012), 62: Kim Oanh et al. (2012), 63: Fulton et al. (2013), 64: de Nazelle et al. (2011), 65: Twardella and Ndrepepa (2011), 66: Kawada (2011), 67: Grabow et al. (2012), 68: Pucher et al. (2010), 69: Section 7.9.2 and WGII Section 11.9, 70: de Hartog et al. (2010), 71: Heath et al. (2006), 72: Saelens et al. (2003), 73: Sallis et al. (2009), 74: Hankey and Brauer (2012), 75: Cervero and Sullivan (2011), 76: Mikler (2010), 77: Cherp et al. (2012), 78: Leung (2011), 79: Knox-Hayes et al. (2013), 80: Sovacool and Brown (2010), 81: WHO (2009), 82: Oltean-Dumbrava et al. (2013), 83: Velasco et al. (2013), 84: Smith et al. (2013), 86: see Section 8.4, 87: Schepers et al. (2013), 88: White (2004), 89: UNEP/GEF (2013), 90: Rao and Wang (2011), 91: Notter et al. (2010), 92: Sioshansi and Denholm (2009), 93: Zackrisson et al. (2010), 94: Michalek et al. (2011), 95: see Section 8.2.2.1.

If biofuels displace high carbon-intensity oil from tar sands or heavy oils, the displacement effect would provide higher GHG emission savings. Estimates of the magnitude of the petroleum rebound effect cover a wide range and depend on modelling assumptions. Two recent modelling studies suggest that biofuels replace about 30–70 % of the energy equivalent quantity of petroleum-based fuel (Drabik and de Gorter, 2011; Chen and Khanna, 2012), while others find replacement can be as low as 12–15 % (Hochman et al., 2010). Under other circumstances, the rebound can be negative. The rebound effect is always subject to the policy context, and can be specifically avoided by global cap and pricing instruments.

8.7.2 Technical risks and uncertainties

Different de-carbonization strategies for transport have a number of technological risks and uncertainties associated with them. Unsustainable mining of resources to supply low-carbon transport technologies such as batteries and fuel cells may create adverse side effects for the local environment (Massari and Ruberti, 2013; Eliseeva and Bünzli, 2011). Mitigation options from lower energy-intensity technologies (e. g., electric buses) and reduced fuel carbon intensity (e. g., biofuels) are particularly uncertain regarding their technological viability, sources of primary energy, and biomass and lifecycle emission reduction potential (see Section 8.3). Biofuels indicators are being developed to ensure a degree of sustainability in their production and use (UNEP/GEF, 2013; Sections 11.13.6 and 11.13.7). For shipping, there is potential for new and shorter routes such as across the Arctic, but these may create risks to vulnerable ecosystems (see Section 8.5).

A focus on improving vehicle fuel efficiency may reduce GHG emissions and potentially improve air quality, but without an increase in modal choice it may not result in improved access and mobility (Steg and Gifford, 2005). The shift toward more efficient vehicles, for example the increasing use of diesel for the LDV fleet in Europe, has also created tradeoffs such as negatively affecting air quality in cities (Kirchstetter et al., 2008). More generally, mitigation options are also likely to be subject to rebound effects to varying degrees (see Sections 8.3 and 8.10).

8.7.3 Technological spillovers

Advancements in technologies developed for the transport sector may have technological spillovers to other sectors. For example advancements in battery technology systems for consumer electronics could facilitate the development of batteries for electric vehicles and vice-versa (Rao and Wang, 2011). The production of land-competitive biofuels can also have direct and indirect effects on biodiversity, water, and food availability (see Sections 11.13.6 and 11.13.7). Other areas where technological spillovers may occur include control and navigation systems and other information technology applications.

8.8 Barriers and opportunities

Barriers and opportunities are processes that hinder or facilitate deployment of new transport technologies and practices. Reducing transport GHG emissions is inherently complex as increasing mobility with LDVs, HDVs, and aircraft has been associated with increasing wealth for the past century of industrialization (Meyer et al., 1965; Glaeser, 2011). The first signs of decoupling fossil fuel-based mobility from wealth generation are appearing in OECD countries (Kenworthy, 2013). To decouple and reduce GHG emissions, a range of technologies and practices have been identified that are likely to be developed in the short- and long-terms (see Section 8.3), but barriers to their deployment exist as do opportunities for those nations, cities, and regions willing to make low-carbon transport a priority. There are many barriers to implementing a significantly lower carbon transport system, but these can be turned into opportunities if sufficient consideration is given and best-practice examples are followed.

8.8.1 Barriers and opportunities to reduce GHGs by technologies and practices

The key transport-related technologies and practices garnered from sections above are set out below in terms of their impact on fuel carbon intensity, improved energy intensity of technologies, system infrastructure efficiency, and transport demand reduction. Each has short- and long-term potentials to reduce transport GHG emissions that are then assessed in terms of their barriers and opportunities (Table 8.5). (Details of policies follow in Section 8.10).

Psychological barriers can impede behavioural choices that might otherwise facilitate mitigation as well as adaptation and environmental sustainability. Many individuals are engaged in ameliorative actions to improve their local environment, although many could do more. Gifford (2011) outlined barriers that included "limited cognition about the problem, ideological worldviews that tend to preclude pro-environmental attitudes and behaviour, comparisons with the responses of other people, sunk costs and behavioural momentum, a dis-credence toward experts and authorities, perceived risks as a result of making change and positive but inadequate confidence to make behavioural change."

The range of barriers to the ready adoption of the above technologies and practices have been described in previous sections, but are summarized in Table 8.5 along with the opportunities available. The challenges involved in removing barriers in each of the 16 elements listed depend on the politics of a region. In most places, reducing fuel carbon and energy intensities are likely to be relatively easy as they are technology-based, though they can meet capital investment barriers in developing regions and may be insufficient in the longer-term. On the other hand, system infrastructure efficiency and transport demand reduction options would require human interventions and social change as well as public investment. Although these may not require as much capital investment, they would still require public acceptance of any transport policy option (see Section 8.10). As implementation approaches, public acceptance fluctuates, so political support may be required at critical times (Pridmore and Miola, 2011).

Table 8.5 | Transport technologies and practices with potential for both short- and long-term GHG reduction and the related barriers and opportunities in terms of the policy arenas of fuel carbon intensity, energy intensity, infrastructure, and activity.

Transport technology or practice	Short-term possibilities	Long-term possibilities	Barriers	Opportunities	References
Fuel carbon intensity: fuel switching *BEV—Battery electric vehicle; PHEV—Plug-in hybrid electric vehicle; FCV—Fuel cell vehicles; CHP—combined heat and power; CNG—Compressed natural gas; LNG—Liquefied natural gas; CBG—Compressed biogas; LBG—Liquefied biogas)*					
1. BEVs and PHEVs based on renewable electricity.	Rapid increase in use likely over next decade from a small base, so only a small impact likely in short-term.	Significant replacement of ICE-powered LDVs.	EV and battery costs reducing but still high. Lack of infrastructure, and recharging standards not uniform. Vehicle range anxiety. Lack of capital and electricity in some least developed countries.	Universal standards adopted for EV rechargers. Demonstration in green city areas with plug-in infrastructure. Decarbonized electricity. Smart grids based on renewables. EV subsidies. New business models, such as community car sharing.	EPRI 2008; Beck ,2009; IEA, 2011; Salter et al., 2011; Kley et al., 2011; Leurent & Windisch, 2011; Graham-Rowe et al., 2012
2. CNG, LNG, CBG and LBG displacing gasoline in LDVs and diesel in HDVs.	Infrastructure available in some cities so can allow a quick ramp–up of gas vehicles in these cities.	Significant replacement of HDV diesel use depends on ease of engine conversion, fuel prices and extent of infrastructure.	Insufficient government programmes, conversion subsidies and local gas infrastructure and markets. Leakage of gas.	Demonstration gas conversion programmes that show cost and health co-benefits. Fixing gas leakage in general.	IEA, 2007; Salter et al., 2011; Alvarez et al., 2012
3. Biofuels displacing gasoline, diesel and aviation fuel.	Niche markets continue for first generation biofuels (3 % of liquid fuel market, small biogas niche markets).	Advanced and drop-in biofuels likely to be adopted around 2020–2030, mainly for aviation.	Some biofuels can be relatively expensive, environmentally poor and cause inequalities by inducing increases in food prices.	Drop-in fuels attractive for all vehicles. Biofuels and bio-electricity can be produced together, e.g., sugarcane ethanol and CHP from bagasse. New biofuel options need to be further tested, particularly for aviation applications.	Ogden et al., 2004; Fargione et al., 2010; IEA, 2010; Plevin et al., 2010; Creutzig et al., 2011; Salter et al., 2011; Pacca and Moreira, 2011; Flannery et al., 2012
Energy intensity: efficiency of technologies *FEV—fuel efficient vehicles ICE—internal combustion engine*					
4. Improved vehicle ICE technologies and on-board information and communication technologies (ICT) in fuel-efficient vehicles.	Continuing fuel efficiency improvements across new vehicles of all types can show large, low-cost, near-term reductions in fuel demand.	Likely to be a significant source of reduction. Behavioural issues (e.g., rebound effect). Consumer choices can reduce vehicle efficiency gains.	Insufficient regulatory support for vehicle emissions standards. On-road performance deteriorates compared with laboratory tests.	Creative regulations that enable quick changes to occur without excessive costs on emissions standards. China and most OECD countries have implemented standards. Reduced registration tax can be implemented for low CO_2eq-based vehicles.	Schipper et al., 2000; Ogden et al., 2004; Small and van Dender, 2007; Sperling and Gordon, 2009; Timilsina and Dulal, 2009; Fuglestvedt et al., 2009; Mikler, 2010; Salter et al., 2011
Structure: system infrastructure efficiency					
5. Modal shift by public transport displacing private motor vehicle use.	Rapid short-term growth already happening.	Significant displacement only where quality system infrastructure and services are provided.	Availability of rail, bus, ferry, and other quality transit options. Density of people to allow more access to services. Levels of services. Time barriers on roads without right of way Public perceptions.	Investment in quality transit infrastructure, density of adjacent land use, and high level of services using innovative financing that builds in these features. Multiple co-benefits especially where walkability health benefits are a focus.	Kenworthy, 2008; Millard-Ball & Schipper, 2011; Newman and Kenworthy, 2011; Salter et al., 2011; Buehler and Pucher, 2011; Newman and Matan, 2013

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Transport technology or practice	Short-term possibilities	Long-term possibilities	Barriers	Opportunities	References
6. Modal shift by cycling displacing private motor vehicle use.	Rapid short-term growth already happening in many cities.	Significant displacement only where quality system infrastructure is provided.	Cultural barriers and lack of safe cycling infrastructure and regulations. Harsh climate.	Demonstrations of quality cycling infrastructure including cultural programmes and bike-sharing schemes.	Bassett et al., 2008; Garrard et al., 2008; Salter et al., 2011; Anon, 2012; Sugiyama et al., 2012
7. Modal shift by walking displacing private motor vehicle use.	Some growth but depends on urban planning and design policies being implemented.	Significant displacement where large-scale adoption of polycentric city policies and walkable urban designs are implemented.	Planning and design policies can work against walkability of a city by too easily allowing cars into walking city areas. Lack of density and integration with transit. Culture of walkability.	Large-scale adoption of polycentric city policies and walkable urban designs creating walking city in historic centres and new ones. Cultural programmes.	Gehl, 2011; Höjer et al., 2011; Leather et al., 2011; Salter et al., 2011
8. Urban planning by reducing the distances to travel within urban areas.	Immediate impacts where dense transit-oriented development (TOD) centres are built.	Significant reductions where widespread polycentric city policies are implemented.	Urban development does not always favour dense TOD centres being built. TODs need quality transit at their base. Integration of professional areas required.	Widespread polycentric city policies implemented with green TODs, backed by quality transit. Multiple co-benefits in sprawl costs avoided and health gains.	Anon, 2004; Anon, 2009; Naess, 2006; Ewing et al., 2008; Cervero and Murakami, 2009; Cervero and Murakami, 2010; Cervero and Sullivan, 2011; Salter et al., 2011; Lefèvre; 2009
9. Urban planning by reducing private motor vehicle use through parking and traffic restraint.	Immediate impacts on traffic density observed.	Significant reductions only where quality transport alternatives are available.	Political barriers due to perceived public opposition to increased costs, traffic and parking restrictions. Parking codes too prescriptive for areas suited to walking and transit.	Demonstrations of better transport outcomes from combinations of traffic restraint, parking and new transit/walking infrastructure investment.	Gwilliam, 2003; ADB, 2011; Creutzig et al., 2011; Shoup, 2011; Newman and Matan, 2013
10. Modal shift by displacing aircraft and LDV trips through high-speed rail alternatives.	Immediate impacts after building rail infrastructure.	Continued growth but only short-medium distance trips suitable.	High-speed rail infrastructure expensive.	Demonstrations of how to build quality fast-rail using innovative finance.	Park and Ha, 2006; Gilbert and Perl, 2010; Åkerman, 2011; Salter et al., 2011
11. Modal shift of freight by displacing HDV demand with rail.	Suitable immediately for medium- and long-distance freight and port traffic.	Substantial displacement only if large rail infrastructure improvements made, the external costs of freight transport are fully internalized, and the quality of rail services are enhanced. EU target to have 30 % of freight tonne-km moving more than 300 km to go by rail (or water) by 2030.	Inadequacies in rail infrastructure and service quality. Much freight moved over distances that are too short for rail to be competitive.	Upgrading of inter-modal facilities. Electrification of rail freight services. Worsening traffic congestion on road networks and higher fuel cost will favour rail.	IEA, 2009; Schiller et al., 2010; Salter et al., 2011
12. Modal shift by displacing truck and car use through waterborne transport.	Niche options already available. EU "Motorways of the Sea" programme demonstrates potential to expand short-sea shipping share of freight market.	Potential to develop beyond current niches, though will require significant investment in new vessels and port facilities.	Lack of vision for water transport options and land-locked population centres. Long transit times. Tightening controls on dirty bunker fuel and SO_x and NO_x emissions raising cost and reducing modal competitiveness.	Demonstrations of quality waterborne transport that can be faster and with lower-carbon emissions than alternatives.	Fuglestvedt et al., 2009; Salter et al. 2011
13. System optimization by improved road systems, freight logistics and efficiency at airports and ports.	Continuing improvements showing immediate impacts.	Insufficient in long term to significantly reduce carbon emissions without changing mode, reducing mobility, or reducing fuel carbon intensity.	Insufficient regulatory support and key performance indicators (KPIs) covering logistics and efficiency.	Creative regulations and KPIs that enable change to occur rapidly without excessive costs.	Pels and Verhoef, 2004; A. Zhang and Y. Zhang, 2006; Fuglestvedt et al., 2009; Kaluza et al., 2010; McKinnon, 2010; Simaiakis and Balakrishnan, 2010; Salter et al., 2011
Activity: demand reduction					
14. Mobility service substitution by reducing the need to travel through enhanced communications.	Niche markets growing and ICT improving in quality and reliability.	Significant reductions possible after faster broadband and quality images available, though ICT may increase the need for some trips.	Technological barriers due to insufficient broadband in some regions.	Demonstrations of improved video-conferencing system quality.	Golob and Regan, 2001; Choo et al., 2005; Wang and Law, 2007; Yi and Thomas, 2007; Zhen et al., 2009; Salter et al., 2011; Mokhtarian and Meenakshisundaram, 2002

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Transport technology or practice	Short-term possibilities	Long-term possibilities	Barriers	Opportunities	References
15. Behavioural change from reducing private motor vehicle use through pricing policies, e.g, network charges and parking fees.	Immediate impacts on traffic density observed.	Significant reductions only where quality transport alternatives are available.	Political barriers due to perceived public opposition to increased pricing costs. Lack of administrative integration between transport, land-use and environment departments in city municipalities.	Demonstrations of better transport outcomes from combinations of pricing, traffic restraint, parking and new infrastructure investment from the revenue. Removing subsidies to fossil fuels important for many co-benefits.	Litman, 2005, 2006; Salter et al., 2011; Creutzig et al., 2012a
16. Behavioural change resulting from education to encourage gaining benefits of less motor vehicle use.	Immediate impacts of 10–15 % reduction of LDV use are possible.	Significant reductions only where quality transport alternatives are available.	Lack of belief by politicians and professionals in the value of educational behaviour change programmes.	Demonstrations of 'travel smart' programmes linked to improvements in sustainable transport infrastructure. Cost effective and multiple co-benefits.	Pandey, 2006; Goodwin and Lyons, 2010; Taylor and Philp, 2010; Ashton-Graham et al., 2011; Höjer et al., 2011; Salter et al., 2011

8.8.2 Financing low-carbon transport

Transport is a foundation for any economy as it enables people to be linked, goods to be exchanged, and cities to be structured (Glaeser, 2011). Transport is critical for poverty reduction and growth in the plans of most regions, nations, and cities. It therefore is a key area to receive development funding. In past decades the amount of funding going to transport through various low-carbon mechanisms had been relatively low, but has had a recent increase. The projects registered in the United Nations Environmental Programme (UNEP) pipeline database for the clean development mechanism (CDM) shows only 42 projects out of 6707 were transport-related (Kopp, 2012). The Global Environment Facility (GEF) has approved only 28 projects in 20 years, and the World Bank's Clean Technology Fund has funded transport projects for less than 17 % of the total. If this international funding does not improve, then transport could move from emitting 22 % of energy-related GHGs in 2009 to reach 80 % by 2050 (ADB, 2012a). Conversely, national appropriate mitigation measures (NAMAs) could attract low-carbon financing in the transport area for the developing world. To support sustainable transport system development, eight multi-lateral development banks have pledged to invest around 170 billion USD_{2010} over the next ten years (Marton-Lefèvre, 2012).

A major part of funding sustainable transport could arise from the redirection of funding from unsustainable transport (Sakamoto et al., 2010; UNEP, 2011; ADB, 2012b). In addition, land-based taxes or fees can capitalize on the value gains brought by sustainable transport infrastructures (Chapter 12.5.2). For example, in locations close to a new rail system, revenue can be generated from land-based taxes and council rates levied on buildings that are seen to rise by 20–50 % compared to areas not adjacent to such an accessible facility (Cervero 1994; Haider and Miller, 2000; Rybeck, 2004). Local municipal financing by land value capture and land taxes could be a primary source of financing for public transit and non-motorized transport infrastructure, especially in rapidly urbanizing Asia (Chapter 12.5.2; Bongardt et al., 2013). For example, a number of value capture projects are underway as part of the rapid growth in urban rail systems, including Indian cities (Newman et al., 2013). The ability to fully outline the costs and benefits of low-carbon transport projects will be critical to accessing these new funding opportunities. R&D barriers and opportunities exist for all of these agendas in transport.

8.8.3 Institutional, cultural, and legal barriers and opportunities

Institutional barriers to low-carbon transport include international standards required for new EV infrastructure to enable recharging; low pricing of parking; lack of educational programmes for modal shift; and polycentric planning policies that require the necessary institutional structures (OECD, 2012; Salter et al., 2011). Cultural barriers underlie every aspect of transport, for example, automobile dependence being built into a culture and legal barriers that can exist to prevent the building of dense, mixed-use community centres that reduce car dependence. Overall, there are political barriers that combine most of the above (Pridmore and Miola, 2011).

Opportunities also exist. Low-carbon transport elements in green growth programmes (OECD, 2011; Hargroves and Smith, 2008) are likely to be the basis of changing economies because they shape cities and create wealth (Glaeser, 2011; Newman et al., 2009). Those nations, cities, businesses, and communities that grasp the opportunities to demonstrate these changes are likely to be the ones that benefit most in the future (OECD, 2012). The process of decoupling economic growth from fossil fuel dependence could become a major feature of the future economy (ADB, 2012a) with sustainable transport being one of four key approaches. Overcoming the barriers to each technology and practice (Table 8.5) could enable each to contribute to a more sustainable transport system and realize the opportunities from technological and social changes when moving towards a decarbonized economy of the future.

8.9 Sectoral implications of transformation pathways and sustainable development

Scenarios that focus on possible reductions of energy use and CO_2 emissions from transport are sourced from either integrated models that incorporate a cross-sector approach to modelling global emissions reductions and other mitigation options, or sectoral models that focus solely on transport and its specific potential for emissions reductions. A comparison of scenarios from both integrated and sectoral models with a focus on long-term concentration goals up until 2100 is conducted in this section. This comparison is complemented by the results of the transport-specific evaluation of cost and potentials in Section 8.6 and supported by a broader integrated assessment in Chapter 6[7].

The integrated and sectoral model transport literature presents a wide range of future CO_2 emissions reduction scenarios and offers two distinct forms of assessment. Both contemplate how changes in passenger and freight activity, structure, energy intensity, and fuel carbon intensity could each contribute to emissions reductions and assist the achievement of concentration goals.

The integrated model literature focuses upon systemic assessments of the impacts of macro-economic policies (such as limits on global/regional emissions or the implementation of a carbon tax) and reviews the relative contributions of a range of sectors to overall global mitigation efforts (Section 6.2.1). Within the WG III AR5 Scenario Database (Annex II.10), transport specific variables are not available for all scenarios. Therefore, the present analysis is based on a sub-sample of almost 600 scenarios[8]. Due to the macro-economic scale of their analysis, integrated models have a limited ability to assess behaviour changes that may result from structural developments impacting on modal shift or journey avoidance, behavioural factors such as travel time and budget might contribute up to 50 % reduction of activity globally in 2100 compared to the 2005 baseline (Girod et al., 2013).

Sectoral scenarios, however, are able to integrate results concerning emission reduction potentials from sector specific interventions (such as vehicle taxation, parking fees, fuel economy standards, promotion of modal shift, etc.). They can be instrumental in evaluating how policies that target structural factors[9] can impact on passenger and freight travel demand reductions (see Sections 8.4 and 8.10). Unlike integrated models, sectoral studies do not attempt to measure transport emissions reductions with respect to the amounts that other sectors could contribute in order to reach long-term concentration goals.

8.9.1 Long term stabilization goals—integrated and sectoral perspectives

A diversity of transformation pathways highlights the possible range of decarbonization options for transport (Section 6.8). Results from both integrated and sectoral models up until 2050 closely match each other. Projected GHG emissions vary greatly in the long term integrated scenarios, reflecting a wide range in assumptions explored such as future population, economic growth, policies, technology development, and acceptance (Section 6.2.3). Without policy interventions, a continuation of current travel demand trends could lead to a more than doubling of transport-related CO_2 emissions by 2050 and more than a tripling by 2100 in the highest scenario projections (Figure 8.9). The convergence of results between integrated and sectoral model studies suggests that through substantial, sustained, and directed policy interventions, transport emissions can be consistent with limiting long-term concentrations to 430–530 ppm CO_2eq.

The growth of global transport demand could pose a significant challenge to the achievement of potential emission reduction goals. The average transport demand growth from integrated scenarios with respect to 2010 levels suggests that total passenger and freight travel will continue to grow in the coming decades up to 2050, with most of this growth taking place within developing country regions where large shares of future population and income growth are expected (Figure 8.10) (UN Secretariat, 2007).

A positive income elasticity and the relative price-inelastic nature of passenger travel partially explain the strength of the relationship between travel and income (Dargay, 2007; Barla et al., 2009). Both integrated and sectoral model projections for total travel demand show that while demand in non-OECD countries grows rapidly, a lower starting point results in a much lower per capita level of passenger travel in 2050 than in OECD countries (Figure 8.10) (IEA, 2009; Fulton

[7] Section 6.2.2 and Annex II.10 provide details on the WG III AR5 Scenario Database, which is the source of more than 1,200 integrated scenarios.

[8] This section builds upon the scenarios which were collated by Chapter 6 in the WG III AR5 Scenario Database and compares them to global scale transport studies. The scenarios were grouped into baseline and mitigation scenarios. As described in more detail in Chapter 6.3.2, the scenarios are further categorized into bins based on 2100 concentrations: between 430–480 ppm CO_2eq, 480–530 ppm CO_2eq, 530–580 ppm CO_2eq, 580–650 ppm CO_2eq, 650–720 ppm CO_2eq, and > 720 ppm CO_2eq. An assessment of geo-physical climate uncertainties, consistent with the dynamics of Earth System Models assessed in WGI, found that the most stringent of these scenarios, leading to 2100 concentrations between 430 and 480 ppm CO_2eq, would lead to an end-of-century median temperature change between 1.6 to 1.8 °C compared to pre-industrial times, although uncertainties in understanding of the climate system mean that the possible temperature range is much wider than this. They were found to maintain temperature change below 2 °C over the course of the century with a likely chance. Scenarios in the concentration category of 650–720 ppm CO_2eq correspond to comparatively modest mitigation efforts, and were found to lead to median temperature rise of approximately 2.6–2.9 °C in 2100 (Chapter 6.3.2). The x-axis of Figures 8.9 to 8.12 show specific sample numbers for each category of scenario reviewed.

[9] These include land use planning that favours high density or polycentric urban forms; public transport oriented developments with mixed uses; and high quality city environments.

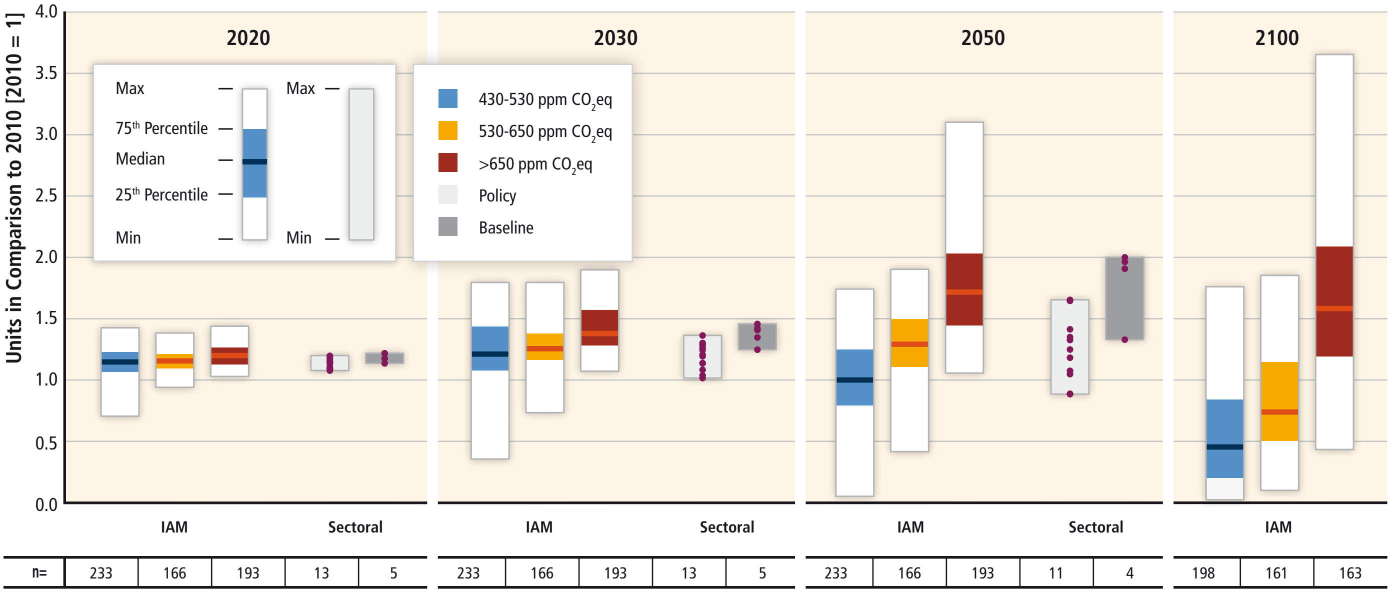


Figure 8.9 | Direct global transport CO_2 emissions. All results for passenger and freight transport are indexed relative to 2010 values for each scenario from integrated models grouped by CO_2eq concentration levels by 2100, and sectoral studies grouped by baseline and policy categories. Sources: Integrated models—WG III AR5 Scenario Database (Annex II.10). Sectoral models: IEA (2008, 2011b, 2012b), WEC (2011a), EIA (2011), IEEJ (2011).

Note: All figures in Section 8.9 show the full range of results for both integrated and sectoral studies. Where the data is sourced from the WG III AR5 Scenario Database a line denotes the median scenario and a box and bolder colours highlight the inter-quartile range. The specific observations from sectoral studies are shown as black dots with light bars (policy) or dark bars (baseline) to give the full ranges. "n" equals number of scenarios assessed in each category.

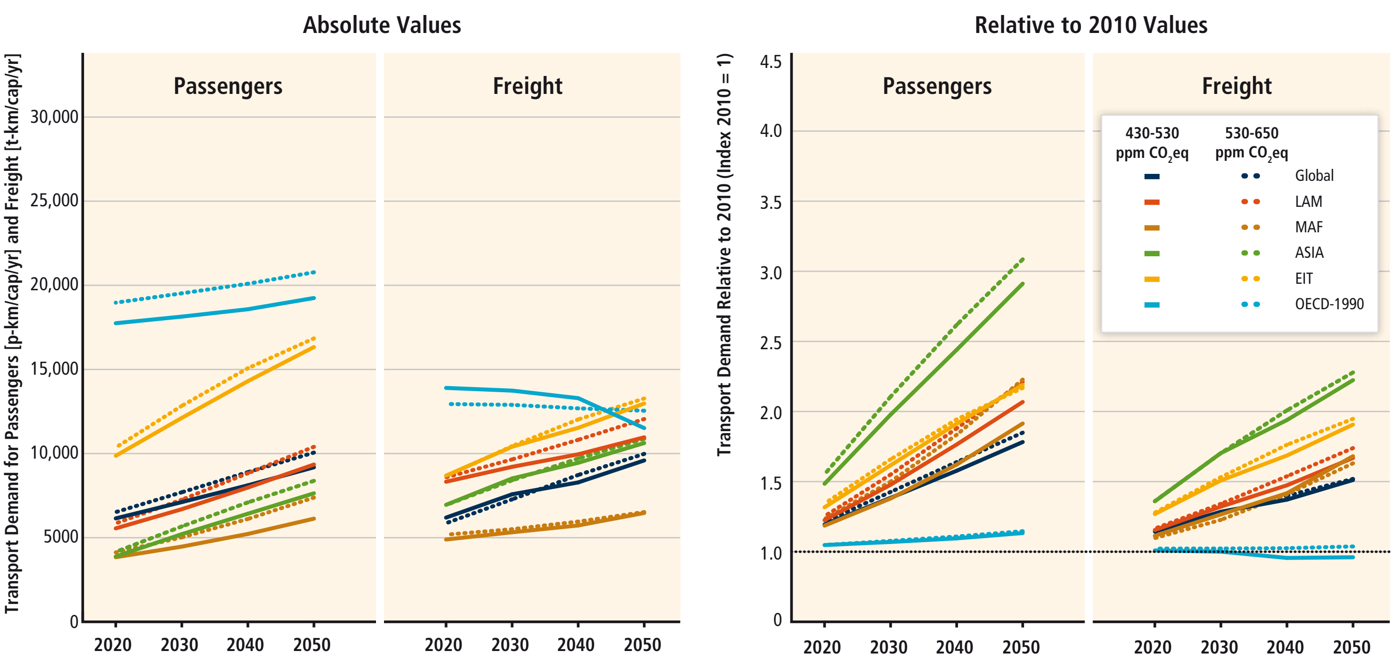


Figure 8.10 | Global passenger (p-km/capita/yr) and freight (t-km/capita/yr) regional demand projections out to 2050 based on integrated models for various CO_2eq concentration levels by 2100—with normalized values highlighting growth and controlling differences in base year values across models. Source: WG III AR5 Scenario Database (Annex II.10).

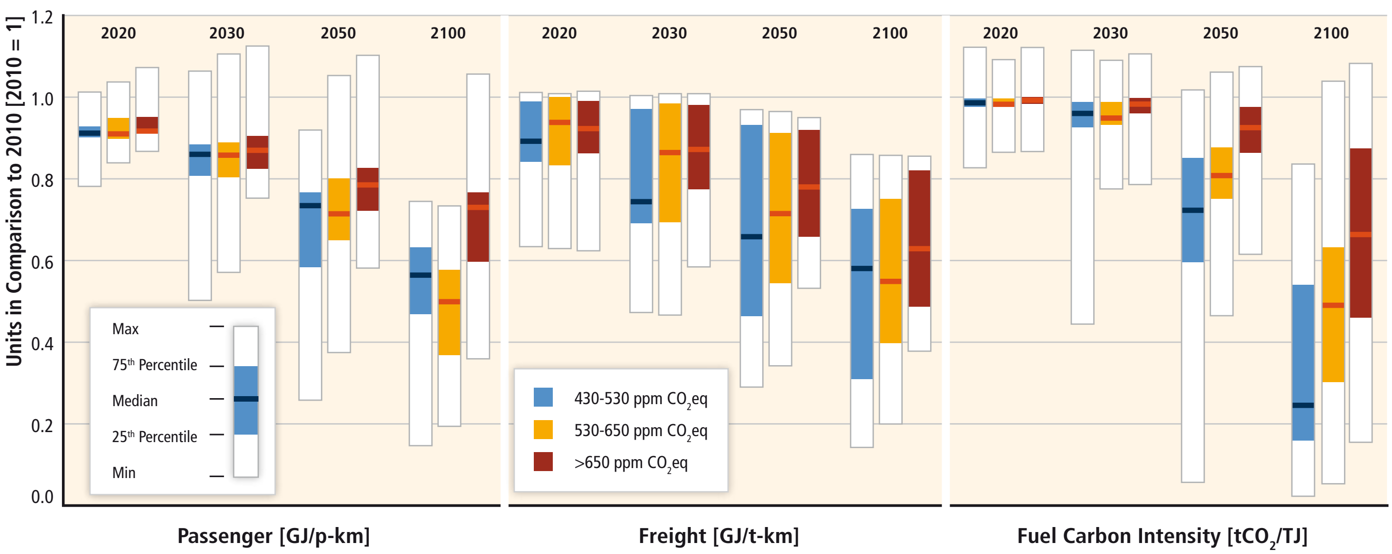
et al., 2013). Consistent with a recent decline in growth of LDV use in some OECD countries (Goodwin and Van Dender, 2013), integrated and sectoral model studies have suggested that decoupling of passenger transport from GDP could take place after 2035 (IEA, 2012; Girod et al., 2012). However, with both transport demand and GDP tied to population growth, decoupling may not be fully completed. At higher incomes, substitution to faster travel modes, such as fast-rail and air travel, explains why total passenger and freight travel continues to rise faster than per capita LDV travel (Schäfer et al., 2009).

Freight transport increases in all scenarios at a slower pace than passenger transport, but still rises as much as threefold by 2050 in comparison to 2010 levels. Freight demand has historically been closely coupled to GDP, but there is potential for future decoupling. Over the long term, changes in activity growth rates (with respect to 2010) for 430–530 ppm CO_2eq scenarios from integrated models suggest that decoupling freight transport demand from GDP can take place earlier than for passenger travel. Modest decreases in freight activity per dollar of GDP suggest that a degree of relative decoupling between freight and income has been occurring across developed countries including Finland (Tapio, 2005), the UK (McKinnon, 2007a) and Denmark (Kveiborg and Fosgerau, 2007). Two notable exceptions are Spain and South Korea, which are at relatively later stages of economic development (Eom et al., 2012). Where decoupling has occurred, it is partly associated with the migration of economic activity to other countries (Corbertt and Winebrake, 2008; Corbertt and Winebrake, 2011). See Sections 3.9.5 and 5.4.1 for a broader discussion of leakage. Opportunities for decoupling could result from a range of changes, including a return to more localized sourcing (McKinnon, 2007b); a major shift in the pattern of consumption to services and products of higher value; the digitization of media and entertainment; and an extensive application of new transport-reducing manufacturing technologies such as 3-D printing (Birtchnell et al., 2013).

Due to the increases in total transport demand, fuel consumption also increases over time, but with GHG emissions at a lower level if policies toward decarbonization of fuels and reduced energy intensity of vehicles are successfully implemented. The integrated scenarios suggest that energy intensity reductions for both passenger and freight transport could continue to occur if the present level of fuel economy standards are sustained over time, or could decrease further with more stringent concentration goals (Figure 8.11).

Projected reductions in energy intensity for freight transport scenarios (EJ/bn t-km) in the scenarios show a wider spread (large ranges in Figure 8.11 between the 25th and 75th percentiles) than for passengers, but still tend to materialize over time. Aviation and road transport have higher energy intensities than rail and waterborne transport (Figure 8.6). Therefore, they account for a larger share of emissions than their share of meeting service demands (Girod et al., 2013). However, limited data availability makes the assessment of changes in modal structure challenging as not all integrated models provide information at a sufficiently disaggregated level or fully represent structural and behavioural choices. Sectoral studies suggest that achieving significant reductions in aviation emissions will require reductions in the rate of growth of travel activity through demand management alongside technological advances (Bows et al., 2009).

In addition to energy intensity reductions, fuel carbon intensity can be reduced further in stringent mitigation scenarios and play an important role in the medium term with the potential for continued improvement throughout the century (Figure 8.11). Scenarios suggest that fuel switch-



n=	91	80	74	91	80	74	91	80	74	83	80	66	85	76	70	85	76	70	85	76	70	77	76	62	228	164	188	228	164	188	228	164	188	198	161	163

Figure 8.11 | Normalized energy intensity scenarios (indexed relative to 2010 values) out to 2100 for passenger (left panel) and freight transport (centre panel), and for fuel carbon intensity based on scenarios from integrated models grouped by CO_2eq concentration levels by 2100 (right panel). Source: WG III AR5 Scenario Database (Annex II.10). Note "n" equals number of scenarios assessed in each category.

ing does not occur to a great extent until after 2020–2030 (Fig 8.12) after which it occurs sooner in more stringent concentration scenarios. The mix of fuels and technologies is difficult to foresee in the long term, especially for road transport, but liquid petroleum fuels tend to dominate at least up until 2050 even in the most stringent mitigation scenario. Within some sectoral studies, assumed breakthroughs in biofuels, fuel cell vehicles, and electrification of road vehicles help achieve deep reductions in emissions by 2050 (Kahn Ribeiro et al., 2012; Williams et al., 2012). Other studies are less confident about fuel carbon intensity reductions, arguing that advanced biofuels, low-carbon electricity, and hydrogen will all require time to make substantial contributions to mitigation efforts. They therefore attribute greater potential for emission reductions to structural and behavioural changes (Salter et al., 2011).

Model assumptions for future technology cost, performance, regulatory environment, consumer choice, and fuel prices result in different shares of fuels that could replace fossil fuels (Table 8.3; Krey and Clarke, 2011). Availability of carbon dioxide capture and storage (CCS) is also likely to have major impact on fuel choices (Luckow et al., 2010; Sathaye et al., 2011). Uncertainty is evident by the wide ranges in all the pathways considered, and are larger after 2050 (Bastani et al., 2012; Wang et al., 2012; Pietzcker et al., 2013). In terms of direct emissions reductions, biofuels tend to have a more important role in the period leading up to 2050. In general, integrated models have been criticized as being optimistic on fuel substitution possibilities, specifically with respect to lifecycle emission assumptions and hence the utilization of biofuels (Sections 8.3 and 11.A.4; Creutzig et al., 2012a; Pietzcker et al., 2013). However, scenarios from integrated models are consistent with sectoral scenarios with respect to fuel shares in 2050 (Figure 8.12). Within the integrated model scenarios, deeper emissions reductions associated with lower CO_2eq concentrations in 2100 are consistent with increasing market penetration of low-carbon electricity and hydrogen in the latter part of the century. Uncertainties as to which fuel becomes dominant, as well as on the role of energy efficiency improvements and fuel savings, are relevant to the stringent mitigation scenarios (van der Zwaan et al., 2013). Indeed, many scenarios show no dominant transport fuel source in 2100, with the median values for electricity and hydrogen sitting between a 22–25 % share of final energy, even for scenarios consistent with limiting concentrations to 430–530 ppm CO_2eq in 2100 (Figure 8.12).

Both the integrated and sectoral model literature present energy efficiency measures as having the greatest promise and playing the largest role for emission reductions in the short term (Skinner et al., 2010; Harvey, 2012; IEA, 2009; McKinnon and Piecyk, 2009; Sorrell et al., 2012). Since models typically assume limited cost reduction impacts, they include slow transitions for new transport technologies to reach large cumulative market shares. For example, a range of both sectoral and integrated studies note that it will take over 15–20 years for either BEVs or FCVs to become competitive with ICE vehicles (Baptista et al., 2010; Eppstein et al., 2011; IEA, 2011c; Girod et al., 2012; Girod et al., 2013; Bosetti and Longden, 2013; van der Zwaan et al., 2013). Since integrated models do not contain a detailed representation of infrastructural changes, their results can be interpreted as a conservative estimate of possible changes to vehicles, fuels, and modal choices (Pietzcker et al., 2013).

The sectoral literature presents a more positive view of transformational opportunities than do the integrated models (IEA, 2008, 2012b; DOE/EIA, 2010; Kahn Ribeiro et al., 2012). Sectoral studies suggest that up to 20 % of travel demand could be reduced by avoided journeys or shifts to low-carbon modes (McCollum and Yang, 2009; Harvey, 2012; IEA, 2012d; Kahn Ribeiro et al., 2012; Anable et al., 2012;

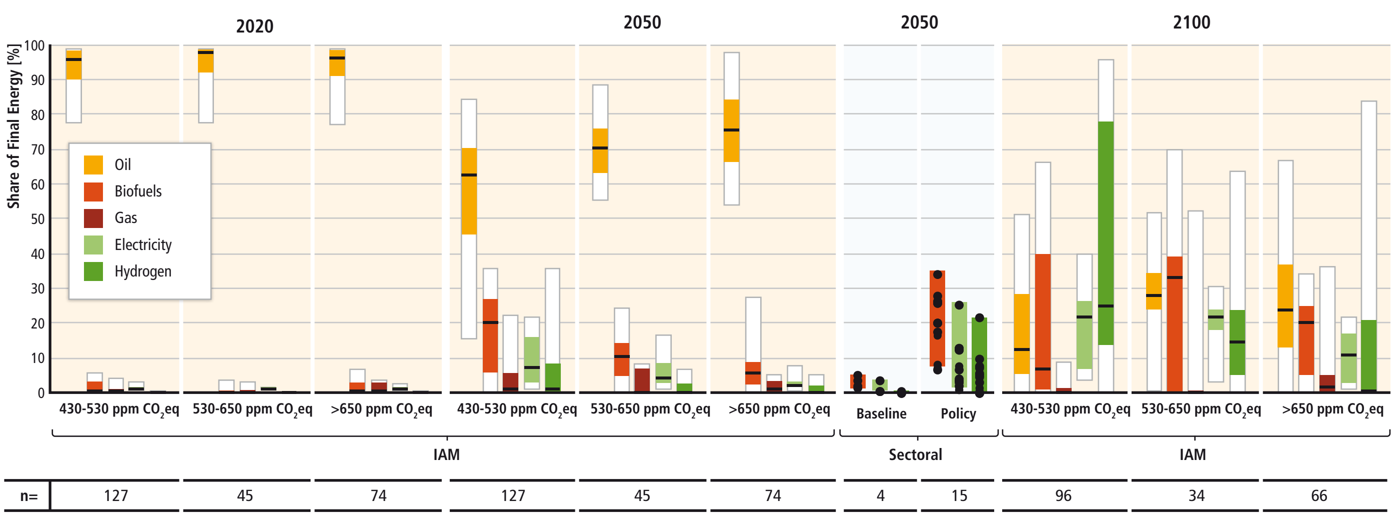


Figure 8.12 | Global shares of final fuel energy in the transport sector in 2020, 2050, and 2100 based on integrated models grouped by CO_2eq concentration levels by 2100 and compared with sectoral models (grouped by baseline and policies) in 2050. Box plots show minimum / maximum, 25th / 75th percentile and median. Source: *Integrated models*—WG III AR5 Scenario Database (Annex II.10). Sectoral models—IEA, 2012; IEA, 2011b; IEA, 2008; WEC, 2011a; EIA, 2011 and IEEJ, 2011.

Note: Interpretation is similar to that for Figs. 8.9 and 8.10, except that the boxes between the 75th and 25th percentiles for integrated model results have different colours to highlight the fuel type instead of GHG concentration categories. The specific observations from sectoral studies are shown as black dots

Box 8.1 | Transport and sustainable development in developing countries

Passenger and freight mobility are projected to double in developing countries by 2050 (IEA, 2012e). This increase will improve access to markets, jobs, education, healthcare and other services by providing opportunities to reduce poverty and increase equity (Africa Union, 2009; Vasconcellos, 2011; United Nations Human Settlements Programme, 2012). Well-designed and well-managed transport infrastructure can also be vital for supporting trade and competitiveness (United Nations Human Settlements Programme, 2012). Driven by urbanization, a rapid transition from slow non-motorized transport modes to faster modes using 2- or 3- wheelers, LDVs, buses, and light rail is expected to continue (Schäfer et al., 2009; Kumar, 2011). In rural areas of Africa and South Asia, the development of all-season, high-quality roads is becoming a high priority (Africa Union, 2009; Arndt et al., 2012). In many megacities, slum area development in peri-urban fringes confines the urban poor to a choice between low paying jobs near home or long commuting times for marginally higher wages (Burdett and Sudjic, 2010). The poor have limited options to change living locations and can afford few motorized trips, so they predominantly walk, which disproportionally burdens women and children (Anand and Tiwari, 2006; Pendakur, 2011). The urban poor in OECD cities have similar issues (Glaeser, 2011). Reducing vulnerability to climate change requires integrating the mobility needs of the poor into planning that can help realize economic and social development objectives (Amekudzi et al., 2011; Bowen et al., 2012).

Total transport emissions from non-OECD countries will likely surpass OECD emissions by 2050 due to motorization, increasing population and higher travel demand (Figure 8.10). However, estimated average personal travel per capita in non-OECD countries at will remain below the average in OECD countries. With countries facing limits to transport infrastructure investment (Arndt et al., 2012), the rapid mobility trends represents a major challenge in terms of traffic congestion, energy demand, and related GHG emissions (IEA, 2012a). Failure to manage the growth of motorized mobility in the near term will inevitably lead to higher environmental cost and greater difficulty to control emissions in the long term (Schäfer et al., 2009; Pietzcker et al., 2013).

A high modal share of public transport use characterizes developing cities (Estache and GóMez-Lobo, 2005) and this prevalence is expected to continue (Deng and Nelson, 2011; Cuenot et al., 2012). However, deficient infrastructure and inadequate services leads to the overloading of para-transit vans, minibuses, jeeps and shared taxis and the use of informal transport services (Cervero and Golub, 2011). By combining technologies, providing new social arrangements, and incorporating a long-term sustainability and climate perspective to investment decisions, these services can be recast and maintained as mobility resources since they service the poor living in inaccessible areas at affordable prices (Figueroa et al., 2013). A central strategy that can have multiple health, climate, environmental, and social benefits is to invest in the integration of infrastructure systems that connect safe routes for walking and cycling with local public transport, thus giving it priority over infrastructure for LDVs that serve only a small share of the population (Woodcock et al., 2009; Tiwari and Jain, 2012). Opportunities for strategic sustainable urban transport development planning exist that can be critical to develop medium sized cities where population increases are expected to be large (Wittneben et al., 2009; ADB, 2012b; Grubler et al., 2012). Vision, leadership, and a coherent programme for action, adaptation, and consolidation of key institutions that can harness the energy and engagement of all stakeholders in a city will be needed to achieve these goals (Dotson, 2011). Today, more than 150 cities worldwide have implemented bus rapid transit (BRT) systems. Innovative features such as electric transit buses (Gong et al., 2012) and the ambitious high-speed rail expansion in China provide evidence of a fast process of planning and policy implementation.

Huo and Wang, 2012). They also estimate that urban form and infrastructure changes can play decisive roles in mitigation, particularly in urban areas where 70 % of the world's population is projected to live in 2050 (Chapter 8.4 and 12.4), although the estimated magnitude varies between 5 % and 30 % (Ewing, 2007; Creutzig and He, 2009; Echenique et al., 2012). Altogether, for urban transport, 20–50 % reduction in GHG emissions is possible between 2010 and 2050 compared to baseline urban development (Ewing, 2007; Eliasson, 2008; Creutzig and He, 2009; Lefèvre, 2009; Woodcock et al., 2009; Ewing and Cervero, 2010; Marshall, 2011; Echenique et al., 2012; Viguié and Hallegatte, 2012; Salon et al., 2012; Creutzig et al., 2012a). Since the lead time for infrastructure development is considerable (Short and Kopp, 2005), such changes can only be made on decadal time scales. Conversely, some developing countries with fast growing economies have shown that rapid transformative processes in spatial development and public transport infrastructure are possible. Further advances may be gaining momentum with a number of significant initiatives for reallocating public funding to sustainable and climate-friendly transport (Bongardt et al., 2011; Wittneben et al., 2009; ADB, 2012; Newman and Matan, 2013).

8.9.2 Sustainable development

Within all scenarios, the future contribution of emission reductions from developing countries carries especially large uncertainties. The accelerated pace with which both urbanization and motorization are proceeding in many non-OECD countries emphasizes serious constraints and potentially damaging developments. These include road and public transport systems that are in dire condition; limited technical and financial resources; the absence of infrastructure governance; poor legal frameworks; and rights to innovate that are needed to act effectively and improve capacity competences (Kamal-Chaoui and Plouin, 2012; Lefèvre, 2012). The outcome is a widening gap between the growth of detrimental impacts of motorization and effective action (Kane, 2010; Li, 2011; Vasconcellos, 2011). A highly complex and changing context with limited data and information further compromise transport sustainability and mitigation in non-OECD countries (Dimitriou, 2006; Kane, 2010; Figueroa et al., 2013). The relative marginal socio-economic costs and benefits of various alternatives can be context sensitive with respect to sustainable development (Amekudzi, 2011). Developing the analytical and data capacity for multi-objective evaluation and priority setting is an important part of the process of cultivating sustainability and mitigation thinking and culture in the long-term.

Potentials for controlling emissions while improving accessibility and achieving functional mobility levels in the urban areas of rapidly growing developing countries can be improved with attention to the manner in which the mobility of the masses progresses in their transition from slower (walking/cycling) to faster motorized modes (Kahn Ribeiro et al., 2012). A major shift towards the use of mass public transport guided by sustainable transport principles, including the maintenance of adequate services and safe infrastructure for non-motorized transport, presents the greatest mitigation potential (Bongardt et al., 2011; La Branche, 2011). Supporting non-motorized travel can often provide access and also support development more effectively, more equitably, and with fewer adverse side-effects, than if providing for motorized travel (Woodcock et al., 2007). Transport can be an agent of sustained urban development that prioritizes goals for equity and emphasizes accessibility, traffic safety, and time savings for the poor with minimal detriment to the environment and human health, all while reducing emissions (Amekudzi et al., 2011; Li, 2011; Kane, 2010). The choice among alternative mitigation measures in the transport sector can be supported by growing evidence on a large number of co-benefits, while some adverse side effects exist that need to be addressed or minimized (see Section 8.7) (Figueroa and Kahn Ribeiro, 2013; Creutzig and He, 2009; Creutzig et al., 2012a, b; Zusman et al., 2012).

8.10 Sectoral policies

Aggressive policy intervention is needed to significantly reduce fuel carbon intensity and energy intensity of modes, encourage travel by the most efficient modes, and cut activity growth where possible and reasonable (see Sections 8.3 and 8.9). In this section, for each major transport mode, policies and strategies are briefly discussed by policy type as regulatory or market-based, or to a lesser extent as informational, voluntary, or government-provided. A full evaluation of policies across all sectors is presented in Chapters 14 and 15. Policies to support sustainable transport can simultaneously provide co-benefits (Table 8.4) such as improving local transport services and enhancing the quality of environment and urban living, while boosting both climate change mitigation and energy security (ECMT, 2004; WBCSD, 2004, 2007; World Bank, 2006; Banister, 2008; IEA, 2009; Bongardt et al., 2011; Ramani et al., 2011; Kahn Ribeiro et al., 2012). The type of policies, their timing, and chance of successful implementation are context dependent (Santos et al., 2010). Diverse attempts have been made by transport agencies in OECD countries to define and measure policy performance (OECD, 2000; CST, 2002; Banister, 2008; Ramani et al., 2011). The mobility needs in non-OECD countries highlight the importance of placing their climate-related transport policies in the context of goals for broader sustainable urban development goals (see Section 8.9; Kahn Ribeiro et al., 2007; Bongardt et al., 2011).

Generally speaking, market-based instruments, such as carbon cap and trade, are effective at incentivizing all mitigation options simultaneously (Flachsland et al., 2011). However, vehicle and fuel suppliers as well as end-users, tend to react weakly to fuel price signals, such as fuel carbon taxes, especially for passenger travel (Creutzig et al., 2011; Yeh and McCollum, 2011). Market policies are economically more efficient at reducing emissions than fuel carbon intensity standards (Holland et al., 2009; Sperling and Yeh, 2010; Chen and Khanna, 2012; Holland, 2012). However, financial instruments, such as carbon taxes, must be relatively large to achieve reductions equivalent to those possible with regulatory instruments. As a result, to gain large emissions reductions a suite of policy instruments will be needed (NRC, 2011c; Sperling and Nichols, 2012), including voluntary schemes, which have been successful in some circumstances, such as for the Japanese airline industry (Yamaguchi, 2010).

8.10.1 Road transport

A wide array of policies and strategies has been employed in different circumstances to restrain private LDV use, promote mass transit modes, manage traffic congestion and promote new fuels in order to reduce fossil fuel use, air pollution, and GHG emissions. These policies and strategies overlap considerably, often synergistically.

The magnitude of urban growth and population redistribution from rural to urban areas in emerging and developing countries is expected to continue (see Sections 8.2 and 12.2). This implies a large increase in demand for motorized transport especially in medium-size cities (Grubler et al., 2012). In regions and countries presently with low levels of LDV ownership, opportunities exist for local and national governments to manage future rising road vehicle demand in ways that support economic growth, provide broad social benefits (Wright and Fulton, 2005; IEA, 2009; Kato et al., 2005) and keep GHG emissions in bounds. Local history and social culture can help shape the specific problem, together with equity implications and policy aspirations that ultimately determine what will become acceptable solutions (Vasconcellos, 2001; Dimitriou, 2006; Kane, 2010; Li, 2011; Verma et al., 2011).

Even if non-OECD countries pursue strategies and policies that encourage LDV use for a variety of economic, social, and environmental motivations, per capita LDV travel in 2050 could remain far below OECD countries. However, in many OECD countries, passenger LDV travel demand per capita appears to have begun to flatten, partly driven by increasing levels of saturation and polices to manage increased road transport demand (Section 8.2.1; Millard-Ball and Schipper, 2011; Schipper, 2011; Goodwin, 2012; IEA, 2012c; Meyer et al., 2012). Even if this OECD trend of slowing growth in LDV travel continues or even eventually heads downwards, it is unlikely to offset projected growth in non-OECD LDV travel or emissions because those populations and economies are likely to continue to grow rapidly along with LDV ownership. Only with very aggressive policies in both OECD and non-OECD countries would total global LDV use stabilize in 2050. This is illustrated in a 2 °C LDV transport scenario generated by Fulton et al. (2013), using mainly IEA (2012c) data. In that policy scenario, LDV travel in OECD countries reaches a peak of around 7500 vehicle km/capita in 2035 then drops by about 20 % by 2050. By comparison, per capita LDV travel in non-OECD countries roughly quadruples from an average of around 500 vehicle km/capita in 2012 to about 2000 vehicle km/capita in 2050, remaining well below the OECD average.

Many countries have significant motor fuel taxes that, typically, have changed little in recent years. This indicates that such a market instrument is not a policy tool being used predominantly to reduce GHG emissions. The typical approach increasingly being used is a suite of regulatory and other complementary policies with separate instruments for vehicles and for fuels. The challenge is to make them consistent and coherent. For instance, the fuel efficiency and GHG emission standards for vehicles in Europe and the United States give multiple credits to plug-in electric vehicles (PEVs) and fuel cell vehicles (FCVs). Zero upstream emissions are assigned, although this is technically incorrect but designed to be an implicit subsidy (Lutsey and Sperling, 2012).

Fuel choice and carbon intensity[10]. Flexible fuel standards that combine regulatory and market features include the Californian low-carbon fuel standard (LCFS) (Sperling and Nichols, 2012) and the European Union fuel quality directive (FQD). Fuel carbon intensity reduction targets for 2020 (10 % for California and 6 % for EU) are expected to be met by increasing use of low-carbon biofuels, hydrogen, and electricity. They are the first major policies in the world premised on the measurement of lifecycle GHG intensities (Yeh and Sperling, 2010; Creutzig et al., 2011), although implementation of lifecycle analyses can be challenging and sometimes misleading since it is difficult to design implementable rules that fully include upstream emissions (Lutsey and Sperling, 2012); emissions resulting from induced market effects; and emissions associated with infrastructure, the manufacturing of vehicles, and the processing and distribution of fuels (for LCA see Annex II.6.3 Kendall and Price, 2012).

Biofuel policies have become increasingly controversial as more scrutiny is applied to the environmental and social equity impacts (Section 11.13). In 2007, the European Union and the United States adopted aggressive biofuel policies (Yeh and Sperling, 2013). The effectiveness of these policies remains uncertain, but follow-up policies such as California's LCFS and EU's FQD provide broader, more durable policy frameworks that harness market forces (allowing trading of credits), and provide flexibility to industry in determining how best to reduce fuel carbon intensity. Other related biofuel policies include subsidies (IEA, 2011d) and mandatory targets (REN21, 2012).

Vehicle energy intensity. The element of transport that shows the greatest promise of being on a trajectory to achieve large reductions in GHG emissions by 2050 is reducing the energy and fuel carbon intensities of LDVs. Policies are being put in place to achieve dramatic improvements in vehicle efficiency, stimulating automotive companies to make major investments. Many countries have now adopted aggressive targets and standards (Figure 8.13), with some standards criticized

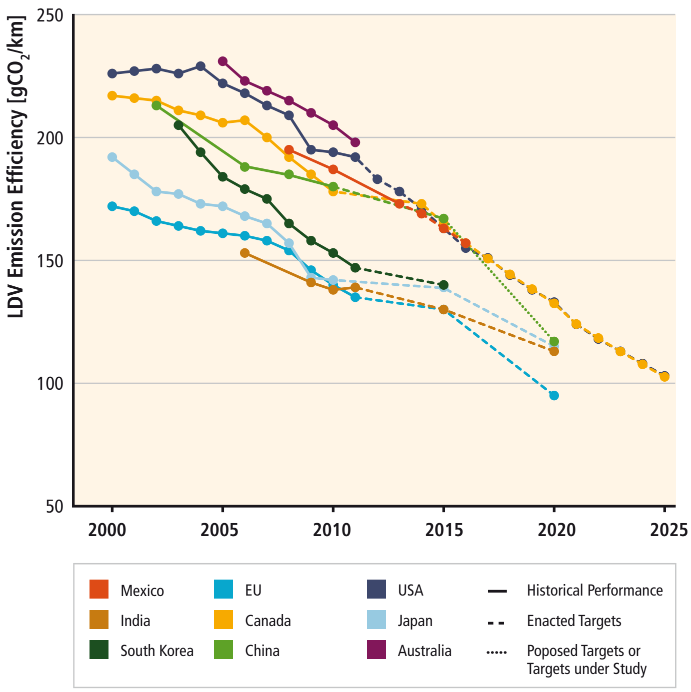


Figure 8.13 | Historic emissions and future (projected and mandated) carbon dioxide emissions targets for LDVs in selected countries and European Union, normalized by using the same New European Driving Cycle (NDEC) that claims to represent real-world driving conditions. Source: ICCT (2007, 2013)

Notes: (1) China's target reflects gasoline LDVs only and may become higher if new energy vehicles are considered. (2) Gasoline in Brazil contains 22 % ethanol but data here are converted to 100 % gasoline equivalent.

[10] The following four sub-sections group policies along the lines of the decomposition as outlined in 8.1 and Figure 8.2

for not representing real-world conditions (Mock et al., 2012). Most are developed countries, but some emerging economies, including China and India, are also adopting increasingly aggressive standards (Wang et al., 2010).

Regulatory standards focused on fuel consumption and GHG emissions vary in their design and stringency. Some strongly stimulate reductions in vehicle size (as in Europe) and others provide strong incentives to reduce vehicle weight (as in the United States) (CCC, 2011). All have different reduction targets. As of April 2010, 17 European countries had implemented taxes on LDVs wholly or partially related to CO_2 emissions. Regulatory standards require strong market instruments and align market signals with regulations as they become tighter over time. Examples are fuel and vehicle purchase taxes and circulation taxes that can limit rebound effects. Several European countries have established revenue-neutral feebate schemes (a combination of *rebates* awarded to purchasers of low carbon emission vehicles and *fees* charged to purchasers of less efficient vehicles) (Greene and Plotkin, 2011). Annual registration fees can have similar effects if linked directly with carbon emissions or with related vehicle attributes such as engine displacement, engine power, or vehicle weight (CARB, 2012). One concern with market-based policies is their differential impact across population groups such as farmers needing robust vehicles to traverse rugged terrain and poor quality roads. Equity adjustments can be made so that farmers and large families are not penalized for having to buy a large car or van (Greene and Plotkin, 2011).

Standards are likely to spur major changes in vehicle technology, but in isolation are unlikely to motivate significant shifts away from petroleum-fuelled ICE vehicles. In the United States, a strong tightening of standards through to 2025 is estimated to trigger only a 1 % market share for PEVs if only economics is considered (EPA, 2011).

A more explicit regulatory instrument to promote EVs and other new, potentially very-low carbon propulsion technologies is a zero emission vehicle mandate, as originally adopted by California in 1990 to improve local air quality, and which now covers almost 30 % of the United States market. This policy, now premised on reducing GHGs, requires about 15 % of new vehicles in 2025 to be a mix of PEVs and FCVs (CARB, 2012).

There are large potential efficiency improvements possible for medium and heavy-duty vehicles (HDVs) (see Section 8.3.1.2), but policies to pursue these opportunities have lagged those for LDVs. Truck types, loads, applications, and driving cycles are much more varied than for LDVs and engines are matched with very different designs and loads, thereby complicating policy-making. However, China implemented fuel consumption limits for HDVs in July 2012 (MIIT, 2011); in 2005 Japan set modest fuel efficiency standards to be met by 2015 (Atabani et al., 2011); California, in 2011, required compulsory retrofits to reduce aerodynamic drag and rolling resistance (Atabani et al., 2011); the United States adopted standards for new HDVs and buses manufactured from 2014 to 2018 (Greene and Plotkin, 2011); and the EU intends to pursue similar actions including performance standards and fuel efficiency labelling by 2014 (Kojima and Ryan, 2010). Aggressive air pollution standards since the 1990s for NO_x and particulate matter emissions from HDVs in many OECD countries have resulted in a fuel consumption penalty in the past of 7 % to 10 % (IEA, 2009; Tourlonias and Koltsakis, 2011). However, emission technology improvements and reductions in black carbon emissions, which strongly impact climate change (see Section 8.2.2.1), will offset some of the negative effect of this increased fuel consumption.

Activity reduction. A vast and diverse mix of policies is used to restrain and reduce the use of LDVs, primarily by focusing on land use patterns, public transport options, and pricing. Other policy strategies to reduce activity include improving traffic management (Barth and Boriboonsomsin, 2008), better truck routing systems (Suzuki, 2011), and smart real-time information to reduce time searching for a parking space. Greater support for innovative services using information and communication technologies, such as dynamic ride sharing and demand-responsive para-transit services (see Section 8.4), creates still further opportunities to shift toward more energy efficient modes of travel.

Policies can be effective at reducing dependence on LDVs as shown by comparing Shanghai with Beijing, which has three times as many LDVs even though the two cities have similar levels of affluence, the same culture, and are of a similar population (Hao et al., 2011). Shanghai limited the ownership of LDVs by establishing an expensive license auction, built fewer new roads, and invested more in public transport, whereas Beijing built an extensive network of high capacity expressways and did little to restrain car ownership or use until recently. The Beijing city administration has curtailed vehicle use by forbidding cars to be used one day per week since 2008, and sharply limited the number of new license plates issued each year since 2011 (Santos et al., 2010) Hao et al., 2011). The main aims to reduce air pollution, traffic congestion, and costs of road infrastructure exemplify how policies to reduce vehicle use are generally, but not always, premised on non-GHG co-benefits. European cities have long pursued demand reduction strategies, with extensive public transport supply, strict growth controls, and more recent innovations such as bicycle sharing. California seeks to create more liveable communities by adopting incentives, policies, and rules to reduce vehicle use, land use sprawl, and GHG emissions from passenger travel. The California law calls for 6–8 % reduction in GHG emissions from passenger travel per capita (excluding changes in fuel carbon intensity and vehicle energy intensity) in major cities by 2020, and 13–16 % per capita by 2035 (Sperling and Nichols, 2012).

The overall effectiveness of initiatives to reduce or restrain road vehicle use varies dramatically depending on local commitment and local circumstances, and the ability to adopt synergistic policies and practices by combining pricing, land use management, and public transport measures. A broad mix of policies successfully used to reduce vehicle use in OECD countries, and to restrain growth in emerging economies, includes pricing to internalize energy, environmental, and health costs; strengthening land use management; and providing more and better public transport.

Policies to reduce LDV activity can be national, but mostly they are local, with the details varying from one local administration to another.

Some policies are intrinsically more effective than others. For instance, fuel taxes will reduce travel demand but drivers are known to be relatively inelastic in their response (Hughes et al., 2006; Small and van Dender, 2007). However, drivers are more elastic when price increases are planned and certain (Sterner, 2007). Pricing instruments such as congestion charges, vehicle registration fees, road tolls and parking management can reduce LDV travel by inducing trip chaining, modal shifts, and reduced use of cars (Litman, 2006). Policies and practices of cities in developing countries can be influenced by lending practices of development banks, such as the Rio+20 commitment to spend approximately 170 billion USD_{2010} on more sustainable transport projects, with a focus on Asia (ADB, 2012c).

System efficiency*.* Improvements have been far greater in freight transport and aviation than for surface passenger transport (rail and road). Freight transport has seen considerable innovation in containerization and intermodal connections, as has aviation, though the effects on GHG emissions are uncertain (and could be negative because of just-in-time inventory management practices). For surface passenger travel, efforts to improve system efficiency and inter-modality are hindered by conflicting and overlapping jurisdictions of many public and private sector entities and tensions between fiscal, safety, and equity goals. Greater investment in roads than in public transport occurred in most cities of developed countries through the second half of the 20th century (Owens, 1995; Goodwin, 1999). The 21st century, though, has seen increasing government investment in bus rapid transit and rail transit in OECD countries (Yan and Crookes, 2010; Tennøy, 2010) along with increasing support for bicycle use.

Since the 1960s, many cities have instigated supportive policies and infrastructure that have resulted in a stable growth in cycling (Servaas, 2000; Hook, 2003; TFL, 2007; NYC, 2012). Several European cities have had high cycle transport shares for many years, but now even in London, UK, with efficient public transport systems, the 2 % cycle share of travel modes is targeted to increase to 5 % of journeys in 2026 as a result of a range of new policies (TFL, 2010). However, in less developed cities such as Surabaya, Indonesia, 10 % of total trips between 1–3 km are already by cycling (including rickshaws) in spite of unsupportive infrastructure and without policies since there are few affordable alternatives (Hook, 2003). Where cycle lanes have been improved, as in Delhi, greater uptake of cycling is evident (Tiwari and Jain, 2012).

8.10.2 Rail transport

Rail transport serves 28 billion passengers globally, carrying them around 2500 billion p-km/yr[11]. Rail also carries 11.4 billion tonne of freight (8845 billion t-km/yr) (Johansson et al., 2012). Policies to further improve system efficiency may improve competitiveness and opportunities for modal shift to rail (Johansson et al., 2012). Specific energy and carbon intensities of rail transport are relatively small compared to some other modes (see Section 8.3). System efficiency can also be assisted through train driver education and training policies (Camagni et al., 2002).

[11] By way of comparison, aviation moves 2.1 billion passengers globally (some 3900 billion p-km/yr).

Fuel intensity*.* Roughly one third of all rail transport is driven by diesel and two-thirds by electricity (Johansson et al., 2012). Policies to reduce fuel carbon intensity are therefore linked to a large extent to those for decarbonizing electricity production (Chapter 7; DLR, 2012). For example, Sweden and Switzerland are running their rail systems using very low carbon electricity (Gössling, 2011).

Energy intensity*.* Driven largely by corporate strategies, the energy intensity of rail transport has been reduced by more than 60 % between 1980 and 2001 in the United States (Sagevik, 2006). Overall reduction opportunities of 45–50 % are possible for passenger transport in the EU and 40–50 % for freight (Andersson et al., 2011). Recent national policies in the United Kingdom and Germany appear to have resulted in 73 % rail freight growth over the period 1995–2007, partly shifted from road freight.

System efficiency*.* China, Europe, Japan, Russia, United States and several Middle-eastern and Northern African countries continue (or are planning) to invest in high-speed rail (HSR) (CRC, 2008). It is envisaged that the worldwide track length of about 15,000 km in 2012 will nearly triple by 2025 due to government supporting policies, allowing HSR to better compete with medium haul aviation (UIC, 2012).

8.10.3 Waterborne transport

Although waterborne transport is comparatively efficient in terms of gCO_2/t-km compared to other freight transport modes (see Section 8.6), the International Maritime Organization (IMO) has adopted mandatory measures to reduce GHG emissions from international shipping (IMO, 2011). This is the first mandatory GHG reduction regime for an international industry sector and for the standard to be adopted by all countries is a model for future international climate change co-operation for other sectors (Yamaguchi, 2012). Public policies on emissions from inland waterways are nationally or regionally based and currently focus more on the reduction of NO_x and particulate matter than on CO_2. However, policy measures are being considered to reduce the carbon intensity of this mode including incentives to promote 'smart steaming', upgrade to new, larger vessels, and switch to alternative fuels, mainly LNG (Panteia, 2013). Few if any, policies support the use of biofuels, natural gas or hydrogen for small waterborne craft around coasts or inland waterways and little effort has been made to assess the financial implications of market (and other) policies on developing countries who tend to import and export low value-to-weight products, such as food and extractible resources (Faber et al., 2012).

Energy intensity. IMO's Energy Efficiency Design Index (EEDI) is to be phased in between 2013 and 2025. It aims to improve the energy efficiency of certain categories of new ships and sets technical standards (IMO, 2011). However, the EEDI may not meet the target if shipping demand increases faster than fuel carbon and energy intensities improve. The voluntary Ship Energy Efficiency Management Plan (SEEMP) was implemented in 2013 (IMO, 2011). For different ship types and sizes it provides a minimum energy efficiency level. As much as 70 % reduction of emissions from new ships is anticipated with the aim to achieve approximately 25–30 % reductions overall by 2030 compared with business-as-usual (IISD, 2011). It is estimated that, in combination, EEDI requirements and SEEMP will cut CO_2 emissions from shipping by 13 % by 2020 and 23 % by 2030 compared to a 'no policy' baseline (Lloyds Register and DNV, 2011).

8.10.4 Aviation

After the Kyoto Protocol directed parties in Annex I to pursue international aviation GHG emission limitation/reduction working through the International Civil Aviation Organization (ICAO) (Petersen, 2008), member states are working together with the industry towards voluntarily improving technologies, increasing the efficient use of airport infrastructure and aircraft, and adopting appropriate economic measures (ICAO, 2007b; ICAO, 2010a). In 2010, ICAO adopted global aspirational goals for the international aviation sector to improve fuel efficiency by an average of 2 % per annum until 2050 and to keep its global net carbon emissions from 2020 at the same level (ICAO, 2010b). These goals exceed the assumptions made in many scenarios (Mayor and Tol, 2010).

Policy options in place or under consideration include regulatory instruments (fuel efficiency and emission standards at aircraft or system levels); market-based approaches (emission trading under caps, fuel taxes, emission taxes, subsidies for fuel efficient technologies); and voluntary measures including emission offsets (Daley and Preston, 2009). Environmental capacity constraints on airports also exist and may change both overall volumes of air transport and modal choice (Upham et al., 2004; Evans, 2010). National policies affect mainly domestic aviation, which covers about 30–35 % of total air transport (IATA, 2009; Lee et al., 2009; Wood et al., 2010). A nationwide cap-and-trade policy could have the unintended consequence of slowing aircraft fleet turnover and, through diverted revenue, of delaying technological upgrades, which would slow GHG reductions, though to what degree is uncertain (Winchester et al., 2013). In the UK, an industry group including airport companies, aircraft manufacturers and airlines has developed a strategy for reducing GHG emissions across the industry (Sustainable Aviation, 2012).

The EU is currently responsible for 35 % of global aviation emissions. The inclusion of air transport in the EU emission trading scheme (ETS) is the only binding policy to attempt to mitigate emissions in this sector (Anger, 2010; Petersen, 2008; Preston et al., 2012). The applicability of ETS policy to non-European routes (for flights to and from destinations outside the EU) (Malina et al., 2012) has been delayed for one year, but the directive continues to apply to flights between destinations in the EU following a proposal by the European Commission in November 2012 in anticipation of new ICAO initiatives towards a global market-based mechanism for all aviation emissions (ICAO, 2012).

Taxing fuels, tickets, or emissions may reduce air transport volume with elasticities varying between −0.3 to −1.1 at national and international levels, but with strong regional differences (Europe has 40 % stronger elasticities than most other world regions, possibly because of more railway options). Airport congestion adds considerable emissions (Simaiakis and Balakrishnan, 2010) and also tends to moderate air transport demand growth to give a net reduction of emissions at network level (Evans and Schäfer, 2011).

Fuel carbon intensity. Policies do not yet exist to introduce low-carbon biofuels. However, the projected GHG emission reductions from the possible future use of biofuels, as assumed by the aviation industry, vary between 19 % of its adopted total emission reduction goal (Sustainable Aviation, 2008) to over 50 % (IATA, 2009),depending on the assumptions made for the other reduction options that include energy efficiency, improved operation and trading emission permits. Sustainable production issues also apply (see Section 8.3.3).

Energy intensity. The energy efficiency of aircraft has improved historically without any policies in force, but with the rate of fuel consumption reducing over time from an initial 3–6 % in the 1950s to between 1 % and 2 % per year at the beginning of the 21st century (Pulles et al., 2002; Fulton and Eads, 2004; Bows et al., 2005; Peeters and Middel, 2007; Peeters et al., 2009). This slower rate of fuel reduction is possibly due to increasing lead-times required to develop, certify, and introduce new technology (Kivits et al., 2010).

System efficiency. The interconnectedness of aviation services can be a complicating factor in adopting policies, but also lends itself to global agreements. For example, regional and national air traffic controllers have the ability to influence operational efficiencies. The use of market policies to reduce GHG emissions is compelling because it introduces a price signal that influences mitigation actions across the entire system. But like other aspects of the passenger transport system, a large price signal is needed with aviation fuels to gain significant reductions in energy use and emissions (Tol, 2007; Peeters and Dubois, 2010; OECD and UNEP, 2011). Complementary policies to induce system efficiencies include measures to divert tourists to more efficient modes such as high-speed rail. However, since short- and medium-haul aircraft now have similar energy efficiencies per passenger km compared to LDVs (Figure 8.6), encouraging people to take shorter journeys (hence by road instead of by air), thereby reducing tourism total travel, has become more important (Peeters and Dubois, 2010). No country has adopted a low-carbon tourism strategy (OECD and UNEP, 2011).

8.10.5 Infrastructure and urban planning

Urban form has a direct effect on transport activity (see Section 12.4). As a consequence, infrastructure policies and urban planning can provide major contributions to mitigation (see Section 12.5). A modal shift from LDVs to other surface transport modes could be partly incentivized by policy measures that impose physical restrictions as well as pricing regimes. For example, LDV parking management is a simple form of cost effective, pricing instrument (Barter et al., 2003; Litman, 2006). Dedicated bus lanes, possibly in combination with a vehicle access charge for LDVs, can be strong instruments to achieving rapid shifts to public transport (Creutzig and He, 2009).

Policies that support the integration of moderate to high density urban property development with transit-oriented development strategies that mix residential, employment, and shopping facilities can encourage pedestrians and cyclists, thereby giving the dual benefits of reducing car dependence and preventing urban sprawl (Newman and Kenworthy, 1996; Cervero, 2004; Olaru et al., 2011). GHG emissions savings (Trubka et al., 2010a; Trubka et al., 2010b) could result in co-benefits of health, productivity, and social opportunity (Trubka et al., 2010c; Ewing and Cervero, 2010; Höjer et al., 2011) if LDV trips could be reduced using polycentric city design and comprehensive smart-growth policies (Dierkers et al., 2008). Policies to support the building of more roads, airports, and other infrastructure can help relieve congestion in the short term, but can also induce travel demand (Duranton and Turner, 2011) and create GHG emissions from construction (Chester and Horvath, 2009).

8.11 Gaps in knowledge and data

The following gaps made assessing the mitigation potential of the transport sector challenging.

Gaps in the basic statistics are still evident on the costs and energy consumption of freight transport, especially in developing countries.

- Data and understanding relating to freight logistical systems and their economic implications are poor, as are the future effects on world trade of decarbonization and climate change impacts. Hence, it is difficult to design new low-carbon freight policies.
- Future technological developments and costs of batteries, fuel cells, and vehicle designs are uncertain.
- The infrastructure requirement for new low-carbon transport fuels is poorly understood.
- Cost of components for novel vehicle powertrains cannot be determined robustly since rates of learning, cost decreases, and associated impacts are unknown.
- Assessments of mitigating transport GHG emissions, the global potential, and costs involved are inconsistent.
- Prices of crude oil products fluctuate widely as do those for alternative transport fuels, leading to large variations in scenario modelling assumptions.
- A better knowledge of consumer travel behaviour is needed, particularly for aviation.
- Limited understanding exists of how and when people will choose to buy and use new types of low-carbon vehicles or mobility services (such as demand responsive transit or car-share).
- There are few insights of behavioural economics to predict mobility systematically and whether producers will incorporate low-carbon technologies that may not maximize profit.
- How travellers will respond to combinations of low-carbon strategies (mixes of land use, transit, vehicle options) is especially important for fast-growing, developing countries where alternative modes to the car-centric development path could be deployed, is unknown.
- Understanding how low-carbon transport and energy technologies will evolve (via experience curves and innovation processes) is not well developed. Most vehicles rely on stored energy, so there is a need to better understand the cost and energy density of non-hydrocarbon energy storage mediums, such as batteries, super-capacitors and pressure vessels.
- Decoupling of transport GHG from economic growth needs further elaboration, especially the policy frameworks that can enable this decoupling to accelerate in both OECD and non-OECD nations.
- The rate of social acceptance of innovative concepts such as LDV road convoys, induction charging of electric vehicles, and driverless cars (all currently being demonstrated) is difficult to predict, as is the required level of related infrastructure investments. Recent rapid developments in metro systems in several cities illustrate how quickly new transport systems can be implemented when the demand, policies, and investments all come together and public support is strong.

8.12 Frequently Asked Questions

FAQ 8.1 How much does the transport sector contribute to GHG emissions and how is this changing?

The transport sector is a key enabler of economic activity and social connectivity. It supports national and international trade and a large global industry has evolved around it. Its greenhouse gas (GHG) emissions are driven by the ever-increasing demand for mobility and movement of goods. Together, the road, aviation, waterborne, and rail transport sub-sectors currently produce almost one quarter of total global energy-related CO_2 emissions [Section 8.1]. Emissions have more than doubled since 1970 to reach 7.0 Gt CO_2eq by 2010 with about 80 % of this increase coming from road vehicles. Black carbon and other aerosols, also emitted during combustion of diesel and marine oil fuels, are relatively short-lived radiative forcers compared with carbon dioxide and their reduction is emerging as a key strategy for mitigation [8.2].

Demands for transport of people and goods are expected to continue to increase over the next few decades [8.9]. This will be exacerbated by strong growth of passenger air travel worldwide due to improved affordability; by the projected demand for mobility access in non-OECD countries that are starting from a very low base; and by projected increases in freight movements. A steady increase of income per capita in developing and emerging economies has already led to a recent rapid growth in ownership and use of 2-wheelers, 3-wheelers and light duty vehicles (LDVs), together with the development of new transport infrastructure including roads, rail, airports, and ports.

Reducing transport emissions will be a daunting task given the inevitable increases in demand. Based on continuing current rates of growth for passengers and freight, and if no mitigation options are implemented to overcome the barriers [8.8], the current transport sector's GHG emissions could increase by up to 50 % by 2035 at continued current rates of growth and almost double by 2050 [8.9]. An increase of transport's share of global energy-related CO_2 emissions would likely result. However, in spite of lack of progress in many countries to date, new vehicle and fuel technologies, appropriate infrastructure developments including for non-motorized transport in cities, transport policies, and behavioural changes could begin the transition required [8.3, 8.4, 8.9].

FAQ 8.2 What are the main mitigation options and potentials for reducing GHG emissions?

Decoupling transport from GDP growth is possible but will require the development and deployment of appropriate measures, advanced technologies, and improved infrastructure. The cost-effectiveness of these opportunities may vary by region and over time [8.6]. Delivering mitigation actions in the short-term will avoid future lock-in effects resulting from the slow turnover of stock (particularly aircraft, trains, and ships) and the long-life and sunk costs of infrastructure already in place [8.2, 8.4].

When developing low-carbon transport systems, behavioural change and infrastructure investments are often as important as developing more efficient vehicle technologies and using lower-carbon fuels [8.1, 8.3].

- **Avoidance:** Reducing transport activity can be achieved by avoiding unnecessary journeys, (for example by tele-commuting and internet shopping), and by shortening travel distances such as through the densification and mixed-zoning of cities.

- **Modal choice:** Shifting transport options to more efficient modes is possible, (such as from private cars to public transport, walking, and cycling), and can be encouraged by urban planning and the development of a safe and efficient infrastructure.

- **Energy intensity:** Improving the performance efficiency of aircraft, trains, boats, road vehicles, and engines by manufacturers continues while optimizing operations and logistics (especially for freight movements) can also result in lower fuel demand.

- **Fuel carbon intensity:** Switching to lower carbon fuels and energy carriers is technically feasible, such as by using sustainably produced biofuels or electricity and hydrogen when produced using renewable energy or other low-carbon technologies.

These four categories of transport mitigation options tend to be interactive, and emission reductions are not always cumulative. For example, an eco-driven, hybrid LDV, with four occupants, and fuelled by a low-carbon biofuel would have relatively low emissions per passenger kilometre compared with one driver travelling in a conventional gasoline LDV. But if the LDV became redundant through modal shift to public and non-motorized transport, the overall emission reductions could only be counted once.

Most mitigation options apply to both freight and passenger transport, and many are available for wide deployment in the short term for land, air, and waterborne transport modes, though not equally and at variable costs [8.6]. Bus rapid transit, rail, and waterborne modes tend to be relatively carbon efficient per passenger or tonne kilometre compared with LDV, HDV, or aviation, but, as for all modes, this varies with the vehicle occupancy rates and load factors involved. Modal shift of freight from short- and medium-haul aircraft and road trucks to high-speed rail and coastal shipping often offers large mitigation potential [Table 8.3]. In addition, opportunities exist to reduce the indirect GHG emissions arising during the construction of infrastructure; manufacture of vehicles; and extraction, processing, and delivery of fuels.

The potentials for various mitigation options vary from region to region, being influenced by the stage of economic development, status and age of existing vehicle fleet and infrastructure, and the fuels available in the region. In OECD countries, transport demand reduction may involve changes in lifestyle and the use of new information and communication technologies. In developing and emerging economies, slowing the rate of growth of using conventional transport modes with relatively high-carbon emissions for passenger and freight transport by providing affordable, low-carbon options could play an important role in achieving global mitigation targets. Potential GHG emissions reductions from efficiency improvements on new vehicle designs in 2030 compared with today range from 40–70 % for LDVs, 30–50 % for HDVs, up to 50 % for aircraft, and for new ships when combining technology and operational measures, up to 60 % [Table 8.3].

Policy options to encourage the uptake of such mitigation options include implementing fiscal incentives such as fuel and vehicle taxes, developing standards on vehicle efficiency and emissions, integrating urban and transport planning, and supporting measures for infrastructure investments to encourage modal shift to public transport, walking, and cycling [8.10]. Pricing strategies can reduce travel demands by individuals and businesses, although successful transition of the sector may also require strong education policies that help to create behavioural change and social acceptance. Fuel and vehicle advances in the short to medium term will largely be driven through research investment by the present energy and manufacturing industries that are endeavouring to meet existing policies as well as to increase their market shares. However, in order to improve upon this business-as-usual scenario and significantly reduce GHG emissions across the sector in spite of the rapidly growing demand, more stringent policies will be needed. To achieve an overall transition of the sector will require rapid deployment of new and advanced technology developments, construction of new infrastructure, and the stimulation of acceptable behavioural changes.

FAQ 8.3 Are there any co-benefits associated with mitigation actions?

Climate change mitigation strategies in the transport sector can result in many co-benefits [8.7]. However, realizing these benefits through implementing those strategies depends on the regional context in terms of their economic, social, and political feasibility as well as having access to appropriate and cost-effective advanced technologies. In developing countries where most future urban growth will occur, increasing the uptake, comfort, and safety of mass transit and non-motorized transport modes can help improve mobility. In least developing countries, this may also improve access to markets and therefore assist in fostering economic and social development. The opportunities to shape urban infrastructure and transport systems to gain greater sustainability in the short- to medium-terms are also likely to be higher in developing and emerging economies than in OECD countries where transport systems are largely locked-in [8.4].

A reduction in LDV travel and ownership has been observed in several cities in OECD countries, but demand for motorized road transport, including 2- and 3-wheelers, continues to grow in non-OECD nations where increasing local air pollution often results. Well-designed policy packages can help lever the opportunities for exploiting welfare, safety, and health co-benefits [8.10]. Transport strategies associated with broader policies and programmes can usually target several policy objectives simultaneously. The resulting benefits can include lower travel costs, improved mobility, better community health through reduced local air pollution and physical activities resulting from non-motorized transport, greater energy security, improved safety, and time savings through reduction in traffic congestion.

A number of studies suggest that the direct and indirect benefits of sustainable transport measures often exceed the costs of their implementation [8.6, 8.9]. However, the quantification of co-benefits and the associated welfare effects still need accurate measurement. In all regions, many barriers to mitigation options exist [8.8], but a wide range of opportunities are available to overcome them and give deep carbon reductions at low marginal costs in the medium- to long-term [8.3, 8.4, 8.6, 8.9]. Decarbonizing the transport sector will be challenging for many countries, but by developing well-designed policies that incorporate a mix of infrastructural design and modification, technological advances, and behavioural measures, co-benefits can result and lead to a cost-effective strategy.

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9 Buildings

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Executive Summary

In 2010 buildings accounted for 32 % of total global final energy use, 19 % of energy-related GHG emissions (including electricity-related), approximately one-third of black carbon emissions, and an eighth to a third of F-gases (*medium evidence, medium agreement*). This energy use and related emissions may double or potentially even triple by mid-century due to several key trends. A very important trend is the increased access for billions of people in developing countries to adequate housing, electricity, and improved cooking facilities. The ways in which these energy-related needs will be provided will significantly determine trends in building energy use and related emissions. In addition, population growth, migration to cities, household size changes, and increasing levels of wealth and lifestyle changes globally will all contribute to significant increases in building energy use. The substantial new construction that is taking place in developing countries represents both a significant risk and opportunity from a mitigation perspective. [Sections 9.1, 9.2]

In contrast to a doubling or tripling, final energy use may stay constant or even decline by mid-century, as compared to today's levels, if today's cost-effective best practices and technologies are broadly diffused (*robust evidence, high agreement*). The technology solutions to realize this potential exist and are well demonstrated. Recent advances in technology, design practices and know-how, coupled with behavioural changes, can achieve a two to ten-fold reduction in energy requirements of individual new buildings and a two to four-fold reduction for individual existing buildings largely cost-effectively or sometimes even at net negative costs. New improved energy efficiency technologies have been developed as existing energy efficiency opportunities have been taken up, so that the potential for cost-effective energy efficiency improvement has not been diminishing. Recent developments in technology and know-how enable construction and retrofit of very low- and zero-energy buildings, often at little marginal investment cost, typically paying back well within the building lifetime (*robust evidence, high agreement*). In existing buildings 50–90 % energy savings have been achieved throughout the world through deep retrofits (*medium evidence, high agreement*). Energy efficient appliances, lighting, information communication (ICT), and media technologies can reduce the substantial increases in electricity use that are expected due to the proliferation of equipment types used and their increased ownership and use (*robust evidence, high agreement*). [9.2, 9.3]

Strong barriers hinder the market uptake of these cost-effective opportunities, and large potentials will remain untapped without adequate policies (*robust evidence, high agreement*). These barriers include imperfect information, split incentives, lack of awareness, transaction costs, inadequate access to financing, and industry fragmentation. In developing countries, corruption, inadequate service levels, subsidized energy prices, and high discount rates are additional barriers. Market forces alone are not likely to achieve the necessary transformation without external stimuli. Policy intervention addressing all stages of the building and appliance lifecycle and use, plus new business and financial models are essential. [9.8, 9.10]

There is a broad portfolio of effective policy instruments available to remove these barriers, some of them being implemented also in developing countries, thus saving emissions at large negative costs (*robust evidence, high agreement*). Overall, the history of energy efficiency programmes in buildings shows that 25–30 % efficiency improvements have been available at costs substantially lower than marginal supply. Dynamic developments in building-related policies in some developed countries have demonstrated the effectiveness of such instruments, as total building energy use has started to decrease while accommodating continued economic, and in some cases, population growth. Building codes and appliance standards with strong energy efficiency requirements that are well enforced, tightened over time, and made appropriate to local climate and other conditions have been among the most environmentally and cost-effective. Net zero energy buildings are technically demonstrated, but may not always be the most cost- and environmentally effective solutions. Experience shows that pricing is less effective than programmes and regulation (*medium evidence, medium agreement*). Financing instruments, policies, and other opportunities are available to improve energy efficiency in buildings, but the results obtained to date are still insufficient to deliver the full potential (*medium evidence, medium agreement*). Combined and enhanced, these approaches could provide significant further improvements in terms of both enhanced energy access and energy efficiency. Delivering low-carbon options raises major challenges for data, research, education, capacity building, and training. [9.10]

Due to the very long lifespans of buildings and retrofits there is a very significant lock-in risk pointing to the urgency of ambitious and immediate measures (*robust evidence, medium agreement*). Even if the most ambitious of currently planned policies are implemented, approximately 80 % of 2005 energy use in buildings globally will be 'locked in' by 2050 for decades, compared to a scenario where today's best practice buildings become the standard in new building construction and existing building retrofit. As a result, the urgent adoption of state-of-the-art performance standards, in both new and retrofit buildings, avoids locking-in carbon intensive options for several decades. [9.4]

In addition to technologies and architecture, behaviour, lifestyle, and culture have a major effect on buildings' energy use; three- to five-fold difference in energy use has been shown for provision of similar building-related energy service levels (*limited evidence, high agreement*). In developed countries, evidence indicates that behaviours informed by awareness of energy and climate issues can reduce demand by up to 20 % in the short term and 50 % of present levels by 2050. Alternative development pathways exist that can moderate the growth of energy use in developing countries through the provision of high levels of building services at much lower energy inputs, incorporating certain elements of traditional lifestyles and architecture, and can avoid such trends. In developed countries, the concept of 'suf-

Table 9.1 | Summary of chapter's main findings organized by major mitigation strategies (identities)

	Carbon efficiency	Energy efficiency of technology	System/(infrastructure) efficiency	Service demand reduction
Mitigation options	Building integrated RES (BiRES, BiPV). Fuel switching to low-carbon fuels such as electricity (9.4.1.2). Use of natural refrigerants to reduce halocarbon emissions (9.3.6). Advanced biomass stoves (9.3.8).	High-performance building envelope (HPE). Efficient appliances (EA). Efficient lighting (EL). Efficient Heating, Ventilation, and Air-Conditioning systems (eHVAC). Building automation and control systems (BACS). Daylighting, heat pumps, indirect evaporative cooling to replace chillers in dry climates, advances in digital building automation and control systems, smart meters and grids (9.3.2). Solar-powered desiccant dehumidification.	Passive House standard (PH). Nearly/net zero and energy plus energy buildings (NZEB) (9.3.3.3). Integrated Design Process (IDP). Urban planning (UP), (9.4.1). District heating/cooling (DH/C). Commissioning (C). Advanced building control systems (9.3.3.2). High efficiency distributed energy systems, co-generation, trigeneration, load levelling, diurnal thermal storage, advanced management (9.4.1.1). 'Smart-grids' (9.4.1.2). Utilization of waste heat (9.4.1.1)	Behavioural change (BC). Lifestyle change (LSC). Smart metering (9.4.1.2)
Potential reductions of energy use/emissions (versus baseline BAU)	Solar electricity generation through buildings' roof-top photo voltaic (PV) installations: energy savings – 15 to – 58 % relative to BAU (Table 9.4)	– 9.5 % to – 68 % energy savings relative to BAU (Table 9.4). Energy savings from advanced appliances: Ovens: – 45 %; Microwave ovens: – 75 %; Dishwashers: up to – 45 %; Clothes washers: – 28 % (by 2030, globally); Clothes dryers: factor of 2 reduction; Air-conditioners: – 50 to – 75 %; Ceiling fans: – 50 to – 57 %; Office computers/ monitors: – 40 %; Circulation pumps for hydronic heating/cooling: – 40 % (by 2020, EU); Residential water heaters: factor of 4 improvement (Table 9.3); Fuel savings: – 30 to – 60 %; Indoor air pollution levels from advanced biomass stoves (as compared to open fires): – 80 to – 90 % (9.3.8).	– 30 to – 70 % CO2 of BAU. PH & NZEB (new versus conventional building): – 83 % (residential heating energy) and – 50 % (commercial heating & cooling energy); Deep retrofits (DR): – 40 to – 80 % (residential, Europe); IDP: up to – 70 % (final energy by 2050; Table 9.4); Potential global building final energy demand reduction: – 5 % to – 27 % (IAMs), – 14 % to – 75 % (bottom up models) (Fig. 9.21). Energy savings by building type: (i) Detached single-family homes: – 50 – 75 % (total energy use); (ii) Multi-family housing: – 80 to – 90 % (space heating requirements); (iii) Multi-family housing in developing countries: – 30 % (cooling energy use), – 60 % (heating energy); (iv) Commercial buildings: – 25 % to – 50 % (total HVAC), – 30 to – 60 % (lighting retrofits) (9.3.4.1).	– 20 to – 40 % of BAU. LSC about – 40 % electricity use (Table 9.4).
Cost-effectiveness	–	Retrofit of separate measures: CCE: 0.01–0.10 USD_{2010}/kWh (Fig. 9.13). Efficient Appliances: CCE: – 0.09 USD_{2010}/kWh/yr (9.3.4.2)	PH & NZEB (new, EU&USA): CCE: 0.2–0.7 USD_{2010}/kWh (Figure 9.11, 9.12); DR (with energy savings of 60–75 %): CCE: 0.05 – 0.25 USD_{2010}/kWh (Fig. 9.13)	
Co-benefits (CB), adverse side effects (AE)	CB: Energy security; lower need for energy subsidies; health and environmental benefits			
	CB: Employment impact; enhanced asset value of buildings; energy/fuel poverty alleviation. AE: Energy access/fuel poverty	CB: Employment; energy/fuel poverty alleviation; improved productivity/competitiveness; asset value of buildings; improved quality of life. AE: rebound and lock-in effects	CB: Employment impact; improved productivity and competitiveness; enhanced asset values of buildings; improved quality of life. AE: Rebound effect, lower lifecycle energy use of low-energy buildings in comparison to the conventional (9.3.9)	
Key barriers	Suboptimal measures, subsidies to conventional fuels	Transaction costs, access to financing, principal agent problems, fragmented market and institutional structures, poor feedback	Energy and infrastructure lock-in (9.4.2), path-dependency (9.4.2) fragmented market and institutional structures, poor enforcement of regulations	Imperfect information, risk aversion, cognitive and behavioural patterns, lack of awareness, poor personnel qualification
Key policies	Carbon tax, feed-in tariffs extended for small capacity; soft loans for renewable technologies	Public procurement, appliance standards, tax exemptions, soft loans	Building codes, preferential loans, subsidised financing schemes, ESCOs, EPCs, suppliers' obligations, white certificates, IDP into Urban Planning, Importance of policy packages rather than single instruments (9.10.1.2)	Awareness raising, education, energy audits, energy labelling, building certificates & ratings, energy or carbon tax, personal carbon allowance

ficiency' has also been emerging, going beyond pure 'efficiency'. Reducing energy demand includes rationally meeting floor space needs. [9.3]

Beyond energy cost savings, most mitigation options in this sector have other significant and diverse co-benefits (*robust evidence, high agreement*). Taken together, the monetizable co-benefits of many energy efficiency measures alone often substantially exceed the energy cost savings and possibly the climate benefits (*medium evidence, medium agreement*), with the non-monetizable benefits often also being significant (*robust evidence, high agreement*). These benefits offer attractive entry points for action into policy-making, even in countries or jurisdictions where financial resources for mitigation are limited (*robust evidence, high agreement*). These entry points include, but are not limited to, energy security; lower need for energy subsidies; health (due to reduced indoor and outdoor air pollution as well as fuel poverty alleviation) and environmental benefits; productivity and net employment gains; alleviated energy and fuel poverties as well as reduced energy expenditures; increased value for building infrastructure; improved comfort and services (*medium evidence, high agreement*). However, these are rarely internalized by policies, while a number of tools and approaches are available to quantify and monetize co-benefits that can help this integration (*medium evidence, medium agreement*). [9.7]

In summary, buildings represent a critical piece of a low-carbon future and a global challenge for integration with sustainable development (*robust evidence, high agreement*). Buildings embody the biggest unmet need for basic energy services, especially in developing countries, while much existing energy use in buildings in developed countries is very wasteful and inefficient. Existing and future buildings will determine a large proportion of global energy demand. Current trends indicate the potential for massive increases in energy demand and associated emissions. However, this chapter shows that buildings offer immediately available, highly cost-effective opportunities to reduce (growth in) energy demand, while contributing to meeting other key sustainable development goals including poverty alleviation, energy security, and improved employment. This potential is more fully represented in sectoral models than in many integrated models, as the latter do not represent any or all of the options to cost-effectively reduce building energy use. Realizing these opportunities requires aggressive and sustained policies and action to address every aspect of the design, construction, and operation of buildings and their equipment around the world. The significant advances in building codes and appliance standards in some jurisdictions over the last decade already demonstrated that they were able to reverse total building energy use trends in developed countries to its stagnation or reduction. However, in order to reach ambitious climate goals, these standards need to be substantially strengthened and adopted for further jurisdictions, building types, and vintages. [9.6, 9.9, 9.10] Table 9.1 summarizes some main findings of the chapter by key mitigation strategy.

9.1 Introduction

This chapter aims to update the knowledge on the building sector since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) from a mitigation perspective. Buildings and activities in buildings are responsible for a significant share of GHG emissions, but they are also the key to mitigation strategies. In 2010, the building sector accounted for approximately 117 Exajoules (EJ) or 32 % of global final energy consumption and 19 % of energy-related CO_2 emissions; and 51 % of global electricity consumption. Buildings contribute to a significant amount of F-gas emissions , with large differences in reported figures due to differing accounting conventions, ranging from around an eighth to a third of all such emissions (9.3.6). The chapter argues that beyond a large emission role, mitigation opportunities in this sector are also significant, often very cost-effective, and are in many times associated with significant co-benefits that can exceed the direct benefits by orders of magnitude. The sector has significant mitigation potentials at low or even negative costs. Nevertheless, without strong actions emissions are likely to grow considerably—and they may even double by mid-century—due to several drivers. The chapter points out that certain policies have proven to be very effective and several new ones are emerging. As a result, building energy use trends have been reversed to stagnation or even reduction in some jurisdictions in recent years, despite the increases in affluence and population.

The chapter uses a novel conceptual framework, in line with the general analytical framework of the contribution of Working Group III (WGIII) to the IPCC Fifth Assessment Report (AR5), which focuses on identities as an organizing principle. This section describes the identity decomposition Chapter 9 chooses to apply for assessing the literature, resting on the general identity framework described in Chapter 6. Building-related emissions and mitigation strategies have been decomposed by different identity logics. Commonly used decompositions use factors such as CO_2 intensity, energy intensity, structural changes, and economic activity (Isaac and Van Vuuren, 2009; Zhang et al., 2009), as well as the IPAT (Income-Population-Affluence-Technology) approach (MacKellar et al., 1995; O' Mahony et al., 2012). In this assessment, the review focuses on the main decomposition logic described in Chapter 6, adopted and further decomposed into four identities key to driving building sector emissions:

$$CO_2 = CI \cdot TEI \cdot SEI \cdot A$$

where CO_2 is the emissions from the building sector; (Identity 1) CI is the carbon intensity; (Identity 2) TEI is the technological energy intensity; (Identity 3) SEI is the structural\systemic energy intensity and (Identity 4) A is the activity. For a more precise interpretation of the factors, the following conceptual equation demonstrates the different components:

$$CO_2 = \frac{CO_2}{FE} \cdot \frac{FE}{UsefulE} \cdot \frac{UsefulE}{ES} \cdot \frac{ES}{pop} \cdot pop \approx CI \cdot TEI \cdot SEI \cdot \frac{A}{pop} \cdot pop$$

in which FE is the final energy; $UsefulE$ is the useful energy for a particular energy service (ES), as occurring in the energy conversion chain, and pop is population. Instead of population in the residential sector the Gross Domestic Product (GDP) is often used as the main decomposition factor for commercial building emissions. Because ES is often difficult to rigorously define and measure, and $UsefulE$ and ES are either difficult to measure or little data are available, this chapter does not attempt a systematic quantitative decomposition, but rather focuses on the main strategic categories for mitigation based on the relationship established in the previous equation:

$$CO_2\ mitigation \approx C_{Eff} \cdot T_{Eff} \cdot SI_{Eff} \cdot DR$$

whereby (1) C_{Eff}, or carbon efficiency, entails fuel switch to low-carbon fuels, building-integrated renewable energy sources, and other supply-side decarbonization; (2) T_{Eff}, or technological efficiency, focuses on the efficiency improvement of individual energy-using devices; (3) SI_{Eff}, or systemic/infrastructural efficiency, encompass all efficiency improvements whereby several energy-using devices are involved, i. e., systemic efficiency gains are made, or energy use reductions due to architectural, infrastructural, and systemic measures; and finally (4) *DR*, or demand reduction, composes all measures that are beyond technological efficiency and decarbonization measures, such as impacts on floor space, service levels, behaviour, lifestyle, use, and penetration of different appliances. The four main emission drivers and mitigation strategies can be further decomposed into more distinct sub-strategies, but due to the limited space in this report and in order to maintain a structure that supports convenient comparison between different sectoral chapters, we focus on these four main identities during the assessment of literature in this chapter and use this decomposition as the main organizing/conceptual framework.

9.2 New developments in emission trends and drivers

9.2.1 Energy and GHG emissions from buildings

Greenhouse gas (GHG) emissions from the building sector have more than doubled since 1970 to reach 9.18 $GtCO_2eq$ in 2010 (Figure 9.1), representing 25 % of total emissions without the Agriculture, Forestry, and Land Use (AFOLU) sector; and 19 % of all global 2010 GHG emissions (IEA, 2012a; JRC/PBL, 2013; see Annex II.8). Furthermore, they account for approximately one-third of black carbon emissions (GEA, 2012), and one-eighth to one-third of F-gas emissions, depending partially on the accounting convention used (UNEP, 2011a; EEA, 2013; US EPA, 2013; JRC/PBL, 2013; IEA, 2012a; see Annex II.8).

Most of GHG emissions (6.02 Gt) are indirect CO_2 emissions from electricity use in buildings, and these have shown dynamic growth in the studied period in contrast to direct emissions, which have roughly stagnated during these four decades (Figure 9.1). For instance, residential indirect emissions quintupled and commercial emissions quadrupled.

Figure 9.2 shows the regional trends in building-related GHG emissions. Organisation for Economic Co-operation Development (OECD) countries have the highest emissions, but the growth in this region between 1970 and 2010 was moderate. For least developed countries, the emissions are low with little growth. The largest growth has taken place in Asia where emissions in 1970 were similar to those in other developing regions, but by today they are closing in on those of OECD countries.

Due to the high share of indirect emissions in the sector, actual emission values very strongly depend on emission factors—mainly that of electricity production—that are beyond the scope of this chapter. Therefore, the rest of this chapter focuses on final energy use (rather than emissions) that is determined largely by activities and measures within the sector.

In 2010 buildings accounted for 32 % (24 % for residential and 8 % for commercial) of total global final energy use (IEA, 2013), or 32.4 PWh, being one of the largest end-use sectors worldwide. Space heating rep-

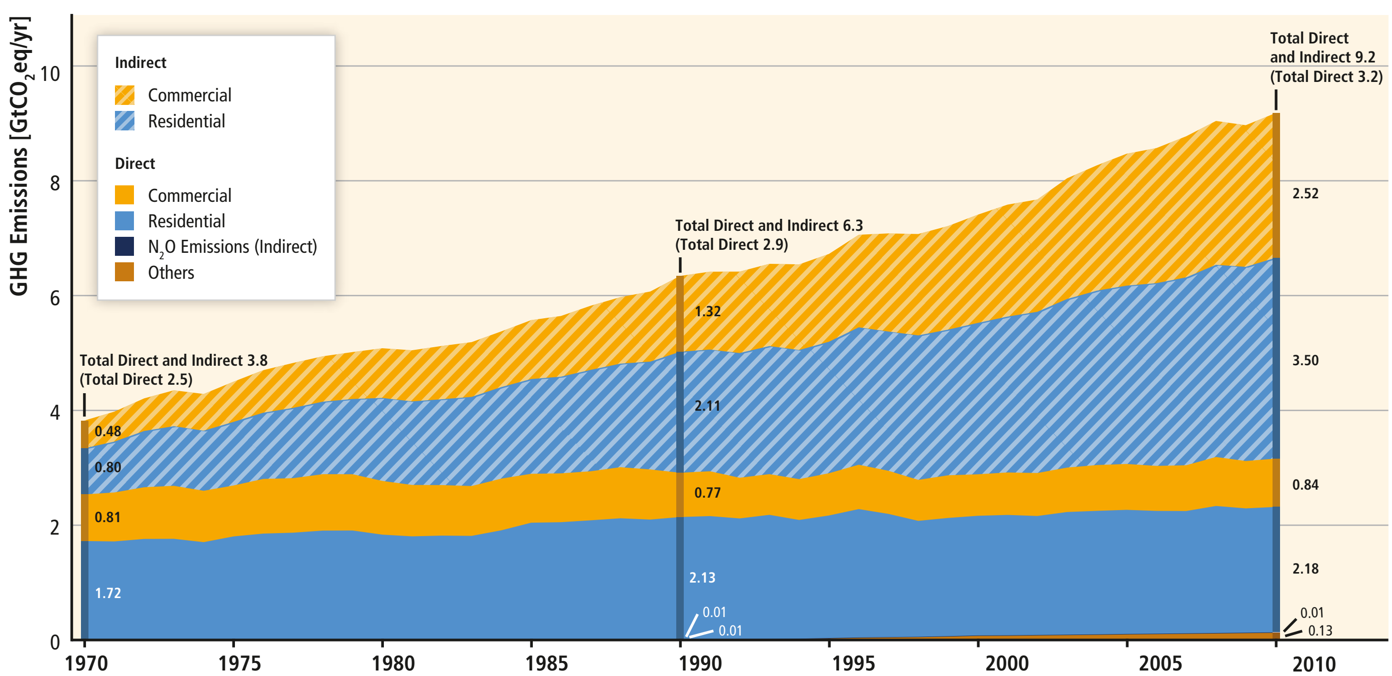


Figure 9.1 | Direct and indirect emissions (from electricity and heat production) in the building subsectors (IEA, 2012a; JRC/PBL, 2013; see Annex II.9).

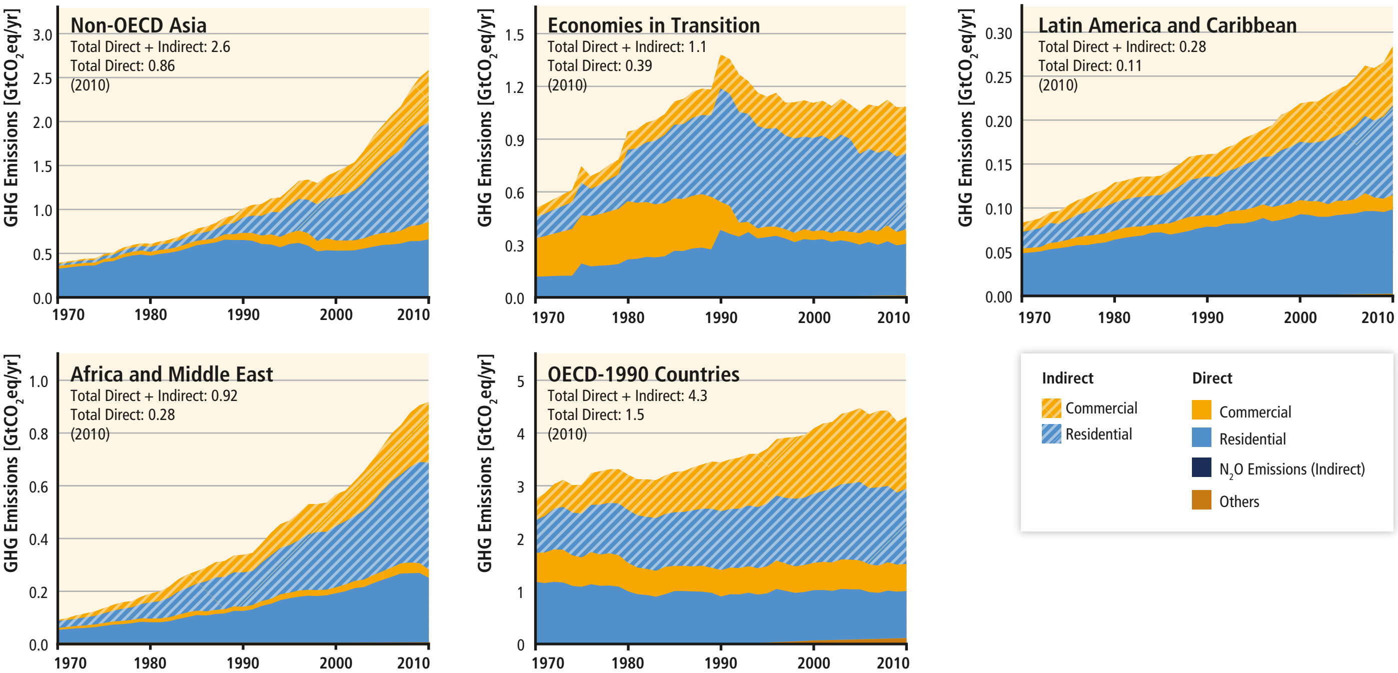


Figure 9.2 | Regional direct and indirect emissions in the building subsectors (IEA, 2012a; JRC/PBL, 2013; see Annex II.9).

Box 9.1 | Least Developed Countries (LDCs) in the context of the developing world

878 million people with an average 2 USD_{2010} per day of gross national income (The World Bank, 2013) live in the LDCs group. Rapid economic development, accompanied by urbanization, is propelling large building activity in developing countries (WBCSD, 2007, 2009; ABC, 2008; Li and Colombier, 2009). The fast growing rates of new construction, which is occurring in emerging economies, is not being witnessed in LDCs. This group of countries is still at the fringe of modern development processes and has special needs in terms of access to housing, modern energy carriers, and efficient and clean-burning cooking devices (Zhang and Smith, 2007; Duflo et al., 2008; WHO, 2009, 2011; Wilkinson et al., 2009; Hailu, 2012; Pachauri, 2012). Around one-third of the urban population in developing countries in 2010 did not have access to adequate housing (UNHSP, 2010) and the number of slum dwellers is likely to rise in the near future (UN-Habitat, 2011). In order to avoid locking in carbon-intensive options for several decades, a shift to electricity and modern fuels needs to be accompanied by energy-saving solutions (technological, architectural), as well as renewable sources, adequate management, and sustainable lifestyles (WBCSD, 2006; Ürge-Vorsatz et al., 2009; Wilkinson et al., 2009; US EERE, 2011; GEA, 2012; Wallbaum et al., 2012).

Modern knowledge and techniques can be used to improve vernacular designs (Foruzanmehr and Vellinga, 2011). Principles of low-energy design often provide comfortable conditions much of the time, thereby reducing the pressure to install energy-intensive cooling equipment such as air conditioners. These principles are embedded in vernacular designs throughout the world, and have evolved over centuries in the absence of active energy systems.

Beyond the direct energy cost savings, many mitigation options in this sector have significant and diverse co-benefits that offer attractive entry points for mitigation policy-making, even in countries/jurisdictions where financial resources for mitigation are limited. These co-benefits include, but are not limited to, energy security, air quality, and health benefits; reduced pressures to expand energy generation capacities in developing regions; productivity, competitiveness, and net employment gains; increased social welfare; reduced fuel poverty; decreased need for energy subsidies and exposure to energy price volatility risks; improved comfort and services; and improved adaptability to adverse climate events (Tirado Herrero et al., 2012; Clinch and Healy, 2001; see also Table 9.7).

resented 32–34 % of the global final energy consumption in both the residential and the commercial building sub-sectors in 2010 (Figure 9.4). Moreover, in the commercial sub-sector, lighting was very important, while cooking and water heating were significant end-uses in residential buildings. In contrast to the dynamically growing total emissions, per capita final energy use did not grow substantially over the two decades between 1990 and 2010 in most world regions (see Figure 9.3). This value stagnated in most regions during the period, except for a slight increase in the Former Soviet Union (FSU) and a dynamic growth in North Africa and Middle East (MEA). Commercial energy use has also grown only moderately in most regions on a per capita basis, with more dynamic growth shown in Centrally Planned Asia (CPA), South Asia (SAS) and MEA. This indicates that most trends to drive building energy use up have been compensated by efficiency gains. In many developing regions this can largely be due to switching from traditional biomass to modern energy carriers that can be utilized much more efficiently.

As shown in Section 9.9 global building energy use may double to triple by mid-century due to several key trends. An estimated 0.8 billion people lack access to adequate housing (UN-Habitat, 2010) while an estimated 1.3 billion people lacked access to electricity in 2010 and about 3 billion people worldwide relied on highly-polluting and unhealthy traditional solid fuels for household cooking and heating (IEA, 2012a; Pachauri et al., 2012; see Section 14.3.2.1).The ways these energy services will be provided will significantly influence the development of building related emissions. In addition, migration to

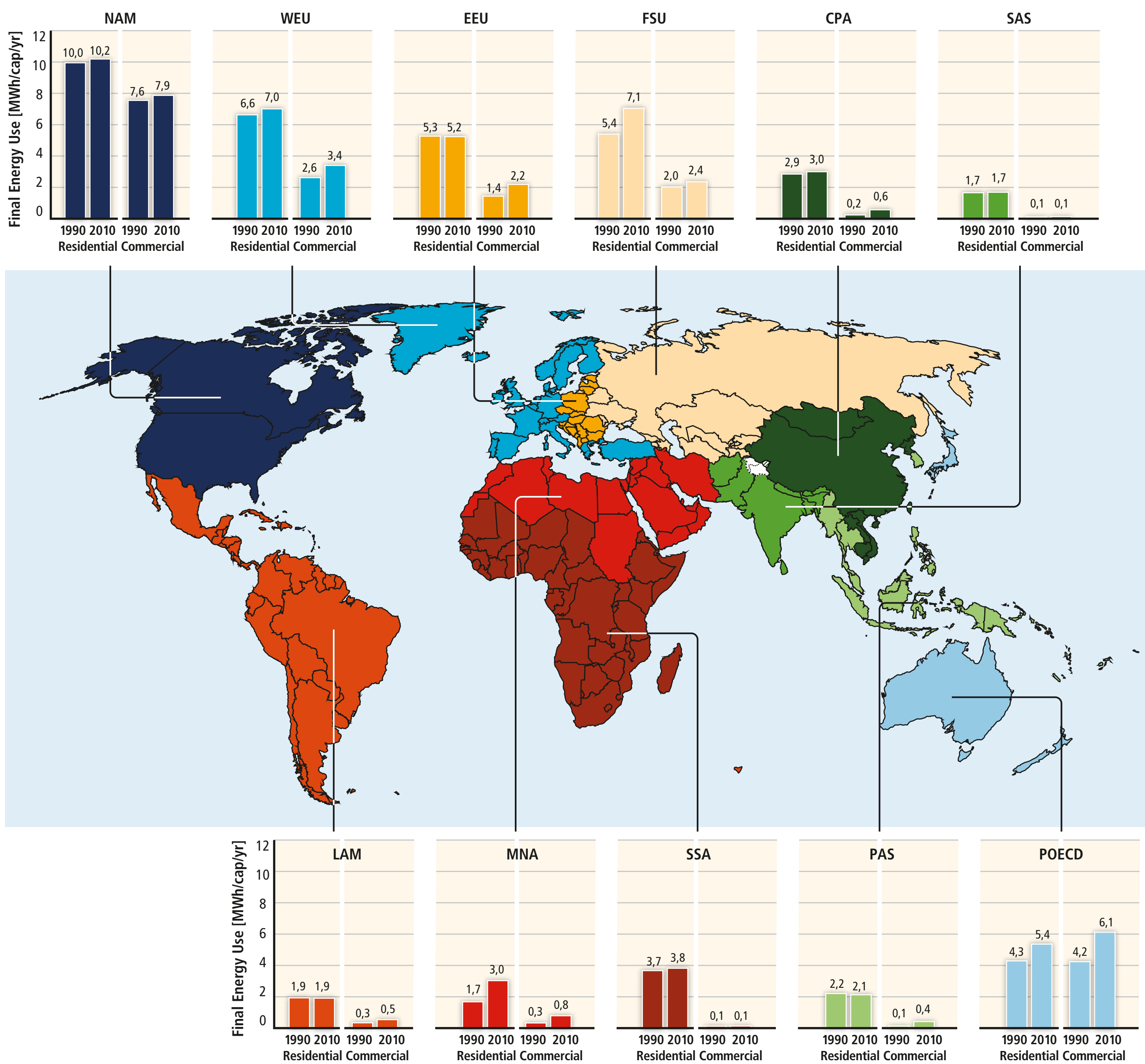


Figure 9.3 | Annual per capita final energy use of residential and commercial buildings for eleven regions (GEA RC11, see Annex II.2.4) in 1990 and 2010. Data from IEA (2012b, 2013).

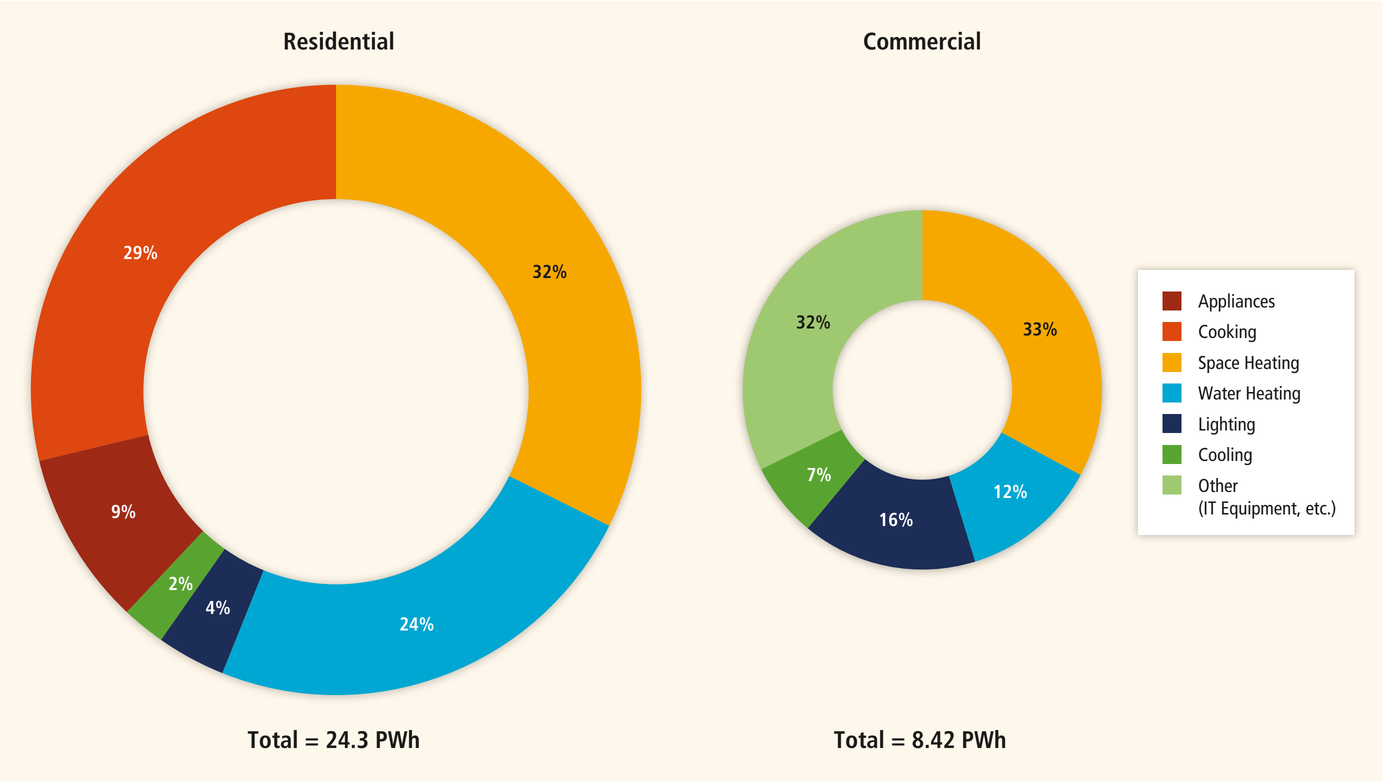


Figure 9.4 | World building final energy consumption by end-use in 2010. Source: IEA (2013).

cities, decreasing household size, increasing levels of wealth and lifestyle changes, including an increase in personal living space, the types and number of appliances and equipment and their use—all contribute to significant increases in building energy use. Rapid economic development accompanied by urbanization and shifts from informal to formal housing is propelling significant building activity in developing countries (WBCSD, 2007). As a result, this substantial new construction, which is taking place in these dynamically growing regions represents both a significant risk and opportunity from a mitigation perspective.

9.2.2 Trends and drivers of thermal energy uses in buildings

Figure 9.5 shows projections of thermal energy uses in commercial and residential buildings in the regions of the world from 2010 to 2050. While energy consumption for thermal uses in buildings in the developed countries (see North America and Western Europe) accounts for most of the energy consumption in the world, its tendency is to grow little in the period shown, while developing countries show an important increase. Commercial buildings represent between 10 to 30 % of total building sector thermal energy consumption in most regions of the world, except for China, where heating and cooling energy consumption in commercial buildings is expected to overtake that of residential buildings. Drivers to these trends and their developments are discussed separately for heating/cooling and other building energy services because of conceptually different drivers. Heating and cooling energy use in residential buildings can be decomposed by the following key identities:

$$energy_{residential} = h \cdot \frac{p}{h} \cdot \frac{area}{p} \cdot \frac{energy}{area}$$

where $energy_{residential}$ stands for the total residential thermal energy demand, *[h]* and *[p/h]* are the activity drivers, with *[h]* being the number of households and the *p/h* number of persons *(p)* living in each household, respectively. *[area/p]* is the use intensity driver, with the floor area (usually m^2) per person; and *[energy/area]* is the energy intensity driver, i.e., the annual thermal energy consumption (usually kWh) per unit of floor area, also referred to as specific energy consumption. For commercial buildings, the heating and cooling use is decomposed as

$$energy_{commercial} = GDP \cdot \frac{area}{GDP} \cdot \frac{energy}{area}$$

where $energy_{commercial}$ stands for the total commercial thermal energy demand, *[GDP]*, i.e., nominal Gross Domestic Product is the activity driver; *[area/GDP]* is the use intensity driver and *[energy/area]* is the energy intensity driver, the annual thermal energy consumption (in kWh) per unit of floor area (in m^2), also referred to as specific energy consumption. Figures 9.6 and 9.7 illustrate the main trends in heating and cooling energy use as well as its drivers globally and by region.

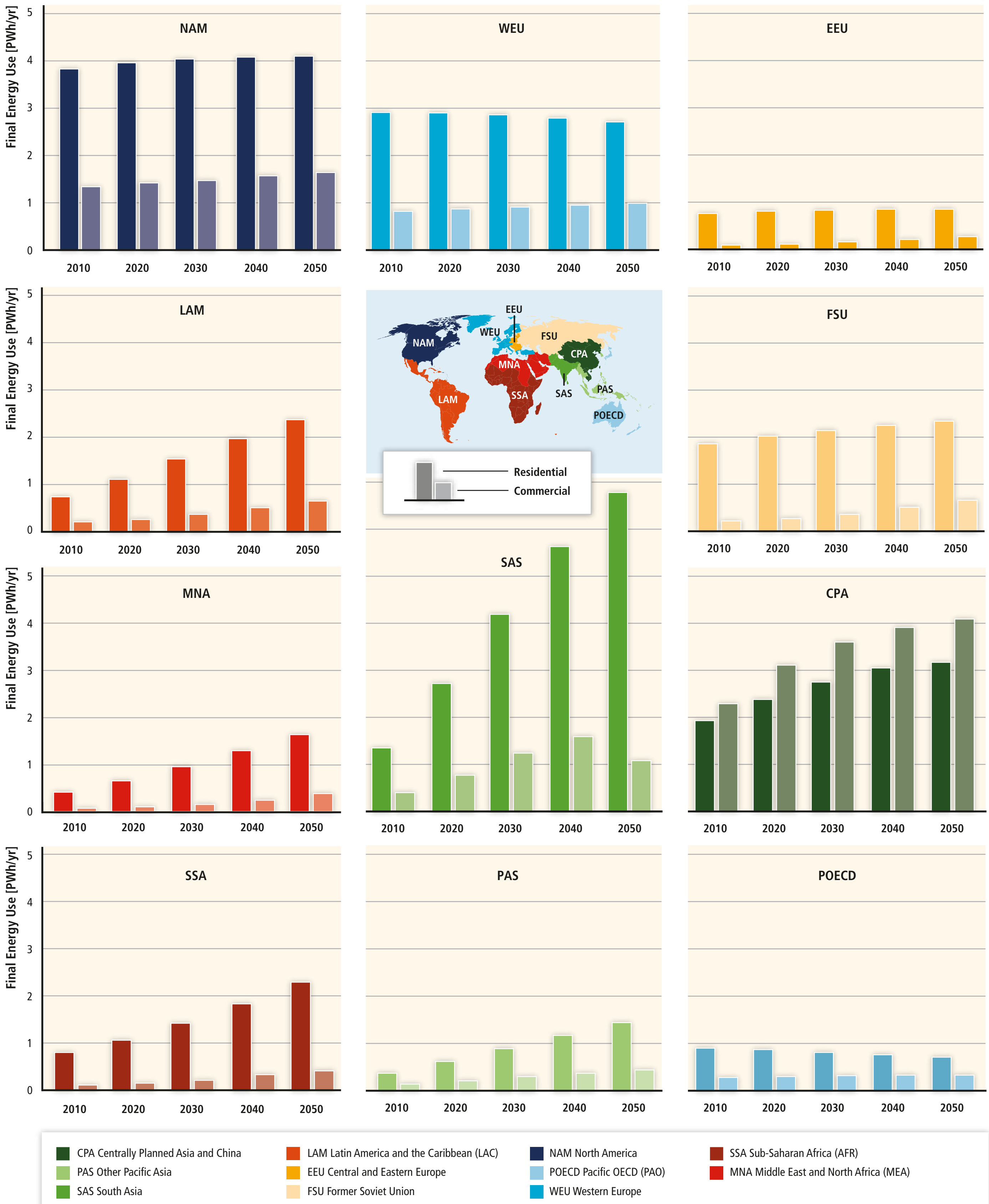


Figure 9.5 | Total annual final thermal energy consumption (PWh/yr) trends in eleven world regions (GEA RC11, see Annex II.2.4) for residential and commercial buildings (GEA region abbreviation added in brackets where different from abbreviation used in this report). Historical data (1980–2000) are from IEA statistics; projections (2010–2050) are based on a frozen (i.e. unchanged over time) efficiency scenario (Ürge-Vorsatz et al., 2013).

Heating and cooling energy use in residential and commercial buildings is expected to grow by 79 % and 84 %, respectively, over the period 2010–2050 (Figure 9.6) in a business-as-usual scenario. In residential buildings, both the growing number of households and the area per household tend to increase energy consumption, while the decrease in the number of persons per household and in specific energy consumption tend to decrease energy consumption. In commercial buildings, the projected decrease of *area/GDP* is 61 %, while energy/area is expected to stay constant over the period 2010–2050. Different tendencies of the drivers are shown for both residential and commercial buildings in the world as whole (Figure 9.6) and in different world regions (Figure 9.7). These figures indicate that in some regions (e.g., NAM and WEU), strong energy building policies are already resulting in declining or stagnating total energy use trends despite the increase in population and service levels.

9.2.3 Trends and drivers in energy consumption of appliances in buildings

In this chapter, we use the word 'appliances' in a broad sense, covering all electricity-using non-thermal equipment in buildings, including lighting and ICT. Traditional large appliances, such as refrigerators and washing machines, are still responsible for most household electricity consumption (IEA, 2012c) albeit with a falling share related to the equipment for information technology and communications (including home entertainment) accounting in most countries for 20 % or more of residential electricity consumption (Harvey, 2008). This rapid growth offers opportunities to roll out more efficient technologies, but this effect to date has been outcompeted by the increased uptake of devices and new devices coming to the market. Energy use of appliances can be decomposed as shown in the following equation from (Cabeza et al., 2013b):

$$energy = \sum_a h \cdot \frac{n}{h} \cdot \frac{energy}{n}$$

Where $\sum_a$ is the sum overall appliances; *[h]* is the activity driver, the number of households; *[n/h]* is the use intensity driver, i.e., the number of appliances of appliance type 'a' per household; and *[energy]* is the energy intensity driver (kWh/yr used per appliance). The number of appliances used increased around the world. Figure 9.8 shows that the energy consumption of major appliances in non-OECD countries is already nearly equal to consumption in the OECD, due to their large populations and widespread adoption of the main white appliances and lighting. In addition, while fans are a minor end-use in most OECD countries, they continue to be extremely important in the warm developing countries.

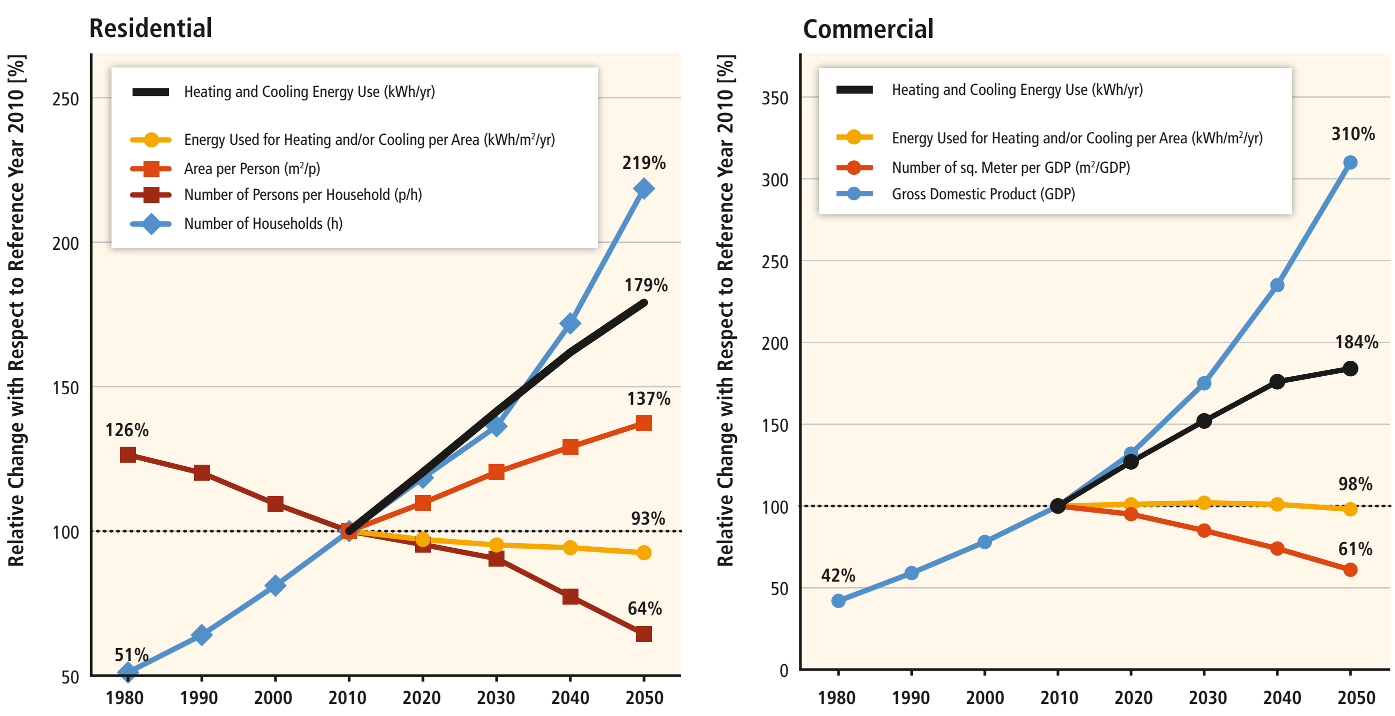
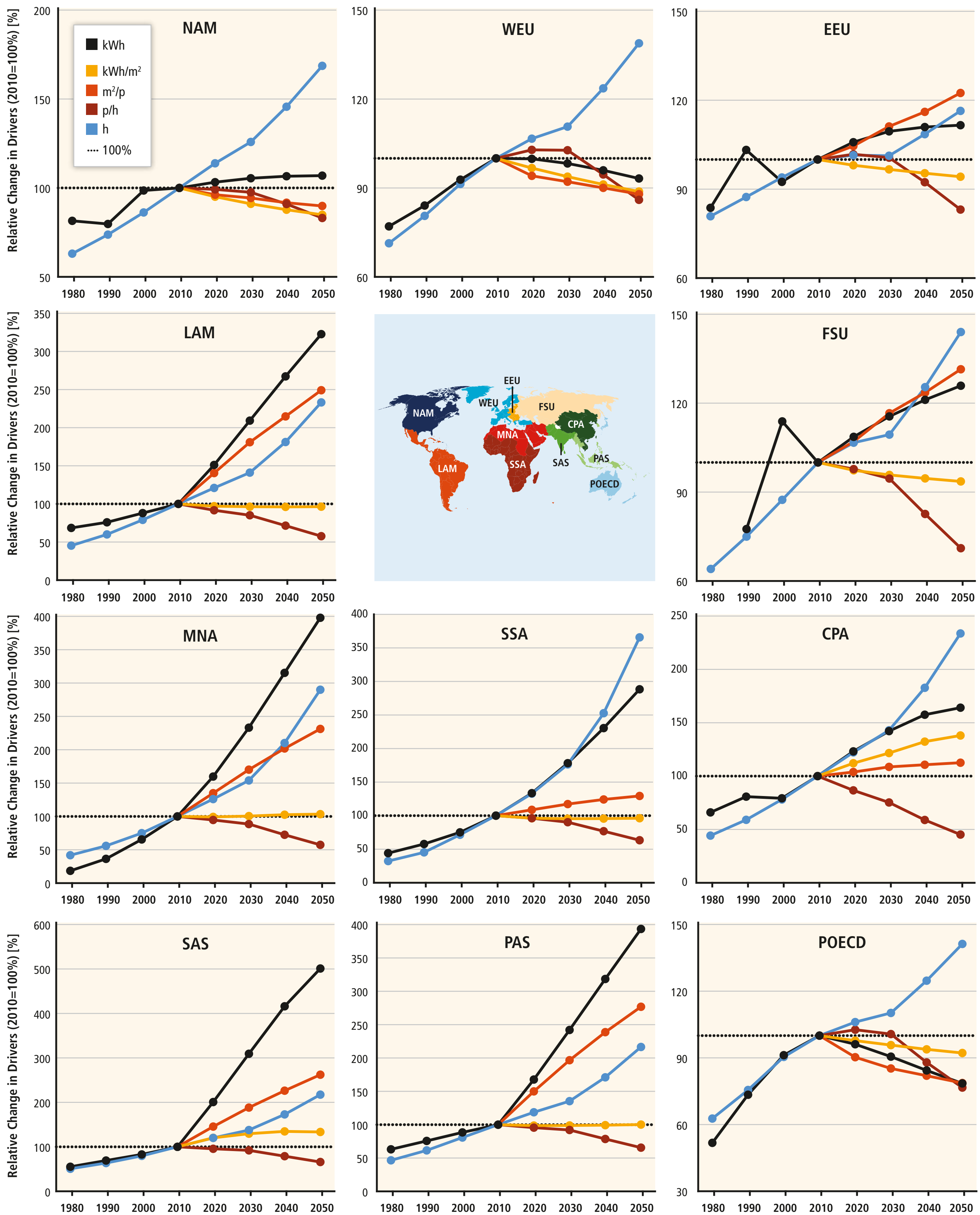


Figure 9.6 | Trends in the different drivers for global heating and cooling thermal energy consumption in residential and commercial buildings. Source: Ürge-Vorsatz et al. (2013) with projection data (2010–2050) from frozen efficiency scenario.



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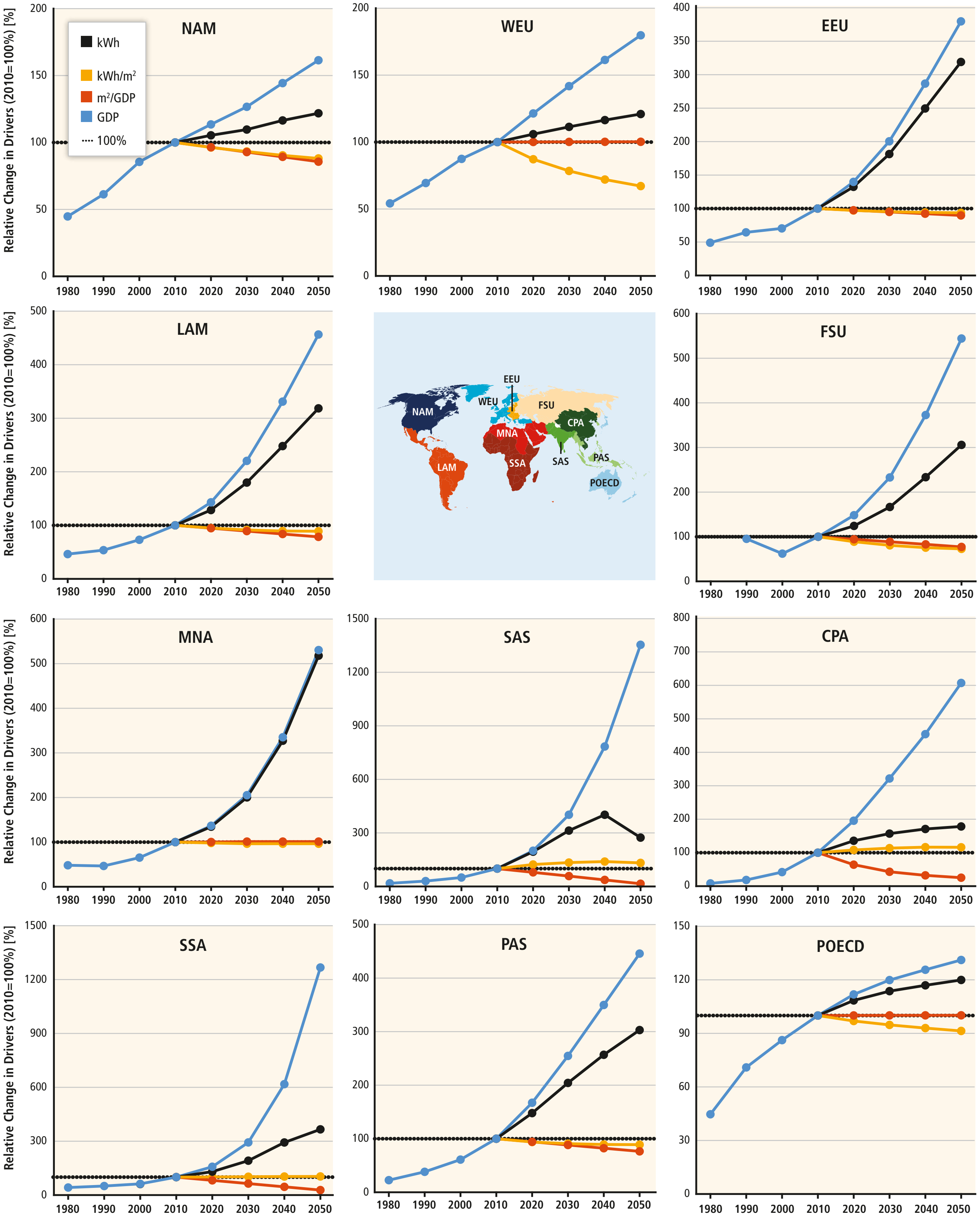

Figure 9.7 | Trends in the drivers of heating and cooling thermal energy consumption of residential (first page) and commercial (this page) buildings in world regions (GEA RC11, see Annex II.2.4). Source: Ürge-Vorsatz et al. (2013) with projection data (2010 – 2050) from frozen efficiency scenario.

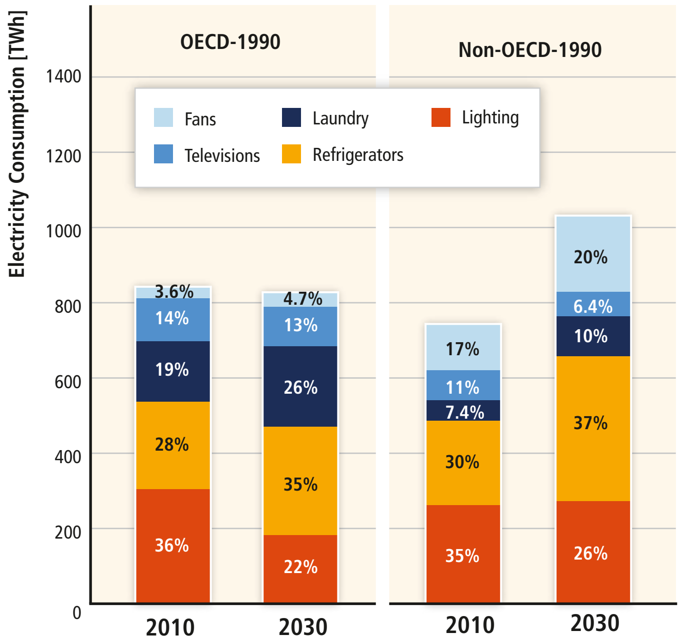

Figure 9.8 | Residential electricity consumption by end-use in a policy scenario from the Bottom-Up Energy Analysis System (BUENAS) model. Source: Cabeza et al. (2013b).

9.3 Mitigation technology options and practices, behavioural aspects

This section provides a broad overview at the strategic and planning level of the technological options, design practices, and behavioural changes that can achieve large reductions in building energy use (50 %–90 % in new buildings, 50 %–75 % in existing buildings). Table 9.2 summarizes the energy savings and CO_2 emission reduction potential according to the factors introduced in Section 9.1 based on material presented in this section or in references given. A synthesis of documented examples of large reductions in energy use achieved in real, new, and retrofitted buildings in a variety of different climates, and of costs at the building level, is presented in this section, while Section 9.4 reviews the additional savings that are possible at the community level and their associated costs, and Section 9.6 presents a synthesis of studies of the costs, their trends, and with integrated potential calculations at the national, regional, and global levels.

9.3.1 Key points from AR4

The AR4 Chapter 6 on Buildings (Levine et al., 2007) contains an extensive discussion of the wide range of techniques and designs to reduce energy use in new buildings. Savings at the system level are generally larger than for individual devices (pumps, motors, fans, heaters, chillers, etc.), as are related net investment-cost savings—usually several times higher (Levine et al., 2007; Harvey, 2008). Integrated Design Process (IDP) allows for the systemic approach, which optimizes building performance iteratively, and involves all design team members from the start (Montanya et al., 2009; Pope and Tardiff, 2011). However, the conventional process of designing and constructing a building and its systems is largely linear, in which design elements and system components are specified, built, and installed without consideration of optimization opportunities in the following design and building phases, thus losing key opportunities for the optimization of whole buildings as systems (Lewis, 2004). As discussed in AR4, essential steps in the design of low-energy buildings are: (1) building orientation, thermal mass, and shape; (2) high-performance envelope specification; (3) maximization of passive features (daylighting, heating, cooling, and ventilation); (4) efficient systems meeting remaining loads; (5) highest possible efficiencies and adequate sizing of individual energy-using devices; and (6) proper commissioning of systems and devices. Cost savings can substantially offset additional high-performance envelope and higher-efficiency equipment costs, of around 35–50 % compared to standard practices of new commercial buildings (or 50–80 % with more advanced approaches). Retrofits can routinely achieve 25–70 % savings in total energy use (Levine et al., 2007; Harvey, 2009).

9.3.2 Technological developments since AR4

Since AR4, there have been important performance improvements and cost reductions in many relevant technologies, and further significant improvements are expected. Examples include (1) daylighting and electric lighting (Dubois and Blomsterberg, 2011); (2) household appliances (Bansal et al., 2011); (3) insulation materials (Baetens et al., 2011; Korjenic et al., 2011; Jelle, 2011); (4) heat pumps (Chua et al., 2010); (5) indirect evaporative cooling to replace chillers in dry climates (Jiang and Xie, 2010); (6) fuel cells (Ito and Otsuka, 2011); (7) advances in digital building automation and control systems (NBI, 2011); and (8) smart meters and grids as a means of reducing peak demand and accommodating intermittent renewable electricity sources (Catania, 2012). Many of these measures can individually reduce the relevant specific energy use by half or more. In addition to the new technologies, practitioners have also increasingly applied more established technology and knowledge both in new building construction and in the existing building retrofits. These practices have been driven in part by targeted demonstration programmes in a number of countries. They have been accompanied by a progressive strengthening of the energy provisions of building codes in many countries, as well as by plans for significant further tightening in the near future (see also Section 9.10). In the following sections we review the literature published largely since AR4 concerning the energy intensity of low-energy new buildings and of deep retrofits of existing buildings.

Table 9.2 | Savings or off-site energy use reductions achievable in buildings for various end uses due to on-site active solar energy systems, efficiency improvements, or behavioural changes.

End Use	On-site C-Free Energy Supply[1]	Device Efficiency	System Efficiency	Behavioural Change
Heating	20 %–95 % [2]	30 %[3]–80 %[4]	90 %[5]	10 %–30 %[6]
Hot water	50 %–100 % [7]	60 %[8]–75 %[9]	40 %[10]	50 %[11]
Cooling	50 %–80 % [12]	50 %[13]–75 %[14]	67 %[15]	50 %–67 %[16]
Cooking	0–30 % [17]	25–75 %[18]–80 %[19]		50 %[20]
Lighting	10–30 %	75 %[21]; 83 %–90 %[22]; 99.83 %[23]	80 %–93 %[24]	70 %[25]
Refrigerators		40 % [25a]		30 %[26]; 50 %[27]
Dishwashers		17+%[27a]		75 %[28]
Clothes washers		30 %[28a]		60 %–85 %[29]
Clothes dryers		50+%[29a]		10 %–15 %[30]–100 %[31]
Office computers & monitors		40 %[31a]		
General electrical loads	10 %–120 %[32]			

Notes: **(1)** Only active solar energy systems. Higher percentage contributions achievable if loads are first reduced through application of device, system, and behavioural efficiencies. Passive solar heating, cooling, ventilation, and daylighting are considered under Systemic Efficiency. **(2)** Space heating. Lower value representative of combi-systems in Europe; upper value is best solar district heating systems with seasonal underground thermal energy storage, after a 5-year spin-up (SAIC, 2013). **(3)** Replacement of 75 % efficient furnace/boiler with 95 % efficient unit (e.g., condensing natural gas boilers). **(4)** Replacement of 80 % efficient furnace or boiler with ground-source heat pump with a seasonal COP for space heating of 4 (from ground-source heat pumps in well-insulated new buildings in Germany (DEE, 2011). **(5)** Reduction from a representative cold-climate heating energy intensity of 150 kWh/m^2/yr to 15 kWh/m^2/yr (Passive House standard, Section 9.3.2). **(6)** Typical value; 2 °C cooler thermostat setting at heating season. Absolute savings is smaller but relative savings is larger the better the thermal envelope of the building (see also Section 9.3.9). **(7)** Water heaters. 50–80 % of residential hot water needs supplied in Sydney, Australia and Germany (Harvey, 2007), while upper limit of 100 % is conceivable in hot desert regions. **(8)** Replacement of a 60 % efficient with a 95 % efficient water heater (typical of condensing and modulating wall-hung natural gas heaters). **(9)** Table 9.4. **(10)** Elimination of standby and distribution heat losses in residential buildings (typically accounting for 30 % water-heating energy use in North America (Harvey, 2007) through use of point-of-use on- demand water heaters. **(11)** Shorter showers, switch from bathing to showering, and other hot-water-conserving behaviour. **(12)** Air conditioning and dehumidification. Range for systems from central to Southern Europe with a relatively large solar collector area in relation to the cooling load (Harvey, 2007). **(13)** Replacement of air conditioners having a COP of 3 (typical in North America) with others with a COP of 6 (Japanese units); Table 9.4. **(14)** Replacement of North American units with units incorporating all potential efficiency improvements; Table 9.4. **(15)** Reduction (even elimination) of cooling loads through better building orientation & envelopes, provision for passive cooling, and reduction of internal heat gains (Harvey, 2007). **(16)** Section 9.3.9. Fans during tolerable brief periods eliminating cooling equipment in moderately hot climates. **(17)** Cooking range, various ovens. **(18)** Range pertains to various kinds of ovens; Table 9.4. **(19)** Replacement of 10 %–15 % with 60 % efficient (traditional biomass) cookstoves (Rawat et al., 2010). **(20)** Same recipe with different cooking practices; Table 9.4/Section 9.3.9. **(21)** Replacement of 10–17 lm/W incandescent lamps with 50–70 lm/W compact fluorescent (Harvey, 2010). **(22)** Replacement of 15 lm/W incandescent lamps with (year 2030) LEDs, 100–160 lm/W (McNeil et al., 2005; US DOE, 2006). **(23)** Replacement of 0.25 lm/W kerosene lamps (Fouquet and Pearson, 2006) with future 150 lm/W LEDs. **(24)** Reduction from average US office lighting energy intensity of the existing stock of 73 kWh/m^2/yr (Harvey, 2013) to 5–15 kWh/m^2/yr state-of-art systems (Harvey, 2013). **(25)** Turning off not needed lights (6000 hours/yr out of 8760 hours/yr). **(25a)** Table 9.4 **(26)** 12.5 ft^3vs 18.5 ft^3 (350 litres, 350 kWh/yr vs 520 litres, 500 kWh/yr) refrigerator-freezers or 18.5 vs 30.5 ft^3 (860 litres, 700 kWh/yr) (Harvey, 2010). **(27)** Elimination of a second ('beer') fridge. **(27a)** Table 9.4 **(28)** Fully loaded operation versus typical part-load operation (Table 9.4). **(28a)** by 2030 (Table 9.4). **(29)** Cold compared to hot water washing, based on relative contribution of water heating to total clothes washer energy use for the best US&EU models (Harvey, 2010). **(29a)** Table 9.4. **(30)** Operation at full load rather than at one-third to half load (Smith, 1997). **(31)** Air drying inside when there is no space heating requirement, or outside. **(31a)** Table 9.4. **(32)** Fraction of on-site electricity demand typically generated by on-site PV with low demand kept low through electricity-efficiency measures.

9.3.3 Exemplary New Buildings

This section presents an overview of the energy performance and incremental cost of exemplary buildings from around the world, based on the detailed compilation of high-performance buildings presented in Harvey (2013). The metrics of interest are the on-site energy intensity—annual energy use per square meter of building floor area (kWh/m^2/yr)—for those energy uses (heating, cooling, ventilation, and lighting) that naturally increase with the building floor area, and energy use per person for those energy uses—such as service hot water, consumer electronics, appliances, and office equipment—that naturally increase with population or the size of the workforce.

9.3.3.1 Energy intensity of new high-performance buildings

The energy performance of new buildings have improved considerably since AR4, as demonstrated in Table 9.3, which summarizes the specific energy consumption for floor-area driven final energy uses by climate type or region.

A number of voluntary standards for heating energy use have been developed in various countries for *residential buildings* (see Table 1 in Harvey, 2013). The most stringent of standards with regard to heating requirements is the Passive House standard, which prescribes a

Table 9.3 | Typical and current best case specific energy consumption (kWh/m^2/yr) for building loads directly related to floor area (Harvey, 2013).

End Use	Climate Region	Residential		Commercial	
		Advanced	Typical	Advanced	Typical
Heating	Cold	15–30	60–200	15–30	75–250
Heating	Moderate	10–20	40–100	10–30	40–100
Cooling	Moderate	0–5	0–10	0–15	20–40
Cooling	Hot-dry	0–10	10–20	0–10	20–50
Cooling	Hot-humid	3–15	10–30	15–30	50–150
Ventilation	All	4–8	0–8	0–20	10–50
Lighting	All	2–4	3–10	5–20	30–80

Notes: Lighting energy intensity for residential buildings is based on typical modern intensities times a factor of 0.3–0.4 to account for an eventual transition to LED lighting. Definitions here for climate regions for heating: Cold > 3000 HDD; Moderate 1000–3000 HDD. Similarly for cooling: moderate < 750 CDD; hot-dry > 750 CDD; hot-humid > 750 CDD. HDD = heating degree days (K-day) and CCD = cooling-degree days (K-day). Energy intensity ranges for commercial buildings exclude hospitals and research laboratories.

heating load (assuming a uniform indoor temperature of 20°C) of no more than 15 kWh/m^2/yr irrespective of the climate. It typically entails a high-performance thermal envelope combined with mechanical ventilation with heat recovery to ensure high indoor air quality. Approximately 57,000 buildings complied with this standard in 31 European countries in 2012, covering 25.15 million square metres (Feist, 2012) with examples as far north as Helsinki, with significant additional floor area that meets or exceeds the standard but have not been certified due to the higher cost of certification. As seen from Table 9.3, this standard represents a factor of 6–12 reduction in heating load in mild climates (such as Southern Europe) and up to a factor of 30 reduction in cold climate regions where existing buildings have little to no insulation. Where buildings are not currently heated to comfortable temperatures, adoption of a high-performance envelope can aid in achieving comfortable conditions while still reducing heating energy use in absolute terms.

Cooling energy use is growing rapidly in many regions where, with proper attention to useful components of vernacular design combined with modern passive design principles, mechanical air conditioning would not be needed. This use includes regions that have a strong diurnal temperature variation (where a combination of external insulation, exposed interior thermal mass, and night ventilation can maintain comfortable conditions), or a strong seasonal temperature variation (so that the ground can be used to cool incoming ventilation air) or which are dry, thereby permitting evaporative cooling or hybrid evaporative/mechanical cooling strategies to be implemented.

Combining insulation levels that meet the Passive House standard for heat demand in Southern Europe with the above strategies, heating loads can be reduced by a factor of 6–12 (from 100–200 kWh/m^2/yr to 10–15 kWh/m^2/yr) and cooling loads by a factor of 10 (from < 30 kWh/m^2/yr to < 3 kWh/m^2/yr) (Schneiders et al., 2009). With good design, comfortable conditions can be maintained ≥80 % of the time (and closer to 100 % of the time if fans are used) without mechanical cooling in relatively hot and humid regions such as Southern China (Ji et al., 2009; Zhang and Yoshino, 2010; Lin and Chuah, 2011), Vietnam (Nguyen et al., 2011), Brazil (Grigoletti et al., 2008; Andreasi et al., 2010; Cândido et al., 2011), and the tropics (Lenoir et al., 2011).

In *commercial buildings*, specific energy consumption of modern office and retail buildings are typically 200–500 kWh/m^2/yr including all end-uses, whereas advanced buildings have frequently achieved less than 100 kWh/m^2/yr in climates ranging from cold to hot and humid. The Passive House standard for heating has been achieved in a wide range of different types of commercial buildings in Europe. Sensible cooling loads (energy that must be removed from, e.g., the air inside a building) can typically be reduced by at least a factor of four compared to recent new buildings—through measures to reduce cooling loads (often by a factor of 2–4) and through more efficient systems in meeting reduced loads (often a factor of two). Dehumidification energy use is less amenable to reduction but can be met through solar-powered desiccant dehumidification with minimal non-solar energy requirements. Advanced lighting systems that include daylighting with appropriate controls and sensors, and efficient electric lighting systems (layout, ballasts, luminaires) typically achieve a factor of two reduction in energy intensity compared to typical new systems (Dubois and Blomsterberg, 2011).

9.3.3.2 Monitoring and commissioning of new and existing buildings

Commissioning is the process of systematically checking that all components of building HVAC (Heating, Ventilation and Air Conditioning) and lighting systems have been installed properly and operate correctly. It often identifies problems that, unless corrected, increase energy use by 20 % or more, but is often not done (Piette et al., 2001). Advanced building control systems are a key to obtaining very low energy intensities in commercial buildings. It routinely takes over one year or more to adjust the control systems so that they deliver the expected savings (Jacobson et al., 2011) through detailed monitoring of energy use once the building is occupied. Wagner et al. (2007) give an example where monitoring of a naturally ventilated and passively cooled bank building in Frankfurt, Germany lead to a reduction in primary energy intensity from about 200 $kWh/m^2/yr$ during the first year of operation to 150 $kWh/m^2/yr$ during the third year (with a predicted improvement to 110 $kWh/m^2/yr$ during the fourth year). Post-construction evaluation also provides opportunities for improving the design and construction of subsequent buildings (Wingfield et al., 2011).

9.3.3.3 Zero energy/carbon and energy plus buildings

Net zero energy buildings (NZEBs) refer to buildings with on-site renewable energy systems (such as PV, wind turbines, or solar thermal) that, over the year, generate as much energy as is consumed by the building. NZEBs have varying definitions around the world, but these typically refer to a net balance of on-site energy, or in terms of a net balance of primary energy associated with fuels used by the building and avoided through the net export of electricity to the power grid (Marszal et al., 2011). Space heating and service hot water has been supplied in NZEBs either through heat pumps (supplemented with electric resistance heating on rare occasions), biomass boilers, or fossil fuel-powered boilers, furnaces, or cogeneration. Musall et al. (2010) identify almost 300 net zero or almost net zero energy buildings constructed worldwide (both commercial and residential). There have also been some NZE retrofits of existing buildings. Several jurisdictions have adopted legislation requiring some portion of, or all, new buildings to be NZEBs by specific times in the future (Kapsalaki and Leal, 2011).

An extension of the NZEB concept is the Positive-Energy Building Concept (having net energy production) (Stylianou, 2011; Kolokotsa et al., 2011). Issues related to NZEBs include (1) the feasibility of NZEBs; (2) minimizing the cost of attaining an NZEB, where feasible; (3) the cost of a least-cost NZEB in comparison with the cost of supplying a building's residual energy needs (after implementing energy efficiency measures) from off-site renewable energy sources; (4) the sustainability of NZEBs; (5) lifecycle energy use; and (6) impact on energy use of alternative uses or treatments of roofs.

To create a NZEB at minimal cost requires implementing energy saving measures in the building in order of increasing cost up to the point where the next energy savings measure would cost more than the cost of on-site renewable energy systems. In approximately one-third of NZEBs worldwide, the reduction in energy use compared to local conventional buildings is about 60 % (Musall et al., 2010). Attaining net zero energy use is easiest in buildings with a large roof area (to host PV arrays) in relation to the building's energy demand, so a requirement that buildings be NZEB will place a limit on the achievable height and therefore on urban density. In Abu Dhabi, for example, NZEB is possible in office buildings of up to five stories if internal heat gains and lighting and HVAC loads are aggressively reduced (Phillips et al., 2009).

9.3.3.4 Incremental cost of low-energy buildings

A large number of published studies on the incremental costs of specific low-energy buildings are reviewed in Harvey (2013). Summary conclusions from this review, along with key studies underlying the conclusions, are given here, with Table 9.4 presenting a small selection to illustrate some of the main findings.

In the *residential sector*, several studies indicate an incremental cost of achieving the Passive House standard in the range of 6–16 % of the construction cost (about 66–265 USD_{2010}/m^2) as compared to standard construction. A variety of locations in the United States, show additional costs of houses that achieve 34–76 % reduction in energy use of about 30–163 USD_{2010}/m^2—this excludes solar PV for both savings and costs (Parker, 2009). The extra cost of meeting the 'Advanced' thermal envelope standard in the UK, which reduces heating energy use by 44 % relative to the 2006 regulations, has been estimated at 7–9 % (about 66–265 USD_{2010}/m^2) relative to a design that meets the 2006 mandatory regulations—which have since been strengthened (Davis Langdon and Element Energy, 2011).

Several cold-climate studies indicate that if no simplification of the heating system is possible as a result of reducing heating requirements, then the optimal (least lifecycle cost, excluding environmental externalities) level of heating energy savings compared to recent code-compliant buildings is about 20–50 % (Anderson et al., 2006; Hasan et al., 2008; Kerr and Kosar, 2011; Kurnitski et al., 2011). However, there are several ways in which costs can be reduced: (1) if the reference building has separate mechanical ventilation and hydronic heating, then the hydronic heating system can be eliminated or at least greatly simplified in houses meeting the Passive House standard (Feist and Schnieders, 2009); (2) perimeter heating units or heating vents can be eliminated with the use of sufficiently insulated windows, thereby reducing plumbing or ductwork costs (Harvey and Siddal, 2008); (3) the building shape can be simplified (reducing the surface area-to-volume ratio), which both reduces construction costs and makes it easier to reach any given low-energy standard (Treberspurg et al., 2010); and (4) in Passive Houses (where heating cost is negligibly small), individual metering units in multi-unit residential buildings could be eliminated (Behr, 2009). As well, it can be expected that costs will decrease with increasing experience and large-scale implementation on the part of the design and construction industries. For residential buildings in regions where cooling rather than heating is the dominant energy use, the key to low cost and emissions is to achieve designs that can maintain comfortable indoor temperatures while permitting elimination of mechanical cooling systems.

Available studies (such as in Table 9.4) indicate that the incremental cost of low-energy buildings in the *commercial sector* is less than in the residential sector, due to the greater opportunities for simplification of the HVAC system, and that it is possible for low-energy commercial buildings to cost less than conventional buildings. In particular, there are a number of examples of educational and small office buildings that have been built to the Passive House standard at no additional cost compared to similar conventional or less-stringently low-energy local buildings (Anwyl, 2011; Pearson, 2011). The Research Support Facilities Building (RSF) at the National Renewable Energy Laboratory (NREL) in Golden, Colorado achieved a 67 % reduction in energy use (excluding the solar PV offset) at zero extra cost for the efficiency measures, as the design team was contractually obliged to deliver a low-energy building at no extra cost (Torcellini et al., 2010). Torcellini and Pless (2012) present many opportunities for cost savings such that low-energy buildings can often be delivered at no extra cost. Other examples of low-energy buildings (50–60 % savings relative to standards at the time) that cost less than conventional buildings are given in McDonell (2003) and IFE (2005). New Buildings Institute (2012) reports examples of net-zero-energy buildings that cost no more than conventional buildings. Even when low-energy buildings cost more, the incremental costs are often small enough that they can be paid back in energy cost savings within a few years or less (Harvey, 2013). The keys to delivering low-energy buildings at zero or little additional cost are through implementation of the Integrated Design Process (IDP; described in Section 9.3.1) and the design-bid-build process. Vaidya et al. (2009) discuss how the traditional, linear design process leads to missed opportunities for energy savings and cost reduction, often leading to the rejection of highly attractive energy savings measures.

9.3.4 Retrofits of existing buildings

As buildings are very long-lived and a large proportion of the total building stock existing today will still exist in 2050 in developed countries, retrofitting the existing stock is key to a low-emission building sector.

9.3.4.1 Energy savings

Numerous case studies of individual retrofit projects (in which measures, savings, and costs are documented) are reviewed in Harvey (2013), but a few broad generalizations are: (1) For detached single-family homes, the most comprehensive retrofit packages have achieved reductions in total energy use by 50–75 %; (2) in multi-family housing (such as apartment blocks), a number of projects have achieved reductions in space heating requirements by 80–90 %, approaching, in many cases, the Passive House standard for new buildings; (3) relatively modest envelope upgrades to multi-family housing in developing countries such as China have achieved reductions in cooling energy use by about one-third to one-half, and reductions in heating energy use by two-thirds; (4) in commercial buildings, savings in total HVAC energy use achieved through upgrades to equipment and control systems, but without changing the building envelope, are typically on the order of 25–50 %; (5) eventual re-cladding of building façades—especially when the existing façade is largely glass with a high solar heat gain coefficient, no external shading, and no provision for passive ventilation, and cooling—offers an opportunity for yet further significant savings in HVAC energy use; and (6) lighting retrofits of commercial buildings in the early 2000s typically achieved a 30–60 % energy savings (Bertoldi and Ciugudeanu, 2005).

9.3.4.2 Incremental cost

Various isolated studies of individual buildings and systematic pilot projects involving many buildings, reviewed in Harvey (2013), indicate potentials (with comprehensive insulation and window upgrades, air sealing, and implementation of mechanical ventilation with heat recovery) reductions in heating energy requirements of 50–75 % in single-family housing and 50–90 % in multi-family housing at costs of about 100–400 USD_{2010}/m^2 above that which would be required for a routine renovation. For a small selection of these studies, see Table 9.4. In the commercial sector, significant savings can often be achieved at very low cost simply through retro-commissioning of equipment. Mills (2011) evaluated the benefits of commissioning and retro-commissioning for a sample of 643 buildings across the United States and reports a 16 % median whole-building energy savings in California, with a mean payback time of 1.1 years. Rødsjø et al. (2010) showed that among the 60 demonstration projects reviewed, the average primary energy demand savings was 76 %, and 13 of the projects reached or almost reached the Passive House standard. Although retrofits generally entail a large upfront cost, they also generate large annual cost savings, and so are often attractive from a purely economic point of view. Korytarova and Ürge-Vorsatz (2012) note that shallow retrofits can result in greater lifecycle costs than deep retrofits. Mata et al. (2010) studied 23 retrofit measures for buildings in Sweden and report a simple technical potential for energy savings in the residential sector of 68 % of annual energy use. They estimated a cost per kWh saved between −0.09 USD_{2010}/kWh (appliance upgrades) and +0.45 USD_{2010}/kWh (façade retrofit). Polly et al. (2011) present a method for determining optimal residential energy efficiency retrofit packages in the United States, and identify near-cost-neutral packages of measures providing between 29 % and 48 % energy savings across eight US locations. Lewis (2004) has compiled information from several studies in old buildings in Europe and indicates that the total and marginal cost of conserved energy both tend to be relatively uniform for savings of up to 70–80 %, but increase markedly for savings of greater than 80 % or for final heating energy intensities of less than about 40 $kWh/m^2/yr$.

9.3.5 Appliances, consumer electronics, office equipment, and lighting

Residential appliances have dramatically improved in efficiency over time, particularly in OECD countries (Barthel and Götz, 2013; Labanca and Paolo, 2013) due to polices such as efficiency standards, labels, and subsides and technological progress. Improvements are also appearing in developing countries such as China (Barthel and Götz, 2013) and less developed countries, such as Ghana (Antwi-Agyei, 2013). Old

Table 9.4 | Summary of estimates for extra investment cost required for selected very low-/zero-energy buildings.

Case	Location	Type	Energy performance	Extra investment costs	CCE (USD_{2010}/kWh)	References
Passive House Projects	Central Europe	New	Passive House standard	5–8 % (143–225 USD_{2010}/m^2)	–	(Bretzke, 2005; Schnieders and Hermelink, 2006)
5 Passive Houses	Belgium	New	62 $kWh/m^2/yr$ total	16 % (252 USD_{2010}/m^2)	–	(Audenaert et al., 2008)
Passive House apartment block	Vienna	New	Passive House standard	5 % (69 USD_{2010}/m^2)	–	(Mahdavi and Doppelbauer, 2010)
12 very low or net zero-energy houses	United States	New		0.07–0.12 USD_{2010}/kWh (CCE)	–	(Parker, 2009)
10 buildings in the SolarBauprogramme	Germany	New	< 100 $kWh/m^2/yr$ primary energy vs. 300–600—conventional	Comparable to the difference in costs between alternative standards for interior finishes	–	(Wagner et al., 2004)
High performance commercial buildings	Vancouver	New	100 $kWh/m^2/yr$ total vs. 180—conventional	10 % lower cost	–	(McDonell, 2003)
Offices and laboratory, Concordia University	Montreal	New		2.30 %	–	(Lemire and Charneux, 2005)
Welsh Information and Technology Adult Learning Centre (CaolfanHyddgen)	Wales	New	Passive House standard	No extra cost compared to BREEAM 'Excellent' standard	–	(Pearson, 2011)
Hypothetical 6,000 m^2 office building	Las Vegas	New	42 % of energy savings	USD_{2010} 2,719	–	(Vaidya et al., 2009)
10-story, 7,000 m^2 residential building	Denmark	New	14 $kWh/m^2/yr$ (heating) vs. 45	3.4 % (115 USD_{2010}/ m^2)	–	(Marszal and Heiselberg, 2009)
Leslie Shao-Ming Sun Field Station, Stanford University	California	New	NZEB	4–10 % more based on hard construction costs	–	(NBI, 2011)
Hudson Valley Clean Energy Headquarters	New York	New	NZEB	665 USD_{2010}/month in mortgage payments but saves 823 USD_{2010}/month in energy costs	–	(NBI, 2011)
IAMU Office	Ankeny, IA	New	NZEB	None	–	(NBI, 2011)
EcoFlats Building	Portland, OR	New	NZEB	None	–	(NBI, 2011)
10-story, 7,000 m^2 residential building	Denmark	New	NZEB	24 % (558 USD_{2010}/m^2)	–	(Marszal and Heiselberg, 2009)
Toronto towers	Toronto	Retrofit	194/95 %	259 USD_{2010}/m^2	0.052	(Kesik and Saleff, 2009)
Multi-family housing	EU	Retrofit	62–150/52 %–86 %	53–124 USD_{2010}/m^2	0.014–0.023	(Petersdorff et al., 2005)
Terrace housing	EU	Retrofit	97–266/59 %–84 %	90–207 USD_{2010}/m^2	0.13–0.023	(Petersdorff et al., 2005)
High-rise housing	EU	Retrofit	70 %–81 %	2.5–5.8 $USD_{2010}/m^2/yr$	0.018–0.028	(Waide et al., 2006)
1950s MFH	Germany	Retrofit	82–247/30 %–90 %	48–416 USD_{2010}/m^2	0.023–0.065	(Galvin, 2010)
1925 SFH	Denmark	Retrofit	120	217 USD_{2010}/m^2	0.071	(Kragh and Rose, 2011)
1929 MFH	Germany	Retrofit	140–200/58 %–82 %	167–340 USD_{2010}/m^2	0.060–0.088	(Hermelink, 2009)
19th century flat	UK	Retrofit	192–234/48 %–59 %	305–762 USD_{2010}/m^2	0.068–0.140	(United House, 2009)

appliances consume 650 TWh worldwide, which is almost 14 % of total residential electricity consumption (Barthel and Götz, 2013).

Table 9.5 summarizes potential reductions in unit energy by household appliances and equipment through improved technologies. The saving potentials identified for individual equipment are typically 40–50 %. Indeed, energy use by the most efficient appliances available today is often 30–50 % less than required by standards; the European A+++ model refrigerator, for example, consumes 50 % less electricity than the current regulated level in the EU (Letschert et al., 2013a), while the most efficient televisions awarded under the Super-efficient Equipment and Appliance Deployment (SEAD) initiative use 33–44 % less electricity than similar televisions (Ravi et al., 2013). Aggregate energy consumption by these items is expected to continue to grow rapidly as the types and number of equipment proliferate, and ownership rates increase with wealth. This will occur unless standards are used to induce close to the maximum technically achievable reduction in unit energy requirements. Despite projected large increase in the stock of domestic appliances, especially in developing countries, total appliance energy consumption could be reduced if the best available technology were installed (Barthel and Götz, 2013; Letschert et al., 2013b). This could yield energy savings of

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Table 9.5 | Potential savings in energy consumption by household appliances and equipment.

Item	Savings potential	Reference
Televisions	Average energy use of units sold in the United States (largely LCDs) was426 kWh/yr in 2008 and 102 kWh/yr in 2012. Further reductions (30–50 % below LCD TVs) are expected with use of organic LED backlighting (likely commercially available by 2015).	(Howard et al., 2012; Letschert et al., 2012)
Televisions	Energy savings of best available TVs compared to market norms are 32–45 % in Europe, 44–58 % in North America, and 55–60 % in Australia	(Park, 2013)
Computer monitors	70 % reduction in on-mode power draw expected from 2011 to 2015	(Park et al., 2013)
Computing	At least a factor of 10 million potential reduction in the energy required per computation (going well beyond the so-called Feynman limit).	(Koomey et al., 2013)
Refrigerator-freezer units	40 % minimum potential savings compared to the best standards, 27 % savings at ≤0.11 USD_{2010}/kWh CCE (Costs of Conserved Energy)	(Bansal et al., 2011; McNeil and Bojda, 2012)
Cooking	50 % savings potential (in Europe), largely through more efficient cooking practices alone	(Fechter and Porter, 1979; Oberascher et al., 2011)
Ovens	25 % and 45 % potential savings through advanced technology in natural gas and conventional electric ovens, respectively, and 75 % for microwave ovens	(Mugdal, 2011; Bansal et al., 2011)
Dishwashers	Typically only 40–45 % loaded, increasing energy use per place setting by 77–97 % for 3 dishwashers studied	(Richter, 2011)
Dishwashers	Current initiative targets 17 % less electricity, 35 % less water than best US standard	(Bansal et al., 2011)
Clothes washers	Global 28 % potential savings by 2030 relative to business-as-usual	(Letschert et al., 2012)
Clothes Dryers	Factor of two difference between best and average units on the market in Europe (0.27 kWh/kg vs 0.59 kWh/kg). More than a factor of 2 reduction in going from United States average to European heat pump dryer (820 kWh/yr vs 380 kWh/yr)	(Werle et al., 2011)
Standby loads	Potential of < 0.005 W for adapters and chargers, < 0.05 for large appliances ('zero' in both cases) (typical mid 2000s standby power draw: 5–15 W)	(Harvey, 2010; Matthews, 2011), (Harvey, 2010) for mid 2000s data
Air conditioners	COP (a measure of efficiency) of 2.5–3.5 in Europe and United States, 5.0–6.5 in Japan (implies up to 50 % energy savings)	(Waide et al., 2011)
Air conditioners	COP of 4.2–6.8 for air conditioners such that the cost of saving electricity does not exceed the local cost of electricity, and a potential COP of 7.3–10.2 if all available energy-saving measures were to be implemented (implies a 50–75 % savings for a given cooling load and operating pattern).	(Shah et al., 2013)
Ceiling fans	50–57 % energy savings potential	(Letschert et al., 2012; Sathaye et al., 2013)
Package of household appliances in Portugal	60 % less energy consumption by best available equipment compared to typically-used equipment	(da Graca et al., 2012)
Office computers and monitors	40 % savings from existing low-to-zero cost measures only	(Mercier and Morrefield, 2009)
Circulation pumps for hydronic heating and cooling	40 % savings from projected energy use in 2020 in Europe (relative to a baseline with efficiencies as of 2004) due to legislated standards already in place	(Bidstrup, 2011)
Residential lighting	Efficacies (lm/W) (higher is better): standard incandescent, 15; CFL, 60; best currently available white-light LEDs, 100; current laboratory LEDs, 250	(Letschert et al., 2012)
Residential water-using fixtures	50–80 % reduction in water use by water-saving fixtures compared to older standard fixtures	(Harvey, 2010)
Residential water heaters	Typical efficiency factor (EF) for gas and electric water heaters in the USA is 0.67 and 0.8 in EU, while the most efficient heat-pump water heaters have EF=2.35 and an EF of 3.0 is foreseeable (factor of 4 improvement)	(Letschert et al., 2012)

2600 TWh/yr by 2030 between the EU, United States, China and India (Letschert et al., 2013a). Ultra-low-power micro-computers in a wide variety of appliances and electronic equipment also have the potential to greatly reduce energy use through better control (Koomey et al., 2013). Conversely, new types of electronic equipment for ICT (e.g., satellite receivers, broadband home gateways, etc.), broadband and network equipment, and dedicated data centre buildings are predicted to increase their energy consumption (Fettweis and Zimmermann, 2008; Bolla et al., 2011; Bertoldi, 2012). Solid State Lighting (SSL) is revolutionizing the field of lighting. In the long term, inorganic light emitting diodes (LEDs) are expected to become the most widely used light sources. White LEDs have shown a steady growth in efficacy for more than fifteen years, with average values of 65–70 lm/W (Schäppi and Bogner, 2013) and the best products achieving 100 lm/W (Moura et al., 2013). LED lighting will soon reach efficacy levels above all the other commercially available light source (Aman et al., 2013), including high efficiency fluorescent lamps.

9.3.6 Halocarbons

The emissions of F-gases (see Chapter 1 Table 1.1 and Chapter 5.3.1) related to the building sector primarily originate from cooling/refrigeration and insulation with foams. The sector's share of total F-gas emissions is subject to high variation due to uncertainties, lack of detailed reporting and differences in accounting conventions. The following section discusses the role of the buildings sector in F-gas emissions under these constraints.

F-gases are used in buildings through several types of products and appliances, including refrigeration, air conditioning, in foams (such as for insulation) as blowing agents, fire extinguishers, and aerosols. The resulting share of the building sector in the total F-gas emissions, similarly to indirect CO_2 emissions from electricity generation, depends on their attribution. Inventories, such as EDGAR (JRC/PBL, 2013), are related to the production and sales of these gases and differing accounting conventions attribute emissions based on the point of their use, emissions, or production (UNEP, 2011a; EEA, 2013; US EPA, 2013). IPCC emission categories provide numbers to different sources of emission but do not systematically attribute these to sectors. Attribution can be done using a production or consumption perspective, rendering different sectoral shares (see Chapter 5.2.3.3). Compounding this variation, there are uncertainties resulting from the lack of attribution of the use of certain emission categories to different sectors they are used in and uncertainties in reported figures for the same emissions by different sources.

As a guidance on the share of F-gases in the building sector, for example, EDGAR (JRC/PBL, 2013; Annex II.9) attributed 12 % of direct F-gas emissions to the building sector in 2010 (JRC/PBL, 2013; Annex II.9). Of a further share of 22.3 % of F-gas emissions (21 % from HFC and SF6 production and 1.3 % from foam blowing) a substantial part can be allocated to the buildings sector. The greatest uncertainty of attribution of IPCC categories to the buildings sector is the share of Refrigeration and Air Conditioning Equipment (2F1a). This totals to up to one-third for the share of (direct plus indirect) buildings in F-gas emissions.

As another proxy, EDGAR estimates that HFCs represent the largest share (GWP adjusted) in the total F-gas emissions, at about 76 % of total 2010 F-gas emissions (JRC/PBL, 2013). Global HFC emissions are reported to be 760 $MtCO_2eq$ by EDGAR (JRC/PBL, 2013); and 1100 $MtCO_2eq$ by the US EPA (2010). These gases are used mostly (55 % of total in 2010) in refrigeration and air-conditioning equipment in homes, other buildings and industrial operations (UNEP, 2011a).

While F-gases represent a small fraction of the current total GHG emissions—around 2 % (see Chapter 1.2 and Chapter 5.2), their emissions are projected to grow in the coming decades, mostly due to increased demand for cooling and because they are the primary substitutes for ozone-depleting substances (US EPA, 2013).

Measures to reduce these emissions include the phase-out of HFCs and minimization of the need for mechanical cooling through high-performance buildings, as discussed in the following sections. The use of F-gases as an expanding agent in polyurethane foam has been banned in the EU since 2008, and by 2005, 85 % of production had already been shifted to hydrocarbons (having a much lower GWP). In Germany, almost all new refrigerators use natural refrigerants (isobutane, HC-600a, and propane, HC-29), which have great potential to reduce emissions during the operation and servicing of HFC-containing equipment (McCulloch, 2009; Rhiemeier and Harnisch, 2009). Their use in insulation materials saves heating and cooling related CO_2 emissions and thus their use in these materials still typically has a net benefit to GHG emissions, but a lifecycle assessment is required to determine the net effect on a case-by-case basis.

9.3.7 Avoiding mechanical heating, cooling, and ventilation systems

In many parts of the world, high-performance mechanical cooling systems are not affordable, especially those used for residential housing. The goal, then is to use principles of low-energy design to provide comfortable conditions as much of the time as possible, thereby reducing the pressure to later install energy-intensive cooling equipment such as air conditioners. These principles are embedded in vernacular designs throughout the world, which evolved over centuries in the absence of mechanical heating and cooling systems. For example, vernacular housing in Vietnam (Nguyen et al., 2011) experienced conditions warmer than 31 °C only 6 % of the time. The natural and passive control system of traditional housing in Kerala, India has been shown to maintain bedroom temperatures of 23–29 °C even as outdoor temperatures vary from 17–36 °C on a diurnal time scale (Dili et al., 2010). While these examples show that vernacular architecture can be an energy efficient option, in order to promote the technology, it is necessary to consider the cultural and convenience factors and perceptions concerning 'modern' approaches, as well as the environmental performance, that influence the decision to adopt or abandon vernacular approaches (Foruzanmehr and Vellinga, 2011). In some cases, modern knowledge and techniques can be used to improve vernacular designs.

9.3.8 Uses of biomass

Biomass is the single largest source of energy for buildings at the global scale, and it plays an important role for space heating, production of hot water, and for cooking in many developing countries (IEA, 2012d). Compared to open fires, advanced biomass stoves provide fuel savings of 30–60 % and reduce indoor air pollution levels by 80–90 % for models with chimneys (Ürge-Vorsatz et al., 2012b). For example, in the state of Arunachal Pradesh, advanced cookstoves with an efficiency of 60 %, has been used in place of traditional cookstoves with an efficiency of 6–8 % (Rawat et al., 2010). Gasifier and biogas cookstoves have also undergone major developments since AR4.

9.3.9 Embodied energy and building materials lifecycle

Research published since AR4 confirms that the total lifecycle energy use of low-energy buildings is less than that of conventional buildings, in spite of generally greater embodied energy in the materials and energy efficiency features (Citherlet and Defaux, 2007; GEA, 2012). However, the embodied energy and carbon in construction materials is especially important in regions with high construction rates, and the availability of affordable low-carbon, low-energy materials that can be part of high-performance buildings determines construction-related emissions substantially in rapidly developing countries (Sartori and Hestnes, 2007; Karlsson and Moshfegh, 2007; Ramesh et al., 2010). A review of lifecycle assessment, lifecycle energy analysis, and material flow analysis in buildings (conventional and traditional) can be found in Cabeza et al. (2013a). Recent research indicates that wood-based wall systems entail 10–20 % less embodied energy than traditional concrete systems (Upton et al., 2008; Sathre and Gustavsson, 2009) and that concrete-framed buildings entail less embodied energy than steel-framed buildings (Xing et al., 2008). Insulation materials entail a wide range of embodied energy per unit volume, and the time required to pay back the energy cost of successive increments insulation through heating energy savings increases as more insulation is added. However, this marginal payback time is less than the expected lifespan of insulation (50 years) even as the insulation level is increased to that required to meet the Passive House standard (Harvey, 2007). The embodied energy of biomass-based insulation products is not lower than that of many non-biomass insulation products when the energy value of the biomass feedstock is accounted for, but is less if an energy credit can be given for incineration with cogeneration of electricity and heat, assuming the insulation is extracted during demolition of the building at the end of its life (Ardente et al., 2008).

9.3.10 Behavioural and lifestyle impacts

Chapter 2 discusses behavioural issues in a broad sense. There are substantial differences in building energy use in the world driven largely by behaviour and culture. Factors of 3 to 10 differences can be found worldwide in residential energy use for similar dwellings with same occupancy and comfort levels (Zhang et al., 2010), and up to 10 times difference in office buildings with same climate and same building functions with similar comfort and health levels (Batty et al., 1991; Zhaojian and Qingpeng, 2007; Zhang et al., 2010; Grinshpon, 2011; Xiao, 2011). The major characteristics of the lower energy use buildings are windows that can be opened for natural ventilation, part time & part space control of indoor environment (thermal and lighting), and variably controllable indoor thermal parameters (temperature, humidity, illumination and fresh air). These are traditional approaches to obtain a suitable indoor climate and thermal comfort. However, since the spread of globalized supply of commercial thermal conditioning, heating/cooling solutions tend towards fully controlled indoor climates through mechanical systems and these typically result in a significantly increased energy demand (TUBESRC, 2009). An alternative development pathway to the ubiquitous use of fully conditioned spaces by automatically operated mechanical systems is to integrate key elements of the traditional lifestyles in buildings, in particular through the use of 'part-time' and 'part-space' indoor climate conditioning, using mechanical systems only for the remaining needs when passive approaches cannot meet comfort demands. Such pathways can reach the energy use levels below 30 $kWh_e/m^2/yr$ as a world average (TUBESRC, 2009; Murakami et al., 2009), as opposed to the 30–50 $kWh_e/m^2/yr$ achievable through building development pathways utilizing fully automatized full thermal conditioning (Murakami et al., 2009; Yoshino et al., 2011).

Behaviour and local cultural factors can drive basic energy use practices, such as how people and organizations adjust their thermostats during different times of the year. During the cooling season, increasing the thermostat setting from 24 °C to 28 °C will reduce annual cooling energy use by more than a factor of three for a typical office building in Zurich and by more than a factor of two in Rome (Jaboyedoff et al., 2004), and by a factor of two to three if the thermostat setting is increased from 23 °C to 27 °C for night-time air conditioning of bedrooms in apartments in Hong Kong (Lin and Deng, 2004). Thermostat settings are also influenced by dress codes and cultural expectations towards attires, and thus major energy savings can be achieved through changes in attire standards, for example Japan's 'Cool Biz' initiative to relax certain business dress codes to allow higher thermostat settings (GEA, 2011).

Behaviour and lifestyle are crucial drivers of building energy use in more complex ways, too. Figure 9.9 shows the electricity use for summer cooling in apartments of the same building (occupied by households of similar affluence and size) in Beijing (Zhaojian and Qingpeng, 2007), ranging from 0.5 to 14.2 $kWh/m^2/yr$. The use difference is

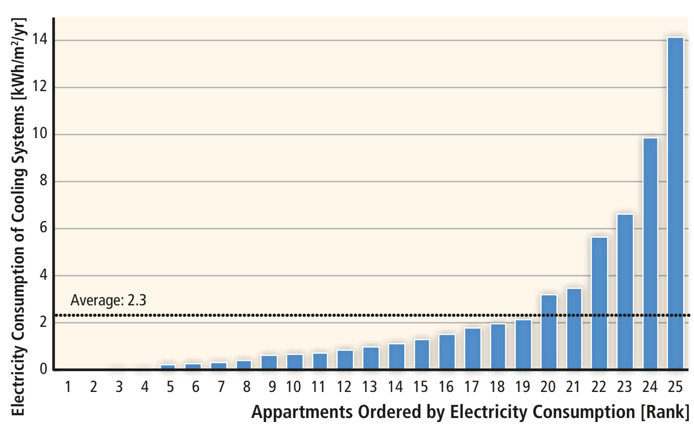

Figure 9.9 | Annual measured electricity per unit of floor space for cooling in an apartment block in Beijing (Zhang et al., 2010).

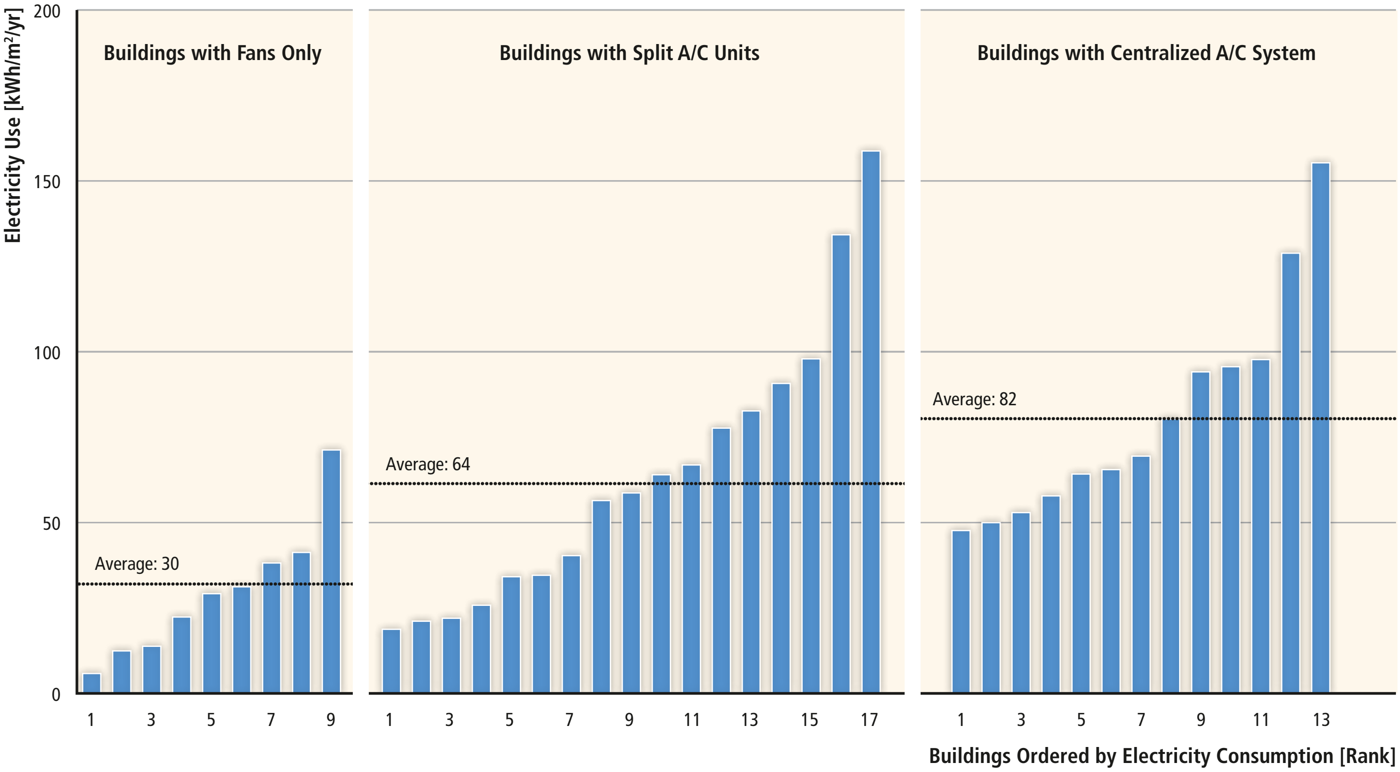

Figure 9.10 | Annual total electricity use per unit of floor space of buildings on a university campus in Beijing, China, 2006 (Zhang et al., 2010).

mainly caused by different operating hours of the split air-conditioner units. Opening windows during summer and relying on natural ventilation can reduce the cooling load while maintaining indoor air quality in most warm climate countries (Batty et al., 1991), compared to solely relying on mechanical ventilation (Yoshino et al., 2011). Buildings with high-performance centralized air-conditioning can use much more energy than decentralized split units that operate part time and for partial space cooling, with a factor of 9 found by (Zhaojian and Qingpeng, 2007; Murakami et al., 2009), as also illustrated in Figure 9.10. There are similar findings for other energy end-uses, such as clothes dryers (the dominant practice in laundering in the United States) consuming about 600–1000 kWh/yr, while drying naturally is dominant in developing and even in many developed countries (Grinshpon, 2011).

Quantitative modelling of the impact of future lifestyle change on energy demand shows that, in developed countries where energy service levels are already high, lifestyle change can produce substantial energy use reductions. In the United States, for example, the short term behavioural change potential is estimated to be at least 20 % (Dietz et al., 2009) and over long periods of time, much more substantial reductions (typically 50 %) are possible, even in developed countries with relatively low consumption (Fujino et al., 2008; Eyre et al., 2010). Similar absolute reductions are not possible in developing countries where energy services demands need to grow to satisfy development needs. However, the rate of growth can be reduced by lower consumption lifestyles (Wei et al., 2007; Sukla et al., 2008). For more on consumption, see also Section 4.4.

Energy use of buildings of similar functions and occupancies can vary by a factor of 2–10, depending on culture and behaviour. For instance, Figure 9.10 and Figure 9.11 show the electricity usage of the HVAC system at two university campuses (in Philadelphia and Beijing) with similar climates and functions. The differences arise from: operating hours of lighting and ventilation (24h/day vs. 12h/day); full mechanical ventilation in all seasons versus natural ventilation for most of the year; and district cooling with selective re-heating versus seasonal decentralized air-conditioning. When the diversity of users' activities is taken into account, different technologies may be needed to satisfy the energy service demand. Therefore, buildings and their energy infrastructure need to be designed, built, and used taking into account culture, norms, and occupant behaviour. One universal standard of 'high efficiency' based on certain cultural activities may increase the energy usage in buildings with other cultural backgrounds, raising costs and emissions without improving the living standards. This is demonstrated in a recent case study of 10 'low-energy demonstration buildings' in China built in international collaborations. Most of these demonstration buildings use more energy in operation than ordinary buildings with the same functions and service levels (Xiao, 2011). Although several energy saving technologies have been applied, occupant behaviours were also restricted by, for instance, using techniques only suitable for full-time and full-space cooling.

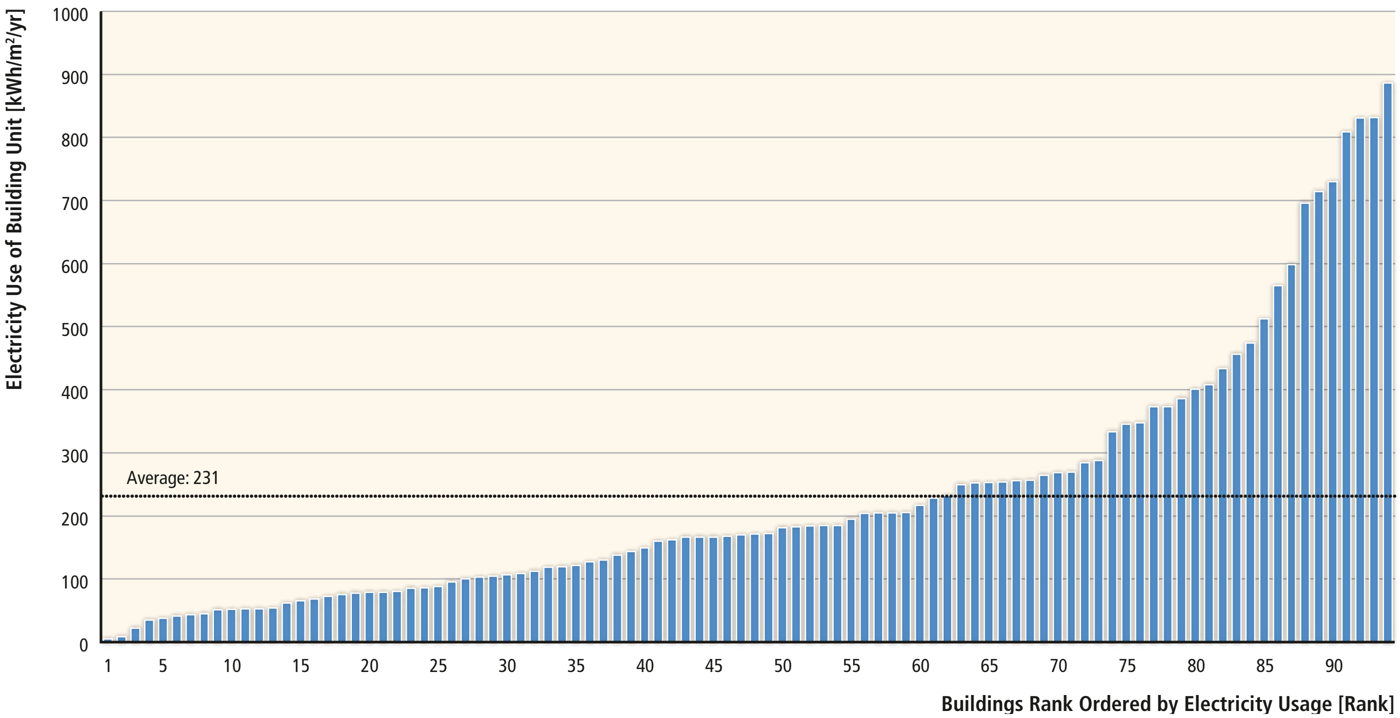

Figure 9.11 | Annual unit area electricity use per unit of floor space of buildings on a university campus in Philadelphia, USA, 2006 (Zhang et al., 2010).

9.4 Infrastructure and systemic perspectives

9.4.1 Urban form and energy supply infrastructure

Land use planning influences greenhouse gas emissions in several ways, including through the energy consumption of buildings. More compact *urban form* tends to reduce consumption due to lower per capita floor areas, reduced building surface to volume ratio, increased shading, and more opportunities for district heating and cooling systems (Ürge-Vorsatz et al., 2012a). Greater compactness often has tradeoffs in regions with significant cooling demand, as it tends to increase the urban heat island effect. However, the overall impact of increased compactness is to reduce GHG emissions. Broader issues of the implications of urban form and land use planning for emissions are discussed in Chapter 12.5. Energy-using activities in buildings and their energy supply networks co-evolve. While the structure of the building itself is key to the amount of energy consumed, the *energy supply networks* largely determine the energy vector used, and therefore the carbon intensity of supply. Changing fuels and energy supply infrastructure to buildings will be needed to deliver large emissions reductions even with the major demand reductions outlined in Section 9.3. This section therefore focuses on the interaction of buildings with the energy infrastructure, and its implications for use of lower carbon fuels.

9.4.1.1 District heating and cooling networks

Heating and cooling networks facilitate mitigation where they allow the use of higher efficiency systems or the use of waste heat or lower carbon fuels (e.g., solar heat and biomass) than can be used cost effectively at the scale of the individual building. High efficiency distributed energy systems, such as gas engines and solid oxide fuel cell cogeneration, generate heat and electricity more efficiently than the combination of centralized power plants and heating boilers, where heat can be used effectively. District energy systems differ between climate zones. Large-scale district heating systems of cold-climate cities predominantly provide space heating and domestic hot water. There are also some examples that utilize non-fossil heat sources, for example biomass and waste incineration (Holmgren, 2006). Despite their energy saving benefits, fossil fuel district heating systems cannot alone deliver very low carbon buildings. In very low energy buildings, hot water is the predominant heating load, and the high capital and maintenance costs of district heating infrastructure may be uneconomic (Thyholt and Hestnes, 2008; Persson and Werner, 2011). The literature is therefore presently divided on the usefulness of district heating to serve very low energy buildings. In regions with cold winters and hot summers, district energy systems can deliver both heating and cooling, usually at the city block scale, and primarily to commercial buildings. Energy savings of 30 % can be achieved using trigeneration, load levelling, diurnal thermal storage, highly-efficient refrigeration, and advanced management (Nagota et al., 2008). Larger benefits are possible by using waste heat from incineration plants (Shimoda et al., 1998) and heat or cold from water source heat pumps (Song et al., 2007).

9.4.1.2 Electricity infrastructure interactions

Universal access to electricity remains a key development goal in developing countries. The capacity, and therefore cost, of electricity infrastructure needed to supply any given level of electricity services depends on the efficiency of electricity use. Electricity is the dominant energy source for cooling and appliances, but energy use for heating is dominated by direct use of fossil fuels in most countries. Electrification of heating can therefore be a mitigation measure, depending on the levels of electricity decarbonization and its end use efficiency. Heat pumps may facilitate this benefit as they allow electrification to be a mitigation technology at much lower levels of electricity decarbonization (Lowe, 2007). Ground-source heat pumps already have a high market share in some countries with low-cost electricity and relatively efficient buildings (IEA HPG, 2010). There is a growing market for low-cost air source heat pumps in mid-latitude countries (Cai et al., 2009; Howden-Chapman et al., 2009; Singh et al., 2010a). In many cases the attractions are that there are not pre-existing whole-house heating systems and that air-source heat pumps can provide both heating and cooling. A review of scenario studies indicates heating electrification may have a key role in decarbonization (Sugiyama, 2012), with heat pumps usually assumed to be the preferred heating technology (IEA, 2010a). This would imply a major technology shift from direct combustion of fossil fuels for building heating. Electricity use, even at high efficiency, will increase winter peak demand (Cockroft and Kelly, 2006) with implications for generation and distribution capacity that have not been fully assessed; there are challenges in retrofitting to buildings not designed for heating with low temperature systems (Fawcett, 2011), and the economics of a high capital cost heating system, such as a heat pump, in a low-energy building are problematic. The literature is inconclusive on the role and scale of electrification of heating as a mitigation option, although it is likely to be location-dependent. However, significant energy demand reduction is likely to be critical to facilitate universal electrification (Eyre, 2011), and therefore transition pathways with limited efficiency improvement and high electrification are implausible. Electricity infrastructure in buildings will increasingly need to use information technology in 'smart grids' to provide consumer information and enable demand response to assist load balancing (see Chapter 7.12.3).

9.4.1.3 Thermal energy storage

Thermal energy storage can use diurnal temperature variations to improve load factors, and therefore reduce heating and cooling system size, which will be particularly important if heating is electrified. Thermal storage technologies could also be important in regions with electricity systems using high levels of intermittent renewable energy. The use of storage in a building can smooth temperature fluctuations and can be implemented by sensible heat (e.g., changing the building envelope temperature), or by storing latent heat using ice or phase change materials, in either passive or active systems (Cabeza et al., 2011). Both thermochemical energy storage (Freire González, 2010) and underground thermal energy storage (UTES) with ground source heat pumps (GSHP) (Sanner et al., 2003) are being studied for seasonal energy storage in buildings or district heating and cooling networks, although UTES and GSHP are already used for short term storage (Paksoy et al., 2009).

9.4.2 Path dependencies and lock-in

Buildings and their energy supply infrastructure are some of the longest-lived components of the economy. Buildings constructed and retrofitted in the next few years to decades will determine emissions for many decades, without major opportunities for further change. Therefore the sector is particularly prone to lock-in, due to favouring incremental change (Bergman et al., 2008), traditionally low levels of innovation (Rohracher, 2001), and high inertia (Brown and Vergragt, 2008).

When a major retrofit or new construction takes place, state-of-the-art performance levels discussed in Section 9.3 are required to avoid locking in sub-optimal outcomes. Sunk costs of district heating, in particular, can be a disincentive to investments in very low energy buildings. Without the highest achievable performance levels, global building energy use will rise (Ürge-Vorsatz et al., 2012a). This implies that a major reduction in building energy use will not take place without strong policy efforts, and particularly the use of building codes that require adoption of the ambitious performance levels set out in Section 9.3 as soon as possible. Recent research (Ürge-Vorsatz et al., 2012a) finds that by 2050 the size of the lock-in risk is equal to almost 80 % of 2005 global building heating and cooling final energy use (see Figure 9.12). This is the gap between a scenario in which today's best cost-effective practices in new construction and retrofits become standard after a transitional period, and a scenario in which levels of building energy performance are changed only to today's best policy ambitions. This alerts us that while there are good developments in building energy efficiency policies, significantly more advances can and need to be made if ambitious climate goals are to be reached, otherwise significant emissions can be 'locked in' that will not be possible to mitigate for decades. The size of the lock-in risk varies significantly by region: e.g., in South-East Asia (including India) the lock-in risk is over 200 % of 2005 final heating and cooling energy use.

9.5 Climate change feedback and interaction with adaptation

Buildings are sensitive to climate change, which influences energy demand and its profile. As climate warms, cooling demand increases and heating demand decreases (Day et al., 2009; Isaac and Van Vuuren, 2009; Hunt and Watkiss, 2011), while passive cooling approaches become less effective (Artmann et al., 2008; Chow and Levermore, 2010). Under a +3.7 °C scenario by 2100, the worldwide reduction in heating energy

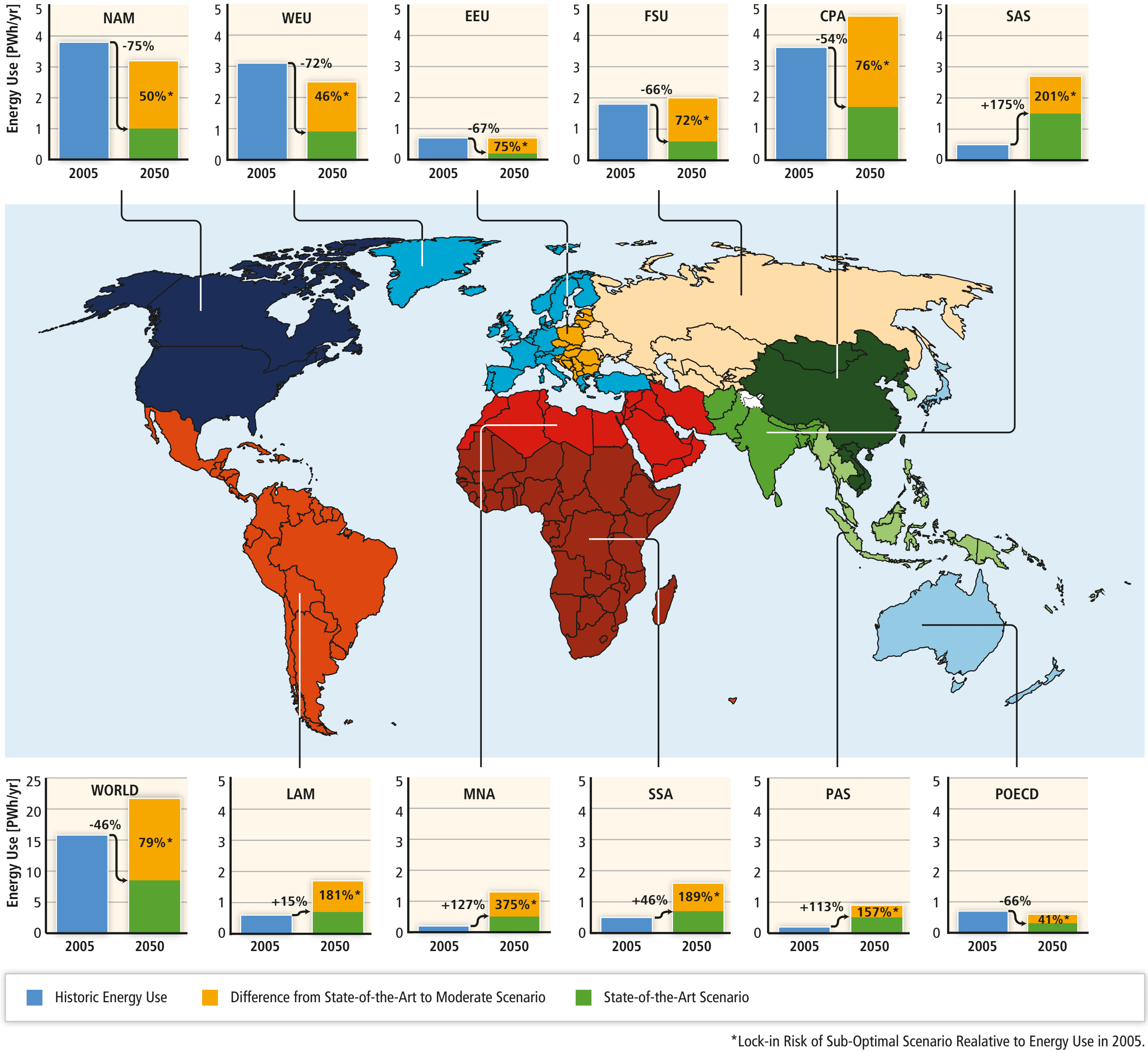

Figure 9.12 | Final building heating and cooling energy use in 2005 and in scenarios from the Global Energy Assessment (GEA) for 2050, organized by eleven regions (Ürge-Vorsatz et al., 2012a). Notes: Green bars, indicated by arrows with numbers (relative to 2005 values), represent the opportunities through the GEA state-of-the-art scenario, while the yellow bars with black numbers show the size of the lock-in risk (difference between the sub-optimal and state-of-the-art scenario). Percent figures are relative to 2005 values. For region definitions see Annex II.2.4.

demand due to climate change may reach 34 % in 2100, while cooling demand may increase by ≥ 70 %; net energy demand could reach – 6 % by 2050 and + 5 % by 2100; with significant regional differences, e. g., ≥ 20 % absolute reductions in heating demand in temperate Canada and Russia; cooling increasing by ≥ 50 % in warmer regions and even higher increases in cold regions (Isaac and Van Vuuren, 2009). Other regional and national studies (Mansur et al., 2008; van Ruijven et al., 2011; Wan et al., 2011; Xu et al., 2012a) reveal the same general tendencies, with energy consumption in buildings shifting from fossil fuels to electricity and affecting peak loads (Isaac and Van Vuuren, 2009; Hunt and Watkiss, 2011), especially in warmer regions (Aebischer et al., 2007). Emissions implications of this shift are related to the fuels and technologies locally used for heat and power generation: a global reference scenario from Isaac and Van Vuuren (2009) shows a net increase in residential emissions of ≥ 0.3 Gt C (≥ 1.1 Gt CO_2eq) by 2100.

There is a wide-range of sensitivities but also many opportunities to respond to changing climatic conditions in buildings: modified design goals and engineering specifications increase resilience (Gerdes et al. 2011; Pyke et al., 2012). There is no consensus on definitions of climate adaptive buildings, but several aims include minimizing energy consumption for operation, mitigating GHG emissions, providing adaptive capacity and resilience to the building stock, reducing costs for maintaining comfort, minimizing the vulnerability of occupants to extreme weather conditions, and reducing risks of disruption to energy supply and addressing fuel poverty (Roaf et al., 2009; Atkinson et al., 2009). Adaptation and mitigation effects may be different by development and urbanization level, climate conditions and building infrastructure. Contemporary strategies for adapting buildings to climate change still often emphasize increasing the physical resilience of building structure and fabric to extreme weather and climatic events, but this can lead to decreased functional adaptability and increased embodied energy and associated GHG emissions. Increased extremes in local weather-patterns can lead to sub-optimal performance of buildings that were designed to provide thermal comfort 'passively' using principles of bioclimatic design. In such circumstances, increased uncertainty over future weather patterns may encourage demand for mechanical space heating and/or cooling regardless of the climate-zone.

There are also several opportunities for heat island reduction, air quality improvement, and *radiation management* (geo-engineering) through building roofs and pavements, which constitute over 60 % of most urban surfaces and with co-benefits such as improved air quality (Ihara et al., 2008; Taha, 2008). Simulations estimate reductions in urban temperatures by up to 0.7 K (Campra et al., 2008; Akbari et al., 2009; Oleson et al., 2010; Millstein and Menon, 2011). Akbari et al., (2009, 2012) estimated that changing the solar reflectance of a dark roof (0.15) to an aged white roof (0.55) results in a *one-time* offset of 1 to 2.5 tCO_2 per 10 m^2 of roof area through enhanced reflection. Global CO_2 one-time offset potentials from cool roofs and pavements amount to 78 $GtCO_2$ (Menon et al., 2010). Increasing the albedo of a 1 m^2 area by 0.01 results in a global temperature reduction of 3×10^{-15} K and offsets emission of 7 kg CO_2 (Akbari et al., 2012).

9.6 Costs and potentials

9.6.1 Summary of literature on aggregated mitigation potentials by key identity

The chapter's earlier sections have demonstrated that there is a broad portfolio of different technologies and practices available to cut building-related emissions significantly. However, whereas these potentials are large at an individual product/building level, an important question is to determine what portion of the stock they apply to, and what the overall potential is if we consider the applicability, feasibility, and replacement dynamics, together with other constraints (Wada et al.,

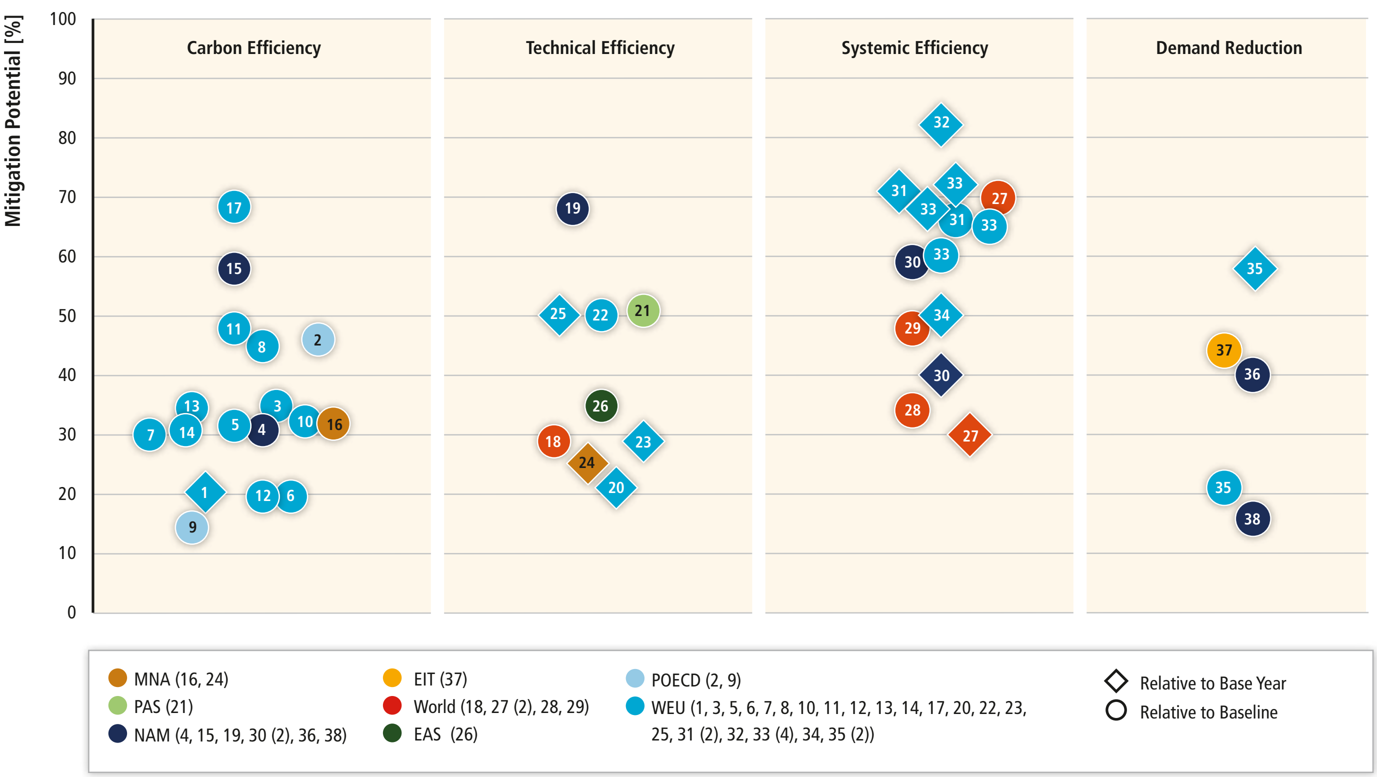

Figure 9.13 | Regional studies on aggregated mitigation potentials grouped by key identity (i.e., main mitigation strategy). Note: Values correspond to the percentage reduction as compared to baseline (circle), if available, otherwise to base year (diamond), studies are numbered, for details see Table 9.6, note that for some studies there are multiple entries (indicated by number in extra bracket). For RC10 region definitions see Annex II.2.1.

Table 9.6 | Summary of literature on aggregated mitigation potentials in buildings categorized by key mitigation strategies.[1]

Region (Study)[2]	Description of mitigation measures/package (year)[3]	End-uses[4]	Type[5]	Sector[6]	Base-end yrs	% change to baseline	% change to base yr[7]
CARBON EFFICIENCY							
EU (1)	Additional solar domestic hot water system	HW	T	RS	2010–20		20 %, pr.e
AU (2), AT (3) CA (4), DK (5) FL (6), DE (7) IT (8), JP (9) NL (10), ES (11) SE (12), CH (13) UK (14), US (15)	Solar electricity generation through buildings' roof-top PV installations	El.	T	BS	yearly	−46 %, −35 %, −31 %, −32 %, −19 %, −30 %, −45 %, −15 %, −32 %, −48 %, −20 %, −35 %, −31 %, −58 %	
IL (16)	All available rooftops are accounted for producing solar energy	El.	T	BS	yearly	−32 %	
ES (17)	An optimal implementation of the Spanish Technical Building Code and usage of 17 % of the available roof surface area	W	T-E	BS	2009	−68.4 %	
TECHNICAL EFFICIENCY							
World (18)	Significant efforts to fully exploit the potential for EE, all cost-effective renewable energy sources (RES) for heat and electricity generation, production of bio fuels, EE equipment	ALL	T	BS	2007–50	−29 %	
US (19)	The cost-effective energy saving targets, assumed for each end-use on the basis of several earlier studies, are achieved by 2030	ALL	T-E	BS	2010–30	−68 %	
NO (20)	Wide diffusion of heat pumps and other energy conservation measures, e.g., replacement of windows, additional insulation, heat recovery etc.	ALL	T	BS	2005–35	−9.50 %	−21 %
TH (21)	Building energy code and building energy labeling are widely implemented, the requirements towards (nearly) zero-energy building (NZEBs) are gradually strengthened by 2030	ALL	T	CS	by 2030	−51 %	
Northern Europe (22)	Improvements in lamp, ballast, luminaire technology, use of task/ambient lighting, reduction of illuminance levels, switch-on time, manual dimming, switch-off occupancy sensors, daylighting	L	T	CS	2011	−50 %	
Catalonia, ES (23)	Implementation of Technical Code of Buildings for Spain, using insulation and construction solutions that ensure the desired thermal coefficients	H/C	T	BS	2005–15		−29 %
BH (24)	Implementation of the envelope codes requiring that the building envelope is well-insulated and efficient glazing is used	C	T	CS	1 year		−25 %
UK (25)	Fabric improvements, heating, ventilation and air-conditioning (HVAC) changes (including ventilation heat recovery), lighting and appliance improvements and renewable energy generation	ALL	T	CS	2005–30		−50 % (CO_2)
CN (26)	Best Practice Scenario (BPS) examined the potential of an achievement of international best-practice efficiency in broad energy use today	APPL	T	RS, CS	2009–30	−35 %	
SYSTEMIC EFFICIENCY							
World (27)	Today's cost-effective best practice integrated design & retrofit becomes a standard	H/C	T-E	BS	2005–50	−70 %	−30 %
World (28)	The goal of halving global energy-related CO_2 emissions by 2050 (compared to 2005 levels); the deployment of existing and new low-carbon technologies	ALL	T-E	BS	2007–50	−34 %	
World (29)	High-performance thermal envelope, maximized the use of passive solar energy for heating, ventilation and daylighting, EE equipment and systems	ALL	T	BS	2005–50	−48 %	
US (30)	Advanced technologies, infrastructural improvements and some displacement of existing stock, configurations of the built environment that reduce energy requirements for mobility, but not yet commercially available	ALL	T-E	BS	2010–50	−59 %	−40 %
EU27 (31)	Accelerated renovation rates up to 4 %; 100 % refurbishment at high standards; in 2010 20 % of the new built buildings are at high EE standard; 100 %—by 2025	ALL	T	RS	2004–30	−66 %	−71 %
DK (32)	Energy consumption for H in new RS will be reduced by 30 % in 2005, 2010, 2015 and 2020; renovated RS are upgraded to the energy requirements applicable for the new ones	H	T-E	RS	2005–50		−82 %

Region (Study)[2]	Description of mitigation measures/package (year)[3]	End-uses[4]	Type[5]	Sector[6]	Base-end yrs	% change to baseline	% change to base yr[7]
CH (33)	Compliance with the standard comparable to the MINERGIE-P5, the Passive House and the standard A of the 2000 Watt society with low-carbon systems for H and W	H/W	T	RS	2000–50	−60 %	−68 %
	Buildings comply with zero energy standard (no heating demand)	H/W	T	RS	2000–50	−65 %	−72 %
DE (34)	The proportion of very high-energy performance dwellings increases by up to 30 % of the total stock in 2020; the share of (nearly) zero-energy buildings (NZEBs) makes up 6 %	H/W	T	BS	2010–20		−25 %(pr.e) −50 % (CO_2)
ENERGY SERVICE DEMAND REDUCTION							
FR (35)	EE retrofits, information acceleration, learning-by-doing and the increase in energy price. Some barriers to EE, sufficiency in H consumption are overcome	H	T	BS	2008–50	−21 %	−58 %
US (36)	Influence of five lifestyle factors reflecting consumers' behavioural patterns on residential electricity consumption was analyzed	El.	T	RS	2005	−40 %	
LT (37)	Change in lifestyle towards saving energy and reducing waste	ALL	T	RS	1 year	−44 %	
US (38)	Commissioning as energy saving measure applied in 643 commercial buildings	ALL	T	CS	1 year	−16 % (existing buildings) −13 % (new buildings)	

Notes:

1) The Table presents the potential of final energy use reduction (if another is not specified) compared to the baseline and/or base year for the end-uses given in the column 3 and for the sectors indicated in the column 5.
2) References: 1: Anisimova (2011), 2–15: IEA (2002), 16: Yue and Huang (2011), 17: Vardimon (2011), 18: Izquierdo et al. (2011), 19: GPI (2010), 20: Brown et al. (2008a), 21: Sartori et al. (2009), 22: Pantong et al. (2011), 23: Dubois and Blomsterberg (2011), 24: Garrido-Soriano et al. (2012), 25: Radhi (2009), 26: Taylor et al. (2010), 27: Zhou et al. (2011a), 28: Ürge-Vorsatz et al. (2012c), 29: IEA (2010b), 30: Harvey (2010), 31: Laitner et al. (2012), 32: Eichhammer et al. (2009), 33: Tommerup and Svendsen (2006), 34: Chan and Yeung (2005), 35: Siller et al. (2007), 36: Schimschar et al. (2011), 37: Giraudet et al. (2012), 38: Sanquist et al. (2012), 39: Streimikiene and Volochovic (2011), 40: Mills (2011).
3) EE – energy efficiency;
4) H – space heating; C – space cooling; W – hot water; L – lighting; APPL – appliances; ALL – all end-uses; El - elecriticy;
5) T – technical; T-E – techno-economical;
6) BS – the whole building sector; RS – residential sector; CS – commercial sector;
7) pr.e. – primary energy.

2012). Figure 9.13 and the corresponding Table 9.6 synthesize the literature on a selection of regional studies on potentials through different types of measures, aggregated to stocks of the corresponding products/buildings at the regional level. The studies are organized by the four key identities discussed at the beginning of the chapter, translating into the four key mitigation strategies that apply to this sector—i. e., carbon efficiency, technological efficiency, systemic efficiency, and energy service demand reduction. However, as pointed out earlier, it is often not possible to precisely distinguish one category from the other, especially given the different categorizations in the studies, therefore the binning should be treated as indicative only. The potentials illustrated in the table and figure are usually given for final energy use (if not specified otherwise) and are mostly presented as a percentage of the respective baseline energy, specified in the original source. The figure demonstrates that the high potentials at the individual product/building level translate into relatively high potentials also at stock-aggregated levels: mitigation or energy saving potentials often go beyond 30 % to even 60 % of the baseline energy use/emission of the stock the measures apply to. The figure also attests that each of the four key mitigation strategies relevant to buildings can bring very large reductions, although systemic efficiency seems to bring higher results than other strategies, and energy service demand reduction has been so far estimated to bring the most modest results from among these strategies, although studies less often assess these options systematically.

The efficiency and cost studies presented here represent a single snapshot in time, implying that as this potential is being captured by policies or measures, the remaining potential dwindles. This has not been reinforced by experience and research. Analyses have shown that technological improvement keeps replenishing the potential for efficiency improvement, so that the potential for cost-effective energy efficiency improvement has not been diminishing in spite of continuously improving standards (NAS, 2010). The National Academy of Science (NAS) study (NAS, 2010) of the energy savings potentials of energy efficiency technologies and programmes across all sectors in the United States note that "[s]tudies of technical and economic energy-savings potential generally capture energy efficiency potential at a single point in time based on technologies that are available at the time a study is conducted. But new efficiency measures continue to be developed and to add to the long-term efficiency potential." These new efficiency opportunities continue to offer substantial cost-effective additional energy savings potentials after previous potentials have been captured so that the overall technical potential has been found to remain at the same order of magnitude for decades (NAS, 2010).

9.6.2 Overview of option-specific costs and potentials

Since the building sector comprises a very large number of end-uses, in each of these many different types of equipment being used, and for each of which several mitigation alternatives exist, giving a comprehensive account of costs and potentials of each, or even many, is out of the scope of this report. The next two sections focus on selected *key* mitigation options and discuss their costs and potentials in more depth. Section 9.6.2 focuses on whole-building approaches for new and retrofitted buildings, while the Section 9.6.3 analyzes a selection of important technologies systematically. Finally, Section 9.6.5 discusses the sensitivity of the findings from the earlier section to various assumptions and inputs.

9.6.2.1 Costs of very high performance new construction

There is increasing evidence that very high performance new construction can be achieved at little, or occasionally even at negative, additional costs (Ürge-Vorsatz et al., 2012a; Harvey, 2013 and Section 9.3). There are various methodologies applied to understand and demonstrate the cost-effectiveness of whole building new construction and retrofit, including project-based incremental cost accounting, population studies, and comparative modelling (Kats, 2009). For commercial buildings, there are instances where these methods have found no additional cost in meeting standards as high as the Passive House standard (see Section 9.3; Lang Consulting, 2013), or where the cost

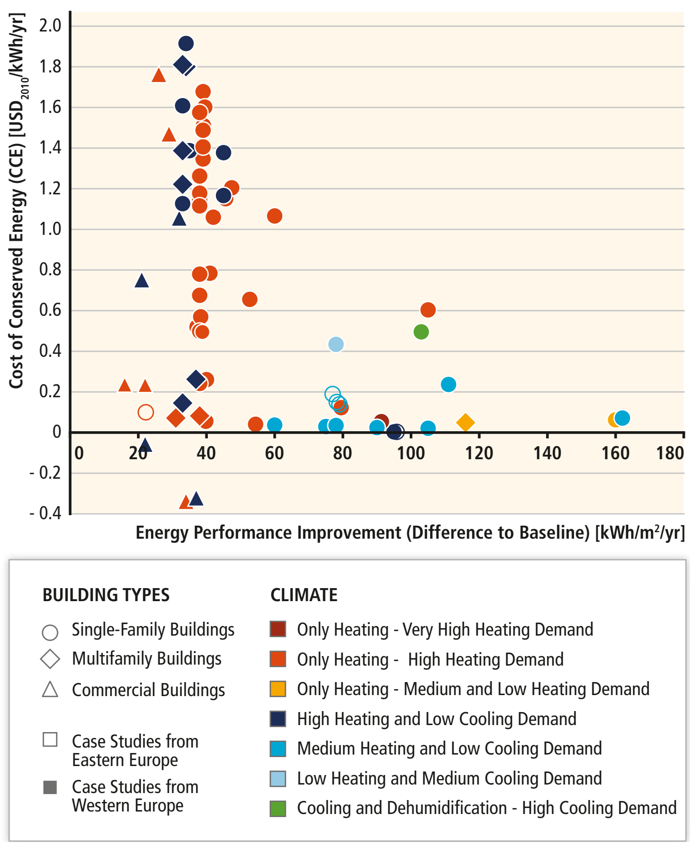

Figure 9.14 | Cost of conserved energy as a function of energy performance improvement (kWh/m²/yr difference to baseline) to reach 'Passive House' or more stringent performance levels, for new construction by different building types and climate zones in Europe. A discount rate of 3 % and the lifetime of 30 years for retrofit and 40 years for new buildings have been assumed. Sources: Hermelink (2006), Galvin (2010), ETK (2011), Gardiner and Theobald (2011), Nieminen (2011), Energy Institute Vorarlberg (2013), PHI (2013), Harvey (2013).

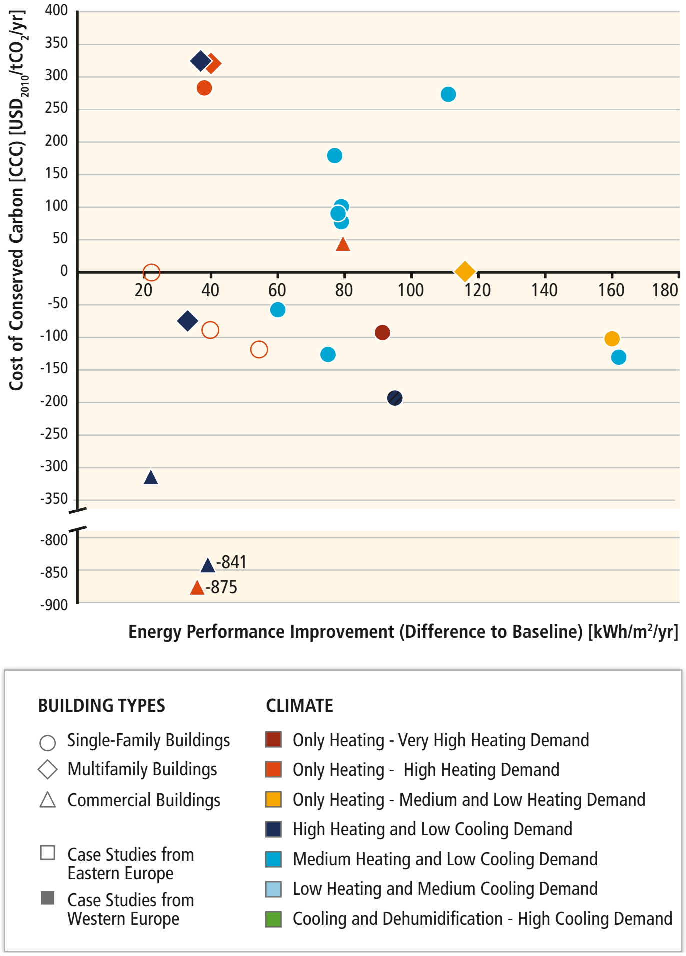

Figure 9.15 | Cost of conserved carbon as a function of specific energy consumption for selected best practices shown in Figure 9.14. A discount rate of 3 % and the lifetime of 30 years for retrofit and 40 years for new buildings have been assumed. Sources: Hermelink (2006), Galvin (2010), ETK (2011), Gardiner and Theobald (2011), Nieminen (2011), Energy Institute Vorarlberg (2013), PHI (2013), Harvey (2013).

of low-energy buildings has been less than that of buildings meeting local energy codes. Surveys of delivered full building construction costs in the United States and Australia comparing conventional and green buildings in a variety of circumstances have been consistently unable to detect a significant difference in delivered price between these two categories. Rather, they find a wide range of variation costs irrespective of performance features (Davis Langdon, 2007; Urban Green Council and Davis Langdon, 2009). Collectively, these studies, along with evidence in 9.3 and the tables in this section indicate that significant improvements in design and operational performance can be achieved today under the right circumstances at relatively low or potentially no increases, or even decreases, in total cost.

The cost and feasibility of achieving various ZNEB definitions have shown that such goals are rarely cost-effective by conventional standards; however, specific circumstances, operational goals, and incentives can make them feasible (Boehland, 2008; Meacham, 2009). Table 9.4 in Section 9.3.5 highlights selected published estimates of the incremental cost of net zero-energy buildings; even for these buildings, there are cases where there appears to have been little additional cost (e.g., NREL Laboratory).The costs of new ZNEBs are heavily dependent on supporting policies, such as net metering and feed-in-tariffs, and anticipated holding times, beyond the factors described below for all buildings. Unlike residential buildings, high-performance commercial buildings can cost less to build than standard buildings, even without simplifying the design, because the cost savings from the downsizing in mechanical and electricity equipment that is possible with a high-performance envelope can offset the extra cost of the envelope. In other cases, the net incremental design and construction cost can be reduced to the point that the time required to payback the initial investment through operating cost savings is quite attractive.

Figure 9.14 shows the resulting cost-effectiveness from a set of documented best practices from different regions measured in cost of conserved energy (CCE). The figure demonstrates well that, despite the very broad typical variation in construction costs due to different designs and non-energy related extra investments, high-performance new construction can be highly cost-effective. Several examples confirming the point established in Section 9.3 that even negative CCEs can be achieved for commercial buildings—i.e., that the project is profitable already at the investment stage, or that the high-performance building costs less than the conventional one. Cost-effectiveness requires that the investments are optimized with regard to the

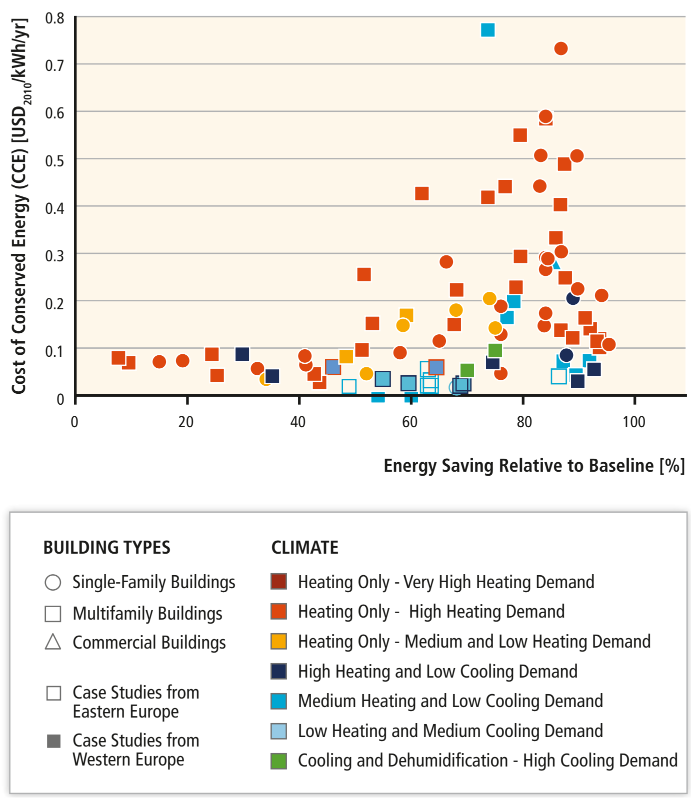

Figure 9.16 | Cost of conserved energy as a function of energy saving in percent for European retrofitted buildings by building type and climate zones. A discount rate of 3 % and the lifetime of 30 years for retrofit and 40 years for new buildings have been assumed. Sources: Hermelink (2006), Galvin (2010), ETK (2011), Gardiner and Theobald (2011), Nieminen (2011), Energy Institute Vorarlberg (2013), PHI (2013), Harvey (2013).

additional vs. reduced (e.g., simplified or no heating system, ductwork, etc.) investment requirements and no non-energy related 'luxury' construction investments are included (see Section 9.3 for further discussion of ensuring cost-effectiveness at the individual building level). It is also important to note that very high-performance construction is still at the demonstration/early deployment level in many jurisdictions, and further cost reductions are likely to occur (see, e.g., GEA, 2012). Figure 9.14 also shows that higher savings compared to the baseline come at a typically lower cost per unit energy saving—i.e., deeper reductions from the baseline tend to increase the cost-efficiency.

Although converting energy saving costs to mitigation costs introduces many problems, especially due to the challenges of emission factors, Figure 9.15 displays the associated mitigation cost estimates of selected points from Figure 9.14 to illustrate potential trends in cost of conserved carbon (CCC). The result is a huge range of CCC, which extends from three-digit negative costs to triple digit positive costs per ton of CO_2 emissions avoided.

9.6.2.2 Costs of deep retrofits

Studies have repeatedly indicated the important distinction between conventional 'shallow' retrofits, often reducing energy use by only 10–30 %, and aggressive 'deep' retrofits (i.e., 50 % or more relative to baseline conditions, especially when considering the lock-in effect. Korytarova and Ürge-Vorsatz (2012) evaluated a range of existing building types to characterize different levels of potential energy savings under different circumstances. They describe the potential risk for shallow retrofits to result in lower levels of energy efficiency and higher medium-term mitigation costs when compared to performance-based policies promoting deep retrofits. Figure 9.16 presents the costs of conserved energy related to a selection of documented retrofit best practices, especially at the higher end of the savings axis. The figure shows that there is sufficient evidence that deep retrofits can be cost-effective in many climates, building types, and cultures. The figure further shows that, while the cost range expands with very large savings, there are many examples that indicate that deep retrofits do not necessarily need to cost more in specific cost terms than the shallow retrofits—i.e., their cost-effectiveness can remain at equally attractive levels for best practices. Retrofits getting closer to 100 % savings start to get more expensive, mainly due to the introduction of presently more expensive PV and other building-integrated renewable energy generation technologies.

9.6.3 Assessment of key factors influencing robustness and sensitivity of costs and potentials

Costs and potentials of the measures described in previous sections depend heavily on various factors and significantly influence the cost-effectiveness of the investments. While these investments vary with the types of measures, a few common factors can be identified.

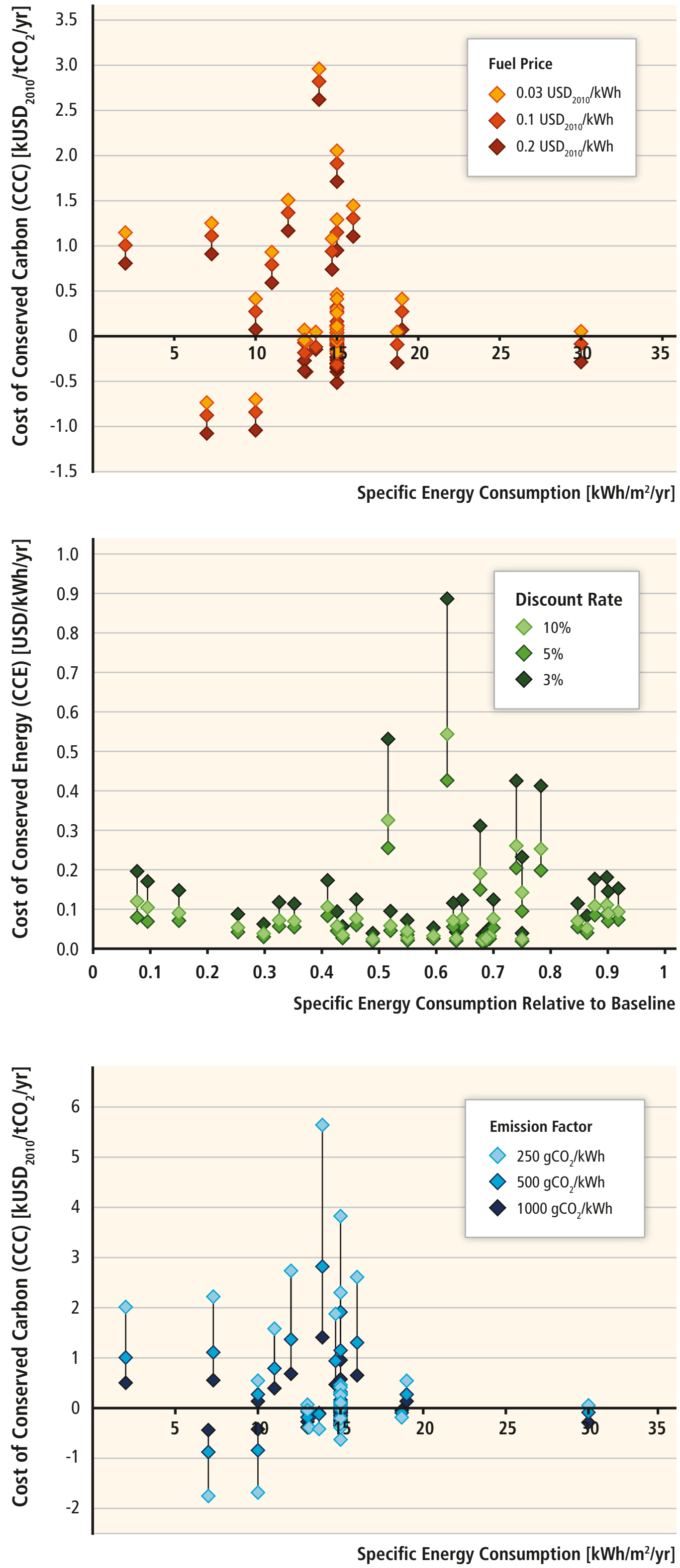

Figure 9.17 | Sensitivity analysis of the key parameters: Top: CCC for new buildings in response to the variation in fuel price; middle: CCE for retrofit buildings in response to the variation in discount rate for selected data points shown in Figure 9.14, Figure 9.15 and Figure 9.16; bottom: CCC for new buildings in response to the variation in emission factor.

For the cost-effectiveness of energy-saving investments, the state of efficiency of the baseline is perhaps the most important determining factor. For instance, a Passive House represents a factor of 10–20 improvement when compared to average building stocks, but only a fraction of this when compared to, for instance, upcoming German new building codes. Figure 9.16 and Figure 9.17 both vary the baseline for the respective measure.

CCE figures and thus 'profitability', fundamentally depend on the discount rate and assumed lifetime of the measure, and CCC depends further on the background emission factor and energy price. Figure 9.17 illustrates, for instance, the major role discount rate, emission factor, and energy price play when determining costs and cost-effectiveness. Beyond the well quantifiable influences, further parameters that contribute to the variability of the cost metrics are climate type, geographic region, building type, etc.

9.7 Co-benefits, risks and spillovers

9.7.1 Overview

Mitigation measures depend on and interact with a variety of factors that relate to broader economic, social, and/or environmental objectives that drive policy choices. Positive side-effects are deemed 'co-benefits'; if adverse and uncertain, they imply risks.[1] Potential co-benefits and adverse side-effects of alternative mitigation measures (Sections 9.7.1–9.7.3), associated technical risks, and uncertainties, as well as their public perception (see the relevant discussion in Sections 9.3.10 and 9.8), can significantly affect investment decisions, individual behaviour, and policymaking priority settings. Table 9.7 provides an overview of the potential co-benefits and adverse side-effects of the mitigation measures assessed in accordance with sustainable development pillars (Chapter 4). The extent to which co-benefits and adverse side-effects will materialize in practice, as well as their net effect on social welfare, differ greatly across regions. It is strongly dependent on local circumstances, implementation practices, scale, and pace of measures deployment (see Section 6.6). Ürge-Vorsatz et al. (2009) and GEA (2012), synthesizing previous research efforts (Mills and Rosenfeld, 1996), recognize the following five major categories of co-benefits attributed to mitigation actions in buildings: (1) health effects (e.g., reduced mortality and morbidity from improved indoor and outdoor air quality), (2) ecological effects (e.g., reduced impacts on ecosystems due to the improved outdoor environment), (3) economic effects (e.g., decreased energy bill payments, employment creation, improved energy security, improved productivity), (4) service provision benefits (e.g., reduction of energy losses during energy transmission and distribution), and (5) social effects (e.g., fuel poverty alleviation, increased comfort due to better control of indoor conditions and the reduction of outdoor noise, increased safety). Taken together, the GEA (2012) found that only the monetizable co-benefits associated with energy efficiency in buildings are at least twice the resulting operating cost savings.

On the other hand, some risks are also associated with the implementation of mitigation actions in buildings emanating mostly from limited energy access and fuel poverty issues due to higher investment and (sometimes) operating costs, health risks in sub-optimally designed airtight buildings, and the use of sub-standard energy efficiency technologies including risks of premature failure. The AR4 (Levine et al., 2007) and other major recent studies (UNEP, 2011b; GEA, 2012) provide a detailed presentation and a comprehensive analysis of such effects. Here, a review of recent advances focuses on selected co-benefits/risks, with a view to providing methods, quantitative information, and examples that can be utilized in the decision-making process.

9.7.2 Socio-economic effects

9.7.2.1 Impacts on employment

Studies (Scott et al., 2008; Pollin et al., 2009; Kuckshinrichs et al., 2010; Köppl et al., 2011; ILO, 2012) have found that greater use of renewables and energy efficiency in the building sector results in positive economic effects through job creation, economic growth, increase of income, and reduced needs for capital stock in the energy sector. These conclusions, however, have been criticized on grounds that include, among others, the accounting methods used, the efficacy of using public funds for energy projects instead of for other investments, and the possible inefficiencies of investing in labour-intensive activities (Alvarez et al., 2010; Carley et al., 2011; Gülen, 2011). A review of the literature on quantification of employment effects of energy efficiency and mitigation measures in the building sector is summarized in Figure 9.18. The bulk of the studies reviewed, which mainly concern developed economies, point out that the implementation of mitigation interventions in buildings generates on average 13 (range of 0.7 to 35.5) job-years per million USD_{2010} spent. This range does not change if only studies estimating net employment effects are considered. Two studies (Scott et al., 2008; Gold et al., 2011) focus on cost savings from unspent energy budgets that can be redirected in the economy, estimating that the resulting employment effects range between 6.0 and 10.2 job-years per million USD_{2010} spent. Several studies (Pollin et al., 2009; Ürge-Vorsatz et al., 2010; Wei et al., 2010; Carley et al., 2011) agree that building retrofits and investments in clean energy technologies are more labour-intensive than conventional approaches (i.e., energy production from fossil fuels, other construction activities). However,

[1] Co-benefits and adverse side-effects describe effects in non-monetary units without yet evaluating the net effect on overall social welfare. Please refer to the respective sections in the framing chapters (particularly 2.4, 3.6.3, and 4.8) as well as to the glossary in Annex I for concepts and definitions.

Table 9.7 | Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) associated with mitigation actions in buildings. Please refer to Sections 7.9, 11.7, and 11.13 for possible upstream effects of low-carbon electricity and biomass supply on additional objectives. Co-benefits and adverse side-effects depend on local circumstances as well as on the implementation practice, pace, and scale (see Section 6.6). For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2.

Co-benefits/Adverse side-effects	Residential buildings	Commercial buildings	Buildings in developed countries	Buildings in developing countries	Retrofits of existing buildings	Exemplary new buildings	Efficient equipment	Fuel switching/RES incorporation/green roofs	Behavioural changes	References
Economic										
↑ Employment impact	X	X	X	X	X	X	X	X		Scott et al. (2008); Pollin et al. (2009); Ürge-Vorsatz et al. (2010); Gold et al. (2011)
↑ Energy security	X	X	X	X	X	X	X	X	X	IEA (2007); Dixon et al. (2010); Borg and Kelly (2011); Steinfeld et al. (2011)
↑ Productivity		X	X	X	X	X	X			Fisk (2002); Kats et al. (2003); Loftness et al. (2003); Singh et al. (2010b)
↑ Enhanced asset values of buildings	X	X	X	X	X	X		X		Miller et al. (2008); Brounen and Kok (2011); Deng et al. (2012b)
↑ Lower need for energy subsidies	X	X	X	X	X	X	X	X	X	Ürge-Vorsatz et al. (2009); GEA (2012)
↑ Disaster resilience	X	X	X	X	X	X				Berdahl (1995); Mills (2003); Coaffee (2008)
Social										
↑ Fuel poverty alleviation (reduced demand for energy)	X		X	X	X		X	X		Tirado Herrero et al. (2012b); Healy (2004); Liddell and Morris (2010); Hills (2011); Ürge-Vorsatz and Tirado Herrero (2012)
↓ Fuel poverty alleviation (in cases of increases in the cost of energy)	X		X	X				X		GEA (2012); Rao (2013)
↓ Energy access (in cases of increases in the cost of energy, high investment costs needed, etc.)	X		X	X	X		X	X		GEA (2012); for a more in-depth discussion please see Section 7.9.1
↑ Noise impact, thermal comfort	X	X	X	X	X	X				Jakob (2006); Stoecklein and Skumatz (2007)
↑ Increased productive time for women and children (for replaced traditional cookstoves)	X			X			X	X		Reddy et al. (2000); Lambrou and Piana (2006); Hutton et al. (2007); Anenberg et al. (2013); Wodon and Blackden (2006)
↓ Rebound effect	X	X	X	X	X	X	X	X		Greening et al. (2000); Sorrell (2007); Hens et al. (2009); Sorrell et al. (2009); Druckman et al. (2011); Ürge-Vorsatz et al. (2012a)
Health/Environmental										
Health impact due to:										
↑ *reduced outdoor pollution*	X	X	X	X	X	X	X	X	X	Levy et al. (2003); Aunan et al. (2004); Mirasgedis et al. (2004); Chen et al. (2007); Crawford-Brown et al. (2012); Milner et al. (2012); see Section 7.9.2
↑ *reduced indoor pollution*	X			X			X	X		Bruce et al. (2006); Zhang and Smith (2007); Duflo et al. (2008); WHO (2009); Wilkinson et al. (2009); Howden-Chapman and Chapman (2012); Milner et al. (2012); WGII Section 11.9.
↑ *improved indoor environmental conditions*	X	X	X	X	X	X			X	Fisk (2002); Singh et al. (2010b); Howden-Chapman and Chapman (2012); Milner et al. (2012)
↑ *fuel poverty alleviation*	X		X	X	X		X	X		Tirado Herrero et al. (2012b); Healy (2004); Liddell and Morris (2010); Hills (2011); Ürge-Vorsatz and Tirado Herrero (2012)
↓ *insufficient ventilation (sick building syndrome), sub-standard energy efficiency technologies, etc.*	X	X	X	X	X		X			Fisk (2002); GEA (2012); Milner et al. (2012)
↑ Ecosystem impact	X	X	X	X	X	X	X	X	X	Aunan et al. (2004); Mirasgedis et al. (2004); Ürge-Vorsatz et al. (2009); Cam (2012)
↑ Reduced water consumption and sewage production	X	X	X	X	X	X	X			Kats et al. (2005); Bansal et al. (2011)
↑ Urban heat island effect	X		X	X	X	X		X		Cam (2012); Xu et al. (2012b); see Sections 9.5 and 12.8

to what extent investing in clean energy creates more employment compared to conventional activities depends also on the structure of the economy in question, level of wages, and if the production of equipment and services to develop these investments occurs or not inside the economy under consideration. To this end, the estimation of net employment benefits instead of gross effects is of particular importance for an integrated analysis of energy efficiency implications on the economy. Investing in clean technologies may create new job activities (e.g., in solar industry, in the sector of new building materials etc.), but the vast majority of jobs can be in traditional areas (Pollin et al., 2009) albeit with different skills required (ILO, 2012).

9.7.2.2 Energy security

Implementation of mitigation measures in the buildings sector can play an important role in increasing the sufficiency of resources to meet national energy demand at competitive and stable prices and improving the resilience of the energy supply system. Specifically, mitigation actions result in: (1) strengthening power grid reliability through the enhancement of properly managed on-site generation and the reduction of the overall demand, which result in reduced power transmission and distribution losses and constraints (Kahn, 2008; Passey et al., 2011); (2) reducing cooling-related peak power demand and shifting demand to off-peak periods (Borg and Kelly, 2011; Steinfeld et al., 2011); and (3) increasing the diversification of energy sources as well as the share of domestic energy sources used in a specific energy system (see for example Dixon et al., 2010). A more general discussion on energy security is provided in Section 6.6.

9.7.2.3 Benefits related to workplace productivity

Investment in low-carbon technologies related to air conditioning and wall thermal properties during construction or renovation improves workplace productivity, as evidenced by a meta-analysis of several studies (Fisk, 2002; Kats et al., 2003; Loftness et al., 2003; Ries et al., 2006; Sustainability Victoria and Kador Group, 2007; Miller et al., 2009; Singh et al., 2010b). On average, energy efficient buildings may result in increased productivity by 1–9 % or even higher for specific activities or case studies. The productivity gains can be attributed to: (1) reduced working days lost due to asthma and respiratory allergies; (2) fewer work hours affected by flu, respiratory illnesses, depression, and stress; and (3) improved worker performance from changes in thermal comfort and lighting. Productivity gains can rank among the highest value co-benefits when these are monetized, especially in countries with high labour costs (GEA, 2012).

9.7.2.4 Rebound effects

Improvements in energy efficiency can be offset by increases in demand for energy services due to the rebound effect. The general issues relating to the effect are set out in Sections 3.9.5 and 5.6. The rebound effect is of particular importance in buildings because of the high proportion of energy efficiency potential in this sector. Studies related to buildings form a major part of the two major reviews of rebound (Greening et al., 2000; Sorrell, 2007). Direct rebound effects tend to be in the range 0–30 % for major energy services in buildings such as heating and cooling (Sorrell et al., 2009; Ürge-Vorsatz et al., 2012b)

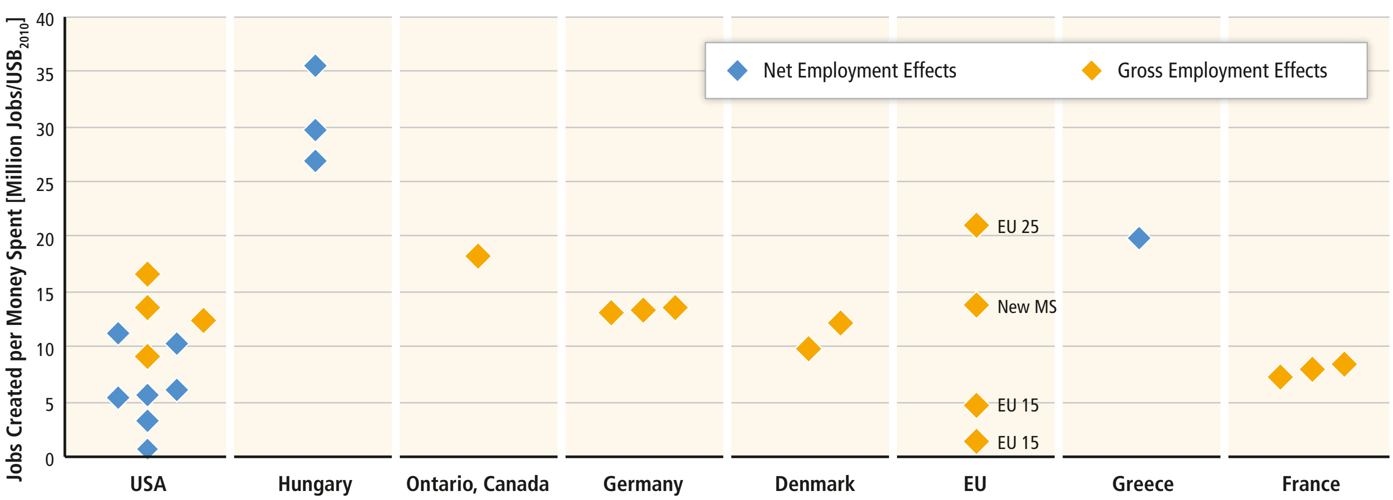

Figure 9.18 | Employment effects attributed to GHG mitigation initiatives from different provinces, countries and regions in the building sector.

Sources used: USA (Scott et al., 2008; Bezdek, 2009; Hendricks et al., 2009; Pollin et al., 2009; Garrett-Peltier, 2011; Gold et al., 2011), Hungary (Ürge-Vorsatz et al., 2010), Ontario, Canada (Pollin and Garrett-Peltier, 2009), Germany (Kuckshinrichs et al., 2010), Denmark (Ege et al., 2009), EU (ETUC, 2008), Greece (Markaki et al., 2013), France (ADEME, 2008). All studies from the USA, Hungary, Ontario Canada and Greece include the direct, indirect and induced employment effects. In ADEME (2008) and ETUC (2008) only the direct effects are taken into account. Ege et al. (2009) includes the direct and indirect effects while this information is not provided in Kuckshinrichs et al. (2010).

in developed countries. For energy services where energy is a smaller fraction of total costs, e.g., electrical appliances, there is less evidence, but values are lower and less than 20 % (Sorrell, 2007). Somewhat higher rebound levels have been found for lower income groups (Hens et al., 2009; Roy, 2000), implying that rebound contributes positively to energy service affordability and development. However, there is limited evidence outside OECD countries (Roy, 2000; Ouyang et al., 2010) and further research is required here. Studies of indirect rebound effects for buildings tend to show low values, e.g., 7 % for thermostat changes (Druckman et al., 2011). Some claims have been made that indirect rebound effects may be very large (Brookes, 2000; Saunders, 2000), even exceeding 100 %, so that energy efficiency improvement would increase energy use. These claims may have had some validity for critical 'general purpose technologies' such as steam engines during intensive periods of industrialization (Sorrell, 2007), but there is no evidence to support large rebound effects for energy efficiency in buildings. Declining energy use in developed countries with strong policies for energy efficiency in buildings indicates rebound effects are low (see Section 9.2). Rebound effects should be taken into account in building energy efficiency policies, but do not alter conclusions about their importance and cost effectiveness in climate mitigation (Sorrell, 2007).

9.7.2.5 Fuel poverty alleviation

Fuel poverty is a condition in which a household is unable to guarantee a certain level of consumption of domestic energy services (especially heating) or suffers disproportionate expenditure burdens to meet these needs (Boardman, 1991; BERR, 2001; Healy and Clinch, 2002; Buzar, 2007; Ürge-Vorsatz and Tirado Herrero, 2012). As such, it has a range of negative effects on the health and welfare of fuel poor households. For instance, indoor temperatures that are too low affect vulnerable population groups like children, adolescent, or the elderly (Liddell and Morris, 2010; Marmot Review Team, 2011) and increase excess winter mortality rates (The Eurowinter Group, 1997; Wilkinson et al., 2001; Healy, 2004). A more analytical discussion on the potential health impacts associated with fuel poverty is presented in Section 9.7.3. Despite the fact that some mitigation measures (e.g., renewables) may result in higher consumer energy prices aggravating energy poverty, substantially improving the thermal performance of buildings (such as Passive House) and educating residents on appropriate energy management can largely alleviate fuel poverty. Several studies have shown that fuel poverty-related monetized co-benefits make up over 30 % of the total benefits of energy efficiency investments and are more important than those arising from avoided emissions of greenhouses gases and other harmful pollutants like SO_2, NO_x, and PM_{10} (Clinch and Healy, 2001; Ürge-Vorsatz and Tirado Herrero, 2012).

9.7.3 Environmental and health effects

9.7.3.1 Health co-benefits due to improved indoor conditions

The implementation of energy efficiency interventions in buildings improves indoor conditions resulting in significant co-benefits for public health, through: (1) reduction of indoor air pollution, (2) improvement of indoor environmental conditions, and (3) alleviation of fuel poverty particularly in cold regions. In developing countries, inefficient combustion of traditional solid fuels in households produces significant gaseous and particulate emissions known as products of incomplete combustion (PICs), and results in significant health impacts, particularly for women and children, who spend longer periods at home (Zhang and Smith, 2007; Duflo et al., 2008; Wilkinson et al., 2009). Indoor air pollution from the use of biomass and coal was responsible for 2 million premature deaths and 41 million disability-adjusted life-years (DALYs) worldwide in 2004 (WHO, 2009), with recent estimates (Lim et al., 2012) reaching as high as 3.5 million premature deaths in 2010. Another half a million premature deaths are attributed to household cook fuel's contribution to outdoor air pollution, making a total of about 4 million (see WGII Chapter 11.9.1.3). Several climate mitigation options such as improved cookstoves, switching to cleaner fuels, changing behaviours, and switching to more efficient and less dangerous lighting technologies address not only climate change but also these health issues (Anenberg et al., 2012; Smith et al., 2013; Rao et al., 2013). Wilkinson et al. (2009) showed that the implementation of a national programme promoting modern low-emissions stove technologies in India could result in significant health benefits amounting to 12,500 fewer DALYs per million population in one year. Bruce et al. (2006) investigated the health benefits and the costs associated with the implementation of selected interventions aiming at reducing indoor air pollution from the use of solid fuels for cooking/space heating in various world regions (Table 9.8).

In both developed and developing countries, better insulation, ventilation, and heating systems in buildings improve the indoor conditions and result in fewer respiratory diseases, allergies and asthma as

Table 9.8 | Healthy years gained per thousand USD_{2010} spent in implementing interventions aiming at reducing indoor air pollution. Source: Bruce et al. (2006).

Intervention	Sub-Saharan Africa	Latin America and Caribbean	Middle East and North Africa	Europe and Central Asia	South Asia	East Asia and the Pacific
Access to cleaner fuels: LPG	1.30—1.79	0.66—1.19	~1.2	0.70—0.76	1.70—2.97	0.55—9.30
Access to cleaner fuels: Kerosene	11.1—15.4	1.46—8.77	~9.7	5.07—5.56	14.8—25.8	4.11—79.5
Improved stoves	36.7—45.9	0.84—0.98	2.03—2.52	n.a.	62.4—70.7	1.58—3.11

well as reduced sick building syndrome (SBS) symptoms (Fisk, 2002; Singh et al., 2010b). On the other hand, insufficient ventilation in airtight buildings has been found to affect negatively their occupants' health, as has the installation of sub-standard energy efficiency technologies due to in-situ toxic chemicals (Fisk, 2002; GEA, 2012; Milner et al., 2012). Of particular importance is the alleviation of fuel poverty in buildings, which is associated with excess mortality and morbidity effects, depression, and anxiety (Green and Gilbertson, 2008). It is estimated that over 10 % to as much as 40 % of excess winter deaths in temperate countries is related to inadequate indoor temperatures (Clinch and Healy, 2001; Marmot Review Team, 2011). In countries such as Poland, Germany, or Spain, this amounts to several thousand—up to 10,000—excess annual winter deaths. These figures suggest that in developed countries, fuel poverty may be causing premature deaths per year similar to or higher than that of road traffic accidents (Bonnefoy and Sadeckas, 2006; Ürge-Vorsatz et al., 2012; Tirado Herrero et al., 2012b). Improved residential insulation is expected to reduce illnesses associated with room temperature thus provide non-energy benefits, such as reduced medical expenses and reduced loss of income due to unpaid sick leave from work and school. A study in the UK found that for each USD_{2010} 1 invested for warming homes reduces the healthcare costs by USD_{2010} 0.49 (Liddell, 2008). Such findings suggest that addressing fuel poverty issues and the resulting health impacts in developing nations are even more important, as a greater share of the population is affected (WHO, 2011).

9.7.3.2 Health and environmental co-benefits due to reduced outdoor air pollution

The implementation of mitigation measures in the building sector reduces the consumption of fossil fuels and electricity, thus improving the outdoor air quality and resulting in: (1) reduced mortality and morbidity, particularly in developing countries and big cities (Smith et al., 2010; Harlan and Ruddell, 2011; see Section 12.8); and (2) less stresses on natural and anthropogenic ecosystems (see Section 7.9.1). Quantification and valuation of these benefits is possible, and allows them to be integrated into cost-benefit analysis. Many studies (Levy et al., 2003; Aunan et al., 2004; Mirasgedis et al., 2004; Chen et al., 2007; Crawford-Brown et al., 2012) have monetized the health and environmental benefits attributed to reduced outdoor air pollution that result from the implementation of energy efficiency measures in buildings. The magnitude of these benefits is of the order of 8–22 % of the value of energy savings in developed countries (Levy et al., 2003; Næss-Schmidt et al., 2012), and even higher in developing nations (see Chapter 6.6). Markandya et al. (2009) estimated that the health benefits expressed in USD_{2010} per ton of CO_2 not emitted from power plants (through for example the implementation of electricity conservation interventions) are in the range of 2 USD_{2010}/tCO_2 in EU, 7 USD_{2010}/tCO_2 in China and 46 USD_{2010}/tCO_2 in India, accounting for only the mortality impacts associated with $PM_{2.5}$ emissions. Please refer to Section 5.7 for other estimates in the assessed literature.

9.7.3.3 Other environmental benefits

Energy efficiency measures that are implemented in buildings result in several other environmental benefits. Specifically, using energy efficient appliances such as washing machines and dishwashers in homes results in considerable water savings (Bansal et al., 2011). More generally, a number of studies show that green design in buildings is associated with lower demand for water, resulting in reduced costs and emissions from the utilities sector. For example, Kats et al. (2005) evaluated 30 green schools in Massachusetts and found an average water use reduction of 32 % compared to conventional schools, achieved through the reuse of the rain water and other non-potable water as well as the installation of water efficient appliances (e.g., in toilets) and advanced controls. Also, the implementation of green roofs, roof gardens, balcony gardens, and sky terraces as well as green façades/walls in buildings, results in: (1) reducing heat gains for buildings in hot climates; (2) reducing the heat island effect; (3) improving air quality; (4) enhancing urban biodiversity, especially with the selection of indigenous vegetation species; (5) absorbing CO_2 emissions, etc. (see Cam, 2012; Xu et al., 2012b; Gill et al., 2007; and Section 12.5.2.2).

9.8 Barriers and opportunities

Strong barriers—many particular to the buildings sector—hinder the market uptake of largely cost-effective opportunities to achieve energy efficiency improvements shown in earlier sections. Large potentials will remain untapped without adequate policies that induce the needed changes in private decisions and professional practices. Barriers and related opportunities vary considerably by location, building type, culture, and stakeholder groups, as vary the options to overcome them, such as policies, measures, and innovative financing schemes. A vast literature on barriers and opportunities in buildings enumerates and describes these factors (Brown et al., 2008b; Ürge-Vorsatz et al., 2012a; Power, 2008; Lomas, 2009; Mlecnik, 2010; Short, 2007; Hegner, 2010; Stevenson, 2009; Pellegrini-Masini and Leishman, 2011; Greden, 2006; Collins, 2007; Houghton, 2011; Kwok, 2010; Amundsen, 2010; Monni, 2008).

Barriers include imperfect information, transaction costs, limited capital, externalities, subsidies, risk aversion, principal agent problems, fragmented market and institutional structures, poor feedback, poor enforcement of regulations, cultural aspects, cognitive and behavioural patterns, as well as difficulties concerning patent protection and technology transfer. In less developed areas, lack of awareness, financing, qualified personnel, economic informality, and generally insufficient service levels lead to suboptimal policies and measures thus causing lock-in effects in terms of emissions. The pace of policy uptake is especially important in developing countries because ongoing development efforts that do not consider co-benefits may lock in suboptimal technologies and infrastructure and result in high costs in future years (Williams et al., 2012).

9

9.9 Sectoral implication of transformation pathways and sustainable development

9.9.1 Introduction

The purpose of this section is to review both the integrated as well as sectoral bottom-up modelling literature from the perspective of what main trends are projected for the future building emissions and energy use developments, and the role of major mitigation strategies outlined in Section 9.1. The section complements the analysis in Section 6.8 with more details on findings from the building sector. The two key pillars of the section are (1) a statistical analysis of a large population of scenarios from integrated models (665 scenarios in total) grouped by their long-term CO_2-equivalent (CO_2eq) concentration level by 2100, complemented by the analysis of sectoral models (grouped by baseline and advanced scenario, since often these do not relate to concentration goals); and (2) a more detailed analysis of a small selection of integrated and end-use/sectoral models. The source of the integrated models is the WGIII AR5 Scenario Database (see Section 6.2.2 for details), and those of the sectoral models are Cornelissen et al. (2012), Deng et al. (2012a), Dowling et al. (2012), GPI (2010), Harvey (2010), IEA (2012c0a), Laustsen (2010), McNeil et al. (2013), Ürge-Vorsatz et al. (2012a3), WBCSD (2009), WEO (2011).

9.9.2 Overview of building sector energy projections

Figure 9.19, together with Figure 9.20 and Figure 9. 21 indicate that without action, global building final energy use could double or possibly triple by mid-century. While the median of integrated model scenarios forecast an approximate 75 % increase as compared to 2010 (Figure 9.19), several key scenarios that model this sector in greater detail foresee a larger growth, such as: AIM, Message, and the Global Change Assessment Model (GCAM), all of which project an over 150 % baseline growth (Figure 9.20). The sectoral/bottom-up literature, however, indicates that this growing trend can be reversed and the sector's energy use can stagnate, or even decline, by mid-century, under advanced scenarios.

The projected development in building final energy use is rather different in the sectoral (bottom-up) and integrated modelling literature, as illustrated in Figure 9.19, Figure 9.20, and Figure 9. 21. For instance, the integrated model literature foresees an increase in building energy consumption in most scenarios with almost none foreseeing stabilization, whereas the vast majority of ambitious scenarios from the bottom-up/sectoral literature stabilize or even decline despite the increases in wealth, floorspace, service levels, and amenities (see Section 9.2). Several stringent mitigation scenarios from integrated mod-

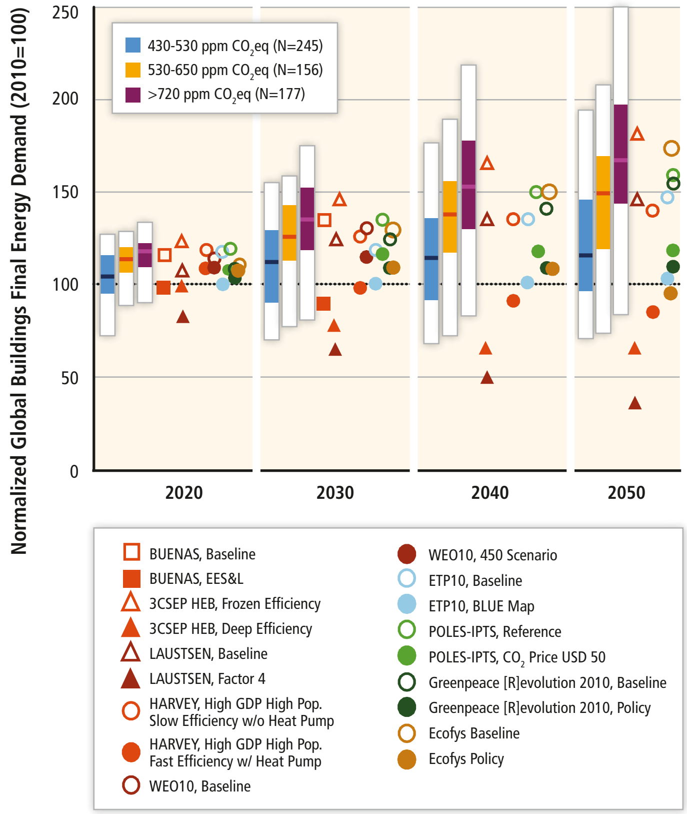

Figure 9.19 | Development of normalized annual global building final energy demand (2010=100) until 2050 in the integrated modelling literature, grouped by the three levels of long-term CO_2eq concentration level by 2100 (245 scenarios with 430–530 ppm CO_2eq, 156 scenarios with 530–650 ppm CO_2eq, and 177 scenarios exceeding 720 ppm CO_2eq—for category descriptions see Chapter 6.3.3; see box plots) and sectoral/bottom-up literature (9 baseline scenarios and 9 advanced scenarios; see square, triangle and circle symbols). Sectoral scenarios covering appliances (A) only are denoted as squares (■), scenarios covering heating/cooling/water heating (HCW) as triangles (▲), scenarios covering heating/cooling/water heating/lighting/appliances (HCWLA) as circles (●). Filled symbols are for baseline scenario, whereas empty symbols are for advanced scenarios. Box plots show minimum, 25th percentile, median, 75th percentile and maximum. Sources: Cornelissen et al. (2012), Deng et al. (2012a), Dowling et al. (2012), GPI (2010), Harvey (2010), IEA (2012c0a), Laustsen (2010), McNeil et al. (2013), Ürge-Vorsatz et al. (2012a3), WBCSD (2009), WEO (2011) and WG III AR5 Scenario Database (Annex II.10).

Note on this section: This section builds upon emissions scenarios, which were collated by Chapter 6 in the WGIII AR5 scenario database (Section 6.2.2), and compares them to detailed building sector studies. The scenarios were grouped into baseline and mitigation scenarios. As described in more detail in Section 6.3.2, the scenarios are further categorized into bins based on 2100 concentrations: between 430–480 ppm CO2eq, 480–530 ppm CO2eq, 530–580 ppm CO2eq, 580–650 ppm CO2eq, 650–720 ppm CO2eq, and > 720 ppm CO2eq by 2100. An assessment of geo-physical climate uncertainties consistent with the dynamics of Earth System Models assessed in WGI found that the most stringent of these scenarios—leading to 2100 concentrations between 430 and 480 ppm CO2eq—would lead to an end-of-century median temperature change between 1.6 to 1.8 °C compared to pre-industrial times, although uncertainties in understanding of the climate system mean that the possible temperature range is much wider than this range. They were found to maintain temperature change below 2 °C over the course of the century with a likely chance. Scenarios in the concentration category of 650–720 ppm CO2eq correspond to comparatively modest mitigation efforts, and were found to lead to median temperature rise of approximately 2.6–2.9 °C in 2100 (see Section 6.3.2 for details).

els are above baseline scenarios from the sectoral literature (Figure 9.20). In general, the sectoral literature sees deeper opportunities for energy use reductions in the building sector than integrated models.

As the focus on selected scenarios in Figure 9.21 suggests, thermal energy use can be reduced more strongly than energy in other building end-uses: reductions in the total are typically as much as, or less than, decreases in heating and cooling (sometimes with hot water) energy use scenarios. Figure 9.21 shows that deep reductions are foreseen only in the thermal energy uses by bottom-up/sectoral scenarios, but appliances can be reduced only moderately, even in sectoral studies. This indicates that mitigation is more challenging for non-thermal end-uses and is becoming increasingly important for ambitious mitigation over time, especially in advanced heating and cooling scenarios where this energy use can be successfully pushed down to a fraction of its 2005 levels. These findings confirm the more theoretical discussions in this chapter, i.e., that in thermal end-uses deeper reductions can be expected while appliance energy use will be more difficult to reduce or even limit its growth. For instance Ürge-Vorsatz et al. (2012d) show a 46 % reduction in heating and cooling energy demand as compared to 2005—even under baseline assumptions on wealth and amenities increases. In contrast, the selected integrated models that focus on detailed building sector modelling project very little reduction in heating and cooling.

Another general finding is that studies show significantly larger reduction potentials by 2050 than by 2030, pointing to the need for a longer-term, strategic policy planning, due to long lead times of building infrastructure modernization (see Section 9.4). In fact, most of these studies and scenarios show energy growth through 2020, with the decline starting later, suggesting that 'patience' and thus policy permanence is vital for this sector in order to be able to exploit its large mitigation potentials.

The trends noted above are very different in the different world regions. As Figure 9.22 demonstrates, both per capita and total final building energy use is expected to decline or close to stabilize even in baseline scenarios in OECD countries. In contrast, the Latin-American and Asian regions will experience major growth both for per capita and total levels, even in the most stringent mitigation scenarios. MAF will experience major growth for total levels, but growth is not projected for per capita levels even in baseline scenarios. This is likely due mainly to the fact that

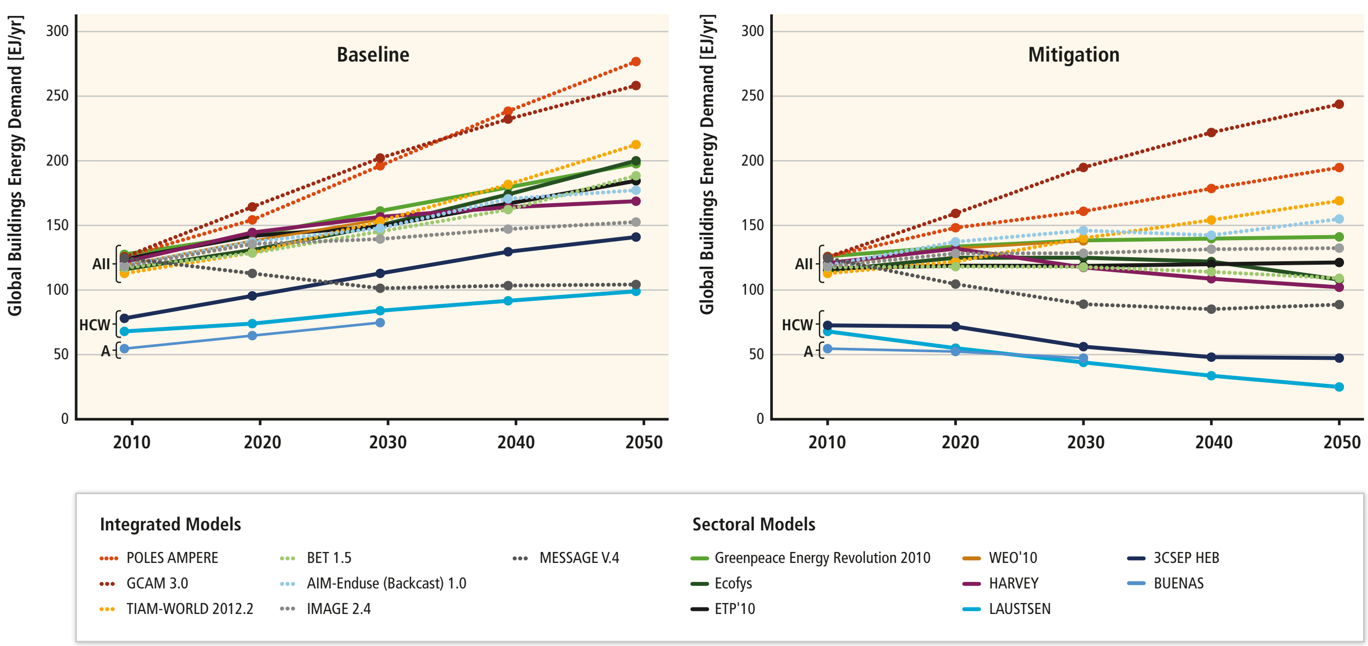

Figure 9.20 | Annual global final energy demand development in the building sector by 2050 (except WEO'10 and BUENAS) in selected sectoral models for baseline (left) and advanced (right) scenarios, for total energy (All, heating/cooling/hot water/lighting/appliances), thermal energy (HCW, includes heating/cooling/hot water), and appliances (A); compared to selected integrated models. Dashed lines show integrated models, solid lines show sectoral/bottom-up models. Sources: Cornelissen et al. (2012), Deng et al. (2012a), Dowling et al. (2012), GPI (2010), Harvey (2010), IEA (2012c0a), Laustsen (2010), McNeil et al. (2013), Ürge-Vorsatz et al. (2012a3), WBCSD (2009), WEO (2011) and WG III AR5 Scenario Database (Annex II.10).

Note: For the analysis to follow, we have chosen seven illustrative integrated models with two scenarios each, covering the full range of year-2050 final energy use in all no-policy scenarios in the WGIII AR5 scenario database and their 450 ppm scenario counterparts. These no-policy scenarios are MESSAGE V.4_EMF27-Base-EERE, IMAGE 2.4_AMPERE2-Base-LowEI-OPT, AIM-Enduse[Backcast] 1.0_LIMITS-StrPol, BET 1.5_EMF27-Base-FullTech, TIAM-WORLD 2012.2_EMF27-Base-FullTech, GCAM 3.0_AMPERE3-Base, and POLES AMPERE_AMPERE3-Base. The mitigation scenario counterparts are MESSAGE V.4_EMF27–450-EERE, IMAGE 2.4_AMPERE2–450-LowEI-OPT, AIM-Enduse[Backcast] 1.0_LIMITS-StrPol-450, BET 1.5_EMF27–450-FullTech, TIAM-WORLD 2012.2_EMF27–450-FullTech, GCAM 3.0_AMPERE3-CF450, and POLES AMPERE_AMPERE3-CF450. In addition, sectoral/bottom-up models and scenarios were also included. The no policy/baseline scenarios are BUENAS Baseline, 3CSEP HEB Frozen efficiency, LAUSTSEN Baseline, WEO'10 Current Policies, ETP'10 Baseline, Ecofys Baseline, and Greenpeace Energy Revolution 2010 Baseline. The advanced scenarios are BUENAS EES&L, 3CSEP HEB Deep efficiency, LAUSTSEN Factor 4, WEO'10 450 Scenario, ETP'10 BLUE Map, Ecofys TER, and Greenpeace Energy Revolution 2010 Revolution.

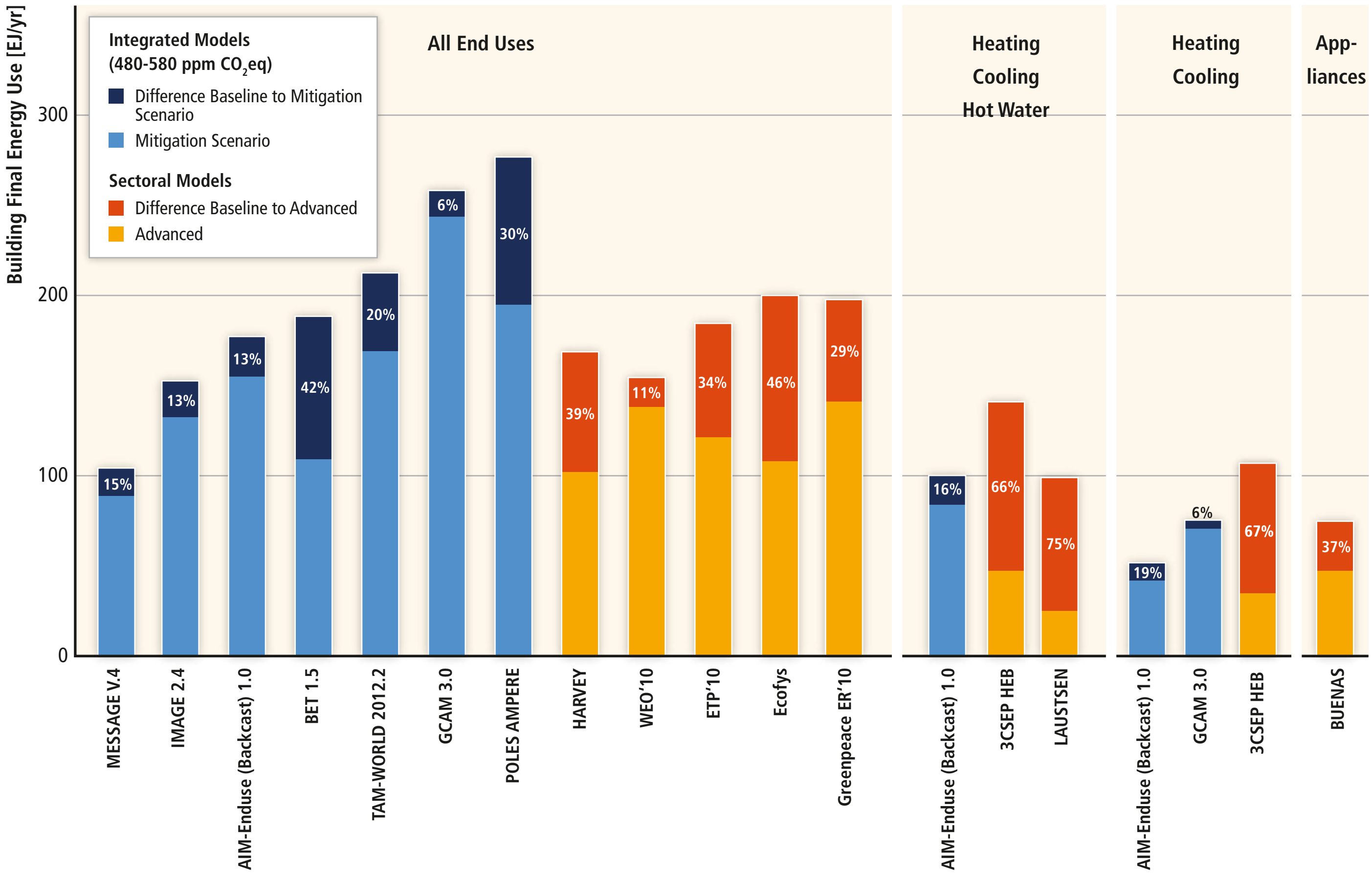

Figure 9.21 | Building final energy use in EJ/yr in 2050 (2030 for BUENAS and WEO'10) for advanced scenarios, modelling four groups of building end-uses as compared to reference ones. Blue bars show scenarios from integrated models meeting 480–580 ppm CO_2eq concentration in 2100, orange/red bars are from sectoral models. Sources: Cornelissen et al. (2012), Deng et al. (2012a), Dowling et al. (2012), GPI (2010), Harvey (2010), IEA (2012c0a), Laustsen (2010), McNeil et al. (2013), Ürge-Vorsatz et al. (2012a3), WBCSD (2009), WEO (2011) and WG III AR5 Scenario Database (Annex II.10)

fuel switching from traditional biomass to modern energy carriers results in significant conversion efficiency gains, thus allowing substantial increases in energy service levels without increasing final energy use.

9.9.3 Key mitigation strategies as highlighted by the pathway analysis

The diversity of the development in final energy demand even among the most stringent mitigation scenarios suggests that different models take different foci for their building mitigation strategies. While most mitigation and advanced bottom-up/sectoral scenarios show flat or reducing global final building energy use, a few integrated models achieve stringent mitigation from rather high final energy demand levels, thereby focusing on energy supply-side measures for reducing emissions. These scenarios have about twice as high per capita final energy demand levels in 2050 as the lowest mitigation scenarios. This suggests a focus on energy supply side measures for decarbonization. In general, Figure 9.19, Figure 9.20, and Figure 9. 21 all demonstrate that integrated models generally place a larger focus on supply-side solutions than on final energy reduction opportunities in the building sector (see Section 6.8)—except for a small selection of studies.

Fuel switching to electricity that is increasingly being decarbonized is a robust mitigation strategy as shown in Sections 6.3.4 and 6.8. However, as Figure 9.23a indicates, this is not fully the case in the buildings sector. The total share of electricity in this sector is influenced little by mitigation stringency except for the least ambitious scenarios: it exhibits an autonomous increase from about 28 % of final energy in 2010 to 50 % and more in 2050 in almost all scenarios, i.e., the use of more electricity as a share of building energy supply is an important baseline trend in the sector. Compared to this robust baseline trend, the additional electrification in mitigation scenarios is rather modest (see also Section 6.8.4).

Figure 9.23b indicates that the higher rates of energy growth (x-axis) in the models involve generally higher rates of electricity growth (y-axis). The two increases are nearly proportional, so that the rates of electricity demand share growth, of which level is indicated by 45° lines, remain mostly below 2 % per year even in the presence of climate policy.

The seven selected integrated models see a very different development in the fuel mix (Figure 9. 24). In the baseline scenarios, interestingly, most scenarios show a fairly similar amount of power use; and the difference in total building final energy use largely stems from the dif-

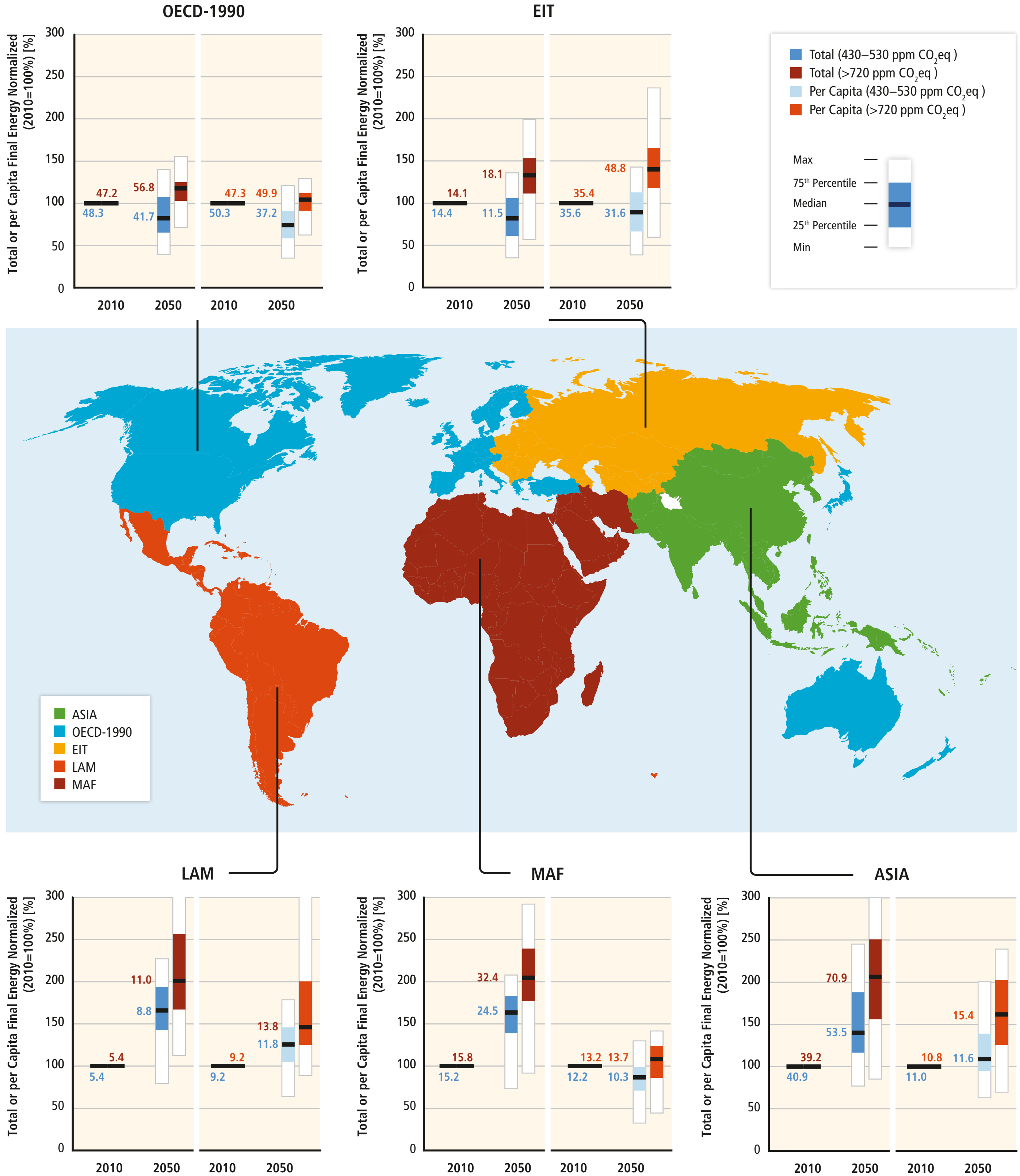

Figure 9.22 | Normalized total (for first two pairs of box plots) and per capita (for next two pairs of box plots) buildings final energy demand in 2010 and 2050 for each of the RC5 regions (Annex II.2.2) in scenarios from integrated models (2010=100). The absolute values of the medians are also shown with the unit of EJ for total buildings final energy demand and the unit of GJ for per capita buildings final energy demand (229 scenarios with 430–530 ppm CO_2eq and 154 scenarios exceeding 720 ppm CO_2eq—for category descriptions see Section 6.3.2). Note that the 2010 absolute values are not equal for the two CO_2eq concentration categories because for most integrated models 2010 is a modelling year implying some variation across models, such as in the treatment of traditional biomass. Sources: WG III AR5 Scenario Database (Annex II.10).

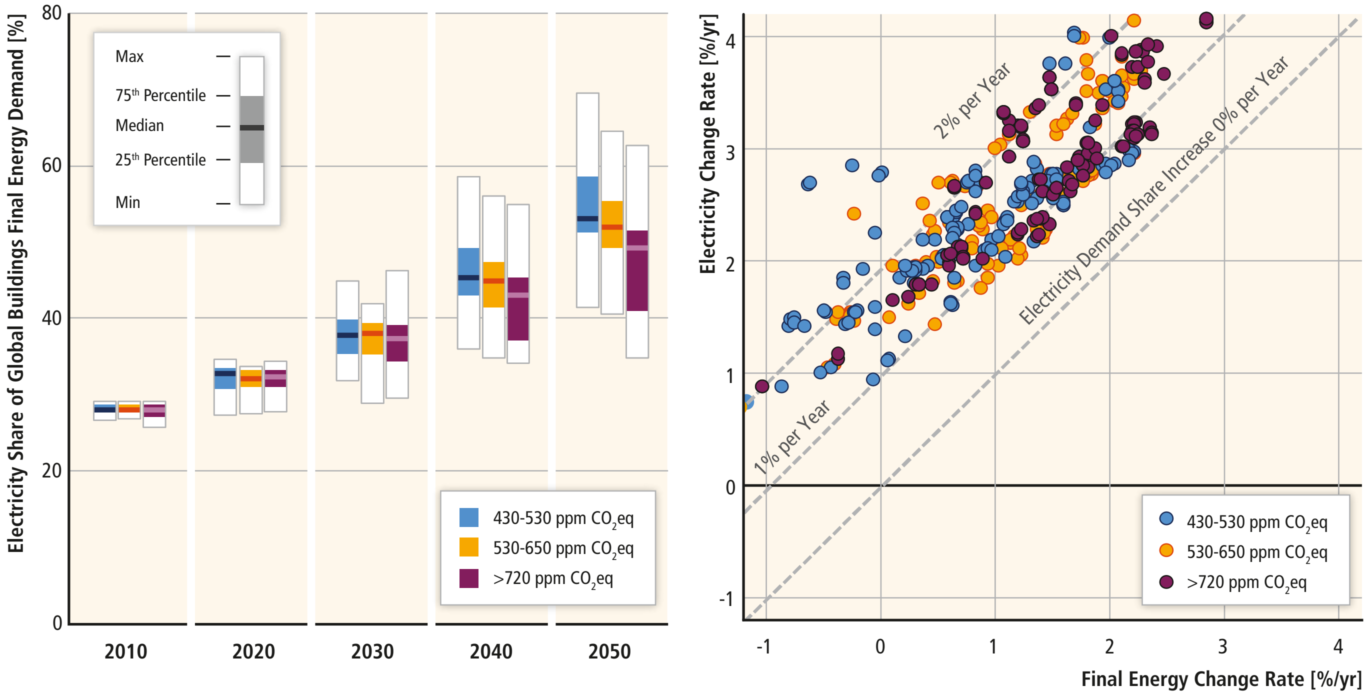

Figure 9.23 | Left panel: The development in the share of electricity in global final energy demand until 2050 in integrated model scenarios (167 scenarios with 430–530 ppm CO_2eq, 138 scenarios with ppm 530–650 CO_2eq, and 149 scenarios exceeding 720 ppm CO_2eq—for category descriptions see Chapter 6.3.3), and right panel decomposition of the annual change in electricity demand share into final energy demand change rate and electricity demand change rate (each gray line indicates a set of points with the same annual change in electricity demand share). Sources: WG III AR5 Scenario Database (Annex II.10).

ferences in the use of other fuels. Particularly large differences are foreseen in the use of natural gas and oil, and, to a lesser extent, biomass. Mitigation scenarios are somewhat more uniform: mostly a bit over half of their fuel mix is comprised of electricity, with the remaining part more evenly distributed among the other fuels except coal that disappears from the portfolio, although some scenarios exclude further individual fuels (such as no biomass in MESSAGE, no oil in BET, no natural gas in Image) by scenarios outcomes.

9.9.4 Summary and general observations of global building final energy use

The material summarized in this section concludes that without action, global building final energy use may double or potentially even triple by mid-century, but with ambitious action it can possibly stabilize or decline as compared to its present levels. However, the integrated and sectoral models do not fully agree with regard to the extent of mitigation potential and the key mitigation strategy, although there is a very wide variation among integrated models with some more agreement across sectoral models' conclusions.

The broad mitigation strategy for buildings implied by sectoral analysis is first to significantly reduce demand for both primary fuels and electricity by using available technologies for energy efficiency improvement, many of which are cost effective without a carbon price. To the extent this is insufficient, further mitigation can be achieved through additional use of low and zero carbon electricity, from a combination of building integrated renewable energy and substitution of fossil fuels with low carbon electricity.

The broad mitigation strategies for buildings implied by integrated models, however, include a greater emphasis on switching to low-carbon energy carriers (predominantly electricity). These strategies place less emphasis on reducing energy demand, possibly because many integrated models do not represent all technical options to reduce building energy consumption cost-effectively which are covered in sectoral studies and because of the implicit assumption of general equilibrium models that all cost-effective opportunities had been taken up already in the baseline which is at odds with empirical data from the buildings sector. Integrated model outputs tend to show energy demand reduction over the coming decades, followed by a more significant role for decarbonization of energy supply (with, in some cases, heavy reliance on bioenergy with carbon dioxide capture and storage (CCS) to offset remaining direct emissions from buildings and the other end-use sectors).

To summarize, sectoral studies show there is a larger potential for energy efficiency measures to reduce building sector final energy use than is most typically shown by integrated models. This indicates that some options for demand reductions in the buildings sector are not included, or at least not fully deployed, by integrated models because of different model assumptions and/or level of richness in technology/option representation (see Section 6.8).

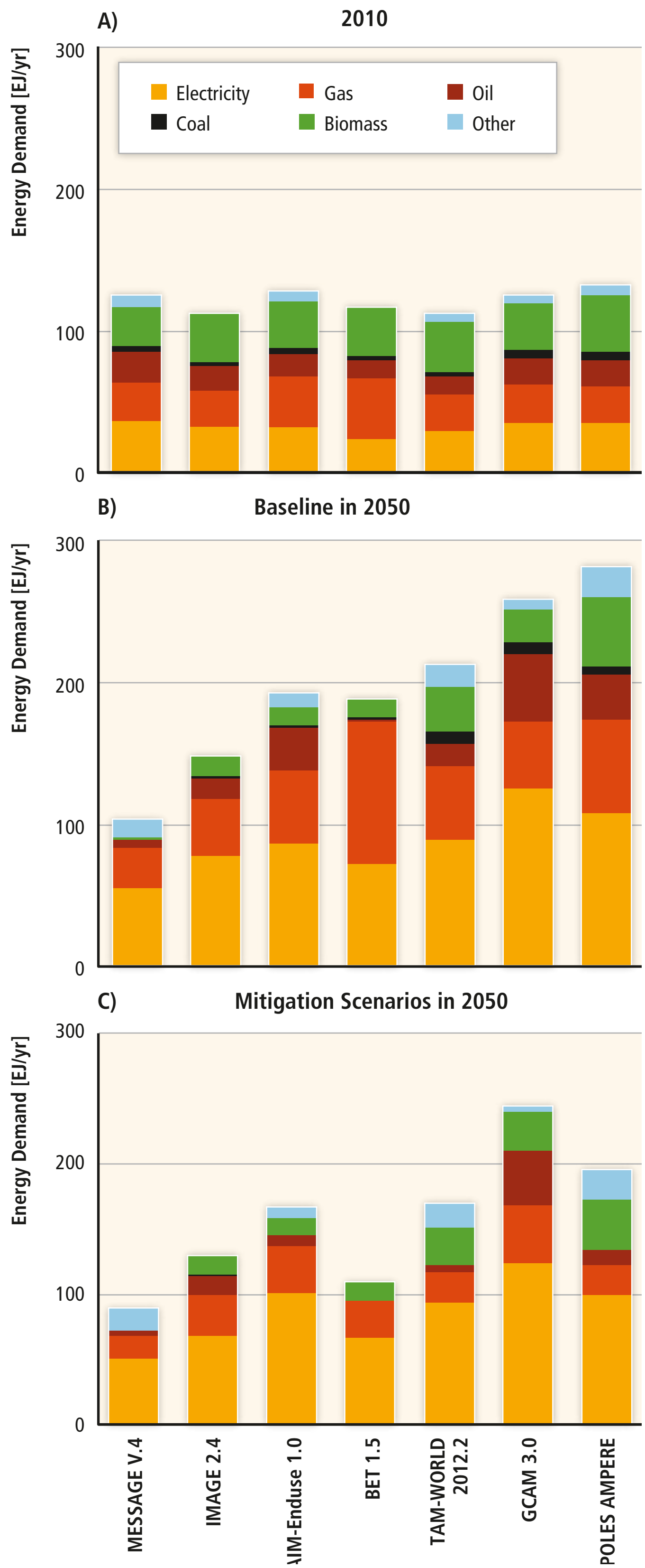

Figure 9.24 | Global buildings final energy demands by fuel for the seven baseline scenarios of seven integrated models and their corresponding mitigation scenarios (480–580 ppm CO_2eq concentration in 2100). AIM-Enduse 1.0 = AIM-Enduse (Backcast) 1.0. Sources: WG III AR5 Scenario Database (Annex II.10).

9.10 Sectoral policies

This section first outlines the policy options to promote energy efficiency in buildings, then provides more detail on the emerging policy instruments since AR4, then focuses on the key new instruments for financing and finally considers the policy issues specific to developing countries.

9.10.1 Policies for energy efficiency in buildings

Section 9.8 shows that many strong barriers prevent the full uptake of energy saving measures. Market forces alone will not achieve the necessary transformation towards low carbon buildings without external policy intervention to correct market failures and to encourage new business and financial models that overcome the first-investment cost hurdle, which is one of the key barriers. There is a broad portfolio of effective policy instruments available that show reductions of emissions at low and negative costs; many of them have been implemented in developed countries and, more recently, in developing countries. When these policies are implemented in a coordinated manner, they can be effective in reversing the trend of growing energy consumption. This chapter shows that building energy use has fallen in several European countries in recent years where strong policies have been implemented. Beside technological improvement in energy efficiency, which has been so far the main focus of most polices, policymakers have recently focused on the need to change consumer behaviour and lifestyle, based on the concept of sufficiency. Particularly in developed countries, the existing building stock is large and renewed only very slowly, and therefore it is important to introduce policies that specifically target the existing stock, e.g., aiming at accelerating rates of energy refurbishment and avoiding lock-in to suboptimal retrofits—for example, the case of China (Dongyan, 2009). Policies also need to be dynamic, with periodic revision to follow technical and market changes; in particular, regulations need regular strengthening, for example for equipment minimum efficiency standards (Siderius and Nakagami, 2013) or building codes (Weiss et al., 2012). Recently there has been more attention to enforcement, which is needed if countries are to achieve the full potential of implemented or planned policies (Ellis et al., 2009; Weiss et al., 2012).

The most common policies for the building sector are summarized in Table 9.9, which includes some examples of the results achieved. Policy instruments for energy efficiency in buildings may be classified in the following categories: (1) *Regulatory measures* are one of the most effective and cost-effective instruments, for example, building codes and appliance standards (Boza-Kiss et al., 2013) if properly enforced (Weiss et al., 2012); see also (Koeppel and Ürge-Vorsatz, 2007; McCormick and Neij, 2009). Standards need to be set at appropriate levels and periodically strengthened to avoid lock-in to sub-optimal performance. (2) *Information instruments* including equipment energy labels, building labels and certificates, and mandatory energy audits can be

Table 9.9 | Policies for energy efficiency in buildings, their environmental effectiveness, i.e., emission reduction impact and societal cost-effectiveness. Source: Based on Boza-Kiss et al. (2013).

Policy title and brief definition	Further information, comments	Environmental effectiveness (selected best practices of annual CO_2 emission reduction)	Cost effectiveness of CO_2 emission reduction (selected best practices, USD_{2010}/tCO_2 per yr)	References
Building codes are sets of standards for buildings or building systems determining minimum requirements of energy performance.	Lately standards have also been adopted for existing buildings (Desogus et al., 2013). Traditionally typical low enforcement has resulted in lower than projected savings. Building codes need to be regularly strengthened to be effective.	EU: 35–45 $MtCO_2$ (2010–2011) LV: 0.002 $MtCO_2$/yr in 2016 (estimated in 2008) ES: 0.35 $MtCO_2$/yr in 2012 UK : 0.02 $MtCO_2$/yr by 2020 (estimated in 2011)	EU region: < 36.5 USD_{2010}/tCO_2 ES: 0.17 USD_{2010}/tCO_2 LV: –206 USD_{2010}/tCO_2	[1,2,3,4]
Appliance standards (MEPS) are rules or guidelines for a particular product class that set a minimum efficiency level, and usually prohibit the sale of underperforming products.	Most OECD countries have adopted MEPS (in the EU under the Eco-design Directive). Voluntary agreements with equipment manufacturers are considered as effective alternatives in some jurisdictions. The Japanese Top Runners Schemes have proven as successful as MEPS (Siderius and Nakagami, 2013) (). Developing countries may suffer a secondary effect, receiving products banned from other markets or inefficient second hand products.	JP: 0.1 $MtCO_2$/yr in 2025 (Top Runner Scheme, 2007) US: 158 $MtCO_2$ cumulative in 2030 (2010), updating the standard—18 $MtCO_2$/yr in 2040 (2010) KE: 0.3 $MtCO_2$/yr (for lighting only) BF: 0.01 $MtCO_2$/yr (lighting only)	JP: 51 USD_{2010}/tCO_2 (Top Runner) Mor: 13 USD_{2010}/tCO_2 AU: –52 USD_{2010}/tCO_2 US: –82 USD_{2010}/tCO_2 EU: –245 USD_{2010}/tCO_2	[5, 6, 7,8]
Energy labelling is the mandatory (or voluntary) provision of information about the energy/other resource use of end-use products at the point of sale.	Examples include voluntary endorsement labelling (e.g., Energy Star) and mandatory energy labelling (e.g., the EU energy label). Technical specifications for the label should be regularly updated to adjust to the best products on the market. MEPS and labels are usually co-ordinated policy measures with common technical analysis.	EU: 237 $MtCO_2$ (1995–2020) OECD N-Am: 792 $MtCO_2$ (1990–2010) OECD EU: 211 $MtCO_2$ (1990–2010) NL: 0.11 $MtCO_2$/yr (1995–2004) DK: 0.03 $MtCO_2$/yr (2004)	AU: –38 USD_{2010}/tCO_2	[9,10,11]
Building labels and certificates rate buildings related to their energy performance and provide credible information about it to users/buyers.	Building labels could be mandatory (for example in the EU) or voluntary (such as BREEAM, CASBEE, Effinergie, LEED, European GreenBuilding label, Minergie and PassivHaus). Labels are beginning to influence market prices (Brounen and Kok, 2011).	SK: 0.05 $MtCO_2$ (during 2008–2010) for mandatory certification SK: 0.001 $MtCO_2$ (during 2008–2010) for promoting voluntary certification and audits	EU: 27 USD_{2010}/tCO_2 (2008–2010) for mandatory certification DK: almost 0 USD_{2010}/tCO_2	[12]
Mandatory energy audits measure the energy performance of existing buildings and identify cost-effective improvement potentials.	Audits should be mandatory and subsidized (in particular for developing countries). Audits are reinforced by incentives or regulations that require the implementation of the cost-effective recommended measures.	SK: 0.001 $MtCO_2$ (during 2008–2010) for promoting voluntary certification and audits FI: 0.036 $MtCO_2$ (2010)	FI: 27.7 USD_{2010}/tCO_2 (2010) mandatory audit programme	[2, 12, 13]
Sustainable public procurement is the organized purchase by public bodies following pre-set procurement regulations incorporating energy performance/sustainability requirements.	Setting a high level of efficiency requirement for all the products that the public sector purchases, as well as requiring energy efficient buildings when renting or constructing them, can achieve a significant market transformation, because the public sector is responsible for a large share of these purchases and investments. In the EU the EED requires Member States to procure only most efficient equipment. In the US this is carried out under FEMP.	SK: 0.01 $MtCO_2$ (introduction of sustainable procurement principle) (2011–2013) CN: 3.7 $MtCO_2$ (1993–2003) MX: 0.002 $MtCO_2$ (2004–2005) UK: 0.34 $MtCO_2$ (2011) AT: 0.02 $MtCO_2$ (2010)	SK: 0.03 USD_{2010}/tCO_2 CN: –10 USD_{2010}/tCO_2	[12, 14, 15, 16]
Promotion of energy services (ESCOs) aims to increase the market and quality of energy service offers, in which savings are guaranteed and investment needs are covered from cost savings.	Energy performance contracting (EPC) schemes enable ESCOs or similar (Duplessis et al., 2012) . Many countries have recently adopted policies for the promotion of EPC delivered via ESCOs (Marino et al., 2011).	EU:40–55$MtCO_2$ by 2010 AT: 0.016 $MtCO_2$/yr in 2008–2010 US: 3.2 $MtCO_2$/yr CN: 34 $MtCO_2$	EU: mostly at no cost AT: no cost HU: < 1 USD_{2010}/tCO_2 US: Public sector: B/C ratio 1.6, Private sector: 2.1	[2, 17,18]
Energy Efficiency Obligations and White Certificates set, record and prove that a certain amount of energy has been saved at the point of end-use. Schemes may incorporate trading.	Suppliers' obligations and white certificates have been introduced in Italy, France, Poland, the UK, Denmark and the Flemish Region of Belgium and in Australia. In all the White Certificates schemes the targets imposed by governments have been so far exceeded (Bertoldi et al., 2010b).	FR: 6.6 $MtCO_2$/yr (2006–2009) IT: 21.5 $MtCO_2$ (2005–2008) UK: 24.2 $MtCO_2$/yr (2002–2008) DK: 0.5 $MtCO_2$/yr (2006–2008) Flanders (BE): 0.15 $MtCO_2$ (2008–2016)	FR: 36 USD_{2010}/tCO_2 IT: 12 USD_{2010}/tCO_2 UK: 24 USD_{2010}/tCO_2 DK: 66 USD_{2010}/tCO_2 Flanders (BE): 201 USD_{2010}/tCO_2	[19, 20, 21, 22, 23, 24, 25, 26, 27]
Carbon markets limit the total amount of allowed emissions. Carbon emission allowances are then distributed and traded.	Carbon cap and trade for the building sector is an emerging policy instrument (e.g., the Tokyo CO_2 Emission Reduction Program, which imposes a cap on electricity and energy emissions for large commercial buildings), although the program is currently under change due to the special measure for the Great East Japan Earthquake.	CDM: 1267 $MtCO_2$ (average cumulative saving per project for 32 registered CDM projects on residential building efficiency, 2004–2012) JI: 699 $MtCO_2$ (cumulative) from the single JI project on residential building energy efficiency (2006–2012)	CDM end-use energy efficiency projects, In:–113 to 96 USD_{2010}/tCO_2 JI projects (buildings): between 122 and 238 USD_{2010}/tCO_2	[28, 29, 30]

Policy title and brief definition	Further information, comments	Environmental effectiveness (selected best practices of annual CO_2 emission reduction)	Cost effectiveness of CO_2 emission reduction (selected best practices, USD_{2010}/tCO_2 per yr)	References
Energy and carbon tax is levied on fossil fuels or on energy using products, based on their energy demand and/or their carbon content respectively.	Fiscal tools can be powerful, because the increased (relative) price of polluting energy sources or less sustainable products is expected to cause a decrease in consumption. However, depending on price electricity, the tax typically should be quite substantial to have an effect on behaviour and energy efficiency investments.	SE: 1.15 $MtCO_2$/yr (2006) DE: 24 $MtCO_2$ cummulative (1999–2010) DK: 2.3 $MtCO_2$ (2005) NL: 3.7–4.85 $MtCO_2$/yr (1996–2020)	SE: 8.5 USD_{2010}/tCO_2 DE: 96 USD_{2010}/tCO_2 NL: −421 to −552 USD_{2010}/tCO_2 (2000–2020)	[31, 32, 33, 34]
Use of taxation can be considered as a type of subsidy, representing a transfer of funds to investors in energy efficiency.	Examples include reduced VAT, accelerated depreciation, tax deductions, feebates etc.	TH: 2.04 $MtCO_2$ (2006–2009) IT: 0.65 $MtCO_2$ (2006–2010) FR: 1 $MtCO_2$ (2002) US: 88 $MtCO_2$ (2006)	TH: 26.5 USD_{2010}/tCO_2	[35, 36, 37]
Grants and subsidies are economic incentives, in the form of funds transfer.	Incentives (e.g., grants and subsidies) for investments in energy efficiency, as provided for building renovation in Estonia, Poland and Hungary	DK: 170 $MtCO_2$ cummulative (1993–2003) UK: 1.41 $MtCO_2$ (2008–2009) CZ: 0.05 $MtCO_2$ (2007) AU: 0.7 $MtCO_2$ (2009–2011) FR: 0.4 $MtCO_2$ (2002–2006)	DK: 0.5 USD_{2010}/tCO_2 UK: 84.8 USD_{2010}/tCO_2 FR: 17.9 USD_{2010}/tCO_2	[35, 37, 38, 39]
Soft loans (including preferential mortgages) are given for carbon-reduction measures with low interest rates.	Governmental a fiscal incentive to banks, which offer preferential interest rates to customers and also incentives based on the performances achieved, e.g., in Germany (CO_2-Rehabilitation Program).	TH: 0.3 $MtCO_2$ (2008–2009) LT: 0.33 $MtCO_2$/yr (2009–2020) PL: 0.98 $MtCO_2$ (2007–2010)	TH: 108 USD_{2010}/tCO_2 (total cost of loan)	[37, 40]
Voluntary and negotiated agreements are tailored contracts between an authority and another entity, aimed at meeting a predefined level of energy savings.	Voluntary programmes can be also applied in the built environment as in the Netherlands and Finland, where housing association and public property owners agree on energy efficiency targets with the government. Some voluntary agreements have a binding character; as the agreed objectives are binding. At city level, an example is the Covenant of Mayors	FI: 9.2 $MtCO_2$ NL: 2.5 $MtCO_2$ (2008–2020) DK: 0.09 $MtCO_2$/yr (1996)	FI: 0.15 USD_{2010}/tCO_2 NL: 14 USD_{2010}/tCO_2 DK: 39 USD_{2010}/tCO_2	[2, 13, 41, 42]
Awareness raising and information campaigns, are programs transmitting general messages to the whole population. ***Individual feedback*** is characterized by the provision of tailored information.	Information campaigns to stimulate behavioural changes (e.g., to turn down the thermostat by 1 °C during the heating season) as well as investments in energy efficiency technologies; new developments are seen in the area of smart metering and direct feedback.	BR: 6–12 $MtCO_2$/yr (2005) UK: 0.01 $MtCO_2$/yr (2005) EU: 0.0004 $MtCO_2$ (2009) FI: 0.001 $MtCO_2$/yr (2010) UK: 0.25 % household energy saving/yr, that is 0.5 $MtCO_2$/yr (cumulated 2011–2020) (billing and metering)	BR: −69 USD_{2010}/tCO_2 UK: 8.4 USD_{2010}/tCO_2 EU: 40.2 USD_{2010}/tCO_2 US: 20–98 USD_{2010}/tCO_2	[2, 43, 44, 45, 46]
Public Leadership Programmes are public practices going beyond the minimum requirements in order to lead by example and demonstrate good examples.		IE: 0.033 $MtCO_2$ (2006–2010) BR: 6.5–12.2 $MtCO_2$/yr	ZA: 25 USD_{2010}/tCO_2 BR: −125 USD_{2010}/tCO_2	[2, 47]

Notes: Country codes (ISO 3166): AT-Austria; AU-Australia; BE- Belgium; BF- Burkina Faso; BR- Brazil; CN- China; CZ-Czech Republic; DE- Germany; DK- Denmark; ES- Spain; EU- European Union; FI- Finland; FR-France; HU- Hungary; IE- Ireland; IN-India; IT-Italy; JP- Japan; KE- Kenya; LT- Lithuania; LV- Latvia; Mor–Morocco; MX- Mexico; NL-The Netherlands; OECD EU- OECD countries in Europe; OECD N-Am: OECD countries in North-America; PL- Poland; SE-Sweden; SK- Slovak Republic; SL- Slovenia; TH- Thailand; UK- United Kingdom; US- United States; ZA South Africa.

References: [1](EC, 2003);[2] (Koeppel and Ürge-Vorsatz, 2007);[3](DECC, 2011); [4] (Government of Latvia, 2011);[5](Kainou, 2007);[6] (AHAM, 2010); [7] (En.lighten, 2010);[8] (US EERE, 2010); [9] (IEA, 2003) [10] (Wiel and McMahon, 2005); [11] (Luttmer, 2006); [12] (Government of Slovakia, 2011); [13] (Government of Finland, 2011); [14] (FI, 2005); [15] (Van Wie McGrory et al., 2006);[16] (LDA, 2011); [17] (AEA, 2011); [19] (MNDH, 2011); [20] (Lees, 2006); [21] (Lees, 2008); [22] (Lees, 2011); [23] (Pavan, 2008); [24] (Bertoldi and Rezessy, 2009); [25](Bertoldi et al., 2010b); [26] (Giraudet et al., 2011); [27] (Langham et al., 2010); [28] (BETMG, 2012); [29] (UNEP Risoe, 2012); [30] (Bertoldi et al., 2013b); [31](Knigge and Görlach, 2005); [32] (Price et al., 2005); [33] (EPC, 2008); [34] (IEA, 2012b); [35] (GMCA, 2009); [36] (APERC, 2010); [37] (BPIE, 2010); [38] (Missaoui and Mourtada, 2010); [39] (Hayes et al., 2011); [40] (Galvin, 2012); [41] (Rezessy and Bertoldi, 2010); [42] (MIKR, 2011); [43] (Uitdenbogerd et al., 2009); [44] (CPI, 2011); [45] (UK DE, 2011); [46] (CB, 2012); [47] (Government of Ireland, 2011).

relatively effective on their own depending on their design, but can also support other instruments, in particular standards (Kelly, 2012; Boza-Kiss et al., 2013). (3) *Direct market intervention instruments* include public procurement, which can have an important role in transforming the market. More recently, governments have supported the development of energy service companies (ESCOs) (see section 9.10.3). (4) *Economic Instruments* include several options, including both tradable permits, taxes, and more focussed incentives. Tradable permits (often called market-based instruments) include tradable white certificates (see section 9.10.2), as well as broader carbon markets (see Chapter 13). Taxes include energy and carbon taxes and have increasingly been implemented to accelerate energy efficiency (UNEP SBCI, 2007). They are discussed in more detail in Chapter 15, and can complement and reinforce other policy instruments in the building sector. Sector specific tax exemptions and reductions, if appropriately structured, can provide a more effective mechanism than energy taxes (UNEP SBCI, 2007). Options include tax deductions building retrofits (Valentini and Pistochini, 2011), value-added tax exemption, and various tax reliefs (Dongyan, 2009), as well as exemptions from business taxes for CDM projects (RSA, 2009). More focussed incentives include low interest loans and incentives which can be very effective in enlarging the market for new efficient products and to overcome first cost barriers for deep retrofits (McGilligan et al., 2010). (5) *Voluntary agreements* include programmes such as industry agreements. Their effectiveness depends on the context and on accompanying policy measures (Bertoldi, 2011). (6) *Advice and leadership programmes* include policies such as information campaigns, advice services, and public leadership programmes to build public awareness and capacity.

A large number of countries have successfully adopted building sector policies. The most popular instruments in developing countries so far have been appliance standards, public procurement, and leadership programmes. Table 9.9 provides more detailed descriptions of the various instruments, a brief identification of some key issues related to their success, and a quantitative evaluation of their environmental and cost-effectiveness from the literature. Although there is a significant spread in the results, and the samples are small for conclusive judgments on individual instruments, the available studies indicate that among the most cost-effective instruments have been building codes and labels, appliance standards and labels, supplier obligations, public procurement, and leadership programmes. Most of these are regulatory instruments. However, most instruments have best practice applications that have achieved CO_2 reductions at low or negative social costs, signalling that a broad portfolio of tools is available to governments to cost-effectively cut building-related emissions.

Appliance standards and labels, building codes, promotion of ESCOs, Clean Development Mechanisms and Joint Implementation (CDM JI), and financing tools (grants and subsidies) have so far performed as the most environmentally effective tools among the documented cases. However, the environmental effectiveness also varies a lot by case. Based on a detailed analysis of policy evaluations, virtually any of these instruments can perform very effectively (environmentally and/or cost-wise) if tailored to local conditions and policy settings, and if implemented and enforced well (Boza-Kiss et al., 2013). Therefore, it is likely that the choice of instrument is less crucial than whether it is designed, applied, implemented, and enforced well and consistently. Most of these instruments are also effective in developing countries, where it is essential that the co-benefits of energy-efficiency policies (see Section 10.7) are well-mapped, quantified and well understood by the policy-makers (Ryan and Campbell, 2012; Koeppel and Ürge-Vorsatz, 2007). Policy integration with other policy domains is particularly effective to leverage these co-benefits in developing countries, and energy-efficiency goals can often be pursued more effectively through other policy goals that have much higher ranking in political agendas and thus may enjoy much more resources and a stronger political momentum than climate change mitigation.

9.10.1.1 Policy packages

No single policy is sufficient to achieve the potential energy savings and that combination (packages) of polices can have combined results that are bigger than the sum of the individual policies (Harmelink et al., 2008; Tambach et al., 2010; Weiss et al., 2012; Murphy et al., 2012). The EU's Energy Efficiency Directive (EED) (European Union, 2012) has, since 2008, required Member States to describe co-ordinated packages of policies in their National Energy Efficiency Action Plans (NEEAP). Market transformation of domestic appliances in several developed countries has been achieved through a combination of minimum standards, energy labels, incentives for the most efficient equipment, and an effective communication campaign for end-users (Boza-Kiss et al., 2013). The specific policies, regulations, programmes and incentives needed are highly dependent on the product, market structure, institutional capacity, and the background conditions in each country. Other packages of measures are mandatory audits and financial incentives for the retrofitting of existing buildings, with incentives linked to the implementation of the audit findings and minimum efficiency requirements; voluntary programmes coupled with tax exemptions and other financial incentives (Murphy et al., 2012); and suppliers' obligations and white certificates (and, in France, tax credits) in addition to equipment labelling and standards—in order to promote products beyond the standards' requirements (Bertoldi et al., 2010b).

9.10.1.2 A holistic approach

Energy efficiency in buildings requires action beyond the point of investment in new buildings, retrofit, and equipment. A holistic approach considers the whole lifespan of the building, including master planning, lifecycle assessment and integrated building design to obtain the broadest impact possible, and therefore needs to begin at the neighbourhood or city level (see Chapter 12). In the holistic approach, building codes, design, operation, maintenance, and post occupancy evaluation are coordinated. Continuous monitoring of building energy use and dynamic codes allow policies to close the gap between design goals and actual building energy performance. The use of modern technologies to provide feedback on consumption in real time allows adjustment of energy performance and as a function of external energy supply. Dynamic information can also be used for energy certificates and databases to disclose building energy performance. Moreover, studies on durability and climate change mitigation show that the lifespan of a technical solution is as important as the choice of material, which signals to the importance of related policies such as eco-design directives and mandatory warranties (Mequignon et al., 2013a; b).

Another challenge is the need to develop the skills and training to deliver, maintain, and manage low carbon buildings. To implement the large number of energy saving projects (building retrofits or new construction) a large, skilled workforce is needed to carry out high-quality work at relatively low cost.

Implementation and enforcement of policies are key components of effective policy. These two components used together are the only way to ensure that the expected results of the policy are achieved. Developed countries are now increasing attention to proper implementation and enforcement (Jollands et al., 2010), for example, to survey equipment efficiency when minimum standards are in place and to check compliance with building codes. For example, EU Member States are required to develop independent control systems for their building labelling schemes (European Union, 2012). Public money invested in implementation and enforcement will be highly cost effective (Tambach et al., 2010), as it contributes to the overall cost-effectiveness of policies. In addition to enforcement, ex-post evaluation of policies is needed to assess their impact and to review policy design and stringency or to complement it with other policies. Implementation and enforcement is still a major challenge for developing countries that lack much of the capacity (e.g., testing laboratories for equipment efficiency) and knowledge to implement policies such as standards, labels and building codes.

9.10.2 Emerging policy instruments in buildings

Recent reports have comprehensively reviewed building-related policies (IPCC, 2007; GEA, 2012); the remainder of this chapter focuses on recent developments and important emerging instruments.

While technical efficiency improvements are still needed and are important to reduce energy demand (Alcott, 2008), increases in energy use are driven primarily by increasing demand for energy services (e.g., built space per capita and additional equipment). To address this, policies need to influence consumer behaviour and lifestyle (Herring, 2006; Sanquist et al., 2012) and the concept of sufficiency has been introduced in the energy efficiency policy debate (Herring, 2006; Oikonomou et al., 2009). Policies to target sufficiency aim at capping or discouraging increasing energy use due to increased floor space, comfort levels, and equipment. Policy instruments in this category include: (1) personal carbon trading (i.e., carbon markets with equitable personal allocations)—this has not yet been introduced and its social acceptability (Fawcett, 2010) and implementation (Eyre, 2010) have to be further demonstrated; (2) property taxation (e.g., related to a building's CO_2 emissions); and (3) progressive appliance standards and building codes, for example, with absolute consumption limits (kWh/person/year) rather than efficiency requirements (kWh/m^2/year) (Harris et al., 2007).

In order to reduce energy demand, policies may include promoting density, high space utilization, and efficient occupant behaviour as increased floor space entails more energy use. This might be achieved, for example, through incentives for reducing energy consumption—the so-called energy saving feed-in tariff (Bertoldi et al., 2010a; 2013a).

9.10.2.1 New developments in building codes (ordinance, regulation, or by-laws)

A large number of jurisdictions have now set, or are considering, very significant strengthening of the requirements for energy performance in building codes. There are debates about the precise level of ambition that is appropriate, especially with regard to NZEB mandates, which can be problematic (see 9.3). The EU is requiring its Member States to introduce building codes set at the cost optimal point using a lifecycle calculation, both for new buildings and those undergoing major renovation. As a result, by the end of 2020, all new buildings must be nearly zero energy by law. Many Member States (e.g., Denmark, Germany) have announced progressive building codes to gradually reduce the energy consumption of buildings towards nearly net zero levels. There is also action within local jurisdictions, e.g., the city of Brussels has mandated that all new social and public buildings must meet Passive House levels from 2013, while all new buildings have to meet these norms from 2015 (Moniteur Belge, 2011; BE, 2012; CSTC, 2012). In China, building codes have been adopted that seek saving of 50 % from pre-existing levels, with much increased provision for enforcement, leading to high expected savings (Zhou et al., 2011b). As demonstrated in sections 9.2 and 9.9, the widespread proliferation of these ambitious building codes, together with other policies to encourage efficiency, have already contributed to total building energy use trends stabilizing, or even slowing down.

9.10.2.2 Energy efficiency obligation schemes and 'white' certificates

Energy efficiency obligation schemes with or without so-called 'white certificates' as incentive schemes have been applied in some Member States of the European Union (Bertoldi et al., 2010a) and Australia (Crossley, 2008), with more recent uses in Brazil and India. White certificates evolved from non-tradable obligations on monopoly energy utilities, also known as suppliers' obligations or energy efficiency resources standards, largely but not only in the United States. Market liberalization initially led to a reduction in such activity (Ürge-Vorsatz et al., 2012b), driven by a belief that such approaches were not needed in, or incompatible with, competitive markets, although this is not correct (Vine et al., 2003). Their main use has been in regulated markets driven by obligations on energy companies to save energy (Bertoldi and Rezessy, 2008). The use of suppliers' obligations began in the UK in 2000, and these obligations are now significant in a number of EU countries, notably UK, France and Italy (Eyre et al., 2009). Energy supplier obligation schemes are a key part of EU policy for energy efficiency and the Energy Efficiency Directive (European Union, 2012) requires all EU Member States to introduce this policy or alternative schemes. Precise objectives, traded quantity and rules differ across countries. Cost effectiveness is typically very good (Bertoldi, 2012). However, white certificates tend to incentivize low cost, mass market measures rather than deep retrofits, and therefore there are concerns that this policy approach may not be best suited to future policy objectives (Eyre et al., 2009).

9.10.3 Financing opportunities

9.10.3.1 New financing schemes for deep retrofits

Energy efficiency in buildings is not a single market: it covers a diverse range of end-use equipment and technologies and requires very large numbers of small, dispersed projects with a diverse range of decision makers. As the chapter has demonstrated, many technologies in the building sector are proven and economic: if properly financed, the investment costs are paid back over short periods from energy cost savings. However, many potentially attractive energy investments do not meet the short-term financial return criteria of businesses, investors, and individuals, or there is no available financing. While significant savings are possible with relatively modest investment premiums, a first-cost sensitive buyer, or one lacking financing, will never adopt transformative solutions. Major causes of this gap are the shortage of relevant finance and of delivery mechanisms that suit the specifics of energy efficiency projects and the lack—in some markets—of pipelines of bankable energy efficiency projects. Creative business models from energy utilities, businesses, and financial institutions can overcome first-cost hurdles (Veeraboina and Yesuratnam, 2013). One innovative example is for energy-efficiency investment funds to capitalize on the lower risk of mortgage lending on low-energy housing; the funds to provide such investment can be attractive to socially responsible investment funds. In Germany, through the KfW development bank, energy efficiency loans with low interest rate are offered making it attractive to end-users. The scheme has triggered many building refurbishments (Harmelink et al., 2008).

Another example is the '*Green Deal*', which is a new initiative by the UK government designed to facilitate the retrofitting of energy saving measures to all buildings. Such schemes allows for charges on electricity bills in order to recoup costs of building energy efficiency improvements by private firms to consumers (Bichard and Thurairajah, 2013). The finance is tied to the energy meter rather than the building owner. The Green Deal was expected primarily to finance short payback measures previously covered by the suppliers' obligation, rather than deep retrofits. However, the UK government does not subsidize the loan interest rate, and commercial interest rates are not generally attractive to end-users. Take-up of energy efficiency in the Green Deal is therefore expected to be much lower than in a supplier obligation (Rosenow and Eyre, 2013).

In areas of the United States with Property Assessed Clean Energy (PACE) legislation in place, municipality governments offer a specific bond to investors and then use this to finance lending to consumers and businesses for energy retrofits (Headen et al., 2010). The loans are repaid over the assigned term (typically 15 or 20 years) via an annual assessment on their property tax bill. Legal concerns about the effect of PACE lending on mortgages for residential buildings (Van Nostrand, 2011) have resulted in the approach being mainly directed to non-domestic buildings.

ESCOs provide solutions for improving energy efficiency in buildings by guaranteeing that energy savings are able to repay the efficiency investment, thus overcoming financial constraints to energy efficiency investments. The ESCO model has been found to be effective in developed countries such as Germany (Marino et al., 2011) and the United States. In the last decade ESCOs have been created in number of developing countries (e.g., China, Brazil, and South Korea) supported by international financial institutions and their respective governments (UNEP SBCI, 2007; Da-li, 2009). Since the introduction of an international cooperation project by the Chinese government and World Bank in 1998, a market-based energy performance contract mechanism and ESCO industry has developed in China (Da-li, 2009) with Chinese government support. Policies for the support of ESCOs in developing countries include the creation of a Super ESCOs (Limaye and Limaye, 2011) by governmental agencies. Financing environments for ESCOs need to be improved to ensure they operate optimally and sources of financing, such as debt and equity, need to be located. Possible financing sources are commercial banks, venture capital firms, equity funds, leasing companies, and equipment manufacturers (Da-li, 2009). In social housing in Europe, funding can be provided through Energy Performance Certificates (EPC), in which an ESCO invests in a comprehensive refurbishment and repays itself through the generated savings. Social housing operators and ESCOs have established the legal, financial, and technical framework to do this (Milin and Bullier, 2011).

9.10.3.2 Opportunities in financing for green buildings

The existing global green building market is valued at approximately 550 billion USD_{2010} and is expected to grow through to 2015, with Asia anticipated to be the fastest growing region (Lewis, 2010). A survey on responsible property investing (RPI) (UNEP FI, 2009), covering key markets around the world, has shown it is possible to achieve a competitive advantage and greater return on property investment by effectively tackling environmental and social issues when investing in real estate (UNEP FI and PRI signatories, 2008). For example, in Japan, new rental-apartment buildings equipped with solar power systems and energy-saving devices had significantly higher occupancy rates than the average for other properties in the neighbourhood, and investment return rates were also higher (MLIT, 2010a; b). A survey comparing rent and vacancy rates of buildings (Watson, 2010) showed rents for LEED certified buildings were consistently higher than for uncertified buildings. In many municipalities in Japan, assessment by the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) and notification of assessment results are required at the time of construction (Murakami et al., 2004). Several financial products are available that provide a discount of more than 1 % on housing loans, depending on the grade received by the CASBEE assessment. This has been contributing to the diffusion of green buildings through financial schemes (IBEC, 2009). In addition, a housing eco-point system was implemented in 2009 in Japan, broadly divided between a home appliances eco-point system and a housing eco-point system. In the housing eco-point system, housing which satisfies the Top Runner-level standards are targeted, both newly constructed and existing buildings. This programme has contributed to the promotion of green buildings, with 160,000 (approximately 20 % of the total market) applications for subsidies for newly constructed buildings in 2010. In existing buildings, the number of window replacements has increased, and has attracted much attention (MLIT, 2012).

9.10.4 Policies in developing countries

Economic instruments and incentives are very important means to encourage stakeholders and investors in the building sector to adopt more energy efficient approaches in the design, construction, and operation of buildings (Huovila, 2007). This section provides an overview of financial instruments commonly applied in the developing world to promote emissions reduction in building sector.

In terms of *carbon markets*, the Clean Development Mechanism (CDM) has a great potential to promote energy efficiency and lower emissions in building sector. However, until recently it has bypassed the sector entirely, due to some methodological obstacles to energy efficiency projects (Michaelowa et al., 2009). However, a 'whole building' baseline and monitoring methodology approved in 2011 may pave the way for more building projects (Michaelowa and Hayashi, 2011). Since 2009, the share of CDM projects in the buildings sector has increased, particularly with regard to efficient lighting schemes (UNEP Risoe, 2012). The voluntary market has complemented the CDM as a financing mechanism, for example for solar home systems projects (Michaelowa et al., 2009; Michaelowa and Hayashi, 2011).

Public benefits charges are financing mechanisms meant to raise funds for energy efficiency measures and to accelerate market transformation in both developed and developing countries (UNEP SBCI, 2007). In Brazil, all energy distribution utilities are required to spend a minimum of 1 % of their revenue on energy efficiency interventions while at least a quarter of this fund is expected to be spent on end-user efficiency projects (UNEP SBCI, 2007).

Utility *demand side management (DSM)* may be the most viable option to implement and finance energy efficiency programs in smaller developing countries (Sarkar and Singh, 2010). In a developing country context, it is common practice to house DSM programmes within the local utilities due to their healthy financial means and strong technical and implementation capacities, for example, in Argentina, South Africa, Brazil, India, Thailand, Uruguay and Vietnam (Winkler and Van Es, 2007; Sarkar and Singh, 2010). Eskom, the South African electricity utility, uses its DSM funds mainly to finance load management and energy efficiency improvement including millions of free issued compact fluorescent lamps that have been installed in households (Winkler and Van Es, 2007).

Capital subsidies, grants and subsidized loans are among the most frequently used instruments for implementation of increased energy efficiency projects in buildings. Financial subsidy is used as the primary supporting fund in the implementation of retrofit projects in China (Dongyan, 2009). In recent years, the World Bank Group has steadily increased energy efficiency lending to the highest lending ever in the fiscal year of 2009 of USD_{2010} 3.3 billion, of which USD_{2010} 1.7 billion committed investments in the same year alone (Sarkar and Singh, 2010). Examples include energy efficient lighting programmes in Mali, energy efficiency projects in buildings in Belarus, carbon finance blended innovative financing to replace old chillers (air conditioning) with energy efficient and chlorofluorocarbon-free (CFC) chillers in commercial buildings in India (Sarkar and Singh, 2010). The Government of Nepal has been providing subsidies in the past few years to promote the use of solar home systems (SHS) in rural households (Dhakal and Raut, 2010). The certified emission reductions (CERs) accumulated from this project were expected to be traded in order to supplement the financing of the lighting program. The Global Environmental Facility (GEF) has directed a significant share of its financial resources to SHS and the World Bank similarly has provided a number of loans for SHS projects in Asia (Wamukonya, 2007). The GEF has provided a grant of 219 million USD_{2010} to finance 23 off-grid SHS projects in 20 countries (Wamukonya, 2007).

9.11 Gaps in knowledge and data

Addressing these main gaps and problems would improve the understanding of mitigation in buildings:

- The lack of adequate bottom-up data leads to a dominance of top down and supply-focused decisions about energy systems.

- Misinformation and simplified techniques pose risks to providing a full understanding of integrated and regionally adequate building systems, and this leads to fragmented actions and weaker results.
- Weak or poor information about opportunities and costs affects optimal decisions and appropriate allocation of financial resources.
- Energy indicators relate to efficiency, but rarely to sufficiency.
- Improved and more comprehensive databases on real, measured building energy use, and capturing behaviour and lifestyles are necessary to develop exemplary practices from niches to standard.
- Continuous monitoring and constant modification of performance and dynamics of codes would allow implementation to catch up with the potential for efficiency improvements and co-benefits; this would also provide better feedback to the policymaking process, to education, to capacity building, and to training.
- Quantification and monetization of (positive and negative) externalities over the building life cycle should be well-integrated into decision-making processes.

9.12 Frequently Asked Questions

FAQ 9.1 What are the recent advances in building sector technologies and know-how since the AR4 that are important from a mitigation perspective?

Recent advances in information technology, design, construction, and know-how have opened new opportunities for a transformative change in building-sector related emissions that can contribute to meeting ambitious climate targets at socially acceptable costs, or often at net benefits. Main advances do not lie in major technological developments, but rather in their extended systemic application, partially as a result of advanced policies, as well as in improvements in the performance and reductions in the cost of several technologies. For instance, there are over 57,000 buildings meeting Passive House standard and 'nearly zero energy' new construction has become the law in the 27 Member States of the European Union. Even higher energy performance levels are being successfully applied to new and existing buildings, including non-residential buildings. The costs have been gradually declining; for residential buildings at the level of Passive House standard they account for 5–8 % of conventional building costs, and some net zero or nearly zero energy commercial buildings having been built at equal or even lower costs than conventional ones (see 9.3 and 9.7).

FAQ 9.2 How much could the building sector contribute to ambitious climate change mitigation goals, and what would be the costs of such efforts?

According to the GEA 'efficiency' pathway, by 2050 global heating and cooling energy use could decrease by as much as 46 % as compared to 2005, if today's best practices in construction and retrofit know-how are broadly deployed (Ürge-Vorsatz et al., 2012c). This is despite the over 150 % increase in floor area during the same period, as well as significant increase in thermal comfort, as well as the eradication of fuel poverty (Ürge-Vorsatz et al., 2012c). The costs of such scenarios are also significant, but according to most models, the savings in energy costs typically more than exceed the investment costs. For instance, GEA (2012) projects an approximately 24 billion USD_{2010} in cumulative additional investment needs for realizing these advanced scenarios, but estimates an over 65 billion USD_{2010} in cumulative energy cost savings until 2050.

FAQ 9.3 Which policy instrument(s) have been particularly effective and/or cost-effective in reducing building-sector GHG emission (or their growth, in developing countries)?

Policy instruments in the building sector have proliferated since the AR4, with new instruments such as white certificates, preferential loans, grants, progressive building codes based on principles of cost-optimum minimum requirements of energy performance and life cycle energy use calculation, energy saving feed-in tariffs as well as suppliers' obligations, and other measures introduced in several countries. Among the most cost-effective instruments have been building codes and labels, appliance standards and labels, supplier obligations, public procurement and leadership programs. Most of these are regulatory instruments. However, most instruments have best practice applications that have achieved CO_2 reductions at low or negative social costs, signalling that a broad portfolio of tools is available to governments to cut building-related emissions cost-effectively. Appliance standards and labels, building codes, promotion of ESCOs, CDM and JI, and financing tools (grants and subsidies) have so far performed as the most environmentally effective tools among the documented cases. However, the environmental effectiveness also varies a lot by case. Based on a detailed analysis of policy evaluations, virtually any of these instruments can perform very effective (environmentally and/or cost-wise) if tailored to local conditions and policy settings, and if implemented and enforced well (Boza-Kiss et al., 2013). Therefore it is likely that the choice of instrument is less crucial than whether it is designed, applied, implemented and enforced well and consistently.

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10 Industry

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Executive Summary

An absolute reduction in emissions from the industry sector will require deployment of a broad set of mitigation options beyond energy efficiency measures (*medium evidence, high agreement*). In the last two to three decades there has been continued improvement in energy and process efficiency in industry, driven by the relatively high share of energy costs. In addition to energy efficiency, other strategies such as emissions efficiency (including e.g., fuel and feedstock switching, carbon dioxide capture and storage (CCS)), material use efficiency (e.g., less scrap, new product design), recycling and re-use of materials and products, product service efficiency (e.g., car sharing, maintaining buildings for longer, longer life for products), or demand reductions (e.g., less mobility services, less product demand) are required in parallel (*medium evidence, high agreement*). [Section 10.4, 10.7]

Industry-related greenhouse gas (GHG) emissions have continued to increase and are higher than GHG emissions from other end-use sectors (*high confidence*). Despite the declining share of industry in global gross domestic product (GDP), global industry and waste/wastewater GHG emissions grew from 10.4 $GtCO_2eq$ in 1990 to 13.0 $GtCO_2eq$ in 2005 to 15.4 $GtCO_2eq$ in 2010. Total global GHG emissions for industry and waste/wastewater in 2010, which nearly doubled since 1970, were comprised of direct energy-related CO_2 emissions of 5.3 $GtCO_2eq$, indirect CO_2 emissions from production of electricity and heat for industry of 5.2 $GtCO_2eq$, process CO_2 emissions of 2.6 $GtCO_2eq$, non-CO_2 GHG emissions of 0.9 $GtCO_2eq$, and waste/wastewater emissions of 1.4 $GtCO_2eq$. 2010 direct and indirect emissions were dominated by CO_2 (85.1 %) followed by CH_4 (8.6 %), HFC (3.5 %), N_2O (2.0 %), PFC (0.5 %) and SF_6 (0.4 %) emissions. Currently, emissions from industry are larger than the emissions from either the buildings or transport end-use sectors and represent just over 30 % of global GHG emissions in 2010 (just over 40 % if Agriculture, Forestry, and Other Land Use (AFOLU) emissions are not included). (*high confidence*) [10.2, 10.3]

Globally, industrial GHG emissions are dominated by the Asia region, which was also the region with the fastest emission growth between 2005 and 2010 (*high confidence*). In 2010, over half (52 %) of global direct GHG emissions from industry and waste/wastewater were from the Asia region (ASIA), followed by the member countries of the Organisation for Economic Co-operation and Development in 1990 (OECD-1990) (25 %), Economies in Transition (EIT) (9 %), Middle East and Africa (MAF) (8 %), and Latin America (LAM) (6 %). Between 2005 and 2010, GHG emissions from industry grew at an average annual rate of 3.5 % globally, comprised of 7 % average annual growth in the ASIA region, followed by MAF (4.4 %), LAM (2 %), and the EIT countries (0.1 %), but declined in the OECD-1990 countries (–1.1 %). [10.3]

The energy intensity of the sector could be reduced by approximately up to 25 % compared to current level through wide-scale upgrading, replacement and deployment of best available technologies, particularly in countries where these are not in practice and for non-energy intensive industries (*robust evidence, high agreement*). Despite long-standing attention to energy efficiency in industry, many options for improved energy efficiency remain. [10.4, 10.7]

Through innovation, additional reductions of approximately up to 20 % in energy intensity may potentially be realized before approaching technological limits in some energy intensive industries (*limited evidence, medium agreement*). Barriers to implementing energy efficiency relate largely to the initial investment costs and lack of information. Information programmes are the most prevalent approach for promoting energy efficiency, followed by economic instruments, regulatory approaches, and voluntary actions. [10.4, 10.7, 10.9, 10.11]

Besides sector specific technologies, cross-cutting technologies and measures applicable in both large energy intensive industries and Small and Medium Enterprises (SMEs) can help to reduce GHG emissions (*robust evidence, high agreement*). Cross-cutting technologies such as efficient motors, electronic control systems, and cross-cutting measures such as reducing air or steam leaks help to optimize performance of industrial processes and improve plant efficiency cost-effectively with both energy savings and emissions benefits [10.4].

Long-term step-change options can include a shift to low carbon electricity, radical product innovations (e.g., alternatives to cement), or carbon dioxide capture and storage (CCS). Once demonstrated, sufficiently tested, cost-effective, and publicly accepted, these options may contribute to significant climate change mitigation in the future (*medium evidence, medium agreement*). [10.4]

The level of demand for new and replacement products has a significant effect on the activity level and resulting GHG emissions in the industry sector (*medium evidence, high agreement*). Extending product life and using products more intensively could contribute to reduction of product demand without reducing the service. Absolute emission reductions can also come through changes in lifestyle and their corresponding demand levels, be it directly (e.g. for food, textiles) or indirectly (e.g. for product/service demand related to tourism). [10.4]

Mitigation activities in other sectors and adaptation measures may result in increased industrial product demand and corresponding emissions (*robust evidence, high agreement*). Production of mitigation technologies (e.g., insulation materials for buildings) or material demand for adaptation measures (e.g., infrastructure materials) contribute to industrial GHG emissions. [10.4, 10.6]

Systemic approaches and collaboration within and across industrial sectors at different levels, e.g., sharing of infrastructure, information, waste and waste management facilities, heating,

and cooling, may provide further mitigation potential in certain regions or industry types (*robust evidence, high agreement*). The formation of industrial clusters, industrial parks, and industrial symbiosis are emerging trends in many developing countries, especially with SMEs. [10.5]

Several emission-reducing options in the industrial sector are cost-effective and profitable (*medium evidence, medium agreement*). While options in cost ranges of 20–50, 0–20, and even below 0 USD_{2010}/tCO_2eq exist, to achieve near-zero emission intensity levels in the industry sector would require additional realization of long-term step-change options (e.g., CCS) associated with higher levelized costs of conserved carbon (LCCC) in the range of 50–150 USD_{2010}/tCO_2. However, mitigation costs vary regionally and depend on site-specific conditions. Similar estimates of costs for implementing material efficiency, product-service efficiency, and service demand reduction strategies are not available. [10.7]

Mitigation measures in the industry sector are often associated with co-benefits (*robust evidence, high agreement*). Co-benefits of mitigation measures could drive industrial decisions and policy choices. They include enhanced competitiveness through cost reductions, new business opportunities, better environmental compliance, health benefits through better local air and water quality and better work conditions, and reduced waste, all of which provide multiple indirect private and social benefits. [10.8]

Unless barriers to mitigation in industry are resolved, the pace and extent of mitigation in industry will be limited and even profitable measures will remain untapped (*robust evidence, high agreement*). There are a broad variety of barriers to implementing energy efficiency in the industry sector; for energy-intensive industry, the issue is largely initial investment costs for retrofits, while barriers for other industries include both cost and a lack of information. For material efficiency, product-service efficiency, and demand reduction, there is a lack of experience with implementation of mitigation measures and often there are no clear incentives for either the supplier or consumer. Barriers to material efficiency include lack of human and institutional capacities to encourage management decisions and public participation. [10.9]

There is no single policy that can address the full range of mitigation measures available for industry and overcome associated barriers (*robust evidence, high agreement*). In promoting energy efficiency, information programs are the most prevalent approach, followed by economic instruments, regulatory approaches and voluntary actions. To date, few policies have specifically pursued material or product service efficiency. [10.11]

While the largest mitigation potential in industry lies in reducing CO_2 emissions from fossil fuel use, there are also significant mitigation opportunities for non-CO_2 gases. Key opportunities comprise, for example, reduction of HFC emissions by leak repair, refrigerant recovery and recycling, and proper disposal and replacement by alternative refrigerants (ammonia, HC, CO_2). Nitrous oxide (N_2O) emissions from adipic and nitric acid production can be reduced through the implementation of thermal destruction and secondary catalysts. The reduction of non-CO_2 GHGs also faces numerous barriers. Lack of awareness, lack of economic incentives, and lack of commercially available technologies (e.g., for HFC recycling and incineration) are typical examples. [10.4, 10.7, 10.9]

Long-term scenarios for industry highlight improvements in emissions efficiency as an important future mitigation strategy (*robust evidence, high agreement*). Detailed industry sector scenarios fall within the range of more general long-term integrated scenarios. Improvements in emissions efficiency in the mitigation scenarios result from a shift from fossil fuels to electricity with low (or negative) CO_2 emissions and use of CCS for industry fossil fuel use and process emissions. The crude representation of materials, products, and demand in scenarios limits the evaluation of the relative importance of material efficiency, product-service efficiency, and demand reduction options. (*robust evidence, high agreement*) [6.8, 10.10]

The most effective option for mitigation in waste management is waste reduction, followed by re-use and recycling and energy recovery (*robust evidence, high agreement*) [10.4, 10.14]. Direct emissions from the waste sector almost doubled during the period from 1970 to 2010. Globally, approximately only 20 % of municipal solid waste (MSW) is recycled and approximately 13.5 % is treated with energy recovery while the rest is deposited in open dumpsites or landfills. Approximately 47 % of wastewater produced in the domestic and manufacturing sectors is still untreated. As the share of recycled or reused material is still low, waste treatment technologies and energy recovery can also result in significant emission reductions from waste disposal. Reducing emissions from landfilling through treatment of waste by anaerobic digestion has the largest cost range, going from negative cost to very high cost. Also, advanced wastewater treatment technologies may enhance GHG emissions reduction in the wastewater treatment but they tend to concentrate in the higher costs options (*medium evidence, medium agreement*). [10.14]

A key challenge for the industry sector is the uncertainty, incompleteness, and quality of data available in the public domain on energy use and costs for specific technologies on global and regional scales that can serve as a basis for assessing performance, mitigation potential, costs, and for developing policies and programmes with high confidence. Bottom-up information on cross-sector collaboration and demand reduction as well as their implications for mitigation in industry is particularly limited. Improved modelling of material flows in integrated models could lead to a better understanding of material efficiency and demand reduction strategies and the associated mitigation potentials. [10.12]

10.1 Introduction

This chapter provides an update to developments on mitigation in the industry sector since the IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report (AR4) (IPCC, 2007), but has much wider coverage. Industrial activities create all the physical products (e.g., cars, agricultural equipment, fertilizers, textiles, etc.) whose use delivers the final services that satisfy current human needs. Compared to the industry chapter in AR4, this chapter analyzes industrial activities over the whole supply chain, from extraction of primary materials (e.g., ores) or recycling (of waste materials), through product manufacturing, to the demand for the products and their services. It includes a discussion of trends in activity and emissions, options for mitigation (technology, practices, and behavioural aspects), estimates of the mitigation potentials of some of these options and related costs, co-benefits, risks and barriers to their deployment, as well as industry-specific policy instruments. Findings of integrated models (long-term mitigation pathways) are also presented and discussed from the sector perspective. In addition, at the end of the chapter, the hierarchy in waste management and mitigation opportunities are synthesized, covering key waste-related issues that appear across all chapters in the Working Group III contribution to the IPCC Fifth Assessment Report (AR5).

Figure 10.1, which shows a breakdown of total global anthropogenic GHG emissions in 2010 based on Bajželj et al. (2013), illustrates the logic that has been used to distinguish the industry sector from other sectors discussed in this report. The figure shows how human demand for energy services, on the left, is provided by economic sectors, through the use of equipment in which devices create heat or work from final energy. In turn, the final energy has been created by processing a primary energy source. Combustion of carbon-based fuels leads to the release of GHG emissions as shown on the right. The remaining anthropogenic emissions arise from chemical reactions in industrial processes, from waste management and from the agriculture and land-use changes discussed in Chapter 11.

Mitigation options can be chosen to reduce GHG emissions at all stages in Figure 10.1, but caution is needed to avoid 'double counting'. The figure also demonstrates that care is needed when allocating emissions to specific products and services ('carbon footprints', for example) while ensuring that the sum of all 'footprints' adds to the sum of all emissions.

Emissions from industry (30 % of total global GHG emissions) arise mainly from material processing, i.e., the conversion of natural resources (ores, oil, biomass) or scrap into materials stocks which are then converted in manufacturing and construction into products. Pro-

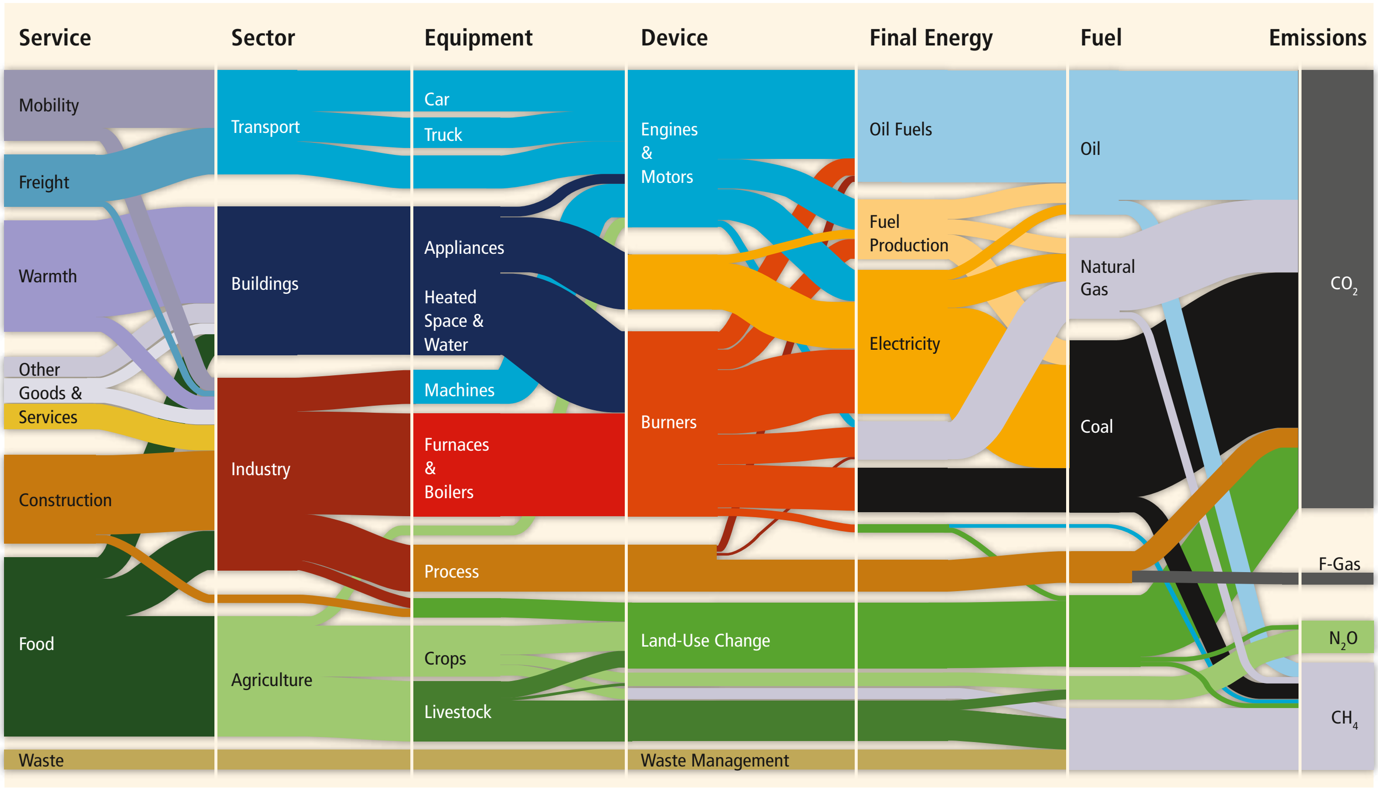


Figure 10.1 | A Sankey diagram showing the system boundaries of the industry sector and demonstrating how global anthropogenic emissions in 2010 arose from the chain of technologies and systems required to deliver final services triggered by human demand. The width of each line is proportional to GHG emissions released, and the sum of these widths along any vertical slice through the diagram is the same, representing all emissions in 2010 (Bajželj et al., 2013).

duction of just iron and steel and non-metallic minerals (predominately cement) results in 44 % of all carbon dioxide (CO_2) emissions (direct, indirect, and process-related) from industry. Other emission-intensive sectors are chemicals (including plastics) and fertilizers, pulp and paper, non-ferrous metals (in particular aluminium), food processing (food growing is covered in Chapter 11), and textiles.

Decompositions of GHG emissions have been used to analyze the different drivers of global industry-related emissions. An accurate decomposition for the industry sector would involve great complexity, so instead this chapter uses a simplified conceptual expression to identify the key mitigation opportunities available within the sector:

$$G = \frac{G}{E} \times \frac{E}{M} \times \frac{M}{P} \times \frac{P}{S} \times S$$

where G is the GHG emissions of the industrial sector within a specified time period (usually one year), E is industrial sector energy consumption and M is the total global production of materials in that period. P is stock of products created from these materials (including both consumables and durables added to existing stocks), and S is the services delivered in the time period through use of those products.

The expression is indicative only, but leads to the main mitigation strategies discussed in this chapter:

G/E is the *emissions intensity* of the sector expressed as a ratio to the energy used: the GHG emissions of industry arise largely from energy use (directly from combusting fossil fuels, and indirectly through purchasing electricity and steam), but emissions also arise from industrial chemical reactions. In particular, producing cement, chemicals, and non-ferrous metals leads to the inevitable release of significant 'process emissions' regardless of energy supply. We refer to reductions in G/E as *emissions efficiency* for the energy inputs and the processes.

E/M is the *energy intensity*: approximately three quarters of industrial energy use is required to create materials from ores, oil or biomass, with the remaining quarter used in the downstream manufacturing and construction sectors that convert materials to products. The energy required can in some cases (particularly for metals and paper) be reduced by production from recycled scrap, and can be further reduced by material re-use, or by exchange of waste heat and exchange of by-products between sectors. Reducing E/M is the goal of *energy efficiency.*

M/P is the *material intensity* of the sector: the amount of material required to create a product and maintain the stock of a product depends both on the design of the product and on the scrap discarded during its production. Both can be reduced by *material efficiency.*

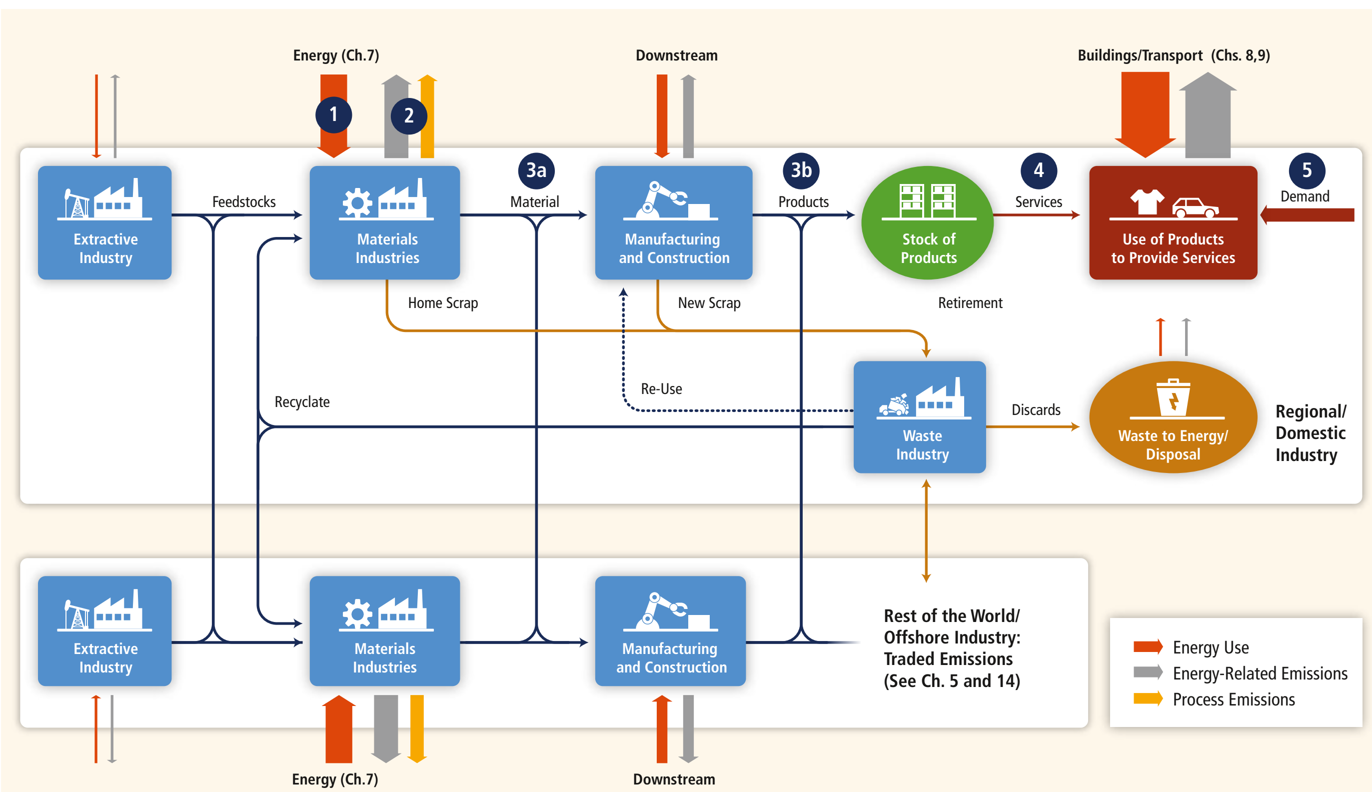


Figure 10.2 | A schematic illustration of industrial activity over the supply chain. Options for climate change mitigation in the industry sector are indicated by the circled numbers: (1) Energy efficiency (e. g., through furnace insulation, process coupling, or increased material recycling); (2) Emissions efficiency (e. g., from switching to non-fossil fuel electricity supply, or applying CCS to cement kilns); (3a) Material efficiency in manufacturing (e. g., through reducing yield losses in blanking and stamping sheet metal or re-using old structural steel without melting); (3b) Material efficiency in product design (e. g., through extended product life, light-weight design, or de-materialization); (4) Product-Service efficiency (e. g., through car sharing, or higher building occupancy); (5) Service demand reduction (e. g., switching from private to public transport).

P/S is the *product-service intensity*: the level of service provided by a product depends on its intensity of use. For consumables (e.g., food or detergent) that are used within the accounting period in which they are produced, service is provided solely by the production within that period. For durables that last for longer than the accounting period (e.g., clothing), services are provided by the stock of products in current use. In this case P is the flow of material required to replace retiring products and to meet demand for increases in total stock. Thus for consumables, P/S can be reduced by more precise use (for example using only recommended doses of detergents or applying fertilizer precisely) while for durables, P/S can be reduced both by using durable products for longer and by using them more intensively. We refer to reductions in P/S as *product-service efficiency*.

S: The total global demand for service is a function of population, wealth, lifestyle, and the whole social system of expectations and aspirations. If the total demand for service were to decrease, it would lead to a reduction in industrial emissions, and we refer to this as *demand reduction.*

Figure 10.2 expands on this simplified relationship to illustrate the main options for GHG emissions mitigation in industry (circled numbers). The figure also demonstrates how international trade of products leads to significant differences between 'production' and 'consumption' measures of national emissions, and demonstrates how the 'waste' industry, which includes material recycling as well as options like 'waste to energy' and disposal, has a significant potential for influencing future industrial emissions.

Figure 10.2 clarifies the terms used for key sectors in this chapter: 'Industry' refers to the totality of activities involving the physical transformation of materials within which 'extractive industry' supplies feedstock to the energy-intensive 'materials industries' which create refined materials. These are converted by 'manufacturing' into products and by 'construction' into buildings and infrastructure. 'Home scrap' from the materials processing industries, 'new scrap' from downstream construction and manufacturing, and products retiring at end-of-life are processed in the 'waste industry.' This 'waste' may be recycled (particularly bulk metals, paper, glass and some plastics), may be re-used to save the energy required for recycling, or may be discarded to landfills or incinerated (which can lead to further emissions on one hand and energy recovery on the other hand).

10.2 New developments in extractive mineral industries, manufacturing industries and services

World production trends of mineral extractive industries, manufacturing, and services, have grown steadily in the last 40 years (Figure 10.3). However, the service sector share in world GDP increased from 50 % in 1970 to 70 % in 2010; while the industry world GDP share decreased from 38.2 to 26.9 % (World Bank, 2013).

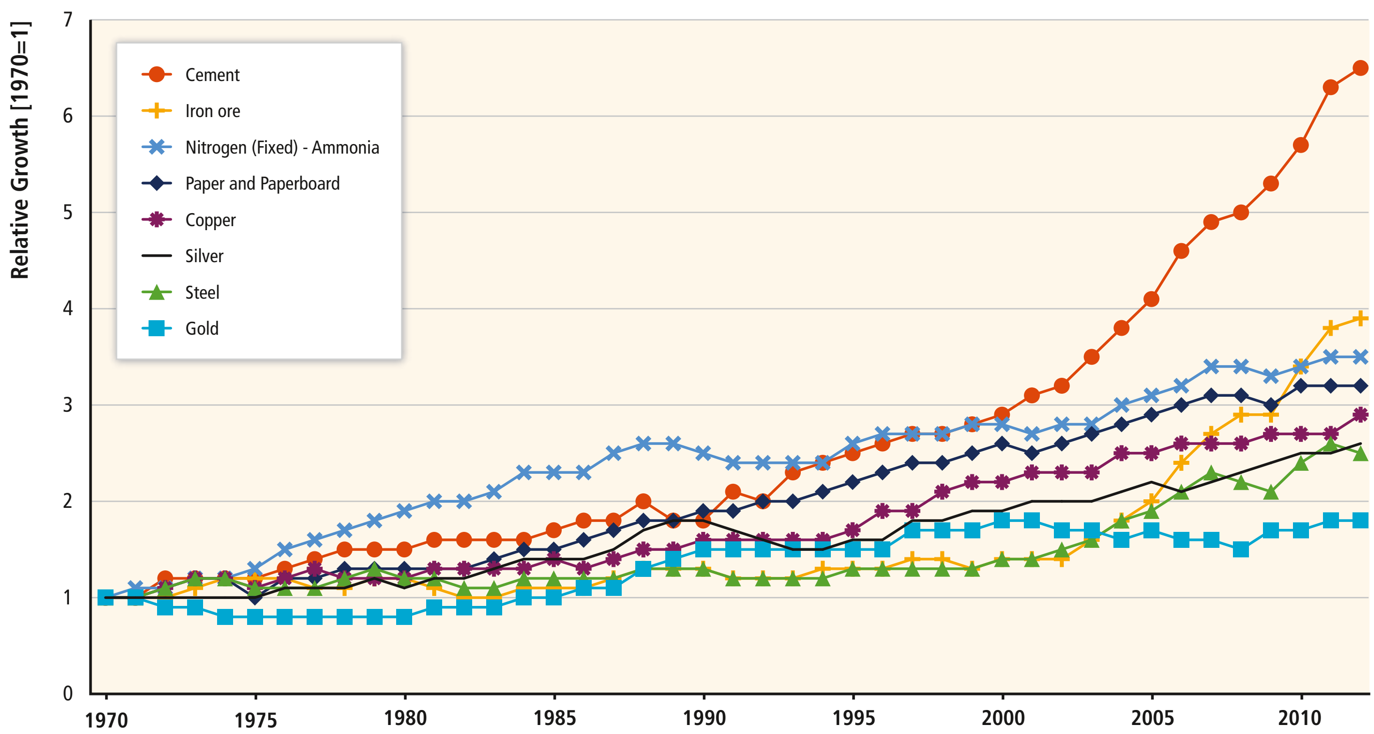


Figure 10.3 | World's growth of main minerals and manufacturing products (1970 = 1). Sources: (WSA, 2012a; FAO, 2013; Kelly and Matos, 2013).

Table 10.1 | Total production of energy-intensive industrial goods for the world top-5 producers of each commodity: 2005, 2012, and average annual growth rate (AAGR) (FAO, 2013; Kelly and Matos, 2013).

Commodity/Country	2005 [Mt]	2012 [Mt]	AAGR
Iron ore			
World	1540	3000	10 %
China	420	1300	18 %
Australia	262	525	10 %
Brazil	280	375	4 %
India	140	245	8 %
Russia	97	100	0.4 %
Steel			
World	1130	1500	4 %
China	349	720	11 %
Japan	113	108	–1 %
U.S.	95	91	–1 %
India	46	76	8 %
Russia	66	76	2 %
Cement			
World	2310	3400	6 %
China	1040	2150	11 %
India	145	250	8 %
U.S.	101	74	–4 %
Brazil	37	70	10 %
Iran	33	65	10 %
Ammonia			
World	121.0	137.0	2 %
China	37.8	44.0	2 %
India	10.8	12.0	2 %
Russia	10.0	10.0	0 %
U.S.	8.0	9.5	2 %
Trinidad & Tobago	4.2	5.5	4 %
Aluminium			
World	31.9	44.9	5 %
China	7.8	19.0	14 %
Russia	3.7	4.2	2 %
Canada	2.9	2.7	–1 %
U.S.	2.5	2.0	–3 %
Australia	1.9	1.9	0 %
Paper			
World	364.7	401.1	1 %
China	60.4	106.3	8 %
U.S.	83.7	75.5	–1 %
Japan	31.0	26.0	–2 %
Germany	21.7	22.6	1 %
Indonesia	7.2	11.5	7 %

Concerning extractive industries for metallic minerals, from 2005 to 2012 annual mining production of iron ore, gold, silver, and copper increased by 10 %, 1 %, 2 %, and 2 % respectively (Kelly and Matos, 2013). Most of the countries in Africa, Latin America, and the transition economies produce more than they use; whereas use is being driven mainly by consumption in China, India, and developed countries (UNCTAD, 2008)[1]. Extractive industries of rare earths are gaining importance because of their various uses in high-tech industry (Moldoveanu and Papangelakis, 2012). New mitigation technologies, such as hybrid and electric vehicles (EVs), electricity storage and renewable technologies, increase the demand for certain minerals, such as lithium, gallium, and phosphates (Bebbington and Bury, 2009). Concerns over depletion of these minerals have been raised, but important research on extraction methods as well as increasing recycling rates are leading to increasing reserve estimates for these materials (Graedel et al., 2011; Resnick Institute, 2011; Moldoveanu and Papangelakis, 2012; Eckelman et al., 2012). China accounts for 97 % of global rare earth extraction (130 Mt in 2010) (Kelly and Matos, 2013).

Regarding manufacturing production, the annual global production growth rate of steel, cement, ammonia, aluminium, and paper—the most energy-intensive industries—ranged from 2 % to 6 % between 2005 and 2012 (Table 10.1). Many trends are responsible for this development (e.g., urbanization significantly triggered demand on construction materials). Over the last decades, as a general trend, the world has witnessed decreasing industrial activity in developed countries with a major downturn in industrial production due to the economic recession in 2009 (Kelly and Matos, 2013). There is continued increase in industrial activity and trade of some developing countries. The increase in manufacturing production and consumption has occurred mostly in Asia. China is the largest producer of the main industrial outputs. In many middle-income countries industrialization has stagnated, and in general Africa and Least Developed Countries (LDCs) have remained marginalized (UNIDO, 2009; WSA, 2012a). In 2012, 1.5 billion tonnes of steel (212 kg/cap) were manufactured; 46 % was produced and consumed in mainland China (522 kg/cap). China also dominates global cement production, producing 2.2 billion tonnes (1,561 kg/cap) in 2012, followed by India with only 250 Mt (202 kg/cap) (Kelly and Matos, 2013; UNDESA, 2013). More subsector specific trends are in Section 10.4.

Globally large-scale production dominates energy-intensive industries; however small- and medium-sized enterprises are very important in many developing countries. This brings additional challenges for mitigation efforts (Worrell et al., 2009; Roy, 2010; Ghosh and Roy, 2011).

[1] For example, in 2008, China imported 50 % of the world's total iron ore exports and produced about 50 % of the world's pig iron (Kelly and Matos, 2013). India demanded 35 % of world's total gold production in 2011 (WGC, 2011), and the United States consumed 33 % of world's total silver production in 2011 (Kelly and Matos, 2013).

Another important change in the world´s industrial output over the last decades has been the rise in the proportion of international trade. Manufactured products are not only traded, but the production process is increasingly broken down into tasks that are themselves outsourced and/or traded; i. e., production is becoming less vertically integrated. In addition to other drivers such as population growth, urbanization, and income increase, the rise in the proportion of trade has been driving production increase for certain countries (Fisher-Vanden et al., 2004; Liu and Ang, 2007; Reddy and Ray, 2010; OECD, 2011). The economic recession of 2009 reduced industrial production worldwide because of consumption reduction, low optimism in credit market, and a decline in world trade (Nissanke, 2009). More discussion on GHG emissions embodied in trade is presented in Chapter 14. Similar to industry, the service sector is heterogeneous and has significant proportion of small and medium sized enterprises. The service sector covers activities such as public administration, finance, education, trade, hotels, restaurants, and health. Activity growth in developing countries and structural shift with rising income is driving service sector growth (Fisher-Vanden et al., 2004; Liu and Ang, 2007; Reddy and Ray, 2010; OECD, 2011). OECD countries are shifting from manufacturing towards service-oriented economies (Sun, 1998; Schäfer, 2005; US EIA, 2010), however, this is also true for some non-OECD countries. For example, India has almost 64 %–66 % of GDP contribution from service sector (World Bank, 2013).

10.3 New developments in emission trends and drivers

In 2010, the industry sector accounted for around 28 % of final energy use (IEA, 2013). Global industry and waste/wastewater GHG emissions grew from 10.37 $GtCO_2eq$ in 1990 to 13.04 $GtCO_2eq$ in 2005 to 15.44 $GtCO_2eq$ in 2010. These emissions are larger than the emissions from either the buildings or transport end-use sectors and represent just over 30 % of global GHG emissions in 2010 (just over 40 % if AFOLU emissions are not included). These total emissions are comprised of:

- Direct energy-related CO_2 emissions for industry[2]
- Indirect CO_2 emissions from production of electricity and heat for industry[3]
- Process CO_2 emissions
- Non-CO_2 GHG emissions
- Direct emissions for waste/wastewater

[2] This also includes CO_2 emissions from non-energy uses of fossil fuels.

[3] The methodology for calculating indirect CO_2 emissions is based on de la Rue du Can and Price (2008) and described in Annex II.5.

Figure 10.4 shows global industry and waste/wastewater direct and indirect GHG emissions by source from 1970 to 2010. Table 10.2 shows primary energy[4] and GHG emissions for industry by emission type (direct energy-related, indirect from electricity and heat production, process CO_2, and non-CO_2), and for waste/wastewater for five world regions and the world total.[5]

Figure 10.5 shows global industry and waste/wastewater direct and indirect GHG emissions by region from 1970 to 2010. This regional breakdown shows that:

- Over half (52 %) of global direct GHG emissions from industry and waste/wastewater are from the ASIA region, followed by OECD-1990 (25 %), EIT (9.4 %), MAF (7.6 %), and LAM (5.7 %).
- Between 2005 and 2010, GHG emissions from industry grew at an average annual rate of 3.5 % globally, comprised of 7.0 % average annual growth in the ASIA region, followed by MAF (4.4 %), LAM (2.0 %), and the EIT countries (0.1 %), but declined in the OECD-1990 countries (–1.1 %).

Regional trends are further discussed in Chapter 5, Section 5.2.1.

Table 10.3 provides 2010 direct and indirect GHG emissions by source and gas. 2010 direct and indirect emissions were dominated by CO_2 (85.1 %), followed by methane (CH_4) (8.6 %), hydrofluorocarbons (HFC) (3.5 %), nitrous oxide (N_2O) (2.0 %), Perfluorocarbons (PFC) (0.5 %) and sulphur hexafluoride (SF_6) (0.4 %) emissions.

10.3.1 Industrial CO_2 emissions

As shown in Table 10.3, industrial CO_2 emissions were 13.14 $GtCO_2$ in 2010. These emissions were comprised of 5.27 $GtCO_2$ direct energy-related emissions, 5.25 $GtCO_2$ indirect emissions from electricity and heat production, 2.59 $GtCO_2$ from process CO_2 emissions and 0.03 $GtCO_2$ from waste/wastewater. Process CO_2 emissions are comprised of process-related emissions of 1.352 $GtCO_2$ from cement production,[6] 0.477 $GtCO_2$ from production of chemicals, 0.242 $GtCO_2$ from lime production, 0.134 $GtCO_2$ from coke ovens, 0.074 $GtCO_2$ from non-ferrous metals production, 0.072 $GtCO_2$ from iron and steel production, 0.061 $GtCO_2$ from ferroalloy production, 0.060 $GtCO_2$ from limestone and dolomite use, 0.049 $GtCO_2$ from solvent and other product use, 0.042 $GtCO_2$ from production of other minerals and 0.024 $GtCO_2$ from non-energy use of lubricants/waxes (JRC/PBL, 2013). Total industrial CO_2 values include emissions from mining and quarrying, from manufacturing, and from construction.

[4] See Glossary in Annex I for definition of primary energy.

[5] The IEA also recently published CO_2 emissions with electricity and heat allocated to end-use sectors (IEA, 2012a). However, the methodology used in this report differs slightly from the IEA approach as explained in Annex II.5

[6] Another source, Boden et al., 2013, indicates that cement process CO_2 emissions in 2010 were 1.65 $GtCO_2$.

Energy-intensive processes in the mining sector include excavation, mine operation, material transfer, mineral preparation, and separation. Energy consumption for mining[7] and quarrying, which is included in 'other industries' in Figure 10.4, represents about 2.7 % of world-wide industrial energy use, varying regionally, and a significant share of national industrial energy use in Botswana and Namibia (around 80 %), Chile (over 50 %), Canada (30 %), Zimbabwe (18.6 %), Mongolia (16.5 %), and South Africa (almost 15 %) in 2010 (IEA, 2012b; c).

[7] Discussion of extraction of energy carriers (e.g., coal, oil, and natural gas) takes place in Chapter 7.

Manufacturing is a subset of industry that includes production of all products (e.g., steel, cement, machinery, textiles) except for energy products, and does not include energy used for construction. Manufacturing is responsible for about 98 % of total direct CO_2 emissions from the industrial sector (IEA, 2012b; c). Most manufacturing CO_2 emissions arise due to chemical reactions and fossil fuel combustion largely used to provide the intense heat that is often required to bring about the physical and chemical transformations that convert raw materials into industrial products. These industries, which include production of chemicals and petrochemicals, iron and steel, cement, pulp and paper, and aluminium, usually account for most of the sector's

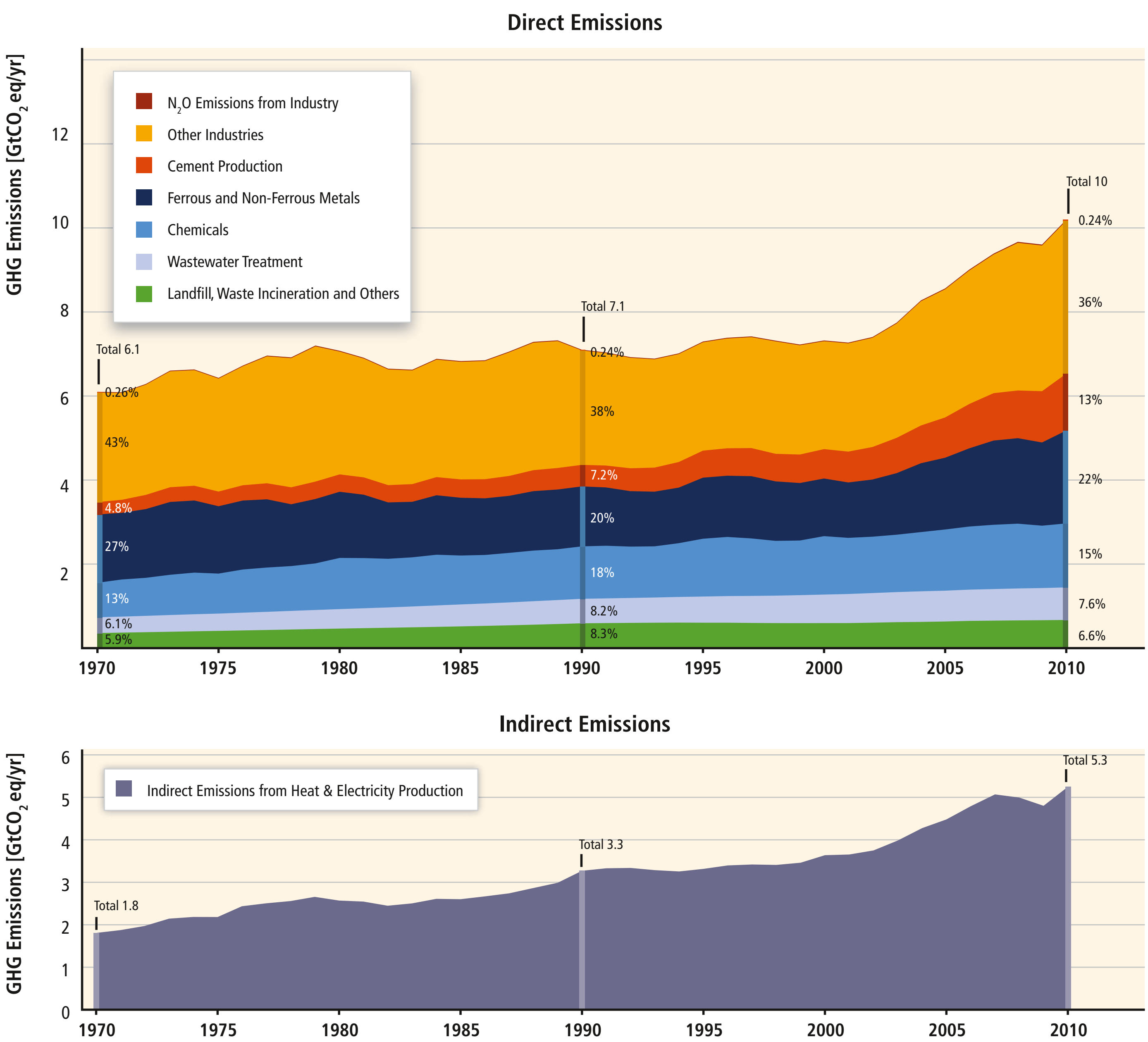


Figure 10.4 | Total global industry and waste/wastewater direct and indirect GHG emissions by source, 1970–2010 ($GtCO_2eq/yr$) (de la Rue du Can and Price, 2008; IEA, 2012a; JRC/PBL, 2013). See also Annex II.9, Annex II.5.

Note: For statistical reasons 'Cement production' only covers process CO_2 emissions (i.e., emissions from cement-forming reactions); energy-related direct emissions from cement production are included in 'other industries' CO_2 emissions.

energy consumption in many countries. In India, the share of energy use by energy-intensive manufacturing industries in total manufacturing energy consumption is 62 % (INCCA, 2010), while it is about 80 % in China (NBS, 2012).

Overall reductions in industrial energy use/manufacturing value-added were found to be greatest in developing economies during 1995–2008. Low-income developing economies had the highest industrial energy intensity values while developed economies had the lowest. Reductions in intensity were realized through technological changes (e.g., changes in product mix, adoption of energy-efficient technologies, etc.) and structural change in the share of energy-intensive industries in the economy. During 1995–2008, developing economies had greater reductions in energy intensity while developed economies had greater reductions through structural change (UNIDO, 2011).

The share of non-energy use of fossil fuels (e.g., the use of fossil fuels as a chemical industry feedstock, of refinery and coke oven products, and of solid carbon for the production of metals and inorganic chemicals) in total manufacturing final energy use has grown from 20 % in 2000 to 24 % in 2009 (IEA, 2012b; c). Fossil fuels used as raw materi-

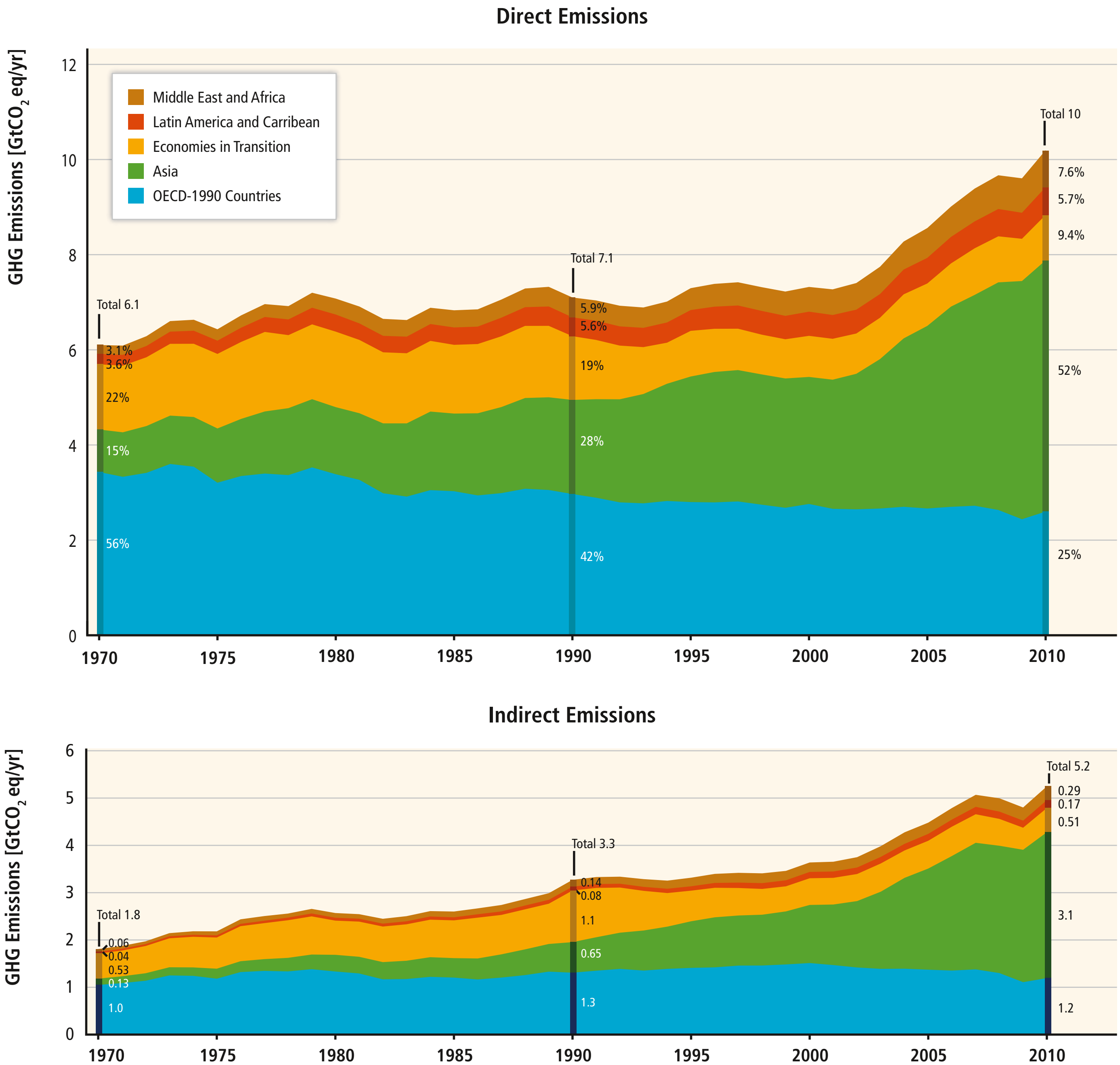


Figure 10.5 | Total global industry and waste/wastewater direct and indirect GHG emissions by region, 1970–2010 ($GtCO_2eq/yr$) (de la Rue du Can and Price, 2008; IEA, 2012a; JRC/PBL, 2013). See also Annex II.9, Annex II.5.

Table 10.2 | Industrial Primary Energy (EJ) and GHG emissions ($GtCO_2eq$) by emission type (direct energy-related, indirect from electricity and heat production, process CO_2, and non-CO_2), and waste/wastewater for five world regions and the world total (IEA, 2012a; b; c; JRC/PBL, 2013; see Annex II.9). For definitions of regions see Annex II.2.

		Primary Energy (EJ)			GHG Emissions ($GtCO_2eq$)		
		1990	2005	2010	1990	2005	2010
ASIA	Direct (energy-related)	20.89	42.83	56.80	1.21	2.08	2.92
	Indirect (electricity + heat)	5.25	15.11	24.38	0.65	2.14	3.08
	Process CO_2 emissions				0.36	0.96	1.49
	Non-CO_2 GHG emissions				0.05	0.25	0.27
	Waste/wastewater				0.35	0.54	0.60
	Total	**26.14**	**57.93**	**81.17**	**2.62**	**5.98**	**8.36**
EIT	Direct (energy-related)	21.98	13.47	13.68	0.79	0.41	0.45
	Indirect (electricity + heat)	6.84	4.10	3.42	1.09	0.59	0.51
	Process CO_2 emissions				0.32	0.23	0.23
	Non-CO_2 GHG emissions				0.11	0.12	0.12
	Waste/wastewater				0.12	0.13	0.15
	Total	**28.82**	**17.56**	**17.10**	**2.43**	**1.48**	**1.47**
LAM	Direct (energy-related)	5.85	8.64	9.45	0.19	0.26	0.28
	Indirect (electricity + heat)	0.97	1.67	1.93	0.08	0.15	0.17
	Process CO_2 emissions				0.08	0.11	0.13
	Non-CO_2 GHG emissions				0.03	0.03	0.03
	Waste/wastewater				0.10	0.14	0.14
	Total	**6.82**	**10.31**	**11.38**	**0.48**	**0.68**	**0.75**
MAF	Direct (energy-related)	5.59	8.91	11.43	0.22	0.30	0.37
	Indirect (electricity + heat)	1.12	1.99	2.58	0.14	0.24	0.29
	Process CO_2 emissions				0.08	0.15	0.21
	Non-CO_2 GHG emissions				0.02	0.02	0.02
	Waste/wastewater				0.10	0.16	0.17
	Total	**6.71**	**10.90**	**14.01**	**0.56**	**0.86**	**1.07**
OECD-1990	Direct (energy-related)	40.93	45.63	42.45	1.55	1.36	1.24
	Indirect (electricity + heat)	11.25	10.92	9.71	1.31	1.37	1.19
	Process CO_2 emissions				0.57	0.56	0.52
	Non-CO_2 GHG emissions				0.35	0.35	0.44
	Waste/wastewater				0.50	0.40	0.39
	Total	**52.18**	**56.55**	**52.16**	**4.28**	**4.04**	**3.79**
World	Direct (energy-related)	95.25	119.47	133.81	3.96	4.41	5.27
	Indirect (electricity + heat)	25.42	33.78	42.01	3.27	4.48	5.25
	Process CO_2 emissions				1.42	2.01	2.59
	Non-CO_2 GHG emissions				0.55	0.77	0.89
	Waste/wastewater				1.17	1.37	1.45
	Total	**120.67**	**153.25**	**175.82**	**10.37**	**13.04**	**15.44**

Note: Includes energy and non-energy use. Non-energy use covers those fuels that are used as raw materials in the different sectors and are not consumed as a fuel or transformed into another fuel. Also includes construction.

als/feedstocks in the chemical industry may result in CO_2 emissions at the end of their life-span in the disposal phase if they are not recovered or recycled (Patel et al., 2005). These emissions need to be accounted for in the waste disposal sector's emissions, although data on waste imports/exports and ultimate disposition are not consistently compiled or reliable (Masanet and Sathaye, 2009). Subsector specific details are also in Section 10.4.

Trade is an important factor that influences production choice decisions and hence CO_2 emissions at the country level. Emission inventories based on consumption rather than production reflect the fact that products produced and exported for consumption in developed countries are an important contributing factor of the emission increase for certain countries such as China, particularly since 2000 (Ahmad and Wyckoff, 2003; Wang and Watson, 2007; Peters and Hertwich, 2008;

Table 10.3 | Industry and waste/wastewater direct and indirect GHG emissions by source and gas, 2010 (in $MtCO_2eq$) (IEA, 2012a; JRC/PBL, 2013).

Source	Gas	2010 Emissions ($MtCO_2eq$)
Ferrous and non ferrous metals	CO_2	2,127
	CH_4	18.87
	SF_6	8.77
	PFC	52.45
	N_2O	4.27
Chemicals	CO_2	1,159
	HFC	206.9
	N_2O	139.71
	SF_6	11.86
	CH_4	4.91
Cement*	CO_2	1,352.35
Indirect (electricity + heat)	CO_2	5,246.79
Landfill, Waste Incineration and Others	CH_4	627.34
	CO_2	32.50
	N_2O	11.05
Wastewater treatment	CH_4	666.75
	N_2O	108.04
Other industries	CO_2	3,222.24
	SF_6	40.59
	N_2O	15.96
	CH_4	9.06
	PFC	20.48
	HFC	332.38
Indirect	N_2O	24.33

Gas		2010 Emissions ($MtCO_2eq$)
Carbon dioxide	CO_2	13,139
Methane	CH_4	1,326.93
Hydrofluorocarbons	HFC	539.28
Nitrous oxide	N_2O	303.35
Perfluorocarbons	PFC	72.93
Sulphur hexafluoride	SF_6	61.21
Carbon Dioxide Equivalent (total of all gases)	**CO_2eq**	**15,443**

Note: CO_2 emissions from cement-forming reactions only; cement energy-related direct emissions are included in 'other industries' CO_2 emissions.

Weber et al., 2008). Chapter 14 provides an in-depth discussion and review of the literature related to trade, embodied emissions, and consumption-based emissions inventories.

10.3.2 Industrial non-CO_2 GHG emissions

Table 10.4 provides emissions of non-CO_2 gases for some key industrial processes (JRC/PBL, 2013). N_2O emissions from adipic acid and nitric acid production and PFC emissions from aluminium production decreased while emissions from HFC-23 from HCFC-22 production increased from 0.075 $GtCO_2eq$ in 1990 to 0.207 $GtCO_2eq$ in 2010. In the period from 1990–2010, fluorinated gases (F-gases) and N_2O were the most important non-CO_2 GHG emissions in manufacturing industry. Most of the F-gases arise from the emissions from different processes including the production of aluminium and HCFC-22 and the manufacturing of flat panel displays, magnesium, photovoltaics, and semiconductors. The rest of the F-gases correspond mostly to HFCs that are used in refrigeration equipment used in industrial processes. Most of the N_2O emissions from the industrial sector are contributed by the chemical industry, particularly from the production of nitric and adipic acids (EPA, 2012a). A summary of the issues and trends that concern developing countries and Least Developed Countries (LDCs) in this chapter is found in Box 10.1.

Table 10.4 | Emissions of non-CO_2 GHGs for key industrial processes (JRC/PBL, 2013)[1]

Process	Emissions ($MtCO_2eq$)		
	1990	2005	2010
HFC-23 from HCFC-22 production	75	194	207
ODS substitutes (Industrial process refrigeration)[2]	0	13	21
PFC, SF_6, NF_3 from flat panel display manufacturing	0	4	6
N_2O from adipic acid and nitric acid production	232	153	104
PFCs and SF_6 from photovoltaic manufacturing	0	0	1
PFCs from aluminium production	107	70	52
SF_6 from manufacturing of electrical equipment	12	7	10
HFCs, PFCs, SF_6 and NF_3 from semiconductor manufacturing	7	21	17
SF_6 from magnesium manufacturing	12	9	8
CH_4 and N_2O from other industrial processes	3	5	6

Note:
1 the data from US EPA (EPA, 2012a) show emissions of roughly the same magnitude, but differ in total amounts per source as well as the growth trends. The differences are significant in some particular sources like HFC-23 from HCFC-22 production, PFCs from aluminium production and N_2O from adipic acid and nitric acid production.
2 Ozone depleting substances (ODS) substitutes values from EPA (2012a).

10.4 Mitigation technology options, practices and behavioural aspects

Figure 10.2, and its associated identity, define six options for climate change mitigation in industry.

- **Energy efficiency (E/M):** Energy is used in industry to drive chemical reactions, to create heat, and to perform mechanical work. The required chemical reactions are subject to thermodynamic limits. The history of industrial energy efficiency is one of innovating to

Box 10.1 | Issues regarding Developing and Least Developed Countries (LDCs)

Reductions in energy intensity (measured as final energy use per industrial GDP) from 1995 to 2008 were larger in developing economies than in developed economies (UNIDO, 2011). The shift from energy-intensive industries towards high-tech sectors (structural change) was the main driving force in developed economies, while the energy intensity reductions in large developing economies such as China, India, and Mexico and transition economies such as Azerbaijan and Ukraine were related to technological changes (Reddy and Ray, 2010; Price et al., 2011; UNIDO, 2011; Sheinbaum-Pardo et al., 2012; Roy et al., 2013). Brazil is a special case were industrial energy intensity increased (UNIDO, 2011; Sheinbaum et al., 2011). The potential for industrial energy efficiency is still very important for developing countries (see Sections 10.4 and 10.7), and possible industrialization development opens the opportunity for the installation of new plants with highly efficient energy and material technologies and processes (UNIDO, 2011).

Other strategies for mitigation in developing countries such as emissions efficiency (e.g., fuel switching) depend on the fuel mix and availability for each country. Product-service efficiency (e.g., using products more intensively) and reducing overall demand for product services must be accounted differently depending on the country's income and development levels. Demand reduction strategies are more relevant for developed countries because of higher levels of consumption. However, some strategies for material efficiency such as manufacturing lighter products (e.g., cars) and modal shifts in the transport sector that reduce energy consumption in industry can have an important role in future energy demand (see Chapter 8.4.2.2).

LDCs have to be treated separately because of their small manufacturing production base. The share of manufacturing value added (MVA) in the GDP of LDCs in 2011 was 9.7 % (7.2 % Africa LDCs; Asia and the Pacific LDCs 13.3 % and no data for Haiti), while it was 21.8 % in developing countries and 16.5 % in developed countries. The LDCs' contribution to world MVA represented only 0.46 % in 2010 (UNIDO, 2011; UN, 2013).

In most LDCs, the share of extractive industries has increased (in many cases with important economic, social, and environmental problems (Maconachie and Hilson, 2013)), while that of manufacturing either decreased in importance or stagnated, with the exceptions of Tanzania and Ethiopia where their relative share of agriculture decreased while manufacturing, services, and mining increased (UNCTAD, 2011; UN, 2013).

Developed and developing countries are changing their industrial structure, from low technology to medium and high technology products (level of technology in production process), but LDCs remain highly concentrated in low technology products. The share of low technology products in the years 1995 and 2009 in LDCs MVA was 68 % and 71 %, while in developing countries it was 38 % and 30 % and in developed countries 33 % and 21 %, respectively (UNIDO, 2011).

Among other development strategies, two alternative possible scenarios could be envisaged for the industrial sector in LDCs: (1) continuing with the present situation of concentration in labour intensive and resource intensive industries or (2) moving towards an increase in the production share of higher technology products (following the trend in developing countries). The future evolution of the industrial sector will be successful only if the technologies adopted are consistent with the resource endowments of LDCs. However, the heterogeneity of LDCs circumstances needs to be taken into account when analyzing major trends in the evolution of the group. A report prepared by the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat summarizes the findings of 70 Technology Needs Assessments (TNA) submitted, including 24 from LDCs. Regarding the relationship between low carbon and sustainable development, the relevant technologies for most of the LDCs are related to poverty and hunger eradication, avoiding the loss of resources, time and capital. Almost 80 % of LDCs considered the industrial structure in their TNA, evidencing that they consider this sector as a key element in their development strategies. The technologies identified in the industrial sector and the proportion of countries selecting them are: fuel switching (42 %), energy efficiency (35 %), mining (30 %), high efficiency motors (25 %), and cement production (25 %) (UNFCCC SBSTA, 2009).

A low carbon development strategy facilitated by access to financial resources, technology transfer, technologies, and capacity building would contribute to make the deployment of national mitigation efforts politically viable. As adaptation is the priority in almost all LDCs, industrial development strategies and mitigation actions look for synergies with national adaptation strategies.

create 'best available technologies' and implementing these technologies at scale to define a reference 'best practice technology', and investing in and controlling installed equipment to raise 'average performance' nearer to 'best practice' (Dasgupta et al., 2012).

Energy efficiency has been an important strategy for industry for various reasons for a long time. Over the last four decades there has been continued improvement in energy efficiency in energy-intensive industries and 'best available technologies' are increasingly approaching technical limits. However, many options for energy efficiency improvement remain and there is still significant potential to reduce the gap between actual energy use and the best practice in many industries and in most countries. For all, but particularly for less energy intensive industries, there are still many energy efficiency options both for process and system-wide technologies and measures. Several detailed analyses related to particular sectors estimate the technical potential of energy efficiency measures in industry to be approximately up to 25 % (Schäfer, 2005; Allwood et al., 2010; UNIDO, 2011; Saygin et al., 2011b; Gutowski et al., 2013). Through innovation, additional reductions of approximately up to 20 % in energy intensity may potentially be realized before approaching technological limits in some energy-intensive industries (Allwood et al., 2010).

In industry, energy efficiency opportunities are found within sector-specific processes as well as in systems such as steam systems, process heating systems (furnaces and boilers), and electric motor systems (e.g., pumps, fans, air compressor, refrigerators, material handling). As a class of technology, electronic control systems help to optimize performance of motors, compressors, steam combustion, heating, etc. and improve plant efficiency cost-effectively with both energy savings and emissions benefits, especially for SMEs (Masanet, 2010).

Opportunities to improve heat management include better heat exchange between hot and cold gases and fluids, improved insulation, capture and use of heat in hot products, and use of exhaust heat for electricity generation or as an input to lower temperature processes (US DoE, 2004a, 2008). However, the value of these options is in many cases limited by the low temperature of 'waste heat'—industrial heat exchangers generally require a temperature difference of ~200 °C—and the difficulty of exchanging heat out of solid materials.

Recycling can also help to reduce energy demand, as it can be a strategy to create material with less energy. Recycling is already widely applied for bulk metals (steel, aluminium, and copper in particular), paper, and glass and leads to an energy saving when producing new material from old avoids the need for further energy intensive chemical reactions. Plastics recycling rates in Europe are currently around 25 % (Plastics Europe, 2012) due to the wide variety of compositions in common use in small products, and glass recycling saves little energy as the reaction energy is small compared to that needed for melting (Sardeshpande et al., 2007). Recycling is applied when it is cost effective, but in many cases leads to lower quality materials, is constrained by lack of supply because collection rates, while high for some materials (particularly steel), are not 100 %, and because with growing global demand for material, available supply of scrap lags total demand. Cement cannot be recycled, although concrete can be crushed and down-cycled into aggregates or engineering fill. However, although this saves on aggregate production, it may lead to increased emissions, due to energy used in concrete crushing and refinement and because more cement is required to achieve target properties (Dosho, 2008).

- **Emissions efficiency (G/E)**: In 2008, 42 % of industrial energy supply was from coal and oil, 20 % from gas, and the remainder from electricity and direct use of renewable energy sources. These shares are forecast to change to 30 % and 24 % respectively by 2035 (IEA, 2011a) resulting in lower emissions per unit of energy, as discussed in Chapter 7. Switching to natural gas also favours more efficient use of energy in industrial combined heat and power (CHP) installations (IEA, 2008, 2009a). For several renewable sources of energy, CHP (IEA, 2011b) offers useful load balancing opportunities if coupled with low-grade heat storage; this issue is discussed further in Chapter 7. The use of wastes and biomass in the energy industry is currently limited, but forecast to grow (IEA, 2009b). The cement industry incinerates (with due care for e.g., dioxins/furans) municipal solid waste and sewage sludge in kilns, providing ~17 % of the thermal energy required by European Union (EU) cement production in 2004 (IEA ETSAP, 2010). The European paper industry reports that over 50 % of its energy supply is from biomass (CEPI, 2012). If electricity generation is decarbonized, greater electrification, for example appropriate use of heat pumps instead of boilers (IEA, 2009b; HPTCJ, 2010), could also reduce emissions. Solar thermal energy for drying, washing, and evaporation may also be developed further (IEA, 2009c) although to date this has not been implemented widely (Sims et al., 2011).

  The International Energy Agency (IEA) forecasts that a large part of emission reduction in industry will occur by carbon dioxide capture and storage (CCS) (up to 30 % in 2050) (IEA, 2009c). Carbon dioxide capture and storage is largely discussed in Chapter 7. In gas processing (Kuramochi et al., 2012a) and parts of the chemical industry (ammonia production without downstream use of CO_2), there might be early opportunities for application of CCS as the CO_2 in vented gas is already highly concentrated (up to 85 %), compared to cement or steel (up to 30 %). Industrial utilization of CO_2 was assessed in the IPCC Special Report on Carbon Dioxide Capture and Storage (SRCCS) (Mazzotti et al., 2005) and it was found that potential industrial use of CO_2 was rather small and the storage time of CO_2 in industrial products often short. Therefore industrial uses of CO_2 are unlikely to contribute to a great extent to climate change mitigation. However, currently CO_2 use is subject of various industrial RD&DD projects (Research and Development, Demonstration and Diffusion).

- In terms of non-CO_2-emissions from industry, HFC-23 emissions, which arise in HCFC-22 production, can be reduced by process optimization and by thermal destruction. N_2O emissions from adipic and nitric acid production have decreased almost by half between 1990 and 2010 (EPA, 2012a) due to the implementation of thermal destruction and secondary catalysts.

Box 10.2 | Service demand reduction and mitigation opportunities in industry sector:

Besides technological mitigation measures, an additional mitigation option (see Figure 10.2.) for the industry sector involves the end uses of industrial products that provide services to consumers (e.g., diet, mobility, shelter, clothing, amenities, health care and services, hygiene). Assessment of the mitigation potential associated with this option is nascent, however, and important knowledge gaps exist (for a more general review of sustainable consumption and production (SCP) policies, see Section 10.11.3 and 4.4.3). The nature of the linkage between service demand and the demand for industrial products is different and shown here through two examples representing both a direct and an indirect link:

- clothing demand, which is linked directly to the textile industry products (strong link)
- tourism demand, which is linked directly to mobility and shelter demand but also indirectly to industrial materials demand (weak link)

Clothing demand: Even in developed economies, consumers appear to have no absolute limit to their demand for clothing, and if prices fall, will continue to purchase more garments: during the period 2000–2005, the advent of 'fast fashion' in the UK led to a drop in prices, but an increase in sales equivalent to one third more garments per year per person with consequent increases in material production and hence industrial emissions (Allwood et al., 2008). This growth in demand relates to 'fashion' and 'conspicuous consumption' (Roy and Pal, 2009) rather than 'need', and has triggered a wave of interest in concepts like 'sustainable lifestyle/fashion'. While much of this interest is related to marketing new fabrics linked to environmental claims, authors such as Fletcher (2008) have examined the possibility that 'commodity' clothing, which can be discarded easily, would be used for longer and valued more, if given personal meaning by some shared activity or association.

Tourism demand: GHG emissions triggered by tourism significantly contribute to global anthropogenic CO_2 emissions. Estimates show a range between 3.9 % to 6 % of global emissions, with a best estimate of 4.9 % (UNWTO et al., 2008). Worldwide, three quarters (75 %) of tourism-related emissions are generated by transport and just over 20 % by accommodation (UNWTO et al., 2008). A minority of travellers (frequent travellers using the plane over long distances) (Gössling et al., 2009) are responsible for the greater share of these emissions (Gössling et al., 2005; TEC and DEEE, 2008; de Bruijn et al., 2010) (see Sections 8.1.2 and 8.2.1).

Mitigation options for tourism (Gössling, 2010; Becken and Hay, 2012) include technical, behavioural, and organizational aspects. Many mitigation options and potentials are the same as those identified in the transport and buildings chapters (see Chapters 8 and 9). However, the demand reduction of direct tourism-related products delivered by the industry in addition to products for buildings and other infrastructure e.g., snow-lifts and associated accessories, artificial snow, etc. can also impact the industry sector as they determine product and material demand of the sector. Thus, the industry sector has only limited influence on emissions from tourism (via reduction of the embodied emissions), but is affected by decisions in mitigation measures in tourism. For example, a sustainable lifestyle resulting in a lower demand for transportation can reduce demand for steel to manufacture cars and contribute to reducing emissions in the industry sector.

A business-as-usual (BAU) scenario (UNWTO et al., 2008) projects emissions from tourism to grow by 130 % from 2005 to 2035 globally; notably the emissions of air transport and accommodation will triple. Two alternative scenarios show that the contribution of technology is limited in terms of achievable mitigation potentials and that even when combining technological and behavioural potentials, no significant reduction can be achieved in 2035 compared to 2005. Insufficient technological mitigation potential and the need for drastic changes in the forms of tourism (e.g., reduction in long haul travel; UNWTO et al., 2008), in the place of tourism (Gössling et al., 2010; Peeters and Landré, 2011) and in the uses of leisure time, implying changes in lifestyles (Ceron and Dubois, 2005; Dubois et al., 2011) are the limiting factors.

Several studies show that for some countries (e.g., the UK) an unrestricted growth of tourism would consume the whole carbon budget compatible with the +2 °C target by 2050 (Bows et al., 2009; Scott et al., 2010). However, some authors also point out that by reducing demand in some small subsectors of tourism (e.g., long haul, cruises) effective emission reductions may be reached with a minimum of damage to the sector (Peeters and Dubois, 2010).

Tourism is an example of human activity where the discussion of mitigation is not only technology-driven, but strongly correlated with lifestyles. For many other activities, the question is how certain mitigation goals would result in consequences for the activity level with indirect implications for industry sector emissions.

Hydrofluorocarbons used as refrigerants can be replaced by alternatives (e. g., ammonia, hydrofluoro-olefins, HC, CO_2). Replacement is also an appropriate measure to reduce HFC emissions from foams (use of alternative blowing agents) or solvent uses. Emission reduction (in the case of refrigerants) is possible by leak repair, refrigerant recovery and recycling, and proper disposal. Emissions of PFCs, SF_6 and nitrogen trifluoride (NF_3) are growing rapidly due to flat panel display manufacturing. Ninety-eight percent of these emissions are in China (EPA, 2012a) and can be countered by fuelled combustion, plasma, and catalytic technologies.

- **Material efficiency in production (M/P):** Material efficiency—delivering services with less new material—is a significant opportunity for industrial emissions abatement, that has had relatively little attention to date (Allwood et al., 2012). Two key strategies would significantly improve material efficiency in manufacturing existing products:

    - *Reducing yield losses in materials production, manufacturing, and construction*. Approximately one-tenth of all paper, a quarter of all steel, and a half of all aluminium produced each year is scrapped (mainly in downstream manufacturing) and internally recycled—see Figure 10.2**.** This could be reduced by process innovations and new approaches to design (Milford et al., 2011).

    - *Re-using old material*. A detailed study (Allwood et al., 2012) on re-use of structural steel in construction concluded that there are no insurmountable technical barriers to re-use, that there is a profit opportunity, and that the potential supply is growing.

- **Material efficiency in product design (M/P):** Although new steels and production techniques have allowed relative light-weighting of cars, in practice cars continue to become heavier as they are larger and have more features. However, many products could be one-third lighter without loss of performance in use (Carruth et al., 2011) if design and production were optimized. At present, the high costs of labour relative to materials and other barriers inhibit this opportunity, except in industries such as aerospace where the cost of design and manufacture for lightness is paid back through reduced fuel use. Substitution of one material by another is often technically possible (Ashby, 2009), but options for material substitution as an abatement strategy are limited: global steel and cement production exceeds 200 and 380 (kg/cap)/yr respectively, and no other materials capable of delivering the same functions are available in comparable quantities; epoxy based composite materials and magnesium alloys have significantly higher embodied energy than steel or aluminium (Ashby, 2009) (although for vehicles this may be worthwhile if it allows significant savings in energy during use); wood is kiln dried, so in effect is energy intensive (Puettmann and Wilson, 2005); and blast furnace slag and fly ash from coal-fired power stations can substitute to some extent for cement clinker.

- **Using products more intensively (P/S):** Products, such as food, that are intended to be consumed in use are in many cases used inefficiently, and estimates show that up to one-third of all food in developed countries is wasted (Gustavsonn et al., 2011). This indicates the opportunity for behaviour change to reduce significantly the demand for industrial production of what currently becomes waste without any service provision. In contrast to these consumable products, most durable goods are owned in order to deliver a 'product service' rather than for their own sake, so potentially the same level of service could be delivered with fewer products. Using products for longer could reduce demand for replacement goods, and hence reduce industrial emissions (Allwood et al., 2012). New business models could foster dematerialization and more intense use of products. The ambition of the 'sustainable consumption' agenda and policies (see Sections 10.11 and 4.4.3) aims towards this goal, although evidence of its application in practice remains scarce.

- **Reducing overall demand for product services (S)** (see Box 10.2): Industrial emissions would be reduced if overall demand for product services were reduced (Kainuma et al., 2013)—if the population chose to travel less (e. g., through more domestic tourism or telecommuting), heat or cool buildings only to the degree required, or reduce unnecessary consumption or products. Clear evidence that, beyond some threshold of development, populations do not become 'happier' (as reflected in a wide range of socio-economic measures) with increasing wealth, suggests that reduced overall consumption might not be harmful in developed economies (Layard, 2011; Roy and Pal, 2009; GEA, 2012), and a literature questioning the ultimate policy target of GDP growth is growing, albeit without clear prescriptions about implementation (Jackson, 2011).

In the rest of this section, the application of these six strategies, where it exists, is reviewed for the major emitting industrial sectors.

10.4.1 Iron and steel

Steel continues to dominate global metal production, with total crude steel production of around 1,490 Mt in 2011. In 2011, China produced 46 % of the world's steel. Other significant producers include the EU-27 (12 %), the United States (8 %), Japan (7 %), India (5 %) and Russia (5 %) (WSA, 2012b). Seventy percent (70 %) of all steel is made from pig iron produced by reducing iron oxide in a blast furnace using coke or coal before reduction in an oxygen blown converter (WSA, 2011). Steel is also made from scrap (23 %) or from iron oxide reduced in solid state (direct reduced iron, 7 %) melted in electric-arc furnaces before refining. The specific energy intensity of steel production varies by technology and region. Global steel sector emissions were estimated to be 2.6 $GtCO_2$ in 2006, including direct and indirect emissions (IEA, 2009c; Oda et al., 2012).

Energy efficiency. The steel industry is pursuing: improved heat and energy recovery from process gases, products and waste streams; improved fuel delivery through pulverized coal injection; improved furnace designs and process controls; and reduced number of temperature cycles through better process coupling such as in Endless Strip Production (ESP) (Arvedi et al., 2008) and use of various energy efficiency technologies (Worrell et al., 2010; Xu et al., 2011a) including coke dry quenching and top pressure recovery turbines (LBNL and AISI, 2010). Efforts to promote energy efficiency and to reduce the production of hazardous wastes are the subject of both international guidelines on environmental monitoring (International Finance Corporation, 2007) and regional benchmarks on best practice techniques (EC, 2012a).

Emissions efficiency: The coal and coke used in conventional iron-making is emissions intensive; switching to gas-based direct reduced iron (DRI) and oil and natural gas injection has been used, where economic and practicable. However, DRI production currently occurs at smaller scale than large blast furnaces (Cullen et al., 2012), and any emissions benefit depends on the emissions associated with increased electricity use for the required electric arc furnace (EAF) process. Charcoal, another coke substitute, is currently used for iron-making, notably in Brazil (Taibi et al.; Henriques Jr. et al., 2010), and processing to improve charcoal's mechanical properties is another substitute under development, although extensive land area is required to produce wood for charcoal. Other substitutions include use of ferro-coke as a reductant (Takeda et al., 2011) and the use of biomass and waste plastics to displace coal (IEA, 2009c). The Ultra-Low CO_2 Steelmaking (ULCOS) programme has identified four production routes for further development: top-gas recycling applied to blast furnaces, HIsarna (a smelt reduction technology), advanced direct reduction, and electrolysis. The first three of these routes would require CCS (discussion of the costs, risks, deployment barriers and policy aspects of CCS can be found in Sections 7.8.2, 7.9, 7.10, and 7.12), and the fourth would reduce emissions only if powered by low carbon electricity. Hydrogen fuel might reduce emissions if a cost effective emissions free source of hydrogen were available at scale, but at present this is not the case. Hydrogen reduction is being investigated in the United States (Pinegar et al., 2011) and in Japan as Course 50 (Matsumiya, 2011). Course 50 aims to reduce CO_2 emissions by approximately 30 % by 2050 through capture, separation and recovery. Molten oxide electrolysis (Wang et al., 2011) could reduce emissions if a low or CO_2-free electricity source was available. However this technology is only at the very early stages of development and identifying a suitable anode material has proved difficult.

Material efficiency: Material efficiency offers significant potential for emissions reductions (Allwood et al., 2010) and cost savings (Roy et al., 2013) in the iron and steel sector. Milford et al. (2011) examined the impact of yield losses along the steel supply chain and found that 26 % of global liquid steel is lost as process scrap, so its elimination could have reduced sectoral CO_2 emissions by 16 % in 2008. Cooper et al. (2012) estimate that nearly 30 % of all steel produced in 2008 could be re-used in future. However, in many economies steel is relatively cheap in comparison to labour, and this difference is amplified by tax policy, so economic logic currently drives a preference for material inefficiency to reduce labour costs (Skelton and Allwood, 2013b).

Reduced product and service demand: Commercial buildings in developed economies are currently built with up to twice the steel required by safety codes, and are typically replaced after around 30–60 years (Michaelis and Jackson, 2000; Hatayama et al., 2010; Pauliuk et al., 2012). The same service (e.g., office space provision) could be achieved with one quarter of the steel, if safety codes were met accurately and buildings replaced not as frequently, but after 80 years. Similarly, there is a strong correlation between vehicle fuel consumption and vehicle mass. For example, in the UK, 4- or 5-seater cars are used for an average of around 4 hours per week by 1.6 people (DfT, 2011), so a move towards smaller, lighter fuel efficient vehicles (FEVs), used for more hours per week by more people could lead to a four-fold or more reduction in steel requirements, while providing a similar mobility service. There is a well-known tradeoff between the emissions embodied in producing goods and those generated during use, so product life extension strategies should account for different anticipated rates of improvement in embodied and use-phase emissions (Skelton and Allwood, 2013a).

10.4.2 Cement

Emissions in cement production arise from fuel combustion (to heat limestone, clay, and sand to 1450 °C) and from the calcination reaction. Fuel emissions (0.8 $GtCO_2$ (IEA, 2009d), around 40 % of the total) can be reduced through improvements in energy efficiency and fuel switching while process emissions (the calcination reaction, ~50 % of the total) are unavoidable, so can be reduced only through reduced demand, including through improved material efficiency. The remaining 10 % of CO_2 emissions arise from grinding and transport (Bosoaga et al., 2009).

Energy efficiency: Estimates of theoretical minimum primary energy consumption for thermal (fuel) energy use ranges between 1.6 and 1.85 GJ/t (Locher, 2006). For large new dry kilns, the 'best possible' energy efficiency is 2.7 GJ/t clinker with electricity consumption of 80 kWh/t clinker or lower (Muller and Harnish, 2008). 'International best practice' final energy ranges from 1.8 to 2.1 to 2.9 GJ/t cement and primary energy ranges from 2.15 to 2.5 to 3.4 GJ/t cement for production of blast furnace slag, fly ash, and Portland cement, respectively (Worrell et al., 2008b). Klee et al. (2011) shows that CO_2 emissions intensities have declined in most regions of the world, with a 2009 global average intensity (excluding emissions from the use of alternative fuels) of 633 kg CO_2 per tonne of cementitious product, a decline of 6 % since 2005 and 16 % since 1990. Many options still exist to improve the energy efficiency of cement manufacturing (Muller and Harnish, 2008; Worrell et al., 2008a; Worrell and Galitsky, 2008; APP, 2010).

Emissions efficiency and fuel switching: The majority of cement kilns burn coal (IEA/WBCSD, 2009), but fossil or biomass wastes can also be burned. While these alternatives have a lower CO_2 intensity depending on their exact composition (Sathaye et al., 2011) and can result in reduced overall CO_2 emissions from the cement industry (CEMBUREAU, 2009), their use can also increase overall energy use per tonne of clinker produced if the fuels require pre-treatment such as drying (Hand, 2007). Waste fuels have been used in cement production for the past 20 years in Europe, Japan, the United States, and Canada (GTZ/Holcim, 2006; Genon and Brizio, 2008); the Netherlands and Switzerland use 83 % and 48 % waste, respectively, as a cement fuel (WBCSD, 2005). It is important that wastes are burned in accordance with strict environmental guidelines as emissions resulting from such wastes can cause adverse environmental impacts such as extremely high concentrations of particulates in ambient air, ground-level ozone, acid rain, and water quality deterioration (Karstensen, 2007)[8].

Cement kilns can be fitted to harvest CO_2, which could then be stored, but this has yet to be piloted and "commercial-scale CCS in the cement industry is still far from deployment" (Naranjo et al., 2011). CCS potential in the cement sector has been investigated in several recent studies: IEAGHG, 2008; Barker et al., 2009; Croezen and Korteland, 2010; Bosoaga et al., 2009. A number of emerging technologies aim to reduce emissions and energy use in cement production (Hasanbeigi et al., 2012b), but there are regulatory, supply chain, product confidence and technical barriers to be overcome before such technologies (such as geopolymer cement) could be widely adopted (Van Deventer et al., 2012).

Material efficiency: Almost all cement is used in concrete to construct buildings and infrastructure (van Oss and Padovani, 2002). For concrete, which is formed by mixing cement, water, sand, and aggregates, two applicable material efficiency strategies are: using less cement initially and reusing concrete components at end of first product life (distinct from down-cycling of concrete into aggregate which is widely applied). Less cement can be used by placing concrete only where necessary, for example Orr et al. (2010) use curved fabric moulds to reduce concrete mass by 40 % compared with a standard, prismatic shape. By using higher-strength concrete, less material is needed; CO_2 savings of 40 % have been reported on specific projects using 'ultra-high-strength' concretes (Muller and Harnish, 2008). Portland cement comprises 95 % clinker and 5 % gypsum, but cement can be produced with lower ratios of clinker through use of additives such as blast furnace slag, fly ash from power plants, limestone, and natural or artificial pozzolans. The weighted average clinker-to-cement ratio for the companies participating in the WBCSD GNR project was 76 % in 2009 (WBCSD, 2011). In China, this ratio was 63 % in 2010 (NDRC, 2011a). In India the ratio is 80 % but computer optimization is improving this (India Planning Commission, 2007). Reusing continuous concrete elements is difficult because it requires elements to be broken up but remain undamaged. Concrete blocks can be reused, as masonry blocks and bricks are reused already, but to date there is little published literature in this area.

Reduced product and service demand: Cement, in concrete, is used in the construction of buildings and infrastructure. Reducing demand for these products can be achieved by extending their lifespans or using them more intensely. Buildings and infrastructure have lifetimes less than 80 years—less than 40 years in East Asia—(Hatayama et al., 2010), however their core structural elements (those that drive demand for concrete) could last over 200 years if well maintained. Reduced demand for building and infrastructure services could be achieved by human settlement design, increasing the number of people living and working in each building, or decreasing per-capita demand for utilities (water, electricity, waste), but has as yet had little attention.

10.4.3 Chemicals (plastics/fertilizers/others)

The chemicals industry produces a wide range of different products on scales ranging over several orders of magnitude. This results in methodological and data collection challenges, in contrast to other sectors such as iron and steel or cement (Saygin et al., 2011a). However, emissions in this sector are dominated by a relatively small number of key outputs: ethylene, ammonia, nitric acid, adipic acid and caprolactam used in producing plastics, fertilizer, and synthetic fibres. Emissions arise both from the use of energy in production and from the venting of by-products from the chemical processes. The synthesis of chlorine in chlor-alkali electrolysis is responsible for about 40 % of the electricity demand of the chemical industry.

Energy efficiency: Steam cracking for the production of light olefins, such as ethylene and propylene, is the most energy consuming process in the chemical industry, and the pyrolysis section of steam cracking consumes about 65 % of the total process energy (Ren et al., 2006). Upgrading all steam cracking plants to best practice technology could reduce energy intensity by 23 % (Saygin et al., 2011a; b) with a further 12 % saving possible with best available technology. Switching to a biomass-based route to avoid steam cracking could reduce CO_2 intensity (Ren and Patel, 2009) but at the cost of higher energy use, and with high land-use requirements. Fertilizer production accounts for around 1.2 % of world energy consumption (IFA, 2009), mostly to produce ammonia (NH_3). 22 % energy savings are possible (Saygin et al., 2011b) by upgrading all plants to best practice technology. Nitrous oxide (N_2O) is emitted during production of adipic and nitric acids. By 2020 annual emissions from these industries are estimated to be 125 $MtCO_2eq$ (EPA, 2012a). Many options exist to reduce emissions, depending on plant operating conditions (Reimer et al., 2000). A broad survey of options in the petrochemicals industry is given by Neelis et al. (2008). Plastics recycling saves energy, but to produce a high value recycled material, a relatively pure waste stream is required: impurities greatly degrade the properties of the recycled material. Some plastics can be produced from mixed waste streams, but gen-

8 See also: http://www2.epa.gov/enforcement/cement-manufacturing-enforcement-initiative

erally have a lower value than virgin material. A theoretical estimate suggest that increasing use of combined heat and power plants in the chemical and petrochemical sector from current levels of 10 to 25 % up to 100 % would result in energy savings up to 2 EJ for the activity level in 2006 (IEA, 2009e).

Emissions efficiency: There are limited opportunities for innovation in the current process of ammonia production via the Haber-Bosch process (Erisman et al., 2008). Possible improvements relate to the introduction of new N_2O emission reduction technologies in nitric acid production such as high-temperature catalytic N_2O decomposition (Melián-Cabrera et al., 2004) which has been shown to reduce N_2O emissions by up to 70–90 % (BIS Production Partner, 2012; Yara, 2012). While implementation of this technology has been largely completed in regions pursuing carbon emission reduction (e. g., the EU through the Emissions Trading Scheme (ETS) or China and other developing countries through Clean Development Mechanism (CDM), the implementation of this technology still offers large mitigation potential in other regions like the former Soviet Union and the United States (Kollmus and Lazarus, 2010). Fuel switching can also lead to significant emission reductions and energy savings. For example, natural gas based ammonia production results in 36 % emission reductions compared to naphtha, 47 % compared to fuel oil and 58 % compared to coal. The total potential mitigation arising from this fuel switching would amount to 27 $MtCO_2eq$/year GHG emissions savings (IFA, 2009).

Material efficiency: Many of the material efficiency measures identified above can be applied to the use of plastics, but this has had little attention to date, although Hekkert et al. (2000) anticipate a potential 51 % saving in emissions associated with the use of plastic packaging in the Netherlands from application of a number of material efficiency strategies. More efficient use of fertilizer gives benefits both in reduced direct emissions of N_2O from the fertilizer itself and from reduced fertilizer production (Smith et al., 2008).

10.4.4 Pulp and paper

Global paper production has increased steadily during the last three decades (except for a minor production decline associated with the 2008 financial crisis) (FAO, 2013), with global demand expansion currently driven by developing nations. Fuel and energy use are the main sources of GHG emissions during the forestry, pulping, and manufacturing stages of paper production.

Energy efficiency: A broad range of energy efficiency technologies are available for this sector, reviewed by Kramer et al. (2009), and Laurijssen et al. (2012). Over half the energy used in paper making is to create heat for drying paper after it has been laid and Laurijssen et al. (2010) estimate that this could be reduced by ~32 % by the use of additives, an increased dew point, and improved heat recovery. Energy savings may also be obtained from emerging technologies (Jacobs and IPST, 2006; Worrell et al., 2008b; Kong et al., 2012) such as black liquor gasification, which uses the by-product of the chemical pulping process to increase the energy efficiency of pulp and paper mills (Naqvi et al., 2010). With commercial maturity expected within the next decade (Eriksson and Harvey, 2004), black liquor gasification can be used as a waste-to-energy method with the potential to achieve higher overall energy efficiency (38 % for electricity generation) than the conventional recovery boiler (9–14 % efficiency) while generating an energy-rich syngas from the liquor (Naqvi et al., 2010). The syngas can also be utilized as a feedstock for production of renewable motor fuels such as bio-methanol, dimethyl ether, and FT-diesel or hydrogen (Pettersson and Harvey, 2012). Gasification combined cycle systems have potential disadvantages (Kramer et al., 2009), including high energy investments to concentrate sufficient black liquor solids and higher lime kiln and causticizer loads compared to Tomlinson systems. Paper recycling generally saves energy and may reduce emissions (although electricity in some primary paper making is derived from biomass-powered CHP plants) and rates can be increased (Laurijssen et al., 2010b). Paper recycling is also important as competition for biomass will increase with population growth and increased use of biomass for fuel.

Emissions efficiency: Direct CO_2 emissions from European pulp and paper production reduced from 0.57 to 0.34 $ktCO_2$ per kt of paper between 1990 and 2011, while indirect emissions reduced from 0.21 to 0.09 $ktCO_2$ per kt of paper (CEPI, 2012). Combined heat and power (CHP) accounted for 95 % of total on-site electricity produced by EU paper makers in 2011, compared to 88 % in 1990 (CEPI, 2012), so has little further potential in Europe, but may offer opportunities globally. The global pulp and paper industry usually has ready access to biomass resources and it generates approximately a third of its own energy needs from biomass (IEA, 2009c), 53 % in the EU (CEPI, 2012). Paper recycling can have a positive impact on energy intensity and CO_2 emissions over the total lifecycle of paper production (Miner, 2010; Laurijssen et al., 2010). Recycling rates in Europe and North America reached 70 % and 67 % in 2011, respectively[9] (CEPI, 2012), leaving a small range for improvement when considering the limit of 81 % estimated by CEPI (2006). In Europe, the share of recovered paper used in paper manufacturing has increased from roughly 33 % in 1991 to around 44 % in 2009 (CEPI, 2012). GHG fluxes from forestry are discussed in Section 11.2.3.

Material efficiency: Higher material efficiency could be achieved through increased use of duplex printing, print on demand, improved recycling yields and the manufacturing of lighter paper. Recycling yields could be improved by the design of easy to remove inks and adhesives and less harmful de-inking chemicals; paper weights for newspapers and office paper could be reduced from 45 and 80 g/m^2 to 42 and 70 g/m^2 respectively and might lead to a 37 % saving in paper used for current service levels (Van den Reek, 1999; Hekkert et al., 2002).

9 American Forest and Paper Association, Paper Recycles—Statistics—Paper & Paperboard Recovery http://www.paperrecycles.org/statistics/paper-paperboard-recovery.

Reduced demand: Opportunities to reduce demand for paper products in the future include printing on demand, removing print to allow paper re-use (Leal-Ayala et al., 2012), and substituting e-readers for paper. The latter has been the subject of substantial academic research (e.g., Gard and Keoleian, 2002; Reichart and Hischier, 2003) although the substitution of electronic media for paper has mixed environmental outcomes, with no clear statistics yet on whether such media reduces paper demand, or whether it leads to a net reduction in emissions.

10.4.5 Non-ferrous (aluminium/others)

Annual production of non-ferrous metals is small compared to steel, and is dominated by aluminium, with 56 Mt made globally in 2009, of which 18 Mt was through secondary (recycled) production. Production is expected to rise to 97 Mt by 2020 (IAI, 2009). Magnesium is also significant, but with global primary production of only 653 Kt in 2009 (IMA, 2009), is dwarfed by aluminium.

Energy efficiency: Aluminium production is particularly associated with high electricity demand. Indirect (electricity-related) emissions account for over 80 % of total GHG emissions in aluminium production. The sector accounts for 3.5 % of global electricity consumption (IEA 2008) and energy accounts for nearly 40 % of aluminium production costs.

Aluminium can be made from raw materials (bauxite) or through recycling. Best practice primary aluminium production—from alumina production through ingot casting—consumes 174 GJ/t primary energy (accounting for electricity production, transmission, distribution losses) and 70.6 GJ/t final energy (Worrell et al., 2008b). Best practice for electrolysis—which consumes roughly 85 % of the energy used for production of primary aluminium—is about 47 GJ/t final energy while the theoretical energy requirement is 22 GJ/t final energy (BCS Inc., 2007). Best practice for recycled aluminium production is 7.6 GJ/t primary energy and 2.5 GJ/t final energy (Worrell et al., 2008b), although in reality, recycling uses much more energy due to pre-processing of scrap, 'sweetening' with virgin aluminium and downstream processing after casting. The U.S. aluminium industry consumes almost three times the theoretical minimum energy level (BCS Inc., 2007). The options for new process development in aluminium production—multipolar electrolysis cells, inert anodes and carbothermic reactions—have not yet reached commercial scale (IEA, 2012d). The IEA estimates that application of best available technology can reduce energy use for aluminium production by about 10 % compared with current levels (IEA, 2012d).

At present, post-consumer scrap makes up only 20 % of total aluminium recycling (Cullen and Allwood, 2013), which is dominated by internal 'home' or 'new' scrap (see Figure 10.2). As per capita stock levels saturate in the 21st century, there could be a shift from primary to secondary aluminium production (Liu et al., 2012a) if recycling rates can be increased, and the accumulation of different alloying elements in the scrap stream can be controlled. These challenges will require improved end of life management and even new technologies for separating the different alloys (Liu et al., 2012a).

Emissions efficiency: Data on emissions intensities for a range of non-ferrous metals are given by (Sjardin, 2003). The aluminium industry alone contributed 3 % of CO_2 emissions from industry in 2006 (Allwood et al., 2010). In addition to CO_2 emissions resulting from electrode and reductant use, the production of non-ferrous metals can result in the emission of high-global warming potential (GWP) GHGs, for example PFCs (such as CF_4) in aluminium or SF_6 in magnesium. PFCs result from carbon in the anode and fluorine in the cryolite. The reaction can be minimized by controlling the process to prevent a drop in alumina concentrations, which triggers the process[10].

Material efficiency: For aluminium, there are significant carbon abatement opportunities in the area of material efficiency and demand reduction. From liquid aluminium to final product, the yield in forming and fabrication is only 59 %, which could be improved by near-net shape casting and blanking and stamping process innovation (Milford et al., 2011). For chip scrap produced from machining operations (in aluminium, for example (Tekkaya et al., 2009), or magnesium (Wu et al., 2010)) extrusion, processes are being developed to bond scrap in the solid state to form a relatively high quality product potentially offering energy savings of up to 95 % compared to re-melting. Aluminium building components (window frames, curtain walls, and cladding) could be reused when a building is demolished (Cooper and Allwood, 2012) and more modular product designs would allow longer product lives and an overall reduction in demand for new materials (Cooper et al., 2012).

10.4.6 Food processing

The food industry as discussed in this chapter includes all processing beyond the farm gate, while everything before is in the agriculture industry and discussed in Chapter 11. In the developed world, the emissions released beyond the farm gate are approximately equal to those released before. Garnett (2011) suggests that provision of human food drives around 17.7 $GtCO_2eq$ in total.

Energy efficiency: The three largest uses of energy in the food industry in the United States are animal slaughtering and processing, wet corn milling, and fruit and vegetable preservation, accounting for 19 %, 15 %, and 14 % of total use, respectively (US EIA, 2009). Increased use of heat exchanger networks or heat pumps (Fritzson and Berntsson, 2006; Sakamoto et al., 2011), combined heat and power, mechanical dewatering compared to rotary drying (Masanet et al., 2008), and thermal and mechanical vapour recompression in evaporation further enhanced by use of reverse osmosis can deliver energy use efficiency. Many of these technologies could also be used in cooking and drying in other parts of the food industry. Savings in energy for refrigeration

10 http://www.aluminum.org/Content/NavigationMenu/TheIndustry/Environment/ReducingPFCEmissionsintheAluminumIndustry/default.html.

could be made with better insulation and reduced ventilation in fridges and freezers. Dairy processing is also among the most energy- and carbon-intensive activities within the global food production industry, with estimated annual emissions of over 128 $MtCO_2$ (Xu and Flapper, 2009, 2011). Within dairy processing, cheese production is the most energy intensive sector (Xu et al., 2009). Ramirez and Block (2006) report that EU dairy operations, having improved in the 1980s and 1990s, are now reaching a plateau of energy intensity, but Brush et al. (2011) provide a survey of best practice opportunities for energy efficiency in dairy operations.

Emissions efficiency: The most cost effective reduction in CO_2 emissions from food production is by switching from heavy fuel oil to natural gas. Other ways of improving emissions efficiency involve using lower-emission modes of transport (Garnett, 2011). In transporting food, there is a tradeoff between local sourcing and producing the food in areas where there are other environmental benefits (Sim et al., 2007; Edwards-Jones et al., 2008). Landfill emissions associated with food waste could be reduced by use of anaerobic digestion processes (Woods et al., 2010).

Demand reduction: Overall demand for food could be reduced without sacrificing well-being (GEA, 2012). Up to one-third of food produced for human consumption is wasted in either in the production/retailing stage, or by consumers (Gunders (2012) estimates 40 % waste in the United States). Gustavsonn et al. (2011) suggest that, in developed countries, consumer behaviour could be changed, and 'best-before-dates' reviewed. Increasing cooling demand, the globalization of the food system with corresponding transport distances, and the growing importance of processed convenience food are also important drivers (GEA, 2012). Globally, approximately 1.5 billion out of 5 billion people over the age of 20 are overweight and 500 million are obese (Beddington et al., 2011). Demand for high-emission food such as meat and dairy products could be replaced by demand for other, lower-emission foods. Meat and dairy products contribute to half of the emissions from food (when the emissions from the up-stream processes are included) according to Garnett (2009), while Stehfest et al. (2009) puts the figure at 18 % of global GHG emissions, and Wirsenius (2003) estimates that two-thirds of food-related phytomass is consumed by animals, which provide just 13 % of the gross energy of human diets. Furthermore, demand is set to double by 2050, as developing nations grow wealthier and eat more meat and dairy foods (Stehfest et al., 2009; Garnett, 2009). In order to maintain a constant total demand for meat and dairy, Garnett (2009) suggests that by 2050 average per capita consumption should be around 0.5 kg meat and 1 litre of milk per week, which is around the current averages in the developing world today.

10.4.7 Textiles and leather

In 2009, textiles and leather manufacturing consumed 2.15 EJ final energy globally. Global consumption is dominated by Asia, which was responsible for 65 % of total world energy use for textiles and leather manufacturing in 2009. In the United States, about 45 % of the final energy used for textile mills is natural gas, about 35 % is net electricity (site), and 14 % coal (US EIA, 2009). In China, final energy consumption for textiles production is dominated by coal (39 %) and site electricity (38 %) (NBS, 2012). In the US textile industry, motor driven systems and steam systems dominate energy end uses. Around 36 % of the energy input to the US textile industry is lost onsite, with motor driven systems responsible for 13 %, followed by energy distribution and boiler losses of 8 % and 7 %, respectively (US DoE, 2004b).

Energy and emissions efficiency: Numerous energy efficiency technologies and measures exist that are applicable to the textile industry (CIPEC, 2007; Hasanbeigi and Price, 2012). For Taiwan, Province of China, Hong et al. (2010) report energy savings of about 1 % in textile industry following the adoption of energy-saving measures in 303 firms (less than 10 % of the total number of local textile firms in 2005) (Chen Chiu, 2009). In India, CO_2 emissions reductions of at least 13 % were calculated based on implementation of operations and maintenance improvements, fuel switching, and adoption of five energy-efficient technologies (Velavan et al., 2009).

Demand reduction: see Box 10.2.

10.4.8 Mining

Energy efficiency: The energy requirements of mining are dominated by grinding (comminution) and the use of diesel-powered material handling equipment (US DoE, 2007; Haque and Norgate, 2013). The major area of energy usage—up to 40 % of the total—is in electricity for comminution (Smith, 2012). Underground mining requires more energy than surface mining due to greater requirements for hauling, ventilation, water pumping, and other operations (US DoE, 2007). Strategies for GHG mitigation are diverse. An overall scheme to reduce energy consumption is the implementation of strategies that upgrade the ore body concentration before crushing and grinding, through resource characterization by geo-metallurgical data and methods (Bye, 2005, 2007, 2011; CRC ORE, 2011; Smith, 2012). Selective blast design, combined with ore sorting and gangue rejection, significantly improve the grade of ore being fed to the crusher and grinding mill, by as much as 2.5 fold. This leads to large reductions of energy usage compared to business-as-usual (CRC ORE, 2011; Smith, 2012).

There is also a significant potential to save energy in comminution through the following options: more crushing, less grinding, using more energy-efficient crushing technologies, removing minerals and gangue from the crushing stage, optimizing the particle size feed for grinding mills from crushing mills, selecting target product size(s) at each stage of the circuit, using advanced flexible comminution circuits, using more efficient grinding equipment, and by improving the design of new comminution equipment (Smith, 2012).

Other important energy savings opportunities are in the following areas: a) separation processes—mixers, agitators and froth flotation cells, b) drying and dewatering in mineral processing, c) materials movement, d) air ventilation and conditioning opportunities, e) processing site energy demand management and waste heat recovery options, f) technology specific for lighting, motors, pumps and fans and air compressor systems, and g) improvement in energy efficiency of product transport from mine site to port (Rathmann, 2007; Raaz and Mentges, 2009; Daniel et al., 2010; Norgate and Haque, 2010; DRET, 2011; Smith, 2012).

Recycling represents an important source of world's metal supply and it can be increased as a means of waste reduction (see Section 10.14) and thus energy saving in metals production. In recent years, around 36 % of world's gold supply was from recycled scrap (WGC, 2011), 25 % of silver (SI and GFMS, 2013), and 35 % of copper (ICSG, 2012).

Emissions efficiency: Substitution of onsite fossil fuel electricity generators with renewable energy is an important mitigation strategy. Cost effectiveness depends on the characteristics of each site (Evans & Peck, 2011; Smith, 2012).

Material efficiency: In the extraction of metal ores, one of the greatest challenges for energy efficiency enhancement is that of the recovery ratio, which refers to the percentage of valuable ore within the total mine material. Lower grades inevitably require greater amounts of material to be moved per unit of product. The recovery ratio for metals averages about 4.5 % (US DoE, 2007). The 'grade' of recyclable materials is often greater than the one of ores being currently mined; for this reason, advancing recycling for mineral commodities would bring improvements in the overall energy efficiency (IIED, 2002).

10.5 Infrastructure and systemic perspectives

Improved understanding of interactions among different industries, and between industry and other economic sectors, is becoming more important in a mitigation and sustainable development context. Strategies adopted in other sectors may lead to increased (or decreased) emissions from the industry sector. Collaborative activities within and across the sector may enhance the outcome of climate change mitigation. Initiatives to adopt a system-wide view face a barrier as currently practiced system boundaries often pose a challenge. A systemic approach can be at different levels, namely, at the micro-level (within a single company, such as process integration and cleaner production), the meso-level (between three or more companies, such as eco-industrial parks) and the macro-level (cross-sectoral cooperation, such as urban symbiosis or regional eco-industrial network). Systemic collaborative activities can reduce the total consumption of materials and energy and can contribute to the reduction of GHG emissions. The rest of this section focuses mainly on the meso- and macro-levels as micro-level options have already been covered in Section 10.4.

10.5.1 Industrial clusters and parks (meso-level)

Small and medium enterprises (SMEs) often suffer not only from difficulties arising due to their size and lack of access to information, but also from being isolated while in operation (Sengenberger and Pyke, 1992). Clustering of SMEs usually in the form of industrial parks can facilitate growth and competitiveness (Schmitz, 1995). In terms of implementation of mitigation options, SMEs in clusters/parks can benefit from by-products exchange (including waste heat) and infrastructure sharing, as well as joint purchase (e.g., of energy efficient technologies). Cooperation in eco-industrial parks (EIPs) reduces the cumulative environmental impact of the whole industrial park (Geng and Doberstein, 2008). Such an initiative reduces the total consumption of virgin materials and final waste and improves the efficiency of companies and their competitiveness. Since the extraction and transformation of virgin materials is usually energy intensive, EIP efforts can abate industrial GHG emissions. For example, in order to encourage target-oriented cooperation, Chinese 'eco-industrial park standards' contain quantitative indicators for material reduction and recycling, as well as pollution control (Geng et al., 2009). Two pioneering eco-industrial parks in China achieved over 80 % solid waste reuse ratio and over 82 % industrial water reuse ratio during 2002–2005 (Geng et al., 2008). The Japanese eco-town project in Kawasaki achieved substitution of 513,000 tonnes of raw material, resulting in the avoidance of 1 % of the current total landfill in Japan during 1997–2006 (van Berkel et al., 2009).

In order to encourage industrial symbiosis[11] at the industrial cluster level, different kinds of technical infrastructure (e.g., pipelines) as well as non-technical infrastructure (e.g., information exchange platforms) are necessary so that both material and energy use can be optimized (Côté and Hall, 1995). Although additional investment for infrastructure building is unavoidable, such an investment can bring both economic and environmental benefits. In India there have been several instances where the government has taken proactive approaches to provide land and infrastructure, access to water, non-conventional (MSW-based) power to private sector industries (such as chemicals, textile, paper, pharmaceutical companies, cement) operating in clusters (IBEF, 2013). A case study in the Tianjin Economic Development Area in northern China indicates that the application of an integrated water optimization model (e.g., reuse of treated wastewater by other firms) can reduce the total water related costs by 10.4 %, fresh water consumption by 16.9 % and wastewater discharge by 45.6 % (Geng et al., 2007). As an additional consequence, due to the strong energy-water nexus, energy use and release of GHG emissions related to fresh water provision or wastewater treatment can be reduced.

[11] Note that industrial symbiosis is further covered in Chapter 4 (Sustainable Development and Equity), Section 4.4.3.3

10

10.5.2 Cross-sectoral cooperation (macro-level)

Besides inter-industry cooperation, opportunities arise from the geographic proximity of urban and industrial areas, leading to transfer of urban refuse as a resource to industrial applications, and vice versa (Geng et al., 2010a). For instance, the cement industry can accept as their inputs not only virgin materials such as limestone and coal, but also various wastes/industrial by-products (see Section 10.4), thus contributing up to 15–20 % CO_2 emission reduction (Morimoto et al., 2006; Hashimoto et al., 2010). In Northern Europe (e.g., Sweden, Finland, and Denmark), for example, both exhaust heat from industries and heat generated from burning municipal wastes are supplied to local municipal users through district heating (Holmgren and Gebremedhin, 2004). Industrial waste can also be used to reduce conventional fuel demand in other sectors. For example, the European bio-DME project[12] aims to supply heavy-duty trucks and industry with dimethyl-ether fuel made from black liquor produced by the pulp industry. However, careful design of regional recycling networks has to be undertaken because different types of waste have different characteristics and optimal collection and recycling boundaries and therefore need different infrastructure support (Chen et al., 2012).

The reuse of materials recovered from urban infrastructures can reduce the demand for primary products (e.g., ore) and thus contribute to climate change mitigation in extractive industries (Klinglmair and Fellner, 2010). So far, reuse of specific materials is only partly established and the potential for future urban mining is growing as the urban stock of materials still increases. While in the 2011 fiscal year in Japan only 5.79 Mt of steel scrap came from the building sector, 13.6 Mt were consumed by the building sector. In total, urban stock of steel is estimated to be 1.33 Gt in Japan where the total annual crude steel production was 0.106 Gt (NSSMC, 2013).

10.5.3 Cross-sectoral implications of mitigation efforts

Currently much attention is focused on improving energy efficiency within the industry sector (Yeo and Gabbai, 2011). However, many mitigation strategies adopted in other sectors significantly affect activities of the industrial sector and industry-related GHG emissions. For example, consumer preference for lightweight cars can incentivize material substitution for car manufacturing (e.g., potential lightweight materials: see Chapter 8), growing demand for rechargeable vehicle batteries (see Chapter 8) and the demand for new materials (e.g., innovative building structures or thermal insulation for buildings: see Chapter 9; high-temperature steel demand by power plants: see Chapter 7). These materials or products consume energy at the time of manufacturing, so changes outside the industry sector that lead to changes in demand for energy-saving products within the industry sector can be observed over a long period of time (ICCA, 2009). Thus, for a careful assessment of mitigation options, a lifecycle perspective is needed so that a holistic emission picture (including embodied emissions) can be presented. For instance, the increase in GHG emissions from increased aluminium production could under specific circumstances be larger than the GHG savings from vehicle weight reduction (Geyer, 2008). Kim et al. (2010) have, however, indicated that in about two decades, closed-loop recycling can significantly reduce the impacts of aluminium-intensive vehicles.

Increasing demand on end-use related mitigation technologies could contribute to potential material shortages. Moss et al. (2011) examined market and political risks for 14 metals that are used in significant quantities in the technologies of the EU's Strategic Energy Technology Plan (SET Plan) so that metal requirements and associated bottlenecks in green technologies, such as electric vehicles, low-carbon lighting, electricity storage and fuel cells and hydrogen, can be recognized.

Following a systemic perspective enables the identification of unexpected outcomes and even potential conflicts between different targets when implementing mitigation options. For example, the quality of many recycled metals is maintained solely through the addition of pure primary materials (Verhoef et al., 2004), thus perpetuating the use of these materials and creating a challenge for the set up of closed loop recycling (e.g., automotive aluminium; Kim et al., 2011). Additionally, due to product retention (the period of use) and growing demand, secondary materials needed for recycling are limited.

10.6 Climate change feedback and interaction with adaptation

There is currently a distinct lack of knowledge on how climate change feedbacks may impact mitigation options and potentials as well as costs in industry[13].

Insights into potential synergy effects (how adaptation options could reduce emissions in industry) or tradeoffs (how adaptation options could lead to additional emissions in industry) are also lacking. However, it can be expected that many adaptation options will generate additional industrial product demand and will lead to additional emissions in the sector. Improving flood defence, for example, in response to sea level rise may lead to a growing demand

[12] Production of DME from biomass and utilization of fuel for transport and industrial use. Project website at: http://www.biodme.eu.

[13] There is limited literature on the impacts of climate change on industry (e.g., availability of water for the food industry and in general for cooling and processing in many different industries), and these are dealt within WG 2 of AR 5, Chapter 10.

for materials for embankment and similar infrastructure. Manufacturers of textile products, machinery for agriculture or construction, and heating/cooling equipment may be affected by changing product requirements in both number and quality due to climate change. There is as yet no comprehensive assessment of these effects, nor any estimate on market effects resulting from changes in demand for products.

10.7 Costs and potentials

The six main categories of mitigation options discussed in Section 10.4 for manufacturing industries can deliver GHG emission reduction benefits at varying levels and at varying costs over varying time periods across subsectors and countries. There is not much comparable, comprehensive, detailed quantitative information and literature on costs and potentials associated with each of the mitigation options. Available mitigation potential assessments (e.g., UNIDO, 2011; IEA, 2012d) are not always supplemented by cost estimates. Also, available cost estimates (e.g., McKinsey&Company, 2009; Akashi et al., 2011) are not always comparable across studies due to differences in the treatment of costs and energy price estimates across regions. There are many mitigation potential assessments for individual industries (examples are included in Section 10.4) with varying time horizons; some studies report the mitigation potential of energy efficiency measures with associated initial investment costs which do not account for the full life time energy cost savings benefits of investments, while other studies report marginal abatement costs (MACs) based on selected technological options. Many sector- or system-specific mitigation potential studies use the concept of cost of conserved energy (CCE) that accounts for annualized initial investment costs, operation and maintenance (O&M) costs, and energy savings using either social or private discount rates (Hasanbeigi et al., 2010b). Those mitigation options with a CCE below the unit cost of energy are referred to as 'cost-effective'. Some studies (e.g., McKinsey&Company, 2009) identify 'negative abatement costs' by including the energy cost savings in the abatement cost calculation.

The sections below provide an assessment of option-specific potential and associated cost estimates using information available in the literature (including underlying databases used by some of such studies) and expert judgement (see Annex III, Technology-specific cost and performance parameters) and distinguish mitigation of CO_2 and non-CO_2 emissions. Generally, the assessment of costs is relatively more uncertain but some indicative results convey information about the wide cost range (costs per tonne of CO_2 reduction) within which various options can deliver GHG reduction benefit. The inclusion of additional multiple benefits of mitigation measures might change the cost-effectiveness of a technology completely, but are not included in this section. Co-benefits are discussed in Section 10.8.

10.7.1 CO_2 emissions

Quantitative assessments of CO_2 emission reduction potential for the industrial sector explored in this section are mainly based on: (1) studies with a global scope (e.g., IEA, UNIDO), (2) MAC studies and (3) various information sources on available technology at industrial units along with plant level and country specific data. IEA estimates a global mitigation potential for the overall industry sector of 5.5 to 7.5 $GtCO_2$ for the year 2050 (IEA, 2012d)[14]. The IEA report (2012d) shows a range of 50 % reduction in four key sectors (iron and steel, cement, chemicals, and paper) and in the range of 20 % for the aluminium sector. From a regional perspective, China and India comprise 44 % of this potential. In terms of how different options contribute to industry mitigation potential, with regard to CO_2 emissions reduction compared with 2007 values, the IEA (2009c) shows implementation of end use fuel efficiency can achieve 40 %, fuel and feedstock switching can achieve 21 %, recycling and energy recovery can achieve 9 %, and CCS can achieve 30 %. McKinsey (2009) provides a global mitigation potential estimate for the overall industry sector of 6.9 $GtCO_2$ for 2030. The potential is found to be the largest for iron and steel, followed by chemicals and cement at 2.4, 1.9 and 1.0 $GtCO_2$ for the year 2030, respectively (McKinsey&Company, 2010). The United Nations Industrial Development Organization (UNIDO) analyzed the potential of energy savings based on universal application of best available technologies. All the potential mitigation values are higher in developing countries (30 to 35 %) compared with developed countries (15 %) (UNIDO, 2011).

Other studies addressing the industrial sector as a whole found potential for future improvements in energy intensity of industrial production to be in the range of up to 25 % of current global industrial final energy consumption per unit output (Schäfer, 2005; Allwood et al., 2010; UNIDO, 2011; Saygin et al., 2011b; Gutowski et al., 2013) (see Section 10.4). Additional savings can be realized in the future through adoption of emerging technologies currently under development or that have not yet been fully commercialized (Kong et al., 2012; Hasanbeigi et al., 2012b, 2013a). Examples of industries from India show that specific energy consumption is steadily declining in all energy intensive sectors (Roy et al., 2013), and a wide variety of measures at varying costs have been adopted by the energy intensive industries (Figure 10.6). However, all sectors still have energy savings potential when compared to world best practice (Dasgupta et al., 2012).

Bottom-up country analyses provide energy savings estimates for specific industrial sub-sectors based on individual energy efficiency technologies and measures. Because results vary among studies, these estimates should not be considered as the upper bound of energy saving potential but rather should give an orientation about the general possibilities.

[14] Expressed here in the form of a deployment potential (difference between the 6 °C and 2 °C scenarios, 6DS and 2DS) rather than the technical potential.

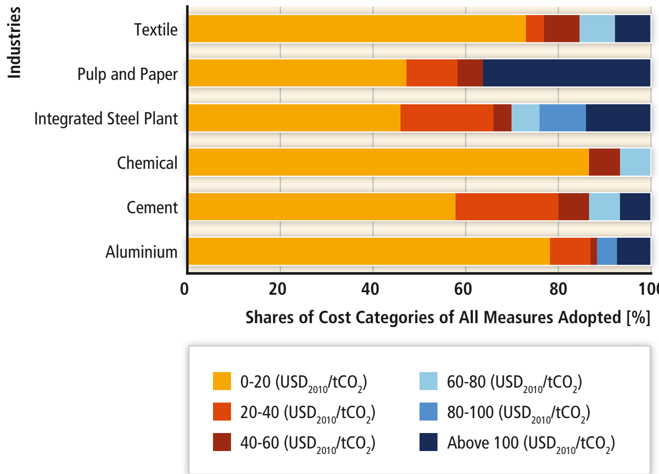


Figure 10.6 | Range of unit cost of avoided CO_2 emissions (USD_{2010}/tCO_2) in India. Source: Database of energy efficiency measures adopted by the winners of the National Awards on Energy Conservations for aluminium (26 measures), cement (42), chemicals (62), ISP: integrated steel plant (30), pulp and paper (46), and textile (75) industry in India during the period of 2007–2012 (BEE, 2012).

In the cement sector, global weighted average thermal energy intensity could drop to 3.2 GJ/t clinker and electric energy intensity to 90 kWh/t cement by 2050 (IEA/WBCSD, 2009). Emissions of 510 $MtCO_2$ would be saved if all current cement kilns used best available technology and increased use of clinker substitutes (IEA, 2009c). Oda et al. (2012) found large differences in regional thermal energy consumption for cement manufacture, with the least efficient region consuming 75 % more energy than the best in 2005. Even though processing alternative fuels requires additional electricity consumption (Oda et al., 2012), their use could reduce cement sector emissions by 0.16 $GtCO_2eq$ per year by 2030 (Vattenfall, 2007) although increasing costs may in due course limit uptake (IEA/WBCSD, 2009). Implementing commercial-scale CCS in the cement industry could contribute to climate change mitigation, but would increase cement production costs by 40–90 % (IEAGHG, 2008). From the cumulative energy savings potential for China's cement industry (2010 to 2030), 90 % is assessed as cost-effective using a discount rate of 15 % (Hasanbeigi et al., 2012a). Electricity and fuel savings of 6 and 1.5 times the total electricity and fuel use in the Indian cement industry in 2010, respectively, can be realized for the period 2010–2030, almost all of which is assessed as cost-effective using a discount rate of 15 % (Morrow III et al., 2013a). About 50 % of the electricity used by Thailand's cement industry in 2005 could have been saved (16 % cost-effectively), while about 20 % of the fuel use could have been reduced (80 % cost-effectively using a discount rate of 30 %) (Hasanbeigi et al., 2010a, 2011). Some subnational level information also shows negative CO_2 abatement costs associated with emissions reductions in the cement sector (e.g., CCAP, 2005).

Nearly 60 % of the estimated electricity savings and all of the fuel savings of the Chinese steel industry for the period 2010–2030 can be realized cost-effectively using a discount rate of 15 % (Hasanbeigi et al., 2013c). Total technical primary energy savings potential of the Indian steel industry from 2010–2030 is equal to around 87 % of total primary Indian steel industry energy use in 2007, of which 91 % of the electricity savings and 64 % of the fuel savings can be achieved cost-effectively using a discount rate of 15 % (Morrow III et al., 2013b). Akashi et al. (2011) indicate that the largest potential for CO_2 emissions savings for some energy-intensive industries remains in China and India. They also indicate that with associated costs under 100 USD/tCO_2 in 2030, the use of efficient blast furnaces in the steel industry in China and India can reduce total emissions by 186 $MtCO_2$ and 165 $MtCO_2$, respectively. This represents a combined total of 75 % of the global CO_2 emissions reduction potential for this technology.

Total technical electricity and fuel savings potential for China's pulp and paper industry in 2010 are estimated to be 4.3 % and 38 %, respectively. All of the electricity and 70 % of the fuel savings can be realized cost-effectively using a discount rate of 30 % (Kong et al., 2013). Fleiter et al. (2012a) found energy saving potentials for the German pulp and paper industry of 21 % and 16 % of fuel and electricity demand in 2035, respectively. The savings result in 3 $MtCO_2$ emissions reduction with two-thirds of this having negative private abatement cost (Fleiter et al., 2012a). Zafeiris (2010) estimates energy saving potential of 6.2 % of the global energy demand of the pulp and paper industry in year 2030. More than 90 % of the estimated savings potential can be realized at negative cost using a discount rate of 30 % (Zafeiris, 2010). The energy intensity of the European pulp and paper industry reduced from 16 to 13.5 GJ per tonne of paper between 1990 and 2008 (Allwood et al., 2012, p. 318; CEPI, 2012). However, energy intensity of the European pulp and paper industry has now stabilized, and few significant future efficiency improvements are forecasted.

In non-ferrous production (aluminium/others), energy accounts for nearly 40 % of aluminium production costs. The IEA forecasts a maximum possible 12 % future saving in energy requirements by future efficiencies. In food processing, reductions between 5 % and 35 % of total CO_2 emissions can be made by investing in increased heat exchanger networks or heat pumps (Fritzson and Berntsson, 2006). Combined heat and power can reduce energy demand by 20–30 %. Around 83 % of the energy used in wet corn milling is for dewatering, drying, and evaporation processes (Galitsky et al., 2003), while 60 % of that used in fruit and vegetable processing is in boilers (Masanet et al., 2008). Thermal and mechanical vapour recompression in drying allows for estimated 15–20 % total energy savings, which could be increased further by use of reverse osmosis (Galitsky et al., 2003). Cullen et al. (2011) suggest that about 88 % savings in energy for refrigeration could be made with better insulation, and reduced ventilation in refrigerators and freezers.

There is very little data available on mineral extractive industries in general. Some analyses reveal that investments in state-of-the-art equipment and further research could reduce energy consumption by almost 50 % (SWEEP, 2011; US DoE, 2007).

Allwood et al. (2010) assessed different strategies to achieve a 50 % cut in the emissions of five sectors (cement, steel, paper, aluminium, and plastics) assuming doubling of demand by 2050. They found that gains in efficiency could result in emissions intensity reductions in the range of 21 %–40 %. Further reductions to reach the required 75 % reduction in emissions intensity can only be achieved by implementing strategies at least partly going beyond the sectors boundaries: i. e., non destructive recycling, reducing demand through light weighting, product life extension, increasing intensity of product use or substitution for other materials, and radical process innovations, notwithstanding significant implementation barriers (see Section 10.9).

Mitigation options can also be analyzed from the perspective of some industry-wide technologies. Around two-thirds of electricity consumption in the industrial sector is used to drive motors (McKane and Hasanbeigi, 2011). Steam generation represents 30 % of global final industrial energy use. Efficiency of motor systems and steam systems can be improved by 20–25 % and 10 %, respectively (GEA, 2012; Brown et al., 2012). Improvements in the design and especially the operation of motor systems, which include motors and associated system components in compressed air, pumping, and fan systems (McKane and Hasanbeigi, 2010, 2011; Saidur, 2010), have the potential to save 2.58 EJ in final energy use globally (IEA, 2007). McKane and Hasanbeigi (2011) developed energy efficiency supply curve models for the United States, Canada, the European Union, Thailand, Vietnam, and Brazil and found that the cost-effective potential for electricity savings in motor system energy use compared to the base year varied between 27 % and 49 % for pumping, 21 % and 47 % for compressed air, and 14 % and 46 % for fan systems. The total technical saving potential varied between 43 % and 57 % for pumping, 29 % and 56 % for compressed air, and 27 % and 46 % for fan systems. Ways to reduce emissions from many industries include more efficient operation of process heating systems (LBNL and RDC, 2007; Hasanuzzaman et al., 2012) and steam systems (NREL et al., 2012), minimized waste heat loss and waste heat recovery (US DoE, 2004a, 2008), advanced cooling systems, use of cogeneration (or combined heat and power) (Oland, 2004; Shipley et al., 2008; Brown et al., 2013), and use of renewable energy sources. Recent analysis show, for example, that recuperators can reduce furnace energy use by 25 % while economizers can reduce boiler energy use by 10 % to 20 %, both with payback periods typically under two years (Hasanuzzaman et al., 2012).

According to data from McKinsey (2010) on MACs for cement, iron, and steel and chemical sectors, and from Akashi et al. (2011) for cement and iron and steel, around 40 % mitigation potential in industry can be realized cost-effectively. Due to methodological reasons, MACs always have to be discussed with caution. It has to be considered that the information about the direct additional cost associated with additional reduction of CO_2 through technological options is limited. Moreover, system perspectives and system interdependencies are not typically taken into account for MACs (McKinsey&Company, 2010; Akashi et al., 2011).

Unless barriers to mitigation in industry are resolved, the pace and extent of mitigation in industry will be limited, and even cost-effective measures will remain untapped. Various barriers that block technology adoption despite low direct costs are often not appropriately accounted for in mitigation cost assessments. Such barriers are discussed in Section 10.9.

In the long term, however, it may be more relevant to look at radically new ways of producing energy-intensive products. Low-carbon cement and concrete might become relevant (Hasanbeigi et al., 2012b); however, from current perspective cost assessments for these technologies are connected with high uncertainties.

10.7.2 Non-CO_2 emissions

Emissions of non-CO_2 gases from different industrial sources are projected to be 0.70 $GtCO_2eq$ in the year 2030 (EPA, 2013), dominated by HFC-23 from HCFC-22 production (46 %) and N_2O from nitric acid and from adipic acid (24 %). In 2030, it is projected that HFC-23 emissions will be related mainly to the production of HCFC-22 for feedstock use, as its use as refrigerant will be phased out in 2035 (Miller and Kuijpers, 2011). The EPA (2013) provides MACs for all non-CO_2 emissions. Emissions resulting from the production of flat panel displays and from photovoltaic cell manufacturing are projected to be small (2 and 12 $MtCO_2eq$ respectively in 2030), but particularly uncertain due to limited information on emissions rates, use of fluorinated gases, and production growth rates.

10.7.3 Summary results on costs and potentials

Based on the available bottom-up information from literature and through expert consultation, a global picture of the four industrial key sub-sectors (cement, steel, chemicals, and pulp and paper) is assessed and presented in Figures 10.7 to 10.10 below. Detailed justification of the figures and description of the options are provided in Annex III. Globally, in 2010, these four selected sub-sectors contributed 5.3 $GtCO_2$ direct energy- and process-related CO_2 emissions (see Section 10.3): iron and steel 1.9 $GtCO_2$, non-metallic minerals (which includes cement) 2.6 $GtCO_2$, chemicals and petrochemicals 0.6 $GtCO_2$, and pulp and paper 0.2 $GtCO_2$. This amounts to 73 % of all direct[15] energy- and process-related CO_2 emissions from the industry sector.

For each of the sub-sectors, only selected mitigation options are covered (for other feasible options in the industry sector refer to Section 10.4): energy efficiency, shift in raw material use to less carbon-intensive alternatives (e. g., reducing the clinker to cement ratio, recycling etc.), fuel mix options, end-of-pipe emission abatement options such

15 These values do not include indirect emissions from electricity and heat production.

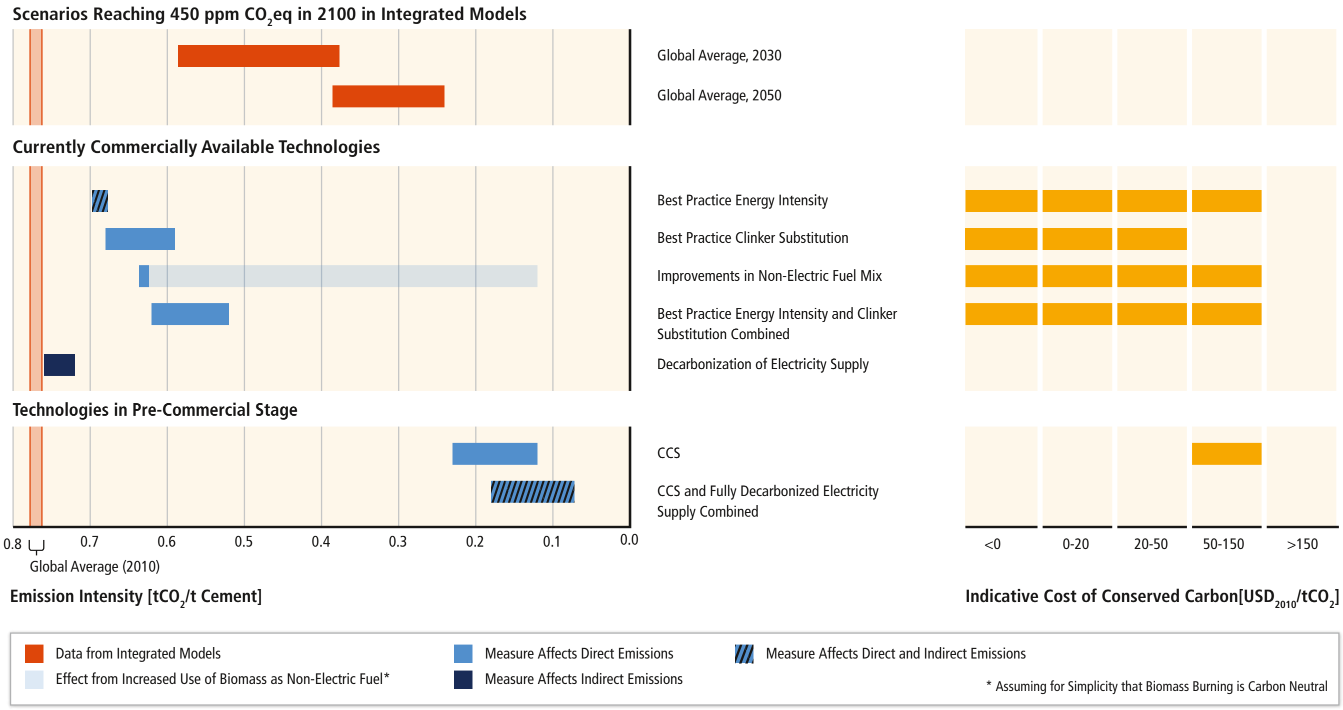


Figure 10.7 | Indicative CO_2 emission intensities and levelized cost of conserved carbon in cement production for various production practices/technologies and in 450 ppm scenarios of selected models (AIM, DNE21+, IEA ETP 2DS) (for data and methodology, see Annex III).

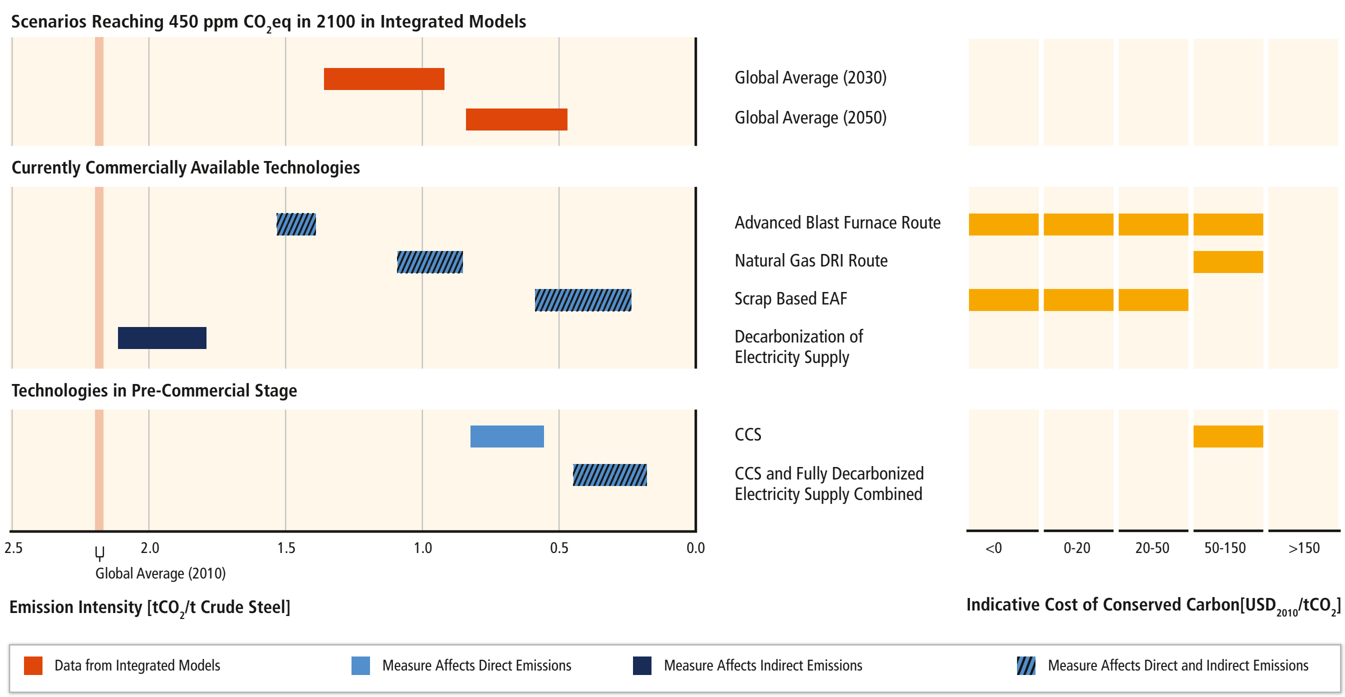


Figure 10.8 | Indicative CO_2 emission intensities and levelized cost of conserved carbon in steel production for various production practices/technologies and in 450 ppm scenarios of selected models (AIM, DNE21+, and IEA ETP 2DS) (for data and methodology, see Annex III).

Figure 10.9 | Indicative global indirect (left) and direct (right) CO_2eq emissions and levelized cost of conserved carbon resulting from chemicals production for various production practices/technologies and CO_2 emissions in IEA ETP 2DS scenario (for data and methodology, see Annex III).

Notes: Graph includes energy-related emissions (including process emissions from ammonia production), N_2O emissions from nitric and adipic acid production and HFC-23 emissions from HFC-22 production. Costs for N_2O abatement from nitric/adipic acid production and for HFC-23 abatement in HFC-22 production based on EPA (2013) and Miller and Kuijpers (2011), respectively.

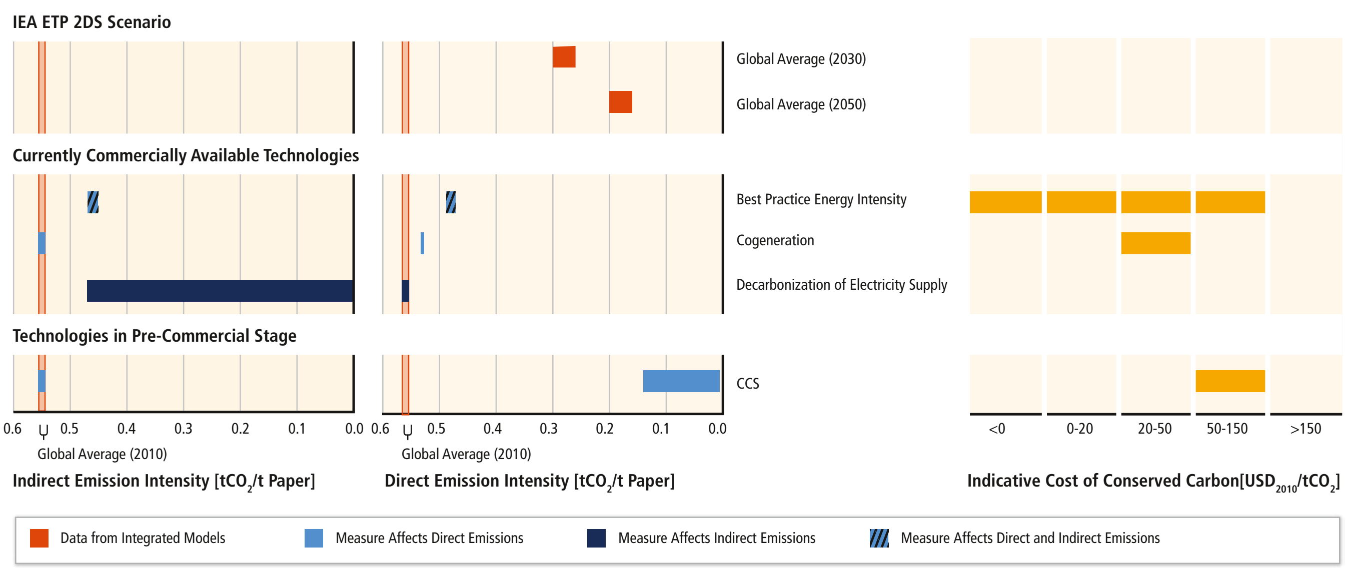


Figure 10.10 | Indicative global indirect (left) and direct (right) CO_2 emission intensities and levelized cost of conserved carbon in paper production for various production practices/technologies and in IEA ETP 2DS scenario (for data and methodology, see Annex III).

as carbon dioxide capture and storage (CCS), use of decarbonized electricity and options for the two most important current sources of non-CO_2 GHG emissions (HFC 23 emissions from HFC 22 production and N_2O emissions from nitric and adipic acid production) in the chemical industry. The potentials are given related to the 2010 emission intensity or absolute emissions. Cost estimates relate to the current costs (expressed in USD_{2010}) of the abatement options unless otherwise stated.

Potentials and costs to decarbonize the electricity sector are covered in Chapter 7. To ensure consistency with that chapter, no estimates are given for the costs related to decarbonizing the electricity mix for the industrial sector.

Costs and potentials are global averages, but based on region-specific information. The technology options are given relative to the global average emission intensity. Some options are not mutually exclusive and potentials can therefore not always be added. As such, none of the individual options can yield full GHG emission abatement, because of the multiple emission sources included (e.g., in the chemical sector CCS and fuel mix improvements cannot reduce N_2O emissions).

Costs relate to costs of abatement taking into account total incremental operational and capital costs. The figures give indicatively the costs of implementing different options; they also exclude options related to material efficiency (e.g., reduction of demand), but include some recycling options (although not in pulp and paper). Figure 10.7 about cement production includes process CO_2 emissions.

Emissions after implementing potential options to reduce the GHG emission intensity of cement, steel, pulp and paper sectors are presented in tCO_2/t product compared to 2010 global average respectively. Future relevant scenarios are also presented. However, for the chemical sector, due to its heterogeneity in terms of products and processes, the information is presented in terms of total emissions. This can be an under-representation of relatively higher mitigation potential in e.g., ammonia production. In addition, unknown/unexplored options such as hydrogen/electricity-based chemicals and fuels are not included, so it is worth noting that the options are exemplary. In the cement industry (Figure 10.7), the potential and costs for clinker substitution and fuel mix changes are dependent on regional availability and the price of clinker substitutes and alternative fuels. Negative cost options in cement manufacturing are in switching to best practice clinker-to-cement ratio. In the iron and steel industry (Figure 10.8), a shift from blast furnace based steelmaking to electric arc furnace steelmaking provides significant negative cost opportunities. However, this potential is highly dependent on scrap availability. The chemical sector (Figure 10.9) includes options related to energy efficiency improvements and options related to reduction of N_2O emissions from nitric and adipic acid production and HFC-23 emissions from HFC-22 production. In pulp and paper manufacturing (Figure 10.10), the estimates exclude increased recycling because the effect on CO_2 emissions is uncertain.

The costs of the abatement options shown in Figure 10.7 vary widely between individual regions and from plant to plant in the cement industry. Factors influencing the costs include typical capital stock turnover rates (some measures can only be applied when plants are replaced), relative energy costs, etc. For clinker substitution and fuel mix improvements, costs depend heavily on the regional availability and price of clinker substitutes and alternative fuels.

For all subsectors, negative abatement cost options exist to a certain extent for shifting to best practice technologies and for fuel shifting. While options in cost ranges of 0–20 and 20–50 USD_{2010}/tCO_2eq are somewhat limited, larger opportunities exist in the 50–150 USD_{2010}/tCO_2eq range (particularly since CCS is included here). The feasibility of CCS depends on global CCS developments. CCS is currently not yet applied (with some exceptions) at commercial scale in the cement, iron and steel, chemical, or pulp/paper industries.

10.8 Co-benefits, risks and spillovers

In addition to mitigation costs and potentials (see Section 10.7), the deployment of mitigation measures will depend on a variety of other factors that relate to broader economic, social, and environmental objectives that drive decisions in the industry sector and policy choices. The implementation of mitigation measures can have positive or negative effects on these other objectives. To the extent that these side-effects are positive, they can be deemed 'co-benefits'; if adverse and uncertain, they imply risks.[16] Co-benefits and adverse side-effects of mitigation measures (10.8.1), the associated technical risks and uncertainties (10.8.2) as well as their public perception (10.8.3) and technological spillovers (10.8.4), can significantly affect investment decisions, individual behaviour, and policymaker priorities. Table 10.5 provides an overview of the potential co-benefits and adverse side-effects of the mitigation measures that are assessed in this chapter. In accordance with the three sustainable development pillars described in Chapter 4, the table presents effects on objectives that may be economic, social, environmental, and health related. The extent to which co-benefits and adverse side-effects will materialize in practice as well as their net effect on social welfare differ greatly across regions, and is strongly dependent on local circumstances and implementation practices, as well as on the scale and pace of the deployment of the different mitigation measures (see Section 6.6).

[16] Co-benefits and adverse side-effects describe effects in non-monetary units without yet evaluating the net effect on overall social welfare. Please refer to the respective sections in the framing chapters (particularly Sections 2.4, 3.6.3, and 4.8) as well as to the glossary in Annex I for concepts and definitions.

10.8.1 Socio-economic and environmental effects

Social embedding of technologies depends on compatibility with existing systems, social acceptance, divisibility, eco-friendliness, relative advantage, etc. (Geels and Schot, 2010; Roy et al., 2013). A typical example is the tradeoff or the choice that is made between investing in mitigation in industry and adaptation in the absence of right incentives for mitigation action (Chakraborty and Roy, 2012a). Slow diffusion of mitigation options (UNIDO, 2011) can be overcome by focusing on, and explicit consideration of, non-direct cost-related characteristics of the technologies (Fleiter et al., 2012c). It is unanimously understood that maintaining competitiveness of industrial products in the market place is an important objective of industries, so implementation of mitigation measures will be a major favoured strategy for industries if they contribute to cost reduction (Bernstein et al., 2007; Winkler et al., 2007; Bassi et al., 2009). Increasing demand for energy in many countries has led to imports and increasing investment in high-cost reliable electric power generation capacity; so mitigation via implementation of energy efficiency measures help to reduce import dependency and investment pressure (Winkler et al., 2007). Labour unions are increasingly expressing their desire for policies to address climate change and support for a transition to 'green' jobs (Räthzel and Uzzell, 2012). Local air and water pollution in areas near industries have led to regulatory restrictions in almost all countries. In many countries, new industrial developments face increasing public resistance and litigation. If mitigation options deliver local air pollution benefits, they will have indirect value and greater acceptance.

The literature (cited in the following sections and in Table 10.5) documents that mitigation measures interact with multiple economic, social, and environmental objectives, although these associated impacts are not always quantified. In general, quantifying the corresponding welfare effects that a mitigation technology or practice entails is challenging, because they are very localized and different stakeholders may have different perspectives of the corresponding losses and gains (Fleiter et al., 2012c) (see Sections 2.4, 3.6.3, 4.2, and 6.6). It is important to note that co-benefits need to be assessed together with direct benefits to overcome barriers in implementation of the mitigation options (e.g., training requirements, losses during technology installation) (Worrell et al., 2003), which may appear otherwise larger for SMEs or isolated enterprises (Crichton, 2006; Zhang and Wang, 2008; Ghosh and Roy, 2011).

Energy efficiency (E/M): Energy efficiency includes a wide variety of measures that also achieve economic efficiency and natural/energy resource saving, which contribute to the achievement of environmental goals and other macro benefits (Roy et al., 2013). At the company level, the impact of energy efficient technology is often found to enhance productivity growth (Zuev et al., 1998; Boyd and Pang, 2000; Murphy, 2001; Worrell et al., 2003; Gallagher, 2006; Winkler et al., 2007; Zhang and Wang, 2008; May et al., 2013). Other benefits to companies, industry, and the economy as a whole come in the form of reduced fuel consumption requirements[17] and imports as well as reduced requirements for new electricity general capacity addition (Sarkar et al., 2003; Geller et al., 2006; Winkler et al., 2007; Sathaye and Gupta, 2010) which contribute to energy security (see Sections 6.6.2.2 and 7.9.1). Energy security in the industrial sector is primarily affected by concerns related to the sufficiency of resources to meet national energy demand at competitive and stable prices. Supply-side vulnerabilities in this sector arise if there is a high share of imported fuels in the industrial energy mix (Cherp et al., 2012a). Cherp et al. (2012a) estimate that the overall vulnerability of industrial energy consumption is lower than in the transport and residential and commercial (R&C) sectors in most countries. Nevertheless, since mitigation policies in industry would likely lead to higher energy efficiency, they may reduce exposure to energy supply and price shocks (Gnansounou, 2008; Kruyt et al., 2009; Sovacool and Brown, 2010; Cherp et al., 2012b).

Reduced fossil fuel burning brings associated reduced costs (Winkler et al., 2007), and reduced local impacts on ecosystems related to fossil fuel extraction and waste disposal liability (Liu and Diamond, 2005; Zhang and Wang, 2008; Chen et al., 2012; Ren et al., 2012; Hasanbeigi et al., 2013b; Lee and van de Meene, 2013; Xi et al., 2013; Liu et al., 2013) (see also Sections 7.9.2 and 7.9.3). In addition, other possible benefits of reduced reliance on fossil fuels include increases in employment and national income (Sathaye and Gupta, 2010) with new business opportunities (Winkler et al., 2007; Nidumolu et al., 2009; Wei et al., 2010; Horbach and Rennings, 2013).

There is wide consensus in the literature on local air pollution reduction benefits from energy efficiency measures in industries (Winkler et al., 2007; Bassi et al., 2009; Ren et al., 2012), such as positive health effects, increased safety and working conditions, and improved job satisfaction (Getzner, 2002; Worrell et al., 2003; Wei et al., 2010; Walz, 2011; Zhang et al., 2011; Horbach and Rennings, 2013) (see also Sections 7.9.2, 7.9.3 and WGII 11.9). Energy efficient technologies can also have positive impacts on employment (Getzner, 2002; Wei et al., 2010; UNIDO, 2011; OECD/IEA, 2012). Despite these multiple co-benefits, sometimes the relatively large initial investment required and the relatively long payback period of some energy efficiency measures can be a disincentive and an affordability issue, especially for SMEs, since the co-benefits are often not monetized (Brown, 2001; Thollander et al., 2007; Ghosh and Roy, 2011; UNIDO, 2011).

Emission efficiency (G/E): The literature documents well that increases in emissions efficiency can lead to multiple benefits (see Table 10.5). Local air pollution reduction is well documented as co-benefit of emissions efficiency measures (Winkler et al., 2007; Bassi et al., 2009; Ren et al., 2012). Associated health benefits (Aunan et al., 2004; Haines et al., 2009) and reduced ecosystem impacts (please refer to Section 7.9.2 for details) are society-wide benefits, while reduc-

[17] Please see Section 10.4 and references cited therein (e.g., Schäfer, 2005; Allwood et al., 2010; UNIDO, 2011; Saygin et al., 2011b; Gutowski et al., 2013).

tions in emission-related taxes or payment liabilities (Metcalf, 2009) are specific to industries, even though compliance costs might increase (Dasgupta et al., 2000; Mestl et al., 2005; Rivers, 2010). The net effect of these benefits and costs has not been studied comprehensively. Quantification of benefits is often done on a case-by-case basis. For example, Mestl et al. (2005) found that the environmental and health benefits of using electric arc furnaces for steel production in the city of Tiyuan (China) could potentially lead to higher benefits than other options, despite being the most costly option. For India, a detailed study (Chakraborty and Roy, 2012b) of 13 energy-intensive industrial units showed that several measures to reduce GHG emissions were adopted because the industries could realize positive effects on their own economic competitiveness, resource conservation such as water, and an enhanced reputation/public image for their commitment to corporate social responsibility towards a global cause.

If existing barriers (see Section 10.9) can be overcome, industrial applications of CCS deployed in the future could provide environmental co-benefits because CCS-enabled facilities have very low emissions rates for critical pollutants even without specific policies being in place for those emissions (Kuramochi et al., 2012b) (see Section 7.9.2 and Figure 7.8 for the air pollution effects of CCS deployment in power plants).

Mitigations options to reduce PFC emissions from aluminium production, N_2O emissions from adipic and nitric acid production (EPA, 2010a), and PFC emissions from semiconductor manufacturing (ISMI, 2005) have proven to enhance productivity and reduce the cost of production. Simultaneously, these measures provide health benefits and better working conditions for labour and local ambient air quality (Heijnes et al., 1999).[18]

Material efficiency (M/P): There is a wide range of benefits to be harnessed from implementing material efficiency options. Private benefits to industry in terms of cost reduction (Meyer et al., 2007) can enhance competitiveness, but national and subnational sales revenue might decline in the medium term due to reduction in demand for intermediate products used in manufacturing (Thomas, 2003). Material use efficiency increases can often be realized via cooperation in industrial clusters (see Section 10.5), while associated infrastructure development (new industrial parks) and associated cooperation schemes lead to additional societal gains (e.g., more efficient use of land through bundling activities) (Lowe, 1997; Chertow, 2000). With the reduction in need for virgin materials (Allwood et al., 2013; Stahel, 2013) and the prioritization of prevention in line with the waste management hierarchy (see Section 10.14.2, Figure 10.16), mining-related social conflicts can decrease (Germond-Duret, 2012), health and safety can be enhanced, recycling-related employment can increase, the amount of waste material (see Section 10.14.2.1 and Figure 10.17) going into landfills can decrease, and new business opportunities related to material efficiency can emerge (Clift and Wright, 2000; Rennings and Zwick, 2002; Widmer et al., 2005; Clift, 2006; Zhang and Wang, 2008; Walz, 2011; Allwood et al., 2011; Raghupathy and Chaturvedi, 2013; Menikpura et al., 2013).

Demand reductions (P/S and S): Demand reduction through adoption of new diverse lifestyles (see Section 10.4) (Roy and Pal, 2009; GEA, 2012; Kainuma et al., 2012; Allwood et al., 2013) and implementation of healthy eating (see Section 11.4.3) and sufficiency goals can result in multiple co-benefits related to health that enhance human well-being (GEA, 2012). Well-being indicators can be developed to evaluate industrial economic activities in terms of multiple effects of sustainable consumption on a range of policy objectives (GEA, 2012).

10.8.2 Technological risks and uncertainties

There are some specific risks and uncertainties with adoption of mitigation options in industry. Potential health, safety, and environmental risks could arise from additional mining activities as some mitigation technologies could substantially increase the need for specific materials (e.g., rare earths, see Section 7.9.2) and the exploitation of new extraction locations or methods. Industrial production is closely linked to extractive industry (see Figure 10.2) and there are risks associated with closing mines if post-closure measures for environmental protection are not adopted due to a lack of appropriate technology or resources. Carbon dioxide capture and storage for industry is an example of a technological option subject to several risks and uncertainties (see Sections 10.7, 7.5.5, 7.6.4 and 7.9.4 for more in-depth discussion on CO_2 storage, transport, and the public perception thereof, respectively).

Specific literature on accidents and technology failure related to mitigation measures in the industry sector is lacking. In general, industrial activities are subject to the main categories of risks and emergencies, namely natural disasters, malicious activities, and unexpected consequences arising from overly complex systems (Mitroff and Alpaslan, 2003; Olson and Wu, 2010). For example, process safety is still a major issue for the chemical industry. Future improvements in process safety will likely involve a holistic integration of complementary activities and be supported by several layers of detail (Pitblado, 2011).

10.8.3 Public perception

From a socio-constructivist perspective, the social response to industrial activity depends on three sets of factors related to: 1) the dynamics of regional development and the historical place of industry in the community, 2) the relationship between residents and the industry and local governance capacities, and 3) the social or socio-economic impacts experienced (Fortin and Gagnon, 2006). Public hearings and stakeholder participation—especially on environmental and social impact assessments—prior to issuance of permission to operate has become mandatory in almost all countries,

[18] See also EPA Voluntary Aluminum Industrial Partnership: http://www.epa.gov/highgwp/aluminum-pfc/faq.html.

and industry expenditures for social corporate responsibility are now often disclosed. Mitigation measures in the industry sector might be considered socially acceptable if associated with co-benefits, such as reducing GHG emissions while also improving local environmental quality as a whole (e.g., energy efficiency measures that reduce local emissions). Public perception related to mitigation actions can be influenced by national political positions in international negotiations and media.

Research on public perception and acceptance with regard to industrial applications of CCS is lacking (for the general discussion of CCS see Chapter 7). To date, broad evidence related to whether public perception of CCS for industrial applications will be significantly different from CCS in power generation units is not available, since CCS is not yet in place in the industry sector (Section 10.7).

Mining activities have generated social conflicts in different parts of the world (Martinez-Alier, 2001; World Bank, 2007; Germond-Duret, 2012; Guha, 2013). The Observatory of Mining Conflicts in Latin America (OMCLA) reported more than 150 active mining conflicts in the region, most of which started in the 2000s[19]. Besides this general experience, the potential for interactions between social tensions and mitigation initiatives in this sector are unknown.

[19] Observatorio de Conflictos Mineros de América Latina. Available at: http://www.conflictosmineros.net.

Table 10.5 | Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the industry sector. Arrows pointing up/down denote positive/negative effect on the respective objective or concern. Co-benefits and adverse side-effects depend on local circumstances as well as on the implementation practice, pace, and scale (see Section 6.6). For possible upstream effects of low-carbon energy supply (incl. CCS), see Section 7.9. For possible upstream effects of biomass supply, see Sections 11.7 and 11.13.6. For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see Sections 3.9, 6.3.6, 13.2.2.3, and 14.4.2. Numbers correspond to references below the table.

Mitigation measures	Effect on additional objectives/concerns		
	Economic	**Social (including health)**	**Environmental**
Technical energy efficiency improvements via new processes and technologies	↑ Energy security (via reduced energy intensity) [1, 2, 3, 4, 13, 29, 57]; ↑ Employment impact [14, 15, 19, 28] ↑ Competitiveness and Productivity [4, 5, 6, 7, 8, 9, 10, 11, 12] ↑ Technological spillovers in DCs (due to supply chain linkages) [59, 60, 61]	↓ Health impact via reduced local pollution [16] ↑ New business opportunities [4, 17–20] ↑ Water availability and quality [26] ↑ Safety, working conditions and job satisfaction [5, 19, 20]	Ecosystem impact via ↓ Fossil fuel extraction [21] ↓ Local pollution [11, 22–24, 25] and ↓ Waste [11, 27]
CO_2 and non-CO_2 GHG emissions intensity reduction	↑ Competitiveness [31, 55] and productivity [52, 53]	↓ Health impact via reduced local air pollution [30, 31, 32, 33, 53] and better work conditions (for PFCs from aluminium) [58]	Ecosystem impact via ↓ Local air pollution [4, 25, 30, 31, 34, 52] ↓ Water pollution [54] ↑ Water conservation [56]
Material efficiency of goods, recycling	↓ National sales tax revenue in medium term [35] ↑ Employment impact in waste recycling market [44, 45] ↑ New infrastructure for industrial clusters [36, 37] ↑ Competitiveness in manufacturing [38]	↑ New business opportunities [11, 39–43] ↓ Local conflicts (reduced resource extraction) [58] ↓ Health impacts and safety concerns [49]	↓ Ecosystem impact via reduced local air and water pollution and waste material disposal [42, 46] ↓ Use of raw/virgin materials and natural resources implying reduced unsustainable resource mining [47, 48]
Product demand reductions	↓ National sales tax revenue in medium term [35]	↑ Wellbeing via new diverse lifestyle choices [48, 50, 51]	↓ Post consumption waste [48]

[1] Sovacool and Brown, 2010; [2] Geller et al., 2006; [3] Gnansounou, 2008; [4] Winkler et al., 2007; [5] Worrell et al., 2003; [6] Boyd and Pang, 2000; [7] May et al., 2013; [8] Goldemberg, 1998; [9] Murphy, 2001; [10] Gallagher, 2006; [11] Zhang and Wang, 2008; [12] Roy et al., 2013; [13] see Section 10.4 and references cited therein; [14] UNIDO, 2011; [15] OECD/IEA, 2012; [16] Zhang et al., 2011; [17] Nidumolu et al., 2009; [18] Horbach and Rennings, 2013; [19] Getzner, 2002; [20] Wei et al., 2010; [21] Liu and Diamond, 2005; [22] Hasanbeigi et al., 2013a; [23] Xi et al., 2013; [24] Chen et al., 2012; [25] Ren et al., 2012; [26] Zhelev, 2005; [27] Lee and van de Meene, 2013; [28] Sathaye and Gupta, 2010; [29] Sathaye and Gupta, 2010; [30] Mestl et al., 2005; [31] Chakraborty and Roy, 2012a; [32] Haines et al., 2009; [33] Aunan et al., 2004; [34] Bassi et al., 2009; [35] Thomas, 2003; [36] Lowe, 1997; [37] Chertow, 2000; [38] Meyer et al., 2007; [39] Widmer et al., 2005; [40] Raghupathy and Chaturvedi, 2013; [41] Clift and Wright, 2000; [42] Allwood et al., 2011; [43] Clift, 2006; [44] Walz, 2011; [45] Rennings and Zwick, 2002; [46] Menikpura et al., 2013; [47] Stahel, 2013; [48] Allwood et al., 2013; [49] GEA, 2012; [50] Kainuma et al., 2012; [51] Roy and Pal, 2009; [52] EPA, 2010b; [53] ISMI, 2005; [54] Heijnes et al., 1999; [55] Rivers, 2010; [56] Chakraborty and Roy, 2012b; [57] Sarkar et al., 2003; [58] Germond-Duret, 2012; [59] Kugler, 2006; [60] Bitzer and Kerekes, 2008; [61] Zhao et al., 2010.

10.8.4 Technological spillovers

Spillovers are difficult to measure, but existing studies (Bouoiyour and Akhawayn, 2005) show that a technology gap is one of the conditions for positive spillovers. Sections 10.4 and 10.7 have already shown that there is gap between the world best practices in energy efficiency and industrial practices in many countries. As such, cross-country investment in mitigation technologies can enhance positive spillovers in host countries. In the industrial technology context, multinational companies try to minimize imitation probability and technology leakage, but studies show that spillover works faster through supply chain linkage inter-industry (Kugler, 2006; Bitzer and Kerekes, 2008; Zhao et al., 2010). In general, studies suggest that technology spillovers in the mitigation context depend on additional technology policies besides direct investment (Gillingham et al., 2009; Le and Pomfret, 2011; Wang et al., 2012a; Costantini et al., 2013; Jeon et al., 2013). These results are relevant for investments on industrial mitigation technologies as well.

10.9 Barriers and opportunities

Besides uncertainties in financial costs of mitigation options assessed in 10.7, a number of non-financial barriers and opportunities assessed in this section hinder or facilitate implementation of measures to reduce GHG emissions in industry. Barriers must be overcome to allow implementation (see Flannery and Kheshgi, 2005), however, in general they are not sufficiently captured in integrated model studies and scenarios (see Section 10.10). Barriers that are often common across sectors are given in Chapter 3. Table 10.6 summarizes barriers and opportunities for the major mitigation options listed in Section 10.4.

Typically, barriers and opportunities can be distinguished into the following categories:

- Technology: includes maturity, reliability, safety, performance, cost of technology options and systems, and gaps in information
- Physical: includes availability of infrastructure, geography, and space available
- Institutional and legal: includes regulatory frameworks and institutions that may enable investment
- Cultural: includes public acceptance, workforce capacity (e.g., education, training, and knowledge), and cultural norms.

10.9.1 Energy efficiency for reducing energy requirements

Even though energy consumption can be a significant cost for industry, a number of barriers limit industrial sector steps to minimize energy use via energy efficiency measures. These barriers include: failure to recognize the positive impact of energy efficiency on profitability, short investment payback thresholds (two to eight years; IEA, 2012e), industrial organizational and behavioural barriers to implementing change; limited access to capital; impact of non-energy policies on energy efficiency; public acceptance of unconventional manufacturing processes; and a wide range of market failures (Bailey et al., 2009; IEA, 2009d). While large energy-intensive industries—such as iron and steel, and mineral processing—are often aware of potential cost savings and consider energy efficiency in investment decisions, this is less common in the commercial and service sectors where the energy cost share is usually low, or for smaller companies where overhead costs for energy management and training personnel can be prohibitive (UNIDO, 2011; Ghosh and Roy, 2011; Schleich and Gruber, 2008; Fleiter et al., 2012d; Hasanbeigi et al., 2009). Of course, investment decisions also consider investment risks, which are generally not reflected in the cost estimates assessed in Section 10.7. The importance of barriers depends on specific circumstances. For example, by surveying the Swedish foundry industry, Rohdin et al. (2007) found that access to capital was reported to be the largest barrier, followed by technical risk and other barriers.

Cogeneration, or combined heat and power (CHP), is an energy efficiency option that can not only reduce GHG emissions by improving system energy efficiency, but can also reduce system cost and decrease dependence on grid power. For industry, however, (IEA, 2009d) CHP faces a complex set of economic, regulatory, social, and political barriers that restrain its wider use including: market restriction securing a fair market value for electricity exported to the grid; high upfront costs compared to large power plants; difficulty concentrating suitable heat loads and lack of integrated planning; grid access; non-transparent and technically demanding interconnection procedures; lack of consumer and policymaker knowledge about CHP energy, cost and emission savings; and industry perceptions that CHP is an investment outside their core business. Regulatory barriers can stem from taxes, tariffs, or permits. For a cogeneration project of an existing facility, the electricity price paid to a cogeneration facility is the most important variable in determining the project's success—more so than capital costs, operating and maintenance cost, and even fuel costs (Meidel, 2005). Prices are affected by rules for electricity markets, which differ from region to region, and which can form either incentives or barriers for cogeneration (Meidel, 2005).

10.9.2 Emissions efficiency, fuel switching, and carbon dioxide capture and storage

There are a number of challenges associated with feedstock and energy substitution in industry. Waste materials and biomass as fuel and feedstock substitutes are limited by their availability, and hence competition could drive up prices and make industrial applications less attractive (IEA, 2009b). A decarbonized power sector would offer new opportunities to reduce CO_2 intensity of some industrial processes via use of electricity, however, decarbonization of power also has barriers (assessed in Section 7.10).

Table 10.6 | Barriers (–) and opportunities (+) for GHG emission reduction options in industry. References and discussion appear in respective sub-sections of 10.9.

	Energy efficiency for reducing energy requirements	Emissions efficiency, fuel switching and CCS	Material efficiency	Product demand reduction	Non-CO_2 GHGs
Technological Aspects: Technology	+ many options available – technical risk + cogeneration mature in heavy industry – non-transparent and technically demanding interconnection procedures for cogeneration	+ fuels and technologies readily available – retrofit challenges + large potential scope for CCS in cement production, iron and steel, and petrochemicals – limited CCS technology development, demonstration and maturity for industry applications	+ options available	– slower technology turnover can slow technology improvement and operational emission reduction	+/– approaches and technologies available for some sources – lack of lower cost technology for PFC emission reduction in existing aluminium production plants
Technological Aspects: Physical	+ less energy and fuel use, lower cooling needs, smaller size – concentrating suitable heat loads for cogeneration – retrofit constraints on cogeneration	– lack of sufficient feedstock to meet demand – CCS retrofit constraints – lack of CO_2 pipeline infrastructure – limited scope and lifetime for industrial CO_2 utilization	+ reduction in raw and waste materials – transport infrastructure and industry proximity for material/waste reuse	+ reduction in raw materials and disposed products	– lack of control of HFC leakage in refrigeration systems
Institutional and Legal	– impact of non-energy policies + energy efficiency policies (10.11) – market barriers – regulatory, tax/tariff and permitting of cogeneration +/– grid access for cogeneration		– fragmented and weak institutions	– regulatory and legal instruments generally do not take account of externalities	– lack of certification of refrigeration systems – regulatory barriers to HFC alternatives in aerosols
Cultural	– lack of trained personnel +/– attention to energy efficiency – lack of acceptance of unconventional manufacturing processes – cogeneration outside core business – lack of consumer and policymaker knowledge of cogeneration	– social acceptance of CCS	+/– public participation – human capacity for management decisions	+/– user preferences drive demand	– lack of information/education about solvent replacements – lack of awareness of alternative refrigerants
Financial	– access to capital and short investment payback requirements – high overhead costs for small or less energy intensive industries +/– factoring in efficiency into investment decisions (e.g., energy management) + cogeneration economic in many cases +/– market value of grid power for cogeneration – high capital cost for cogeneration	– lack of sufficient financial incentive for widespread CCS deployment – liability risk for CCS – high CCS capital cost and long project development times	– upfront cost and potentially longer payback period + reduced production costs	– businesses, governments, and labour favour increased production	– recycled HFCs not cost competitive with new HFCs – cost of HFC incineration

The application of CCS to the industries covered in this chapter share many of the barriers to its application to power generation (see Section 7.10). Barriers for application of CCS in industry include space constraints when applied in retrofit situations (Concawe, 2011); high capital costs and long project development times; investment risk associated with poorly defined liability; the trade-exposed nature of many industries, which can limit viable CCS business models; current lack in general of financial incentives to offset the additional cost of CCS; and the immaturity of CO_2 capture technology for cement, iron and steel, and petrochemical industries (Kheshgi et al., 2012).

10.9.3 Material efficiency

There are technically feasible opportunities to improve material efficiency in industry (Allwood et al., 2011). One opportunity is a circular economy, which is a growing model across various countries and which aims to systematically fulfil the hierarchy principles of material efficiency "reduce, re-use, recycle" (see Section 10.14). This approach however, has barriers which include a lack of human and institutional capacities to encourage management decisions and public participation (Geng and Doberstein, 2008), as well as fragmented and weak institutions (Geng et al., 2010b). Improving material efficiency by integrating different industries (see Section 10.5) is often limited by specific local conditions, infrastructure requirements (e.g., pipelines) and the complexity of multiple users (Geng et al., 2010b).

10.9.4 Product demand reduction

Improved product design or material properties, respectively, can help to extend the product's lifetime and can lead to lower product demand. However it has to be considered that extended lifetime may not actually satisfy current user preferences, and the user may choose to replace an older, functioning product with a new one (van Nes and Cramer, 2006; Allwood et al., 2011). In addition, continually providing newer products may result in lower operational emissions (e.g., improved energy efficiency). In this case, longer product lifetimes might not automatically lead to lower overall emissions. For example, from a lifecycle balance point of view, it may be better to replace specific energy-intensive products such as washing machines, before their end-of-life to make use of more efficient substitutes (Scholl et al., 2010; Intlekofer et al., 2010; Fischer et al., 2012; Agrawal et al., 2012).

Businesses are rewarded for growing sales volumes and can prefer process innovation over product innovation (e.g., EIO 2011; 2012). Existing markets generally do not take into account negative externalities associated with resource use nor do they adequately incorporate the risks of resource-related conflicts (Bleischwitz et al., 2012; Transatlantic Academy, 2012), yet existing national accounting systems based on GDP indicators also support the pursuit of actions and policies that aim to increase demand spending for more products (Jackson, 2009; Roy and Pal, 2009). Labour unions often have an ambivalent position in terms of environmental policies and partly see environmental goals as a threat for their livelihood (Räthzel and Uzzell, 2012).

10.9.5 Non-CO_2 greenhouse gases

Non-CO_2 greenhouse gas emissions are an important contributor to industry process emissions (note that emissions of CO_2 from calcination are another important contributor: for barriers to controlling these emissions by CO_2 capture and storage see Section 10.9.2). Barriers to preventing or avoiding the release of HFCs, CFCs, HCFCs, PFC, and SF_6 in industry and from its products include: lack of awareness of alternative refrigerants and lack of guidance as to their use in a given or new system (UNEP and EC, 2010); lack of certification and control of leakage of HFCs from refrigeration (Heijnes et al., 1999); cost of recycled HFCs in markets where there is direct competition from newly produced HFCs (Heijnes et al., 1999); lack of information and communication and education about solvent replacements (Heijnes et al., 1999; IPCC/TEAP, 2005); cost of adaptation of existing aluminium production for PFC emission reduction and the absence of lower cost technologies in such situations (Heijnes et al., 1999); cost of incineration of HFCs emitted in HCFC production (Heijnes et al., 1999); regulatory barriers to alternatives to some HFC use in aerosols (IPCC/TEAP, 2005). UNEP (2010) found that there are technically and economically feasible substitutes for HCFCs, however, transitional costs remain a barrier for smaller enterprises.

10.10 Sectoral implications of transformation pathways and sustainable development

This section assesses transformation pathways for the industry sector over the 21st century by examining a wide range of published scenarios. This section builds upon scenarios which were collated by Chapter 6 in the WG III AR5 Scenario Database (see Annex II.10), which span a wide range of possible energy future pathways and which rely on a wide range of assumptions (e.g., population, economic growth, policies, and technology development and its acceptance). Against that background, scenarios for the industrial sector over the 21st century associated with different atmospheric CO_2eq concentrations in 2100 are assessed in Section 10.10.1, and corresponding implications for sustainable development and investment are assessed in Section 10.10.2 from a sector perspective.

10.10.1 Industry transformation pathways

The different possible trajectories for industry final energy demand (globally and for different regions), emissions, and carbon intensity under a wide range of CO_2eq concentrations over the 21st century are shown in Figure 10.11, Figure 10.12 and Figure 10.13[20]. These scenarios exhibit economic growth in general over the 21st century as well as growth specifically in the industry sector. Detailed scenarios of the industry sector extend to 2050 and exhibit increasing material production, e.g., iron/steel and cement (Sano et al., 2013; IEA, 2009b; Akashi et al., 2013). Scenarios generated by general equilibrium models, which include economic feedbacks (see Table 6.1), implicitly include changes in material flow due to, for example, changes in prices that may be driven by a price on carbon; however, these models do not generally provide detailed subsectoral material flows. Options for reducing material demand and inter-input substitution elasticities (Roy et al.,

[20] This section builds upon emissions scenarios which were collated by Chapter 6 in the WGIII AR5 scenario database (see Section 6.2.2), and compares them to detailed scenarios for industry referenced in this section. The scenarios included both baseline and mitigation scenarios. As described in more detail in Section 6.3.2, the scenarios shown in this section are categorized into bins based on 2100 concentrations: between 430–530 ppm CO_2eq, 530–650 ppm CO_2eq, and > 650 ppm CO_2eq by 2100. The relation between these bins of emission scenarios and the increase in global mean temperature since pre-industrial times is reviewed in Section 6.3.2.

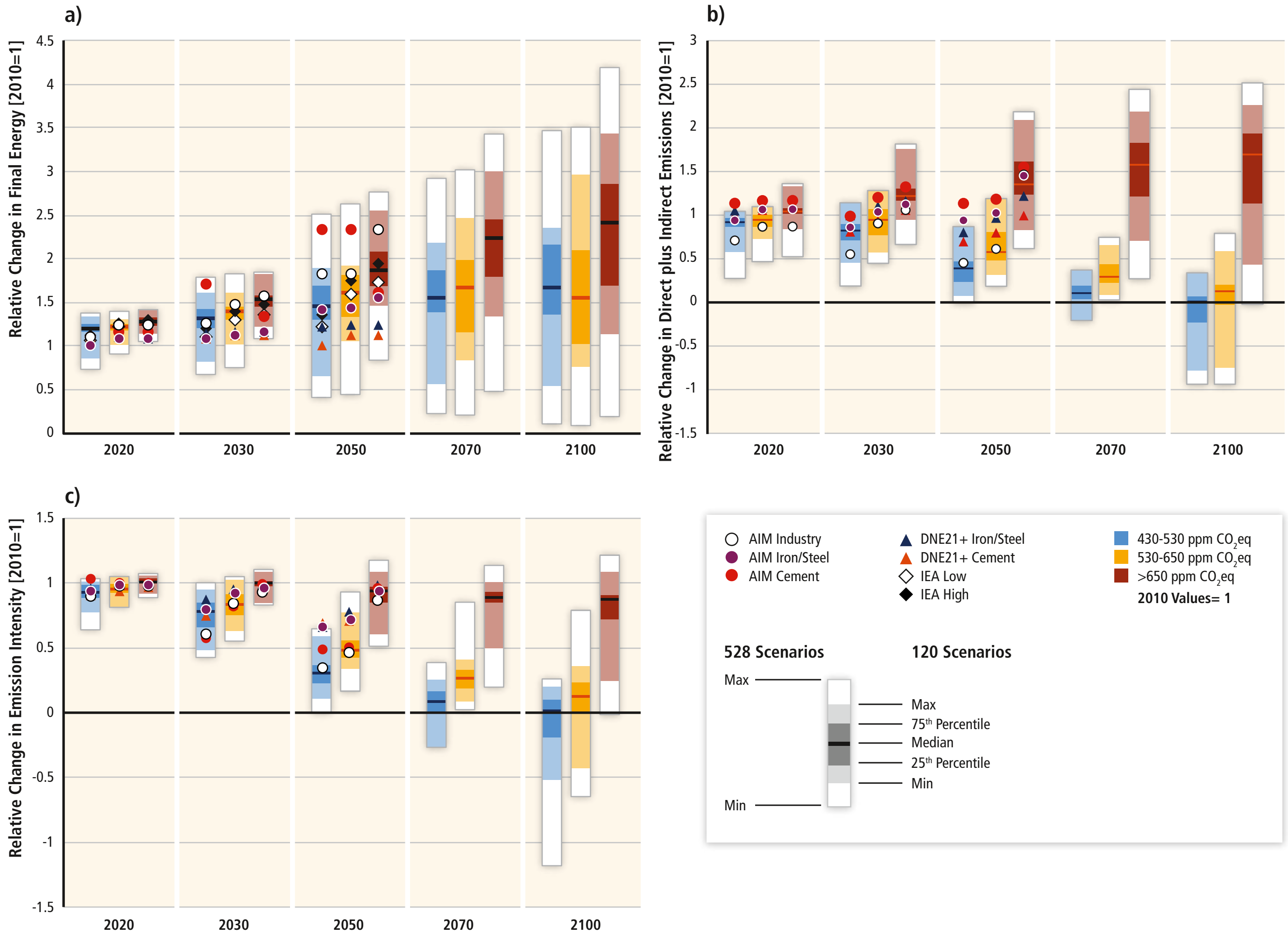


Figure 10.11 | Industry sector scenarios over the 21st century that lead to low (430–530 ppm CO_2eq), medium (530–650 ppm CO_2eq) and high (> 650 ppm CO_2eq) atmospheric CO_2eq concentrations in 2100 (see Table 6.3 for definitions of categories). All results are indexed relative to 2010 values for each scenario. Panels show: (a) final energy demand; (b) direct plus indirect CO_2eq emissions; (c) emission intensity (emissions from (b) divided by energy from (a)). Indirect emissions are emissions from industrial electricity demand. The median scenario (horizontal line symbol) surrounded by the darker colour bar (inner quartiles of scenarios) and lighter bar (full range) represent those 120 scenarios assessed in Chapter 6 with model default technology assumptions which submitted detailed final energy and emissions data for the industrial sector; white bars show the full range of scenarios including an additional 408, with alternate economic, resource, and technology assumptions (e.g., altering the economic and population growth rates, excluding some technology options or increasing response of energy efficiency improvement) (Source: WG III AR5 Scenario Database, see Annex II.10). Symbols are provided for selected scenarios for industry and industry sub-sectors (iron and steel, cement) for the IEA ETP (IEA, 2012d), AIM Enduse (Akashi et al., 2013 and Table A.II.14) and DNE21+ models (Sano et al., 2013a, b; and Table A.II.14) for their baseline, 550 ppm and 450 ppm CO_2eq scenarios to 2050.

2006; Sanstad et al., 2006) are used with various assumptions in the models that can better be characterized as gaps in integrated models currently in use.

Final energy (FE) demand from industry increases in most scenarios, as seen in Figure 10.11(a) driven by the growth of the industry sector; however, FE is weakly dependent on the 2100 CO_2eq concentration in the scenarios, and the range of FE demand spanned by the scenarios becomes wide in the latter half of the century (compare also Figure 6.37). In these scenarios, energy productivity improvements help to limit the increase in FE. For example, results of the DNE21+ and AIM models include a 56 % and 114 % increase in steel produced from 2010 to 2050 and a decrease in FE per unit production of 20–22 % and 28–34 % (these are the ranges spanned by the reference, 550 and 450 ppm CO_2eq scenarios for each model), respectively (Akashi et al., 2013; Sano et al., 2013). While energy efficiency of industry improves with time, the growth of CCS in some scenarios leads to increases in FE demand. Growth of final energy for cement production to 2050, for example, is seen in Figure 10.11(a) due to energy required for CCS in the cement industry mitigation scenarios (i.e., going from AIM cement > 650 ppm CO_2eq scenario to the < 650 ppm CO_2eq scenarios).

After 2050, emissions from industry, including indirect emissions resulting from industrial electricity demand become very low, and in some scenarios even negative as seen in Figure 10.11(b). The emission intensity of FE shown in Figure 10.11(c) decreases in most scenarios over the century, and decreases more strongly for low CO_2eq concentration levels. A decrease in emission intensity is generally the dominant mechanism for decrease in direct plus indirect emissions in the < 650 ppm CO_2eq scenarios shown in Figure 10.11. In scenarios

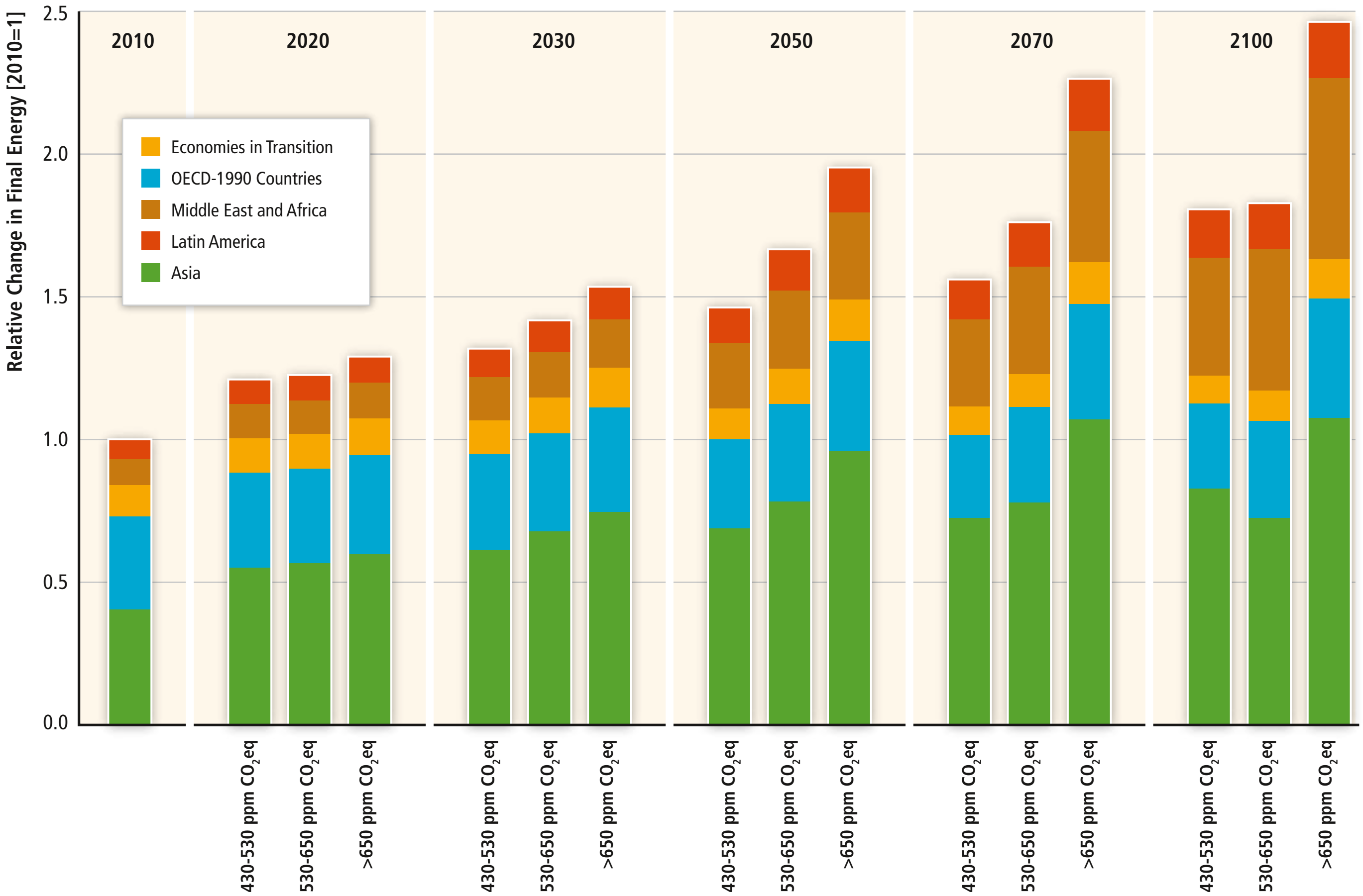


Figure 10.12 | Final energy demand from the industry sector shown for the RC5 regions (see Annex II.2 for definition) over the 21st century. Bars are compiled using information from 105 of the 120 scenarios assessed in Chapter 6, with model default technology assumptions that submitted detailed final energy and emissions data for the industrial sector. Bar height corresponds to the median scenario with respect to final energy demand relative to 2010; breakdown fractions correspond to the mean of scenarios. Source: WG III AR5 Scenario Database (see Annex II.10)

with strong decreases in emission intensity, this is generally due to some combination of application of CCS to direct industry emissions, and a shift to a lower-carbon carrier of energy—for example, a shift to low- or negative-carbon sources of electricity. Low carbon electricity is assessed in Chapter 7 and bioenergy with CCS—which could in theory result in net CO_2 removal from the atmosphere—is assessed in Chapter 11, Section 11.13.

Figure 10.12 shows the regional breakdown of final energy demand by world regions for different scenarios for the industrial sector. Over the 21st century, scenarios indicate that the growth of industry FE demand continues to be greatest in Asia, followed by the Middle East and Africa, although at a slower growth rate than seen over the last decade (see Section 10.3). The OECD-1990, Latin America, and Reforming Economies regions are expected to comprise a decreasing fraction of the world's industrial FE.

Figure 10.13 shows the projected changes in the shares of industry sector energy carriers—electricity, solids (primarily coal), and liquids, gases and hydrogen—from 2010 to 2100 for 120 scenarios (compare also Figure 6.38 with low carbon fuel shares in industrial final energy). Scenarios for all CO_2eq concentration levels show an increase in the share of electricity in 2100 compared to 2010, and generally show a decrease in the share of liquids/gases/hydrogen. Some of the < 650 ppm CO_2eq scenarios show an increase in the share of solids in 2100 compared to 2010 and some show a decrease. For the > 650 ppm CO_2eq scenarios, the change in shares from 2010 to 2100 is generally smaller than the change in shares for the < 650 ppm CO_2eq scenarios. A shift towards solids could lead to reduced emissions if the scenarios include the application of CCS to the emissions from solids. A shift towards electricity could lead to reduced emissions if the electricity generation is from low emission energy sources. The strong decrease in indirect emissions from electricity demand in most 430–530 ppm CO_2eq scenarios is shown in Figure 6.34 (see Section 6.8), with electricity emissions already negative in some scenarios by 2050. Each pathway implies some degree of lock-in of technology types and their supporting infrastructure, which has important implications; e.g., iron/steel in the basic oxygen furnace (BOF) route might follow a pathway with a higher solid fuel share but with CCS for direct emissions reduction by the industry. A decarbonized power sector provides the means to reduce the emission intensity of electricity use in the industrial sector, but barriers, such as a lack of a sufficient carbon price, exist (IEA, 2009b; Bassi et al., 2009). Barriers to decarbonization of electricity are discussed in more detail in Section 7.10.

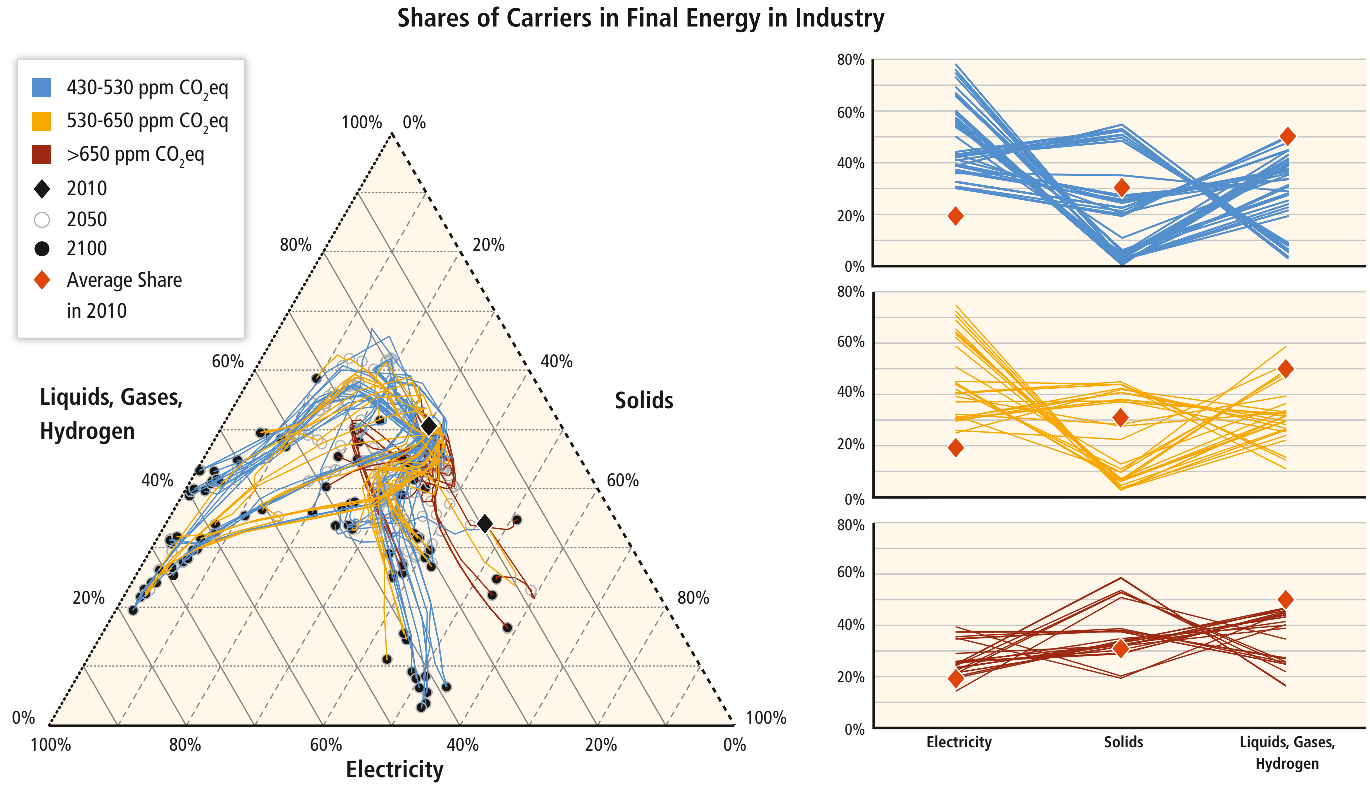


Figure 10.13 | The ternary panel on the left provides the industry final energy share trajectories across three groups of energy carriers: electricity, solids, and liquids-gases-hydrogen. The path of each scenario's trajectory is shown by a single line with symbols at the start in 2010 (the diamond towards the lower right accounts for 3 of 120 trajectories generated from one model that start in 2010 at a higher solids and lower liquids, gases, hydrogen share than the remainder of the trajectories which start at the upper diamond), in 2050 and at the end in 2100. The lines in the three panels on the right show the shares of energy carriers for each of the trajectories in the ternary diagram in 2100; the diamonds show the average share across a panel's models in 2010. Results are shown for those 120 scenarios assessed in Chapter 6, with model default technology assumptions that submitted detailed final energy and emissions data for the industrial sector. Source: WG III AR5 Scenario Database (see Annex II.10)

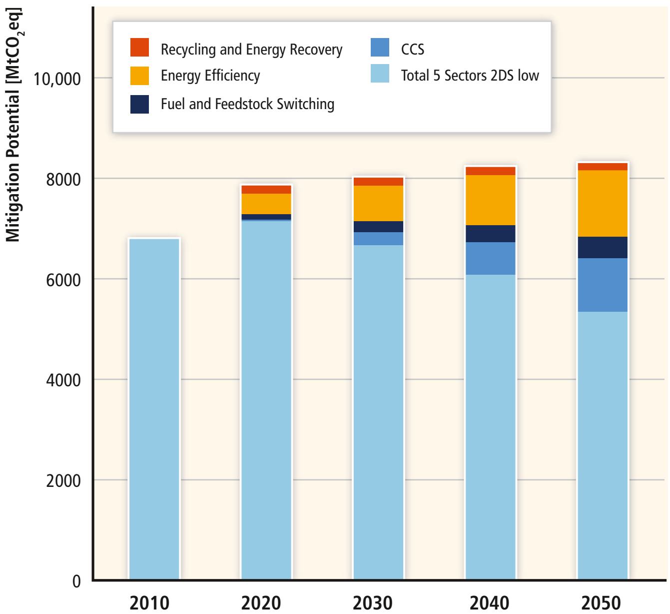
The IEA (2012d) 2DS scenario (Figure 10.14) shows a primary contribution to mitigation in 2050 from energy efficiency followed by recycling and energy recovery, fuel and feedstock switching, and a strong application of CCS to direct emissions. Carbon dioxide capture and storage has limited application before 2030, since CO_2 capture has yet to be applied at commercial scale in major industries such as cement or iron/steel and faces various barriers (see Section 10.9). Increased application of CCS is a precondition for rapid transitions and associated high levels of technology development and investment as well as social acceptance. The AIM 450 CO_2eq scenario (Akashi et al., 2013) has, for example, a stronger contribution from CCS than the IEA 2DS from 2030 onward, whereas the DNE21+ 450 ppm CO_2eq scenario (Sano et al., 2013) has a weaker contribution as shown in Figure 10.14. These more detailed industry sector scenarios fall within the range of the full set of scenarios shown in Figure 10.11.

10.10.2 Transition, sustainable development, and investment

Transitions in industry will require significant investment and offer opportunities for sustainable development (e.g., employment). Investment and development opportunities may be greatest in regions where industry is growing, particularly because investment in new facilities provides the opportunity to 'leapfrog', or avoid the use of less-efficient higher emissions technologies present in existing facilities, thus offering the opportunity for more sustainable development (for discussion of co-benefits and adverse side-effects when implementing mitigation options, see Section 10.8).

The wide range of scenarios implies that there will be massive investments in the industry sector over the 21st century. Mitigation scenarios generally imply an even greater investment in industry with shifts in investment focus. For example, due to an intensive use of mitigation technologies in the IEA's Blue Scenarios (IEA, 2009d), global investments in industry are 2–2.5 trillion USD higher by the middle of the century than in the reference case; successfully deploying these technologies requires not only consideration of competing investment options, but also removal of barriers and seizing of new opportunities (see Section 10.9).

The stringent mitigation scenarios discussed in Section 10.10.1 envisage emission intensity reductions, in particular due to deployment of CCS. However, public acceptance of widespread diffusion of CCS might hinder the realization of such scenarios. Taking the potential resistance into account, some alternative mitigation scenarios may require reduc-



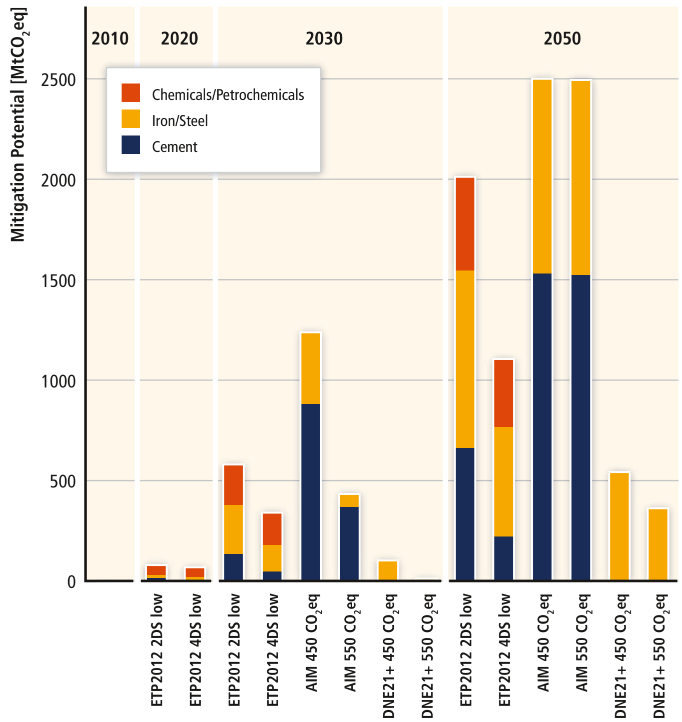


Figure 10.14 | Mitigation of direct CO_2eq annual emissions in five major industrial sectors: iron/steel, cement, chemicals/petrochemicals, pulp/paper, and aluminium. The left panel shows results from IEA scenarios (IEA, 2012d), broken down by mitigation option. The tops of the bars show the IEA 4DS low demand scenario, the light blue bars show the 2DS low demand scenario. The bar layers show the mitigation options that contribute to the emission difference from the 4DS to the 2DS low demand scenario. The right panel shows mitigation by CCS of direct industrial emissions in IEA, AIM Enduse (Akashi et al., 2013 and Table A.II.14) and DNE21+ (Sano et al., 2013a, b; and Table A.II.14) models. Scenarios are shown for those subsectors where CCS was reported.

tion of energy service demand (Kainuma et al., 2013). For the industry sector, options to reduce material demand or reduce demand for products become important as the latter do not rely on investment challenges, although they face a different set of barriers and can have high transaction costs (see Section 10.9).

Industry-related climate change mitigation options vary widely and may positively or negatively affect employment. Identifying mitigation options that enhance positive effects (e.g., due to some energy efficiency improvements) and minimize the negative outcomes is therefore critical. Some studies have argued that climate change mitigation policies can lead to unemployment and economic downturn (e.g. Babiker and Eckaus, 2007; Chateau et al., 2011) because such policies can threaten labour demand (e.g. Martinez-Fernandez et al., 2010) and can be regressive (Timilsina, 2009). Alternatively, other studies suggest that environmental regulation could stimulate eco-innovation and investment in more efficient production techniques and result in increased employment (OECD, 2009). Particularly, deployment of efficient energy technologies can lead to higher employment (Wei et al., 2010; UNIDO, 2011) depending on how redistribution of investment funds takes place within an economy (Sathaye and Gupta, 2010).

10.11 Sectoral policies

It is important to note that there is no single policy that can address the full variety of mitigation options for the industry sector. In addition to overarching policies (see Chapter 15 in particular, and Chapters 14 and 16), combinations of sectoral policies are needed. The diverse and relatively even mix of policy types in the industrial sector reflects the fact that there are numerous barriers to energy and material efficiency in the sector (see Section 10.9), and that industry is quite heterogeneous. In addition, the level of energy efficiency of industrial facilities varies significantly, both within subsectors and within and across regions. Most countries or regions use a mix of policy instruments, many of which interact. For example, energy audits for energy-intensive manufacturing firms are regularly combined with voluntary/negotiated agreements and energy management schemes (Anderson and Newell, 2004; Price and Lu, 2011; Rezessy and Bertoldi, 2011; Stenqvist and Nilsson, 2012). Tax exemptions are often combined with an obligation to conduct energy audits (Tanaka, 2011). Current practice acknowledges the importance of policy portfolios (e.g., Brown et al., 2011), as well as the necessity to consider national contexts and unintended behaviour of industrial companies. In terms of the latter, carbon leakage is relevant in the discussion of policies for industry (for a more in-depth analysis of carbon leakage see Chapter 5).

So far, only a few national governments have evaluated their industry-specific policy mixes (Reinaud and Goldberg, 2011). For the UK, Barker et al. (2007) modelled the impact of the UK Climate Change Agreements (CCAs) and estimated that from 2000 to 2010 they would result in a reduction of total final demand for energy of 2.6 % and a reduction in CO_2 emissions of 3.3 %. The CCAs established targets for industrial energy-efficiency improvements in energy-intensive industrial sectors; firms that met the targets qualified for a reduction of 80 % on the Climate Change Levy (CCL) rates on energy use in these sectors. Barker et al. (2007) also show that the macro-economic effect on the UK economy from the policies was positive.

In addition to dedicated sector-specific mitigation policies, co-benefits (see Section 10.8 and this report's framing chapters) should be considered. For example, local air quality standards have an indirect effect on mitigation as they set incentives for substitution of inefficient production technologies. Given the priorities of many governments, these indirect policies have played a relatively more effective role than climate policies, e.g. in India (Roy, 2010).

10.11.1 Energy efficiency

The use of energy efficiency policy in industry has increased appreciably in many IEA countries as well as major developing countries since the late 1990s (Roy, 2007; Worrell et al., 2009; Tanaka, 2011; Halsnæs et al., 2014). A review of 575 policy measures found that, as of 2010, information programmes are the most prevalent (40 %), followed by economic instruments (35 %), and measures such as regulatory approaches and voluntary actions (24 %) (Tanaka, 2011). Identification of energy efficiency opportunities through energy audits is the most popular measure, followed by subsidies, regulations for equipment efficiency, and voluntary/negotiated agreements. A classification of the various types of policies and their coverage are shown in Figure 10.15 and experiences in a range of these policies are analyzed below.

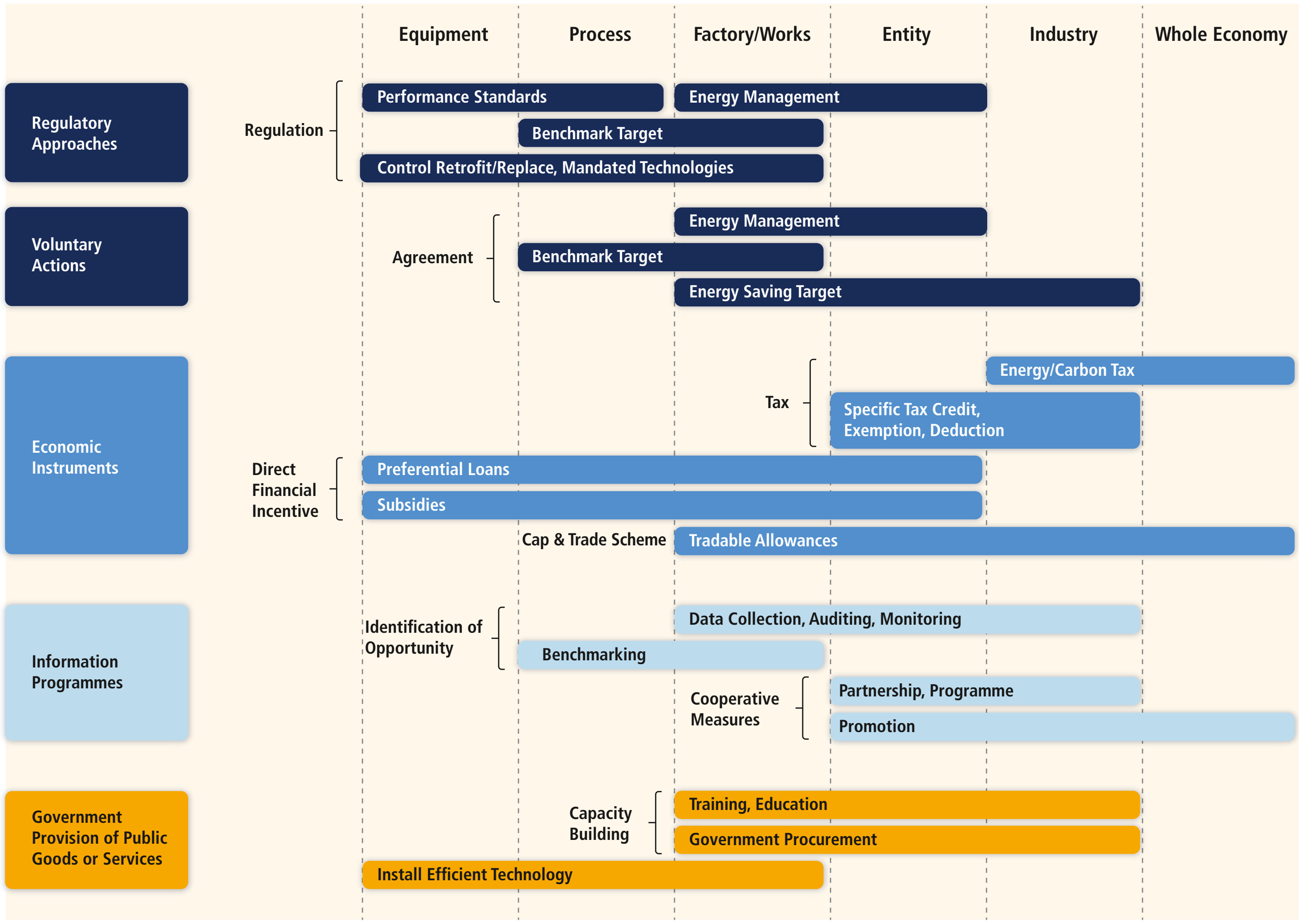


Figure 10.15 | Selected policies for energy efficiency in industry and their coverage (from Tanaka, 2011).

Greenhouse gas cap-and-trade and carbon tax schemes that aim to enhance energy efficiency in energy-intensive industry have been established in developed countries, particularly in the last decade, and are recently emerging in some developing countries. The largest example of these economic instruments by far is the European Emissions Trading Scheme (ETS). A more in-depth analysis of these overarching mechanisms is provided in Chapter 15.

Among regulatory approaches, regulations and energy efficiency standards for equipment have increased dramatically since 1992 (Tanaka, 2011). With regards to target-driven policies, one of the key initiatives for realizing the energy intensity reduction goals in China was the Top-1,000 Energy-Consuming Enterprises programme that required the establishment of energy-saving targets, energy use reporting systems and energy conservation plans, adoption of incentives and investments, and audits and training. The programme resulted in avoided CO_2 emissions of approximately 400 $MtCO_2$ compared to a business-as-usual baseline, and has been expanded to include more facilities under the new Top-10,000 enterprise programme. (Lin et al., 2011; Price et al., 2011; NDRC, 2011b)

Many firms (in particular SMEs) with rather low energy costs as a share of their revenue allocate fewer resources to improving energy efficiency, resulting in a low level of knowledge about the availability of energy-efficiency options (Gruber and Brand, 1991; Ghosh and Roy, 2011). Energy audits help to overcome such information barriers (Schleich, 2004) and can result in the faster adoption of energy-efficient measures (Fleiter et al., 2012b). The effectiveness of 22 industrial energy auditing programmes in 15 countries has been reviewed by Price and Lu (2011), who give recommendations on the success factors (e.g., use of public databases for benchmarking, use of incentives for participation in audits).

Energy Management Systems (EnMS) are a collection of business processes, carried out at plants and firms, designed to encourage and facilitate systematic improvement in energy efficiency. The typical elements of EnMS include maintenance checklists, measurement processes, performance indicators and benchmarks, progress reporting, and on-site energy managers (McKane, 2007). The adoption of EnMS schemes in industry can be mandatory, as in Japan, Italy, Turkey, or Portugal (Tanaka, 2011) or voluntary, and can be guided by standards, such as the international standard ISO 50001[21]. Backlund et al. and Thollander and Palm (2012; 2013) argue that improvement in practices identified by EnMS and audits should be given a greater role in studies of potential for energy efficiency, as most studies concentrate only on the technological and economic potentials.

There are a number of case studies that argue for the environmental and economic effectiveness of EnMS and energy audits (Anderson and Newell, 2004; Ogawa et al., 2011; Shen et al., 2012). Some studies report very quick payback for energy efficiency investments identified during such assessments (Price et al., 2008). For example, a programme in Germany offering partial subsidies to SMEs for energy audits was found to have saved energy at a cost to the German government of 2.4–5.7 USD_{2010}/tCO_2 (Fleiter et al., 2012b). In another case, the energy audit program by the Energy Conservation Centre of Japan (ECCJ), was found to provide positive net benefits for society, defined as the net benefit to private firms minus the costs to government, of 65 USD_{2010}/tCO_2 (Kimura and Noda, 2010). On the other hand, there are also studies that report mixed results of some mandatory EMS and energy audits, where some companies did not achieve any energy efficiency improvements (Kimura and Noda, 2010).

Many countries use benchmarking to compare energy use among different facilities within a particular sector (Tanaka, 2008; Price and McKane, 2009). In the Netherlands, for example, the Benchmarking Covenants encourage companies to compare themselves to others and to commit to becoming among the most energy-efficient in the world. However, in many countries high-quality energy efficiency data for benchmarking is lacking (Saygin et al., 2011b).

Negotiated, or voluntary agreements (VAs), have been found in various assessments to be effective and cost-efficient (Rezessy and Bertoldi, 2011). Agreement programmes (e.g., in Ireland, France, the Netherlands, Denmark, UK, Sweden) were often responsible for increasing the adoption of energy-efficiency and mitigation technologies by industries beyond what would have been otherwise adopted without the programmes (Price et al., 2010; Stenqvist and Nilsson, 2012). Some key factors contributing to successful VAs appear to be a strong institutional framework, a robust and independent monitoring and evaluation system, credible mechanisms for dealing with non-compliance, capacity-building and—very importantly—accompanying measures such as free or subsidized energy audits, mandatory energy management plans, technical assistance, information and financing for implementation (Rezessy and Bertoldi, 2011), as well as dialogue between industry and government (Yamaguchi, 2012). Further discussion and examples of the effectiveness of VAs can be found in Chapter 15.

10.11.2 Emissions efficiency

Policies directed at increasing energy efficiency (discussed above) most often result in reduction of CO_2 intensity as well, in particular when the aim is to make the policy part of a wider policy mix addressing multiple policy objectives. Examples of emissions efficiency policy strategies include support schemes and fiscal incentives for fuel switching, R&D programmes for CCS, and inclusion of reduction of non-CO_2 gases in voluntary agreements (e.g., Japanese voluntary action plan Keidanren, see Chapter 15).

Regarding gases with a relatively high GWP such as HFCs, PFCs, and SF_6, successful policy examples exist for capture in the power

[21] http://www.iso.org/iso/home/standards/management-standards/iso50001.htm.

sector (e.g., Japan; Nishimura and Sugiyama, 2008), but there is not much experience in the industry sector. The CDM has driven abatement of the industrial gases HFC-23 and N_2O in developing countries because of monetary incentives (Michaelowa and Buen, 2012)[22]. Including high GWP emissions within the same cap and trade programme (and therefore prices) as energy-related emissions may draw opposition from the industries concerned, so special programmes for these gases could be a better alternative (Hall, 2007). Another option suggested is to charge an upfront fee that would then be refunded when the gases are later captured and destroyed (Hall, 2007).

10.11.3 Material efficiency

Policy instruments for material or resource use efficiency in general are only just starting to be promoted for mitigation of GHG emissions in industry; consequently, effective communication to industry on the need and potential for an integrated approach is still lacking (Lettenmeier et al., 2009). Similarly, waste management policies are still not driven by climate concerns, although the potential for GHG emission reductions through waste management is increasingly recognized and accounted for (see Section 10.14, e.g., Worrell and van Sluisveld, 2013). Several economic instruments (e.g., taxes and charges) related to waste disposal have been shown to be effective in preventing waste, although they do not necessarily lead to improved design measures being taken further upstream (Hogg et al., 2011).

A number of policy packages are directly and indirectly aimed at reducing material input per unit of product or unit of service demand. Some examples are the European Action Plan on Sustainable Consumption and Production (SCP) and Sustainable Industry (EC, 2008a), the EU's resource efficiency strategy and roadmap (EC, 2011, 2012b), and Germany's resource efficiency programme, ProgRess (BMU, 2012). SCP policies[23] include both voluntary and regulatory instruments, such as the EU Eco-design Directive, as well as the Green Public Procurement policies. Aside from setting a framework and long-term goals for future legislation and setting up networks and knowledge bases, these packages include few specific policies and, most importantly, do not set quantitative targets nor explicitly address the link between material efficiency and GHG emission reductions.

Some single policies (as opposed to policy packages) related to material efficiency do include an assessment of their impacts in terms of GHG emissions. For example, the UK's National Industrial Symbiosis Programme (NISP) brokers the exchange of resources between companies (for an explanation of industrial symbiosis, see Section 10.5). An assessment of the savings through the NISP estimated that over 6 $MtCO_2eq$ were saved over the first five years (Laybourn and Morrissey, 2009). The PIUS-Check initiative by the German state of North Rhine-Westphalia (NRW) offers audits to companies where the relevant material flows are analyzed and recommendations for improvements are made. These PIUS-checks have been particularly successful in metal processing industries, and it is estimated that they have saved 20 thousand tonnes of CO_2 (EC, 2009).

In the Asia and Pacific region there are a number of region-specific policy instruments for climate change mitigation through SCP, such as the China Refrigerator Project, which realized emissions reductions of about 11 $MtCO_2$ between 1999 and 2005 by combining several practices including sustainable product design, technological innovation, eco-labelling, and awareness raising of consumers and retailers (SWITCH-Asia Network Facility, 2009). However, there is still a lack of solid ex-post assessments on SCP policy impacts.

Besides industry-specific policies there are policies with a different sector focus that influence industrial activity indirectly, by reducing the need for products (e.g., car pooling incentive schemes can lead to the production of less cars) or industrial materials (e.g., vehicle fuel economy targets can incentivize the design of lighter vehicles). A strategic approach in order to reflect the economy-wide resource use and the global risks may consist of national accounting systems beyond GDP[24] (Jackson, 2009; Roy and Pal, 2009; Arrow et al., 2010; GEA, 2012), including systems to account for increasing resource productivity (OECD, 2008; Bringezu and Bleischwitz, 2009) and of new international initiatives to spur systemic eco-innovations in key areas such as cement and steel production, light-weight cars, resource efficient construction, and reducing food waste.

10.12 Gaps in knowledge and data

The key challenge for making an assessment of the industry sector is the diversity in practices, which results in uncertainty, lack of comparability, incompleteness, and quality of data available in the public domain on process and technology specific energy use and costs. This diversity makes assessment of mitigation potential with high confidence at global and regional scales extremely difficult. Sector data are generally collected by industry/trade associations (international or national), are highly aggregated, and generally give little information about individual processes. The enormous variety of processes and technologies adds to the complexity of assessment (Tanaka, 2008, 2012; Siitonen et al., 2010).

22 For a more in-depth analysis of CDM as a policy instrument, see Chapter 13, Sections 13.7.2 and 13.13.1.2.

23 SCP policies are also covered in Chapter 4 (Sustainable Development and Equity, Section 4.4.3.1 SCP policies and programmes)

24 For example, the EU's "Beyond GDP Initiative": http://www.beyond-gdp.eu/

Other major gaps in knowledge identified are:

- A systematic approach and underlying methodologies to avoid double counting due to the many different ways of attributing emissions (10.1).
- An in-depth assessment of mitigation potential and associated costs achievable particularly through material efficiency and demand-side options (10.4).
- Analysis of climate change impacts on industry and industry-specific mitigation options, as well as options for adaptation (10.6).
- Comprehensive information on sector and sub-sector specific option-based mitigation potential and associated costs based on a comparable methodology and transparent assumptions (10.7).
- Effect on long-term scenarios of demand reduction strategies through an improved modelling of material flows, inclusion of regional producer behaviour model parameters in integrated models (10.10).
- Understanding of the net impacts of different types of policies, the mitigation potential of linked policies e.g., resource efficiency/energy efficiency policies, as well as policy as drivers of carbon leakage effects (10.11).

10.13 Frequently Asked Questions

FAQ 10.1 How much does the industry sector contribute to GHG emissions?

Global industrial GHG emissions accounted for just over 30 % of global GHG emissions in 2010. Global industry and waste/wastewater GHG emissions grew from 10 $GtCO_2eq$ in 1990 to 13 $GtCO_2eq$ in 2005 to 15 $GtCO_2eq$ in 2010. Over half (52 %) of global direct GHG emissions from industry and waste/wastewater are from the ASIA region, followed by OECD-1990 (25 %), EIT (9 %), MAF (8 %), and LAM (6 %). GHG emissions from industry grew at an average annual rate of 3.5 % globally between 2005 and 2010. This included 7 % average annual growth in the ASIA region, followed by MAF (4.4 %) and LAM (2 %), and the EIT countries (0.1 %), but declined in the OECD-1990 countries (–1.1 %). (10.3)

In 2010, industrial GHG emissions were comprised of direct energy-related CO_2 emissions of 5.3 $GtCO_2eq$, 5.2 $GtCO_2eq$ indirect CO_2 emissions from production of electricity and heat for industry, process CO_2 emissions of 2.6 $GtCO_2eq$, non-CO_2 GHG emissions of 0.9 $GtCO_2eq$, and waste/wastewater emissions of 1.4 $GtCO_2eq$. (10.3)

2010 direct and indirect emissions were dominated by CO_2 (85.1 %) followed by CH_4 (8.6 %), HFC (3.5 %), N_2O (2.0 %), PFC (0.5 %) and SF_6 (0.4 %) emissions. Between 1990 and 2010, N_2O emissions from adipic acid and nitric acid production and PFC emissions from aluminium production decreased while HFC-23 emissions from HCFC-22 production increased. In the period 1990–2005, fluorinated gases (F-gases) were the most important non-CO_2 GHG source in manufacturing industry. (10.3)

FAQ 10.2 What are the main mitigation options in the industry sector and what is the potential for reducing GHG emissions?

Most industry sector scenarios indicate that demand for materials (steel, cement, etc.) will increase by between 45 % to 60 % by 2050 relative to 2010 production levels. To achieve an absolute reduction in emissions from the industry sector will require a broad set of mitigation options going beyond current practices. Options for mitigation of GHG emissions from industry fall into the following categories: energy efficiency, emissions efficiency (including fuel and feedstock switching, carbon dioxide capture and storage), material efficiency (for example through reduced yield losses in production), re-use of materials and recycling of products, more intensive and longer use of products, and reduced demand for product services. (10.4, 10.10)

In the last two to three decades there have been strong improvements in energy and process efficiency in industry, driven by the relatively high share of energy costs. Many options for energy efficiency improvement still remain, and there is still potential to reduce the gap between actual energy use and the best practice in many industries. Based on broad deployment of best available technologies, the GHG emissions intensity of the sector could be reduced through energy efficiency by approximately 25 %. Through innovation, additional reductions of approximately 20 % in energy intensity may potentially be realized before approaching technological limits in some energy intensive industries. (10.4, 10.7)

In addition to energy efficiency, material efficiency—using less new material to provide the same final service—is an important and promising option for GHG reductions that has had little attention to date. Long-term step-change options, including a shift to low carbon electricity or radical product innovations (e.g., alternatives to cement), may have the potential to contribute to significant mitigation in the future. (10.4)

FAQ 10.3 How will the level of product demand, interactions with other sectors, and collaboration within the industry sector affect emissions from industry?

The level of demand for new and replacement products has a significant effect on the activity level and resulting GHG emissions in the industry sector. Extending product life and using products more intensively could contribute to reduction of product demand without reducing the service. However, assessment of such strategies needs a careful net-balance (including calculation of energy demand in the production process and associated GHG emissions). Absolute emission reductions can also come about through changes in lifestyle and their corresponding demand levels, be it directly (e.g., for food, textiles) or indirectly (e.g., for product/service demand related to tourism). (10.4)

Mitigation strategies in other sectors may lead to increased emissions in industry if they require enhanced use of energy intensive materials (e.g., higher production of solar cells (PV) and insulation materials for buildings). Moreover, collaborative interactions within the industry sector and between the industry sector and other economic sectors have significant potential for mitigation (e.g., heat cascading). In addition, inter-sectoral cooperation, i.e., collaborative interactions among industries in industrial parks or with regional eco-industrial networks, can contribute to mitigation. (10.5)

FAQ 10.4 What are the barriers to reducing emissions in industry and how can these be overcome? Are there any co-benefits associated with mitigation actions in industry?

Implementation of mitigation measures in industry faces a variety of barriers. Typical examples include: the expectation of high return on investment (short payback period); high capital costs and long project development times for some measures; lack of access to capital for energy efficiency improvements and feedstock/fuel change; fair market value for cogenerated electricity to the grid; and costs/lack of awareness of need for control of HFC leakage. In addition, businesses today are mainly rewarded for growing sales volumes and can prefer process innovation over product innovation. Existing national accounting systems based on GDP indicators also support the pursuit of actions and policies that aim to increase demand for products and do not trigger product demand reduction strategies. (10.9)

Addressing the causes of investment risk, and better provisioning of user demand in the pursuit of human well-being could enable the reduction of industry emissions. Improvements in technologies, efficient sector specific policies (e.g., economic instruments, regulatory approaches and voluntary agreements), and information and energy management programmes could all contribute to overcome technological, financial, institutional, legal, and cultural barriers. (10.9, 10.11)

Implementation of mitigation measures in industries and related policies might gain momentum if co-benefits (10.8) are considered along with direct economic costs and benefits (10.7). Mitigation actions can improve cost competitiveness, lead to new market opportunities, and enhance corporate reputation through indirect social and environmental benefits at the local level. Associated positive health effects can enhance public acceptance. Mitigation can also lead to job creation and wider environmental gains such as reduced air and water pollution and reduced extraction of raw materials which in turn leads to reduced GHG emissions. (10.8)

10.14 Appendix: Waste

10.14.1 Introduction

Waste generation and reuse is an integral part of human activity. Figure 10.2 and Section 10.4 have shown how industries enhance resource use efficiency through recycling or reuse before discarding resources to landfills, which follows the waste hierarchy shown in Figure 10.16. Several mitigation options exist at the pre-consumer stage. Most important is reduction in waste during production processes. With regard to post-consumer waste, associated GHG emissions heavily depend on how waste is treated.

This section provides a summary of knowledge on current emissions from wastes generated from various economic activities (focusing on solid waste and wastewater) and discusses the mitigation options to reduce emissions and recover materials and energy from solid wastes.

10.14.2 Emissions trends

10.14.2.1 Solid waste disposal

The 'hierarchy of waste management' as shown in Figure 10.16, places waste reduction at the top, followed by re-use, recycling, energy recovery (including anaerobic digestion), treatment without energy recovery (including incineration and composting) and four types of landfills ranging from modern sanitary landfills that treat liquid effluents and also attempt to capture and use the generated biogas, through to traditional non-sanitary landfills (waste designated sites that lack controlled measures) and open burning. Finally, at the bottom of the pyramid are crude disposal methods in the form of waste dumps (designated or non-designated waste disposal sites without any kind of treatment) that are still dominant in many parts of the world. The hierarchy shown in Figure 10.16 provides general guidance. However, lifecycle assessment of the overall impacts of a waste management strategy for specific waste composition and local circumstances may change the priority order (EC, 2008b).

Municipal solid wastes (MSW) are the most visible and troublesome residues of human society. The total amount of MSW generated globally has been estimated at about 1.5 Gt per year (Themelis, 2007) and it is expected to increase to approximately 2.2 Gt by 2025 (Hoornweg and Bhada-Tata, 2012). Of the current amount, approximately 300 Mt are recycled, 200 Mt are treated with energy recovery, another 200 Mt are disposed in sanitary landfills, and the remaining 800 Mt are discarded in non-sanitary landfills or dumps. Thus, much of the recoverable matter in MSW is dispersed through mixing with other materials and exposure to reactive environmental conditions. The implications for GHG and other emissions are related not only to the direct emissions from waste management, but also to the emissions from production of materials to replace those lost in the waste.

Figure 10.17 presents global emissions from waste from 1970 until 2010 based on EDGAR version 4.2. Methane emissions from solid waste disposal almost doubled between 1970 and 2010. The drop in CH_4 emissions from solid waste disposal sites (SWDS) starting around 1990 is most likely related to the decrease in such emissions in Europe and the United States. However, it is important to note that the First Order Decay (FOD) model used in estimating emissions from solid waste disposal sites in the EDGAR database does not account for climate and soil micro-climate conditions like California Landfill Methane Inventory Model (CALMIM) (see Spokas et al., 2011; Spokas and Bogner, 2011; Bogner et al., 2011).

Global waste emissions per unit of GDP decreased 27 % from 1970 to 1990 and 34 % from 1990 to 2010, with a decrease of 48 % for the entire period (1970–2010). Global waste emissions per capita increased 10 % between 1970 and 1990, decreased 5 % from 1990 to 2010, with a net increase of 5 % for the entire period 1970–2010 (Figure 10.17). Several reasons may explain these trends: GHG emissions from waste in EU, mainly from solid waste disposal on land and wastewater handling decreased by 19.4 % in the decade 2000–2009; the decline is notable when compared to total EU27 emissions over the same period, which decreased by 9.3 %[25]. Energy production from waste in the EU in 2009 was more than double that generated in 2000, while biogas has experienced a 270 % increase in the same period. With the introduction of the Landfill Directive 10 1999/31/EC, the EU has established a powerful tool to reduce the amount of biodegradable municipal waste disposed in landfills (Blodgett and Parker, 2010). Moreover, methane emissions from landfills in the United States

[25] Eurostat 2013, available at http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Climate_change_-_driving_forces.

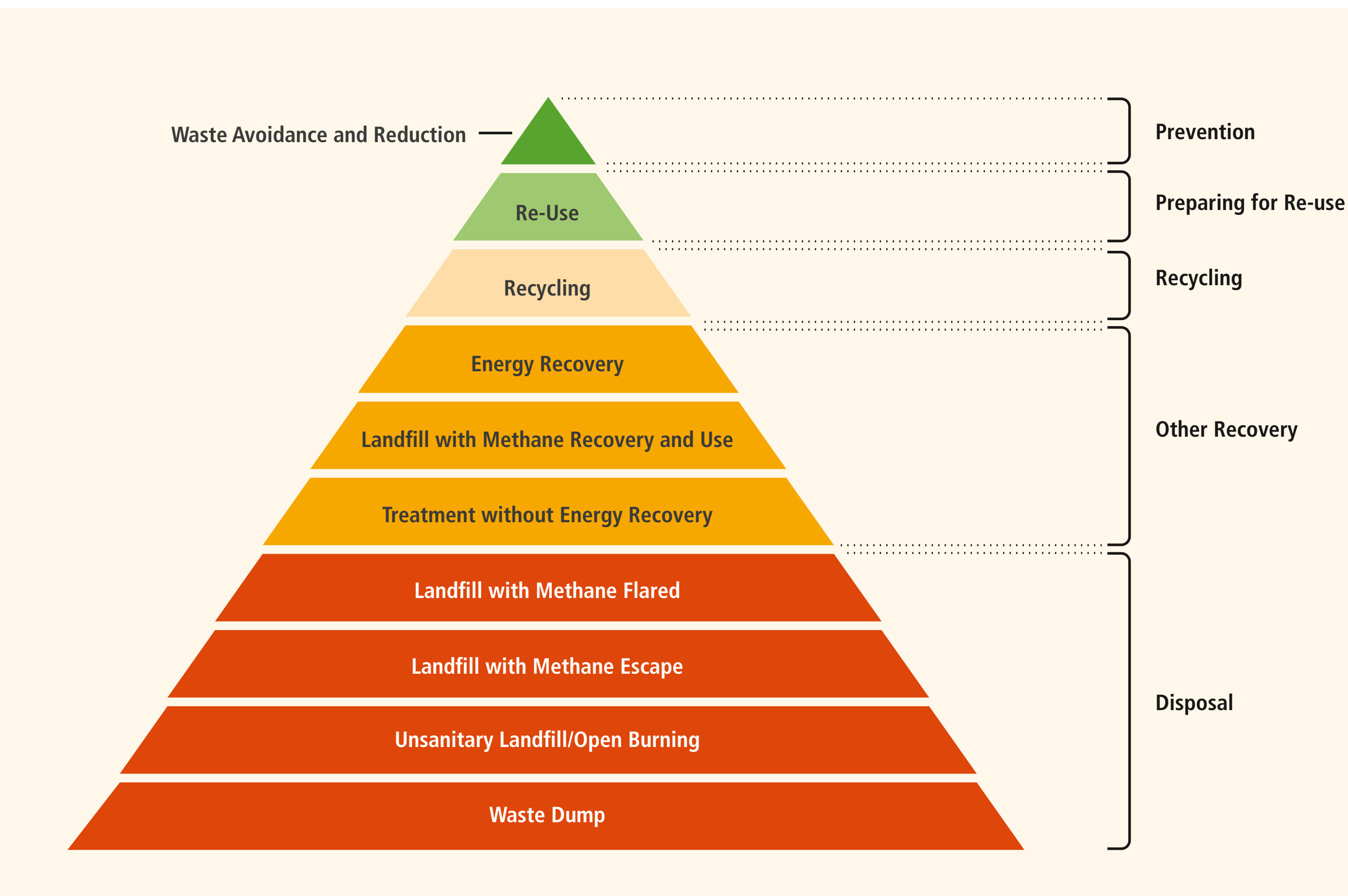


Figure 10.16 | The hierarchy of waste management. The priority order and colour coding is based on the five main groups of waste hierarchy classification (Prevention; Preparing for Re-Use; Recycling; Other Recovery e.g., Energy Recovery; and Disposal) outlined by the European Commission (EC, 2008b).

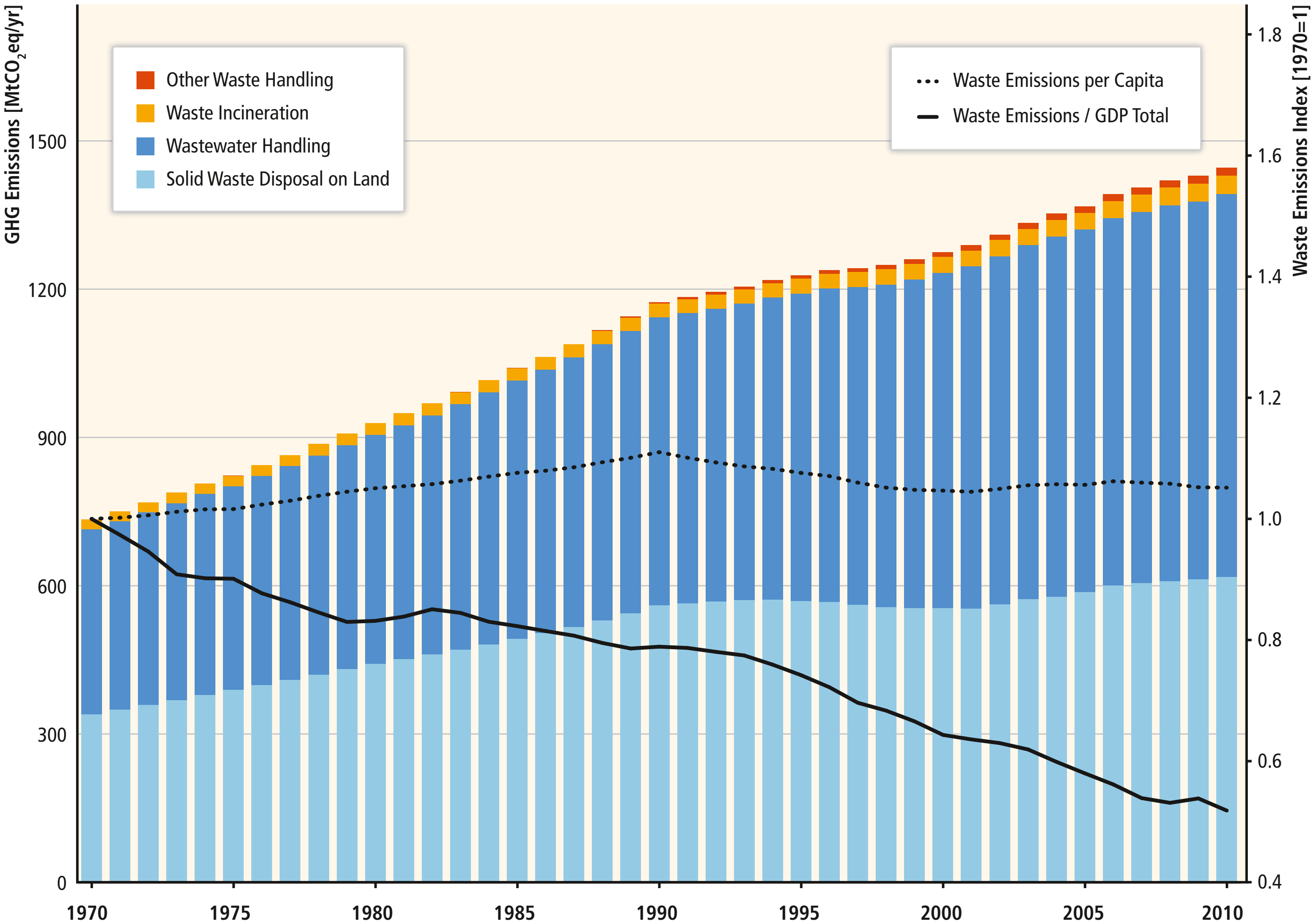


Figure 10.17 | Global waste emissions $MtCO_2eq$/year, global waste emissions per GDP and global waste emissions per capita referred to 1970 values. Based on JRC/PBL (2013), see Annex II.9.

decreased by approximately 27 % from 1990 to 2010. This net emissions decrease can be attributed to many factors, including changes in waste composition, an increase in the amount of landfill gas collected and combusted, a higher frequency of composting, and increased rates of recovery of degradable materials for recycling, e.g., paper and paperboard (EPA, 2012b).

China's GHG emissions in the waste sector increased rapidly in the 1981 to 2009 period, along with the growing scale of waste generation by industries as well as households in urban and rural areas (Qu and Yang, 2011). A 79 % increase in landfill methane emissions was estimated between 1990 (2.4 Mt) and 2000 (4.4 Mt) due to changes in both the amount and composition of municipal waste generated (Streets et al., 2001) and emission of China's waste sector will peak at 33.2 $MtCO_2eq$ in 2024 (Qu and Yang, 2011). In India (INCCA, 2010), the waste sector contributed 3 % of total national CO_2 emission equivalent of which 22 % is from municipal solid waste and the rest are from domestic wastewater (40 %) and industrial wastewater (38 %). Domestic wastewater is the dominant source of CH_4 in India. The decrease of GHG emissions in the waste sector in the EU and the United States from 1990 to 2009 has not been enough to compensate for the increase of emissions in other regions resulting in an overall increasing trend of total waste-related GHG emissions in that period.

10.14.2.2 Wastewater

Methane and nitrous oxide emissions from wastewater steadily increased during the last decades reaching 667 and 108 $MtCO_2eq$ in 2010, respectively. Methane emissions from domestic/commercial and industrial categories are responsible for 86 % of wastewater GHG emissions during the period 1970–2010, while the domestic/commercial sector was responsible for approximately 80 % of the methane emissions from wastewater category.

10.14.3 Technological options for mitigation of emissions from waste

10.14.3.1 Pre-consumer waste

Waste reduction

Pre-consumer (or post-industrial) waste is the material diverted from the waste stream during a manufacturing process that does not reach the end user. This does not include the reutilization of materials generated in a process that can be re-used as a substitute for raw materials (10.4) without being modified in any way. Waste reduction at the pre-consumer stage can be achieved by optimizing the use of raw materials, e.g., arranging the pattern of pieces to be cut on a length of fabric or metal sheet enable maximum utilization of material with minimum of waste.

Recycling and reuse

Material substitution through waste generated from an industrial process or manufacturing chain can lead to reduction in total energy requirements (10.4) and hence emissions. Section 10.4 discusses options for recycling and reuse in the manufacturing industries. The same section also discusses the use of municipal solid waste as energy source or feedstock, e.g., for the cement industry, as well as the possible use of industrial waste for mineralization approaches for CCS.

10.14.3.2 Post-consumer waste

Pre-consumer (or post-industrial) waste is the material resulting from a manufacturing process, which joins the waste stream and does not reach the end use. The top priority of the post-consumer waste management is reduction followed by re-use and recycling.

Waste reduction

To a certain extent, the amount of post-consumer waste is related to lifestyle. On a per capita basis, Japan and the EU have about 60 % of the US waste generation rates based significantly on different consumer behavior and regulations. Globally, a visionary goal of 'zero waste' assists countries in designing waste reduction strategies, technologies, and practices, keeping in mind other resource availability like land. Home composting has been successfully used in some regions, which reduces municipal waste generation rates (Favoino and Hogg, 2008; Andersen et al., 2010).

Non-technological behavioural strategies aim to avoid or reduce waste, for instance by decoupling waste generation from economic activity levels such as GDP (Mazzanti and Zoboli, 2008). In addition, strategies are in place that aim to enhance the use of materials and products that are easy to recycle, reuse, and recover (Sections 10.4, 10.11) in close proximity facilities.

Post-consumer waste can be linked with pre-consumer material through the principle of Extended Producer Responsibility in order to divert the waste going to landfills. This principle or policy is the explicit attribution of responsibility to the waste-generating parties, preferably already in the pre-consumer phase. In Germany, for example, the principle of producer responsibility for their products in the post-consuming phase is made concrete by the issuing of regulations (de Jong, 1997). Sustainable consumption and production and its influence on waste minimization are discussed also in Section 10.11.

Recycling/reuse

If reduction of post-consumer waste cannot be achieved, reuse and recycling is the next priority in order to reduce the amount of waste produced and to divert it from disposal (Valerio, 2010). Recycling of post-consumer waste can be achieved with high economic value to protect the environment and conserve the natural resources (El-Haggar, 2010). Section 10.4 discusses this in the context of reuse in industries.

As cities have become hotspots of material flows and stock density (Baccini and Brunner, 2012, p. 31) (see Chapter 12), MSW can be seen as a material reservoir that can be mined. This can be done not only through current recycling and/or energy recovery processes (10.4), but also by properly depositing and concentrating substances (e.g., metals, paper, plastic) in order to make their recuperation technically and economically viable in the future. The current amount of materials accumulated mainly in old/mature settlements, for the most part located in developed countries (Graedel, 2010), exceeds the amount of waste currently produced (Baccini and Brunner, 2012, p. 50).

With a high degree of agreement, it has been suggested that urban mining (as a contribution towards a zero waste scenario) could reduce important energy inputs of material future demands in contrast to domestically produced and, even more important for some countries, imported materials, while contributing to future material accessibility.

Landfilling and methane capture from landfills

It has been estimated (Themelis and Ulloa, 2007) that annually about 50 Mt of methane is generated in global landfills, 6 Mt of which are captured at sanitary landfills. Sanitary landfills that are equipped to capture methane at best capture 50 % of the methane generated; however, significantly higher collection efficiencies have been demonstrated at certain well designed and operated landfills with final caps/covers of up to 95 %.

The capital investment needed to build a sanitary landfill is less than 30 % of a waste-to-energy (WTE) plant of the same daily capacity. However, because of the higher production of electricity (average of 0.55 MWh of electricity per metric tonne of MSW in the U.S. vs 0.1

MWh for a sanitary landfill), a WTE plant is usually more economic over its lifetime of 30 years or more (Themelis and Ulloa, 2007). In other regions, however, the production of methane from landfills may be lower due to the reduction of biodegradable fraction entering the landfills or operating costs may be lower. Therefore, economics of both options may be different in such cases.

Landfill aeration

Landfill aeration can be considered as an effective method for GHG emissions reduction in the future (Ritzkowski and Stegmann, 2010). In situ aeration is one technology that introduces ambient air into MSW landfills to enhance biological processes and to inhibit methane production (Chai et al., 2013). Ambient air is introduced in the landfill via a system of gas wells, which results in accelerated aerobic stabilization of deposited waste. The resulting gas is collected and treated (Heyer et al., 2005; Prantl et al., 2006). Biological stabilization of the waste using in-situ aeration provides the possibility to reduce both the actual emissions and the emission potential of the waste material (Prantl et al., 2006).

Landfill aeration, which is not widely applied yet, is a promising technology for treating the residual methane from landfills utilizing landfill gas for energy when energy recovery becomes economically unattractive (Heyer et al., 2005; Ritzkowski et al., 2006; Rich et al., 2008). In the absence of mandatory environmental regulations that require the collection and flaring of landfill gas, landfill aeration might be applied to closed landfills or landfill cells without prior gas collection and disposal or utilization. For an in situ aerated landfill in northern Germany, for example, landfill aeration achieved a reduction in methane emissions by 83 % to 95 % under strictly controlled conditions (Ritzkowski and Stegmann, 2010). Pinjing et al. (2011) show that landfill aeration is associated with increased N_2O emissions.

Composting and anaerobic digestion

Municipal solid waste (MSW) contains 'green' wastes such as leaves, grass, and other garden and park residues, and also food wastes. Generally, green wastes are source-separated and composted aerobically (i.e., in presence of oxygen) in windrows. However, food wastes contain meat and other substances that, when composted in windrows, emit unpleasant odours. Therefore, food wastes need to be anaerobically digested in closed biochemical reactors. The methane generated in these reactors can be used in a gas engine to produce electricity, or for heating purposes. Source separation, collection, and anaerobic digestion of food wastes are costly and so far have been applied to small quantities of food wastes in a few cities (e.g., Barcelona, Toronto, Vienna; Arsova, 2010), except in cases where some food wastes are co-digested with agricultural residues. In contrast, windrow composting is practiced widely; for example, 62 % of the U.S. green wastes (22.7 million tonnes) were composted aerobically in 2006 (Arsova et al., 2008), while only 0.68 million tonnes of food wastes (i.e., 2.2 % of total food wastes; EPA, 2006a) were recovered.

Energy recovery from waste

With the exception of metals, glass, and other inorganic materials, MSW consists of biogenic and petrochemical compounds made of carbon and hydrogen atoms.

The energy contained in solid wastes can be recovered by means of several thermal treatment technologies including combustion of as-received solid wastes on a moving grate, shredding of MSW and combustion on a grate or fluidized bed, mechanical-biological treatment (MBT) of MSW into compost, refuse-derived fuel (RDF) or biogas from anaerobic digestion, partial combustion and gasification to a synthetic gas that is then combusted in a second chamber, and pyrolysis of source-separated plastic wastes to a synthetic oil. At this time, an estimated 90 % of the world's WTE capacity (i.e., about 180 Mt per year) is based on combustion of as-received MSW on a moving grate; the same is true of the nearly 120 new WTE plants that were built worldwide in the period of 2000–2007 (Themelis, 2007).

WTE plants require sophisticated Air Pollution Control (APC) systems that constitute a large part of the plant. In the last twenty years, because of the elaborate and costly APC systems, modern WTE plants have become one of the cleanest high temperature industrial processes (Nzihou et al., 2012). Source separation of high moisture organic wastes from the MSW increases the thermal efficiency of WTE plants.

Most of the mitigation options mentioned above require expenditures and, therefore, are more prevalent in developed countries with higher GDP levels. A notable exception to this general rule is China, where government policy has encouraged the construction of over 100 WTE plants during the first decade of the 21st century (Dong, 2011). Figure 10.18 shows the share of different management practices concerning the MSW generated in several nations (Themelis and Bourtsalas, 2013). China, with 18 % WTE and less than 3 % recycling, is at the level of Slovakia.

The average chemical energy stored in MSW is about 10 MJ/kg (lower heating value, LHV), corresponding to about 2.8 MWh per tonne. The average net thermal efficiency of U.S. WTE plants (i.e., electricity to the grid) is 20 %, which corresponds to 0.56 MWh per tonne of MSW. However, additional energy can be recovered from the exhaust steam of the turbine generator. For example, some plants in Denmark and elsewhere recover 0.5 MWh of electricity plus 1 MWh of district heating. A full discussion of the R1 factor, used in the EU for defining overall thermal efficiency of a WTE plant can be found in Themelis et al. (2013).

Studies of the biogenic and fossil-based carbon based on C14-C12 measurements on stack gas of nearly forty WTE plants in the United States have shown that about 65 % of the carbon content of MSW is biogenic (i.e., from paper, food wastes, wood, etc.) (Themelis et al., 2013) .

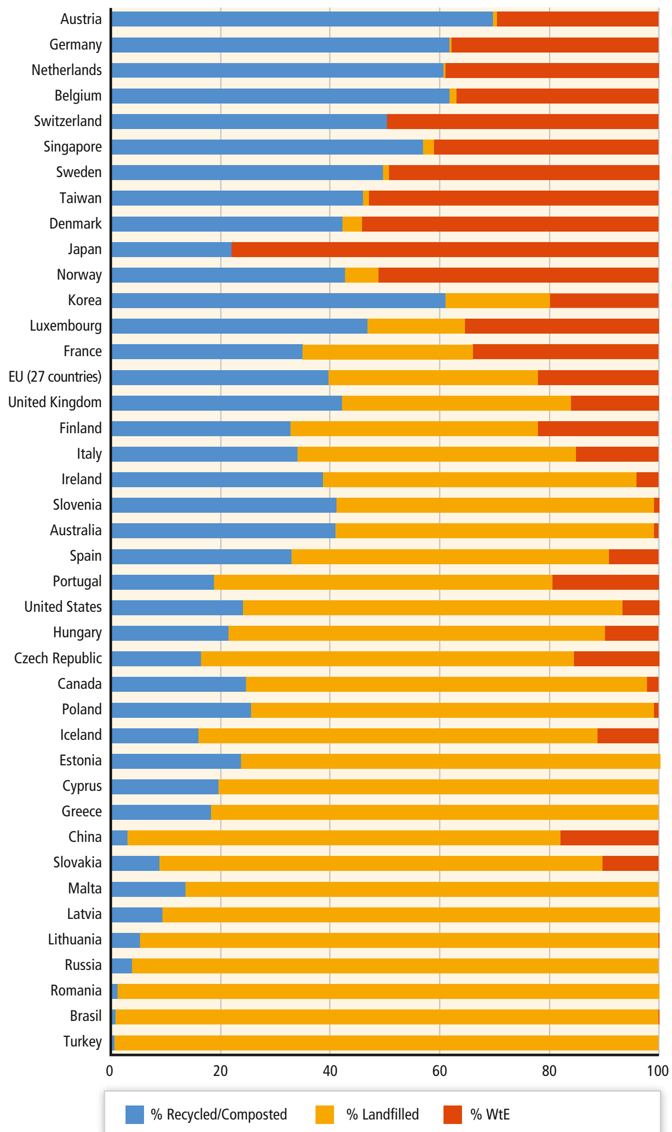


Figure 10.18 | Management practices concerning MSW in several nations (based on World Bank and national statistics, methodology described in Themelis and Bourtsalas (2013).

10.14.3.3 Wastewater

As a preventive measure, primary and secondary aerobic and land treatment help reduce CH_4 emissions during wastewater treatment. Alternatively, CH_4 emissions from wastewater, including sludge treatment under anaerobic conditions, can be captured and used as an energy source (Karakurt et al., 2012). Nitrous oxide is mainly released during biological nitrogen removal in wastewater treatment plants, primarily in aerated zones thus improved plant design and operational strategies (availability of dissolved oxygen, chemical oxygen demand and nitrogen ratio COD/N) have to be achieved in order to avoid the stripping of nitrous emissions (Kampschreur et al., 2009; Law et al., 2012).

Most developed countries rely on centralized aerobic/anaerobic wastewater treatment plants to handle their municipal wastewater. In developing countries, there is little or no collection and treatment of wastewater, anaerobic systems such as latrines, open sewers, or lagoons (Karakurt et al., 2012). Approximately 47 % of wastewater produced in the domestic and manufacturing sectors is untreated, particularly in South and Southeast Asia, but also in Northern Africa as well as Central and South America (Flörke et al., 2013). Wastewater treatment plants are highly capital-intensive but inflexible to adapt to growing demands, especially in rapidly expanding cities. Therefore, innovations related to decentralized wastewater infrastructure are becoming promising. These innovations include satellite systems, actions to achieve reduced wastewater flows, recovery and utilization of the energy content present in wastewater, recovery of nutrients, and the production of water for recycling, which will be needed to address the impacts of population growth and climate change (Larsen et al., 2013).

Industrial wastewater from the food industry usually has both high biochemical and chemical oxygen demand and suspended solid concentrations of organic origin that induce a higher GHG production per volume of wastewater treated compared to municipal wastewater treatment. The characteristics of the wastewater and the off-site GHG emissions have a significant impact on the total GHG emissions attributed to the wastewater treatment plants (Bani Shahabadi et al., 2009). For example, in the food processing industry with aerobic/anaerobic/hybrid process, the biological processes in the treatment plant made for the highest contribution to GHG emissions in the aerobic treatment system, while off-site emissions are mainly due to material usage and represent the highest emissions in anaerobic and hybrid treatment systems. Industrial cluster development in developing countries like China and India are enhancing wastewater treatment and recycling (see also Section 10.5).

Regional variation in wastewater quality matters in terms of performance of technological options. Conventional systems may be technologically inadequate to handle the locally produced sewage in arid areas like the Middle East. In these areas, domestic wastewater are up to five times more concentrated in the amount of biochemical and/or chemical oxygen demand per volume of sewage in comparison with United States and Europe, causing large amounts of sludge production. In these cases, choosing an appropriate treatment technology for the community could be a sustainable solution for wastewater management and emissions control. Example solutions include upflow anaerobic sludge blanket, hybrid reactors, soil aquifer treatment, approaches based on pathogens treatment, and reuse of the treated effluent for agricultural reuse (Bdour et al., 2009).

Wetlands can be a sustainable solution for municipal wastewater treatment due to their low cost, simple operation and maintenance, minimal secondary pollution, favourable environmental appearance, and other ecosystem service benefits (Mukherjee, 1999; Chen et al., 2008, 2011; Mukherjee and Gupta, 2011). It has been demonstrated that wetlands are a less energy intensive option than conventional wastewater treatment systems despite differences in costs across technologies and socio-economic contexts (Gao et al., 2012), but such systems are facing challenges in urban areas from demand for land for other economic activities (Mukherjee, 1999).

It has been highlighted that wastewater treatment with anaerobic sludge digestion and methane recovery and use for energy purposes reduces methane emissions (Bani Shahabadi et al., 2009; Foley et al., 2010; Massé et al., 2011; Fine and Hadas, 2012; Abbasi et al., 2012; Liu et al., 2012b; Wang et al., 2012b). Anaerobic digestion also provides an efficient means to reduce pollutant loads when high-strength organic wastewater (food waste, brewery, animal manure) have to be treated (Shin et al., 2011), although adequate regulatory policy incentives are needed for widespread implementation in developed and developing countries (Massé et al., 2011).

Advanced treatment technologies such as membrane filtration, ozonation, aeration efficiency, bacteria mix, and engineered nanomaterials (Xu et al., 2011b; Brame et al., 2011) may enhance GHG emissions reduction in wastewater treatment, and some such technologies, for example membranes, have increased the competitiveness and decentralization (Fane, 2007; Libralato et al., 2012).

The existence of a shared location and infrastructure can also facilitate the identification and implementation of more synergy opportunities to reduce industrial water provision and wastewater treatment, therefore abating GHG emissions from industry. The concept of eco-industrial parks is discussed in Section 10.5.

10.14.4 Summary results on costs and potentials

Figure 10.19 and Figure 10.20 present the potentials and costs of selected mitigation options to reduce the GHG emissions of the two waste sectors that represent 90 % of waste related emissions: solid waste disposal (0.67 $GtCO_2eq$) and domestic wastewater (0.77 $GtCO_2eq$) emissions (JRC/PBL, 2013). For solid waste, potentials are presented in tCO_2eq/t solid waste and for wastewater and in $tCO_2eq/t\ BOD_5$ as % compared to current global average.

Six mitigation options for solid waste and three mitigation options for wastewater are assessed and presented in the figures. The reference case and the basis for mitigation potentials were derived from IPCC 2006 guidelines. Abatement costs and potentials are based on EPA (2006b; 2013).

The actual costs and potentials of the abatement options vary widely across regions and design of a treatment methodology. Given that technology options to reduce emissions from industrial and municipal waste are the same, it is not further distinguished in the approach. Furthermore, the potential of reductions from emissions from landfills are directly related to climatic conditions as well as to the age and amount of landfill, both of which are not included in the chosen approach. Emission factors are global annual averages (derived from IPCC 2006 guideline aggregated regional averages). The actual emission factor differs between types of waste, climatic regions, and age of

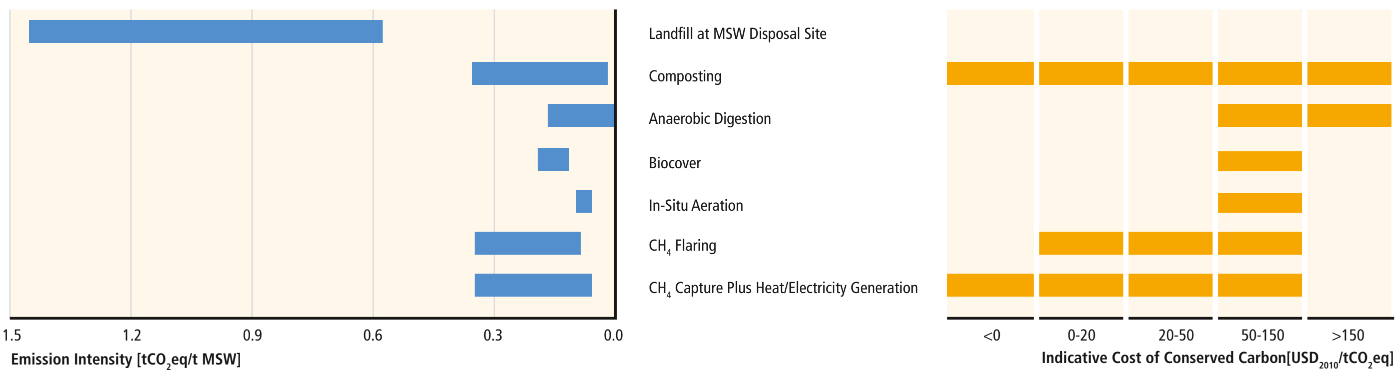


Figure 10.19 | Indicative CO_2eq emission intensities and levelized cost of conserved carbon of municipal solid waste disposal practices/technologies (for data and methodology, see Annex III).

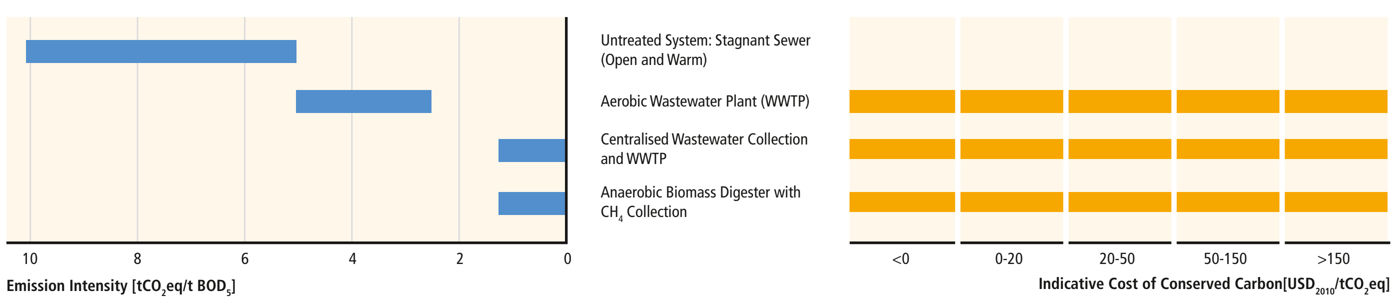


Figure 10.20 | Indicative CO_2eq emission intensities and levelized cost of conserved carbon of different wastewater treatments (for underlying data and methodology, see Annex III).

the landfill, explaining the wide range for each technology. The mitigation potential for waste is derived by comparing the emission range from a reference technology (e.g., a landfill) with the emission range for a chosen technology. The GHG coverage for solid waste is focused on methane, which is the most significant emission from landfilling; other GHG gases such as N_2O only play a minor role in the landfill solid waste sector and are neglected in this study (except for composting).

In the case of landfills, the top five emitting countries account for 27 % of the total abatement potential in the sector (United States 2 %, China 6 %, Mexico 9 %, Malaysia 3 %, and Russia 2 %). The distribution of the remaining potential per region is: Africa 16 %, Central and South America 9 %, Middle East 9 %, Europe 19 %, Eurasia 2 %, Asia 15 %, and North America 4 % (EPA, 2013).

In the case of wastewater, 58 % of the abatement potential is concentrated in the top five emitting countries (United States 7 %, Indonesia 9 %, Mexico 10 %, Nigeria 10 %, and China 23 %). The distribution of the remaining potential per region is: Africa 5 %, Central and South America 5 %, Middle East 14 %, Europe 5 %, Eurasia 4 %, and Asia 10 % (EPA, 2013).

The United States EPA has produced two studies with cost estimates of abatement in the solid waste sector (EPA, 2006b, 2013) which found a large range for options to reduce landfill (e.g., incineration, anaerobic digestion, and composting) of up to 590 USD_{2010}/tCO_2eq if the technology is only implemented for the sake of GHG emission reduction. However, the studies highlight that there are significant opportunities for CH_4 reductions in the landfill sector at carbon prices below 20 USD_{2010}. Improving landfill practices mainly by flaring and CH_4 utilization are low cost options, as both generate costs in the lower range (0—50 USD_{2010}/tCO_2eq).

The costs of the abatement options shown vary widely between individual regions and from plant to plant. The cost estimates should, for that reason, be regarded as indicative only and depend on a number of factors including capital stock turnover, relative energy costs, regional climate conditions, waste fee structures, etc. Furthermore, the method does not reflect the time variation in solid waste disposal and the degradation process as it assumes that all potential methane is released the year the solid waste is disposed.

The unit tonne biological oxygen demand (t BOD) stands for the organic content of wastewater ('loading') and represents the oxygen consumed by wastewater during decomposition. The average for domestic wastewater is in a range of 110–400 mg/l and is directly connected to climate conditions. Costs and potentials are global averages, but based on region-specific information. Options that are more often used in developing countries are not considered since data availability is limited. However, options like septic tanks, open sewers, and lagoons are low cost options with an impact of reducing GHG emission compared to untreated wastewater that is stored in a stagnant sewer under open and warm conditions.

The methane correction factor applied is based on the IPCC guidelines and gives an indication of the amount of methane that is released by applying the technology; furthermore emissions from N_2O have not been included as they play an insignificant role in domestic wastewater. Except in countries with advanced centralized wastewater treatment plants with nitrification and denitrification steps (IPCC, 2006), establishing a structured collection system for wastewater will always have an impact on GHG emissions in the waste sector.

Cost estimates of abatement in the domestic wastewater are provided in EPA (2006b; 2013), which find a large range for the options of 0 to 530 USD_{2010}/tCO_2eq with almost no variation across options. The actual costs of the abatement options shown vary widely between individual regions and from the design set up of a treatment methodology. Especially for wastewater treatment, the cost ranges largely depend on national circumstances like climate conditions (chemical process will be accelerated under warm conditions), economic development, and cultural aspects. The data availability for domestic wastewater options, especially on costs, is very low and would result in large ranges, which imply large uncertainties for each of the option. Mitigation potentials for landfills (in terms of % of potential above emissions for 2030) is double compared with wastewater (EPA, 2013). The mitigation potential for wastewater tends to concentrate in the higher costs options due to the significant costs of constructing public wastewater collection systems and centralized treatment facilities.

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11

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Executive Summary

Agriculture, Forestry, and Other Land Use (AFOLU) is unique among the sectors considered in this volume, since the mitigation potential is derived from both an enhancement of removals of greenhouse gases (GHG), as well as reduction of emissions through management of land and livestock (*robust evidence; high agreement*). The land provides food that feeds the Earth's human population of ca. 7 billion, fibre for a variety of purposes, livelihoods for billions of people worldwide, and is a critical resource for sustainable development in many regions. Agriculture is frequently central to the livelihoods of many social groups, especially in developing countries where it often accounts for a significant share of production. In addition to food and fibre, the land provides a multitude of ecosystem services; climate change mitigation is just one of many that are vital to human well-being (*robust evidence; high agreement*). Mitigation options in the AFOLU sector, therefore, need to be assessed, as far as possible, for their potential impact on all other services provided by land. [Section 11.1]

The AFOLU sector is responsible for just under a quarter (~10–12 $GtCO_2eq/yr$) of anthropogenic GHG emissions mainly from deforestation and agricultural emissions from livestock, soil and nutrient management (*robust evidence; high agreement*) [11.2]. Anthropogenic forest degradation and biomass burning (forest fires and agricultural burning) also represent relevant contributions. Annual GHG emissions from agricultural production in 2000–2010 were estimated at 5.0–5.8 $GtCO_2eq/yr$ while annual GHG flux from land use and land-use change activities accounted for approximately 4.3–5.5 $GtCO_2eq/yr$. Leveraging the mitigation potential in the sector is extremely important in meeting emission reduction targets (*robust evidence; high agreement*) [11.9]. Since publication of the IPCC Fourth Assessment Report (AR4), emissions from the AFOLU sector have remained similar but the share of anthropogenic emissions has decreased to 24 % (in 2010), largely due to increases in emissions in the energy sector (*robust evidence, high agreement*). In spite of a large range across global Forestry and Other Land Use (FOLU) flux estimates, most approaches indicate a decline in FOLU carbon dioxide (CO_2) emissions over the most recent years, largely due to decreasing deforestation rates and increased afforestation (*limited evidence, medium agreement*). As in AR4, most projections suggest declining annual net CO_2 emissions in the long run. In part, this is driven by technological change, as well as projected declining rates of agriculture area expansion, which, in turn, is related to the expected slowing in population growth. However, unlike AR4, none of the more recent scenarios projects growth in the near-term [11.9].

Opportunities for mitigation include supply-side and demand-side options. On the supply side, emissions from land-use change (LUC), land management and livestock management can be reduced, terrestrial carbon stocks can be increased by sequestration in soils and biomass, and emissions from energy production can be saved through the substitution of fossil fuels by biomass (*robust evidence; high agreement*) [11.3]. On the demand side, GHG emissions could be mitigated by reducing losses and wastes of food, changes in diet and changes in wood consumption (*robust evidence; high agreement*) [11.4] though quantitative estimates of the potential are few and highly uncertain. Increasing production without a commensurate increase in emissions also reduces emission intensity, i.e., the GHG emissions per unit of product that could be delivered through sustainable intensification; another mechanism for mitigation explored in more detail here than in AR4. Supply-side options depend on the efficacy of land and livestock management (*medium evidence; high agreement*) [11.6]. Considering demand-side options, changes in human diet can have a significant impact on GHG emissions from the food production lifecycle (*medium evidence; medium agreement*) [11.4]. There are considerably different challenges involved in delivering demand-side and supply-side options, which also have very different synergies and tradeoffs.

The nature of the sector means that there are potentially many barriers to implementation of available mitigation options, including accessibility to AFOLU financing, poverty, institutional, ecological, technological development, diffusion and transfer barriers (*medium evidence; medium agreement*) [11.7, 11.8]. Similarly, there are important feedbacks to adaptation, conservation of natural resources, such as water and terrestrial and aquatic biodiversity (*robust evidence; high agreement*) [11.5, 11.8]. There can be competition between different land uses if alternative options to use available land are mutually exclusive, but there are also potential synergies, e.g., integrated systems or multi-functionality at landscape scale (*medium evidence; high agreement*) [11.4]. Recent frameworks, such as those for assessing environmental or ecosystem services, provide one mechanism for valuing the multiple synergies and tradeoffs that may arise from mitigation actions (*medium evidence; medium agreement*) [11.1]. Sustainable management of agriculture, forests, and other land is an underpinning requirement of sustainable development (*robust evidence; high agreement*) [11.4].

AFOLU emissions could change substantially in transformation pathways, with significant mitigation potential from agriculture, forestry, and bioenergy mitigation measures (*medium evidence; high agreement*). Recent multi-model comparisons of idealized implementation transformation scenarios find land emissions (nitrous oxide, N_2O; methane, CH_4; CO_2) changing by −4 to 99 % through 2030, and 7 to 76 % through 2100, with the potential for increased emissions from land carbon stocks. Land-related mitigation, including bioenergy, could contribute 20 to 60 % of total cumulative abatement to 2030, and 15 to 40 % to 2100. However, policy coordination and implementation issues are challenges to realizing this potential [11.9]. Large-scale biomass supply for energy, or carbon sequestration in the AFOLU sector provide flexibility for the development of mitigation technologies in the energy supply and energy end-use sectors, as many technologies already exist and some of them are commercial (*limited evidence; medium agreement*) [11.3], but there are potential implications for biodiversity, food security, and other services provided by land (*medium evidence, high* *agreement*) [11.7]. Implementation challenges, including institutional barriers and inertia related to governance issues, make the costs and net emission reduction potential of near-term mitigation uncertain. In mitigation scenarios with idealized comprehensive climate policies, agriculture, forestry, and bioenergy contribute substantially to the reduction of global CO_2, CH_4, and N_2O emissions, and to the energy system, thereby reducing policy costs (*medium evidence; high agreement*) [11.9]. More realistic partial and delayed policies for global land mitigation have potentially significant spatial and temporal leakage, and economic implications, but could still be cost-effectively deployed (*limited evidence; limited agreement*) [11.9].

Economic mitigation potential of supply-side measures in the AFOLU sector is estimated to be 7.18 to 10.60 (full range: 0.49–10.60) GtCO$_2$eq/yr in 2030 for mitigation efforts consistent with carbon prices up to 100 USD/tCO$_2$eq, about a third of which can be achieved at < 20 USD/tCO$_2$eq (*medium evidence; medium agreement*) [11.6]. These estimates are based on studies that cover both forestry and agriculture and that include agricultural soil carbon sequestration. Estimates from agricultural sector-only studies range from 0.3 to 4.6 GtCO$_2$eq/yr at prices up to 100 USD/tCO$_2$eq, and estimates from forestry sector-only studies from 0.2 to 13.8 GtCO$_2$eq/yr at prices up to 100 USD/tCO$_2$eq (*medium evidence; medium agreement*) [11.6]. The large range in the estimates arises due to widely different collections of options considered in each study, and because not all GHGs are considered in all of the studies. The composition of the agricultural mitigation portfolio varies with the carbon price, with the restoration of organic soils having the greatest potential at higher carbon prices (100 USD/tCO$_2$eq) and cropland and grazing land management at lower (20 USD/tCO$_2$eq). In forestry there is less difference between measures at different carbon prices, but there are significant differences between regions, with reduced deforestation dominating the forestry mitigation potential in Latin America and Caribbean (LAM) and Middle East and Africa (MAF), but very little potential in the member countries of the Organisation for Economic Co-operation and Development (OECD-1990) and Economies in Transition (EIT). Forest management, followed by afforestation, dominate in OECD-1990, EIT, and Asia (*medium evidence, strong agreement*) [11.6]. Among demand-side measures, which are under-researched compared to supply-side measures, changes in diet and reductions of losses in the food supply chain can have a significant, but uncertain, potential to reduce GHG emissions from food production (0.76–8.55 GtCO$_2$eq/yr by 2050), with the range being determined by assumptions about how the freed land is used (*limited evidence; medium agreement*) [11.4]. More research into demand-side mitigation options is merited. There are significant regional differences in terms of mitigation potential, costs, and applicability, due to differing local biophysical, socioeconomic, and cultural circumstances, for instance between developed and developing regions, and among developing regions (*medium evidence; high agreement*) [11.6].

The size and regional distribution of future mitigation potential is difficult to estimate accurately because it depends on a number of inherently uncertain factors. Critical factors include population (growth), economic and technological developments, changes in behaviour over time (depending on cultural and normative backgrounds, market structures and incentives), and how these translate into demand for food, fibre, fodder and fuel, as well as development in the agriculture, aquaculture and forestry sectors. Other factors important to mitigation potential are potential climate change impacts on carbon stocks in soils and forests including their adaptive capacity (*medium evidence; high agreement*) [11.5]; considerations set by biodiversity and nature conservation requirements; and interrelations with land degradation and water scarcity (*robust evidence; high agreement*) [11.8].

Bioenergy can play a critical role for mitigation, but there are issues to consider, such as the sustainability of practices and the efficiency of bioenergy systems (*robust evidence, medium agreement*) [11.4.4, Box 11.5, 11.13.6, 11.13.7]. Barriers to large-scale deployment of bioenergy include concerns about GHG emissions from land, food security, water resources, biodiversity conservation and livelihoods. The scientific debate about the overall climate impact related to land use competition effects of specific bioenergy pathways remains unresolved (*robust evidence, high agreement*) [11.4.4, 11.13]. Bioenergy technologies are diverse and span a wide range of options and technology pathways. Evidence suggests that options with low lifecycle emissions (e. g., sugar cane, Miscanthus, fast growing tree species, and sustainable use of biomass residues), some already available, can reduce GHG emissions; outcomes are site-specific and rely on efficient integrated 'biomass-to-bioenergy systems', and sustainable land-use management and governance. In some regions, specific bioenergy options, such as improved cookstoves, and small-scale biogas and biopower production, could reduce GHG emissions and improve livelihoods and health in the context of sustainable development (*medium evidence, medium agreement*) [11.13].

Policies governing practices in agriculture and in forest conservation and management need to account for both mitigation and adaptation. One of the most visible current policies in the AFOLU sector is the implementation of REDD+ (see Annex I), that can represent a cost-effective option for mitigation (*limited evidence; medium agreement*) [11.10], with economic, social, and other environmental co-benefits (e. g., conservation of biodiversity and water resources).

11

11.1 Introduction

Agriculture, Forestry, and Other Land Use (AFOLU[1]) plays a central role for food security and sustainable development (Section 11.9). Plants take up carbon dioxide (CO_2) from the atmosphere and nitrogen (N) from the soil when they grow, re-distributing it among different pools, including above and below-ground living biomass, dead residues, and soil organic matter. The CO_2 and other non-CO_2 greenhouse gases (GHG), largely methane (CH_4) and nitrous oxide (N_2O), are in turn released to the atmosphere by plant respiration, by decomposition of dead plant biomass and soil organic matter, and by combustion (Section 11.2). Anthropogenic land-use activities (e.g., management of croplands, forests, grasslands, wetlands), and changes in land use/cover (e.g., conversion of forest lands and grasslands to cropland and pasture, afforestation) cause changes superimposed on these natural fluxes. AFOLU activities lead to both sources of CO_2 (e.g., deforestation, peatland drainage) and sinks of CO_2 (e.g., afforestation, management for soil carbon sequestration), and to non-CO_2 emissions primarily from agriculture (e.g., CH_4 from livestock and rice cultivation, N_2O from manure storage and agricultural soils and biomass burning (Section 11.2).

The main mitigation options within AFOLU involve one or more of three strategies: *reduction/prevention* of emissions to the atmosphere by conserving existing carbon pools in soils or vegetation that would otherwise be lost or by reducing emissions of CH_4 and N_2O (Section 11.3); *sequestration*—enhancing the uptake of carbon in terrestrial reservoirs, and thereby removing CO_2 from the atmosphere (Section 11.3); and reducing CO_2 emissions by *substitution* of biological products for fossil fuels (Appendix 1) or energy-intensive products (Section 11.4). Demand-side options (e.g., by lifestyle changes, reducing losses and wastes of food, changes in human diet, changes in wood consumption), though known to be difficult to implement, may also play a role (Section 11.4).

Land is the critical resource for the AFOLU sector and it provides food and fodder to feed the Earth's population of ~7 billion, and fibre and fuel for a variety of purposes. It provides livelihoods for billions of people worldwide. It is finite and provides a multitude of goods and ecosystem services that are fundamental to human well-being (MEA, 2005). Human economies and quality of life are directly dependent on the services and the resources provided by land. Figure 11.1 shows the many provisioning, regulating, cultural and supporting services provided by land, of which climate regulation is just one. Implementing mitigation options in the AFOLU sector may potentially affect other services provided by land in positive or negative ways.

In the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (SAR) (IPCC, 1996) and in the IPCC Fourth Assessment Report (AR4) (IPCC, 2007a), agricultural and forestry mitigation were dealt with in separate chapters. In the IPCC Third Assessment Report (TAR) (IPCC, 2001), there were no separate sectoral chapters on either agriculture or forestry. In the IPCC Fifth Assessment Report (AR5), for the first time, the vast majority of the terrestrial land surface, comprising agriculture, forestry and other land use (AFOLU) (IPCC, 2006), is considered together in a single chapter, though settlements (which are important, with urban areas forecasted to triple in size from 2000 global extent by 2030; Section 12.2), are dealt with in Chapter 12. This approach ensures that all land-based mitigation options can be considered together; it minimizes the risk of double counting or inconsistent treatment (e.g., different assumptions about available land) between different land categories, and allows the consideration of systemic feedbacks between mitigation options related to the land surface (Section 11.4). Considering AFOLU in a single chapter allows phenomena common across land-use types, such as competition for land (Smith et al., 2010; Lambin and Meyfroidt, 2011) and water (e.g., Jackson et al., 2007), co-benefits (Sandor et al., 2002; Venter et al., 2009), adverse side-effects (Section 11.7) and interactions between mitigation and adaptation (Section 11.5) to be considered consistently. The complex nature of land presents a unique range of barriers and opportunities (Section 11.8), and policies to promote mitigation in the AFOLU sector (Section 11.10) need to take account of this complexity.

In this chapter, we consider the competing uses of land for mitigation and for providing other services (Sections 11.7; 11.8). Unlike the chapters on agriculture and forestry in AR4, impacts of sourcing bioenergy from the AFOLU sector are considered explicitly in a dedicated appendix (Section 11.13). Also new to this assessment is the explicit consideration of food/dietary demand-side options for GHG mitigation in the AFOLU sector (Section 11.4), and some consideration of freshwater fisheries and aquaculture, which may compete with the agriculture and forestry sectors, mainly through their requirements for land and/or water, and indirectly, by providing fish and other products to the same markets as animal husbandry.

This chapter deals with AFOLU in an integrated way with respect to the underlying scenario projections of population growth, economic growth, dietary change, land-use change (LUC), and cost of mitigation. We draw evidence from both 'bottom-up' studies that estimate mitigation potentials at small scales or for individual options or technologies and then scale up, and multi-sectoral 'top-down' studies that consider AFOLU as just one component of a total multi-sector system response (Section 11.9). In this chapter, we provide updates on emissions trends and changes in drivers and pressures in the AFOLU sector (Section 11.2), describe the practices available in the AFOLU sector (Section 11.3), and provide refined estimates of mitigation costs and potentials for the AFOLU sector, by synthesising studies that have become available since AR4 (Section 11.6). We conclude the chapter by identifying gaps in knowledge and data (Section 11.11), providing a selection of Frequently Asked Questions (Section 11.12), and presenting an Appendix on bioenergy to update the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (IPCC, 2011; see Section 11.13).

[1] The term AFOLU used here consistent with the (IPCC, 2006) Guidelines is also consistent with Land Use, Land-Use Change and Forestry (LULUCF) (IPCC, 2003), and other similar terms used in the scientific literature.

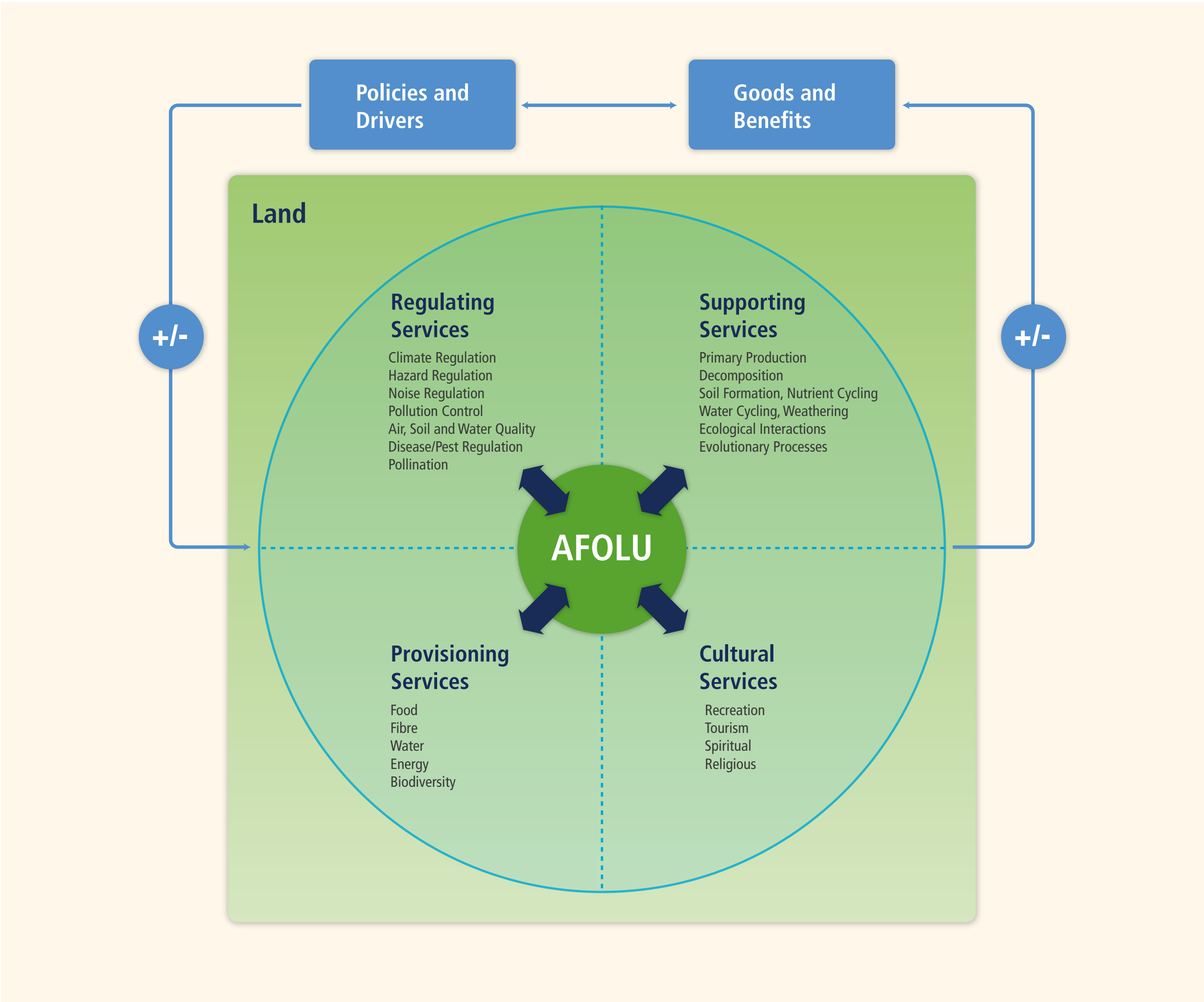


Figure 11.1 | Multiple ecosystem services, goods and benefits provided by land (after MEA, 2005; UNEP-WCMC, 2011). Mitigation actions aim to enhance climate regulation, but this is only one of the many functions fulfilled by land.

11.2 New developments in emission trends and drivers

Estimating and reporting the anthropogenic component of gross and net AFOLU GHG fluxes to the atmosphere, globally, regionally, and at country level, is difficult compared to other sectors. First, it is not always possible to separate anthropogenic and natural GHG fluxes from land. Second, the input data necessary to estimate GHG emissions globally and regionally, often based on country-level statistics or on remote-sensing information, are very uncertain. Third, methods for estimating GHG emissions use a range of approaches, from simple default methodologies such as those specified in the IPCC GHG Guidelines[2] (IPCC, 2006), to more complex estimates based on terrestrial carbon cycle modelling and/or remote sensing information. Global trends in total GHG emissions from AFOLU activities between 1971 and 2010 are shown in Figure 11.2; Figure 11.3 shows trends of major drivers of emissions.

[2] Parties to the United Nations Framework Convention on Climate Change (UNFCCC) report net GHG emissions according to IPCC methodologies (IPCC, 2006). Reporting is based on a range of methods and approaches dependent on available data and national capacities, from default equations and emission factors applicable to global or regional cases and assuming instantaneous emissions of all carbon that will be eventually lost from the system following human action (Tier 1) to more complex approaches such as model-based spatial analyses (Tier 3).

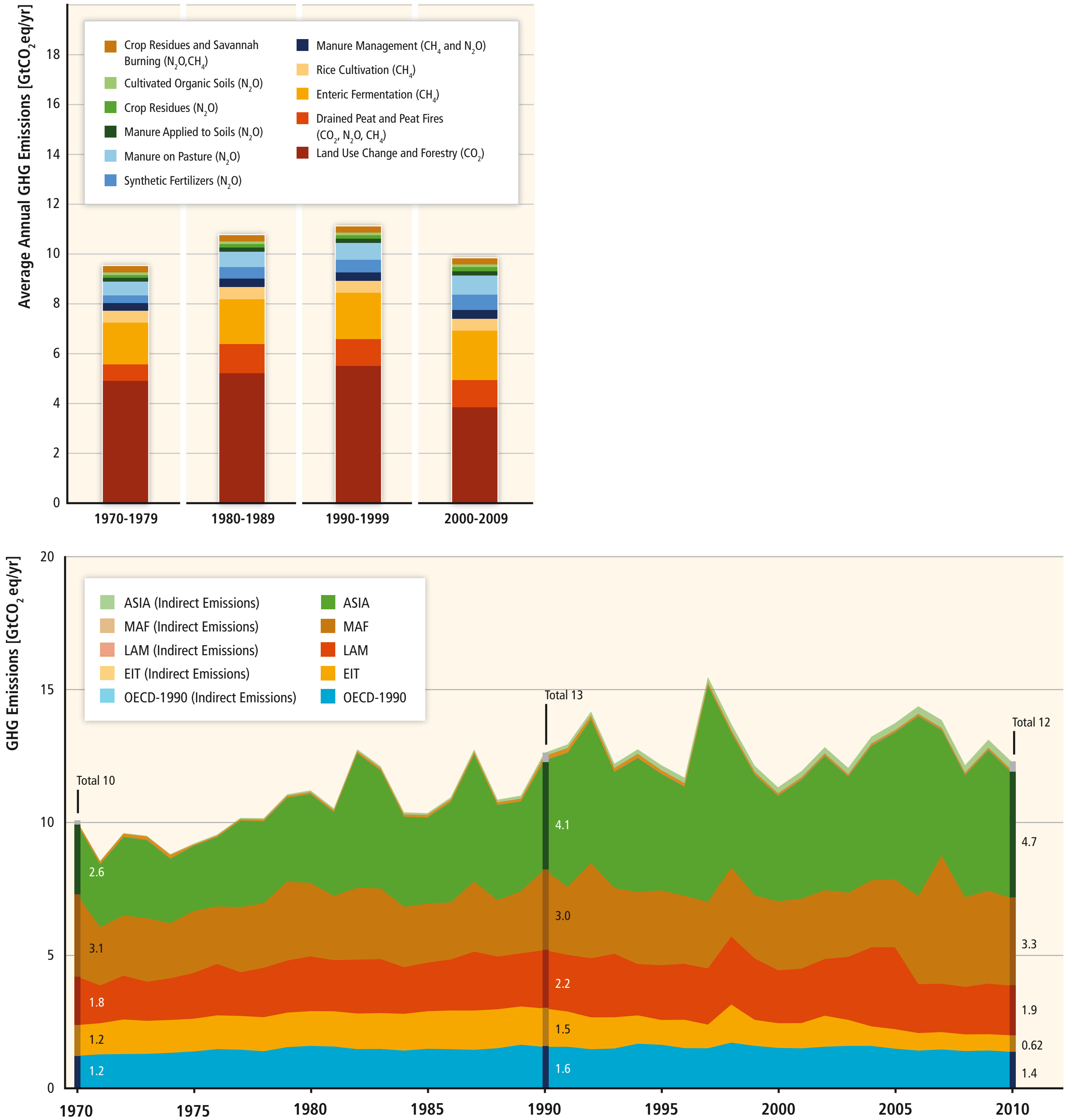
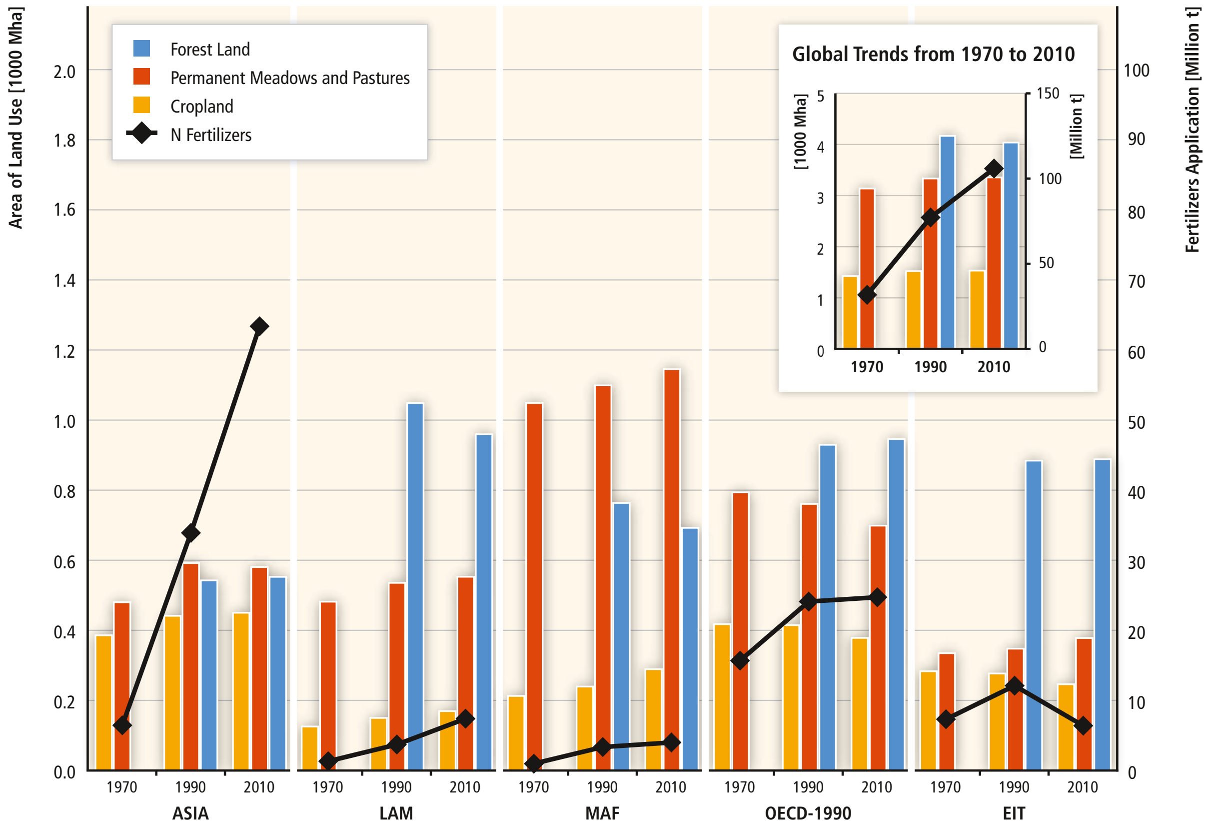


Figure 11.2 | Top: AFOLU emissions for the last four decades. For the agricultural sub-sectors emissions are shown for separate categories, based on FAOSTAT, (2013). Emissions from crop residues, manure applied to soils, manure left on pasture, cultivated organic soils, and synthetic fertilizers are typically aggregated to the category 'agricultural soils' for IPCC reporting. For the Forestry and Other Land Use (FOLU) sub-sector data are from the Houghton bookkeeping model results (Houghton et al., 2012). Emissions from drained peat and peat fires are, for the 1970s and the 1980s, from JRC/PBL (2013), derived from Hooijer et al. (2010) and van der Werf et al. (2006) and for the 1990s and the 2000s, from FAOSTAT, 2013. Bottom: Emissions from AFOLU for each RC5 region (see Annex II.2) using data from JRC/PBL (2013), with emissions from energy end-use in the AFOLU sector from IEA (2012a) included in a single aggregated category, see Annex II.9, used in the AFOLU section of Chapter 5.7.4 for cross-sectoral comparisons. The direct emission data from JRC/PBL (2013; see Annex II.9) represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthopogenic emission sources in the FOLU sub-sector. Differences between FAOSTAT/Houghton data and JRC/PBL (2013) are discussed in the text. See Figures 11.4 and 11.6 for the range of differences among available databases for AFOLU emissions.



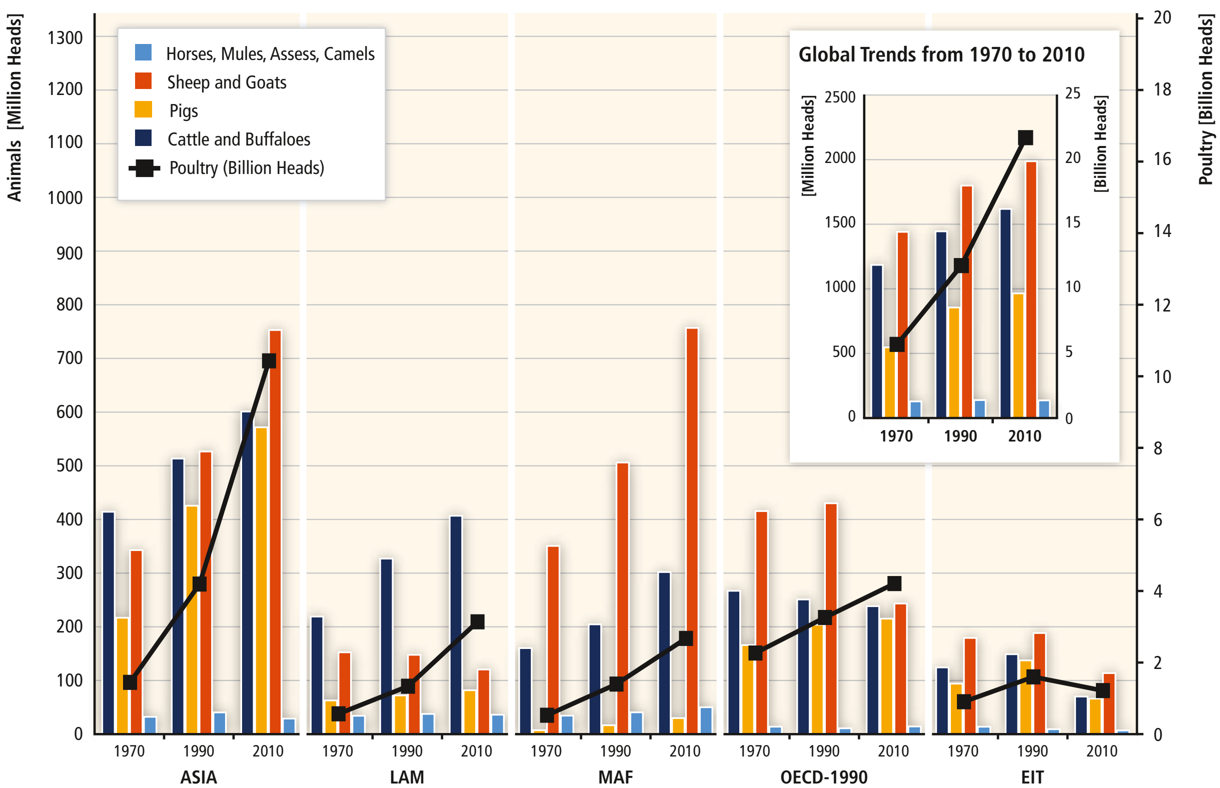


Figure 11.3 | Global trends from 1971 to 2010 in (top) area of land use (forest land—available only from 1990; 1000 Mha) and amount of N fertilizer use (million tonnes), and (bottom) number of livestock (million heads) and poultry (billion heads). Data presented by regions: 1) Asia, 2) LAM, 3) MAF, 4) OECD-1990, 5) EIT (FAOSTAT, 2013). The area extent of AFOLU land-use categories, from FAOSTAT, (2013): 'Cropland' corresponds to the sum of FAOSTAT categories 'arable land' and 'temporary crops' and coincides with the IPCC category (IPCC, 2003); 'Forest' is defined according to FAO (2010); countries reporting to UNFCCC may use different definitions. 'Permanent meadows and pasture', are a subset of IPCC category 'grassland' (IPCC, 2003), as the latter, by definition, also includes unmanaged natural grassland ecosystems.

11.2.1 Supply and consumption trends in agriculture and forestry

In 2010 world agricultural land occupied 4889 Mha, an increase of 7 % (311 Mha) since 1970 (FAOSTAT, 2013). Agricultural land area has decreased by 53 Mha since 2000 due to a decline of the cropland area (Organisation for Economic Co-operation and Development (OECD)-1990, Economies in Transition (EIT)) and a decrease in permanent meadows and pastures (OECD-1990 and Asia). The average amount of cropland and pasture land per capita in 1970 was 0.4 and 0.8 ha and by 2010 this had decreased to 0.2 and 0.5 ha per capita, respectively (FAOSTAT, 2013).

Changing land-use practices, technological advancement and varietal improvement have enabled world grain harvests to double from 1.2 to 2.5 billion tonnes per year between 1970 and 2010 (FAOSTAT, 2012). Average world cereal yields increased from 1600 to 3030 kg/ha over the same period (FAOSTAT, 2012) while there has also been a 233 % increase in global fertilizer use from 32 to 106 Mt/yr, and a 73 % increase in the irrigated cropland area (FAOSTAT, 2013).

Globally, since 1970, there has been a 1.4-fold increase in the numbers of cattle and buffalo, sheep and goats (which is closely linked to the trend of CH_4 emissions in the sector; Section 11.2.2), and increases of 1.6- and 3.7-fold for pigs and poultry, respectively (FAOSTAT, 2013). Major regional trends between 1970 and 2010 include a decrease in the total number of animals in Economies in Transition (EIT) and OECD-1990 (except poultry), and continuous growth in other regions, particularly Middle East and Africa (MAF) and Asia (Figure 11.3, bottom panel). The soaring demand for fish has led to the intensification of freshwater and marine fisheries worldwide, and an increased freshwater fisheries catch that topped 11 Mt in 2010, although the marine fisheries catch has slowly declined (78 Mt in 2010; FAOSTAT, 2013). The latter is, however, compensated in international markets by tremendous growth of aquaculture production to 60 Mt wet weight in 2010, of which 37 Mt originate from freshwater, overwhelmingly in Asia (FAOSTAT, 2013).

Between 1970 and 2010, global daily per capita food availability, expressed in energy units, has risen from 10,008 to 11,850 kJ (2391 to 2831 kcal), an increase of 18.4 %; growth in MAF (10,716 kJ in 2010) has been 22 %, and in Asia, 32 % (11,327 kJ in 2010; FAOSTAT, 2013). The percentage of animal products in daily per capita total food consumption has increased consistently in Asia since 1970 (7 to 16 %), remained constant in MAF (8 %) and, since 1985, has decreased in OECD-1990 countries (32 to 28 %), comprising, respectively, 1,790, 870 and 3,800 kJ in 2010 (FAOSTAT, 2013).

11.2.2 Trends of GHG emissions from agriculture

Organic and inorganic material provided as inputs or output in the management of agricultural systems are typically broken down through bacterial processes, releasing significant amounts of CO_2, CH_4, and N_2O to the atmosphere. Only agricultural non-CO_2 sources are reported as anthropogenic GHG emissions, however. The CO_2 emitted is considered neutral, being associated to annual cycles of carbon fixation and oxidation through photosynthesis. The agricultural sector is the largest contributor to global anthropogenic non-CO_2 GHGs, accounting for 56 % of emissions in 2005 (U.S. EPA, 2011). Other important, albeit much smaller non-CO_2 emissions sources from other AFOLU categories, and thus not treated here, include fertilizer applications in forests. Annual total non-CO_2 GHG emissions from agriculture in 2010 are estimated to be 5.2–5.8 $GtCO_2eq/yr$ (FAOSTAT, 2013; Tubiello et al., 2013) and comprised about 10–12 % of global anthropogenic emissions. Fossil fuel CO_2 emissions on croplands added another

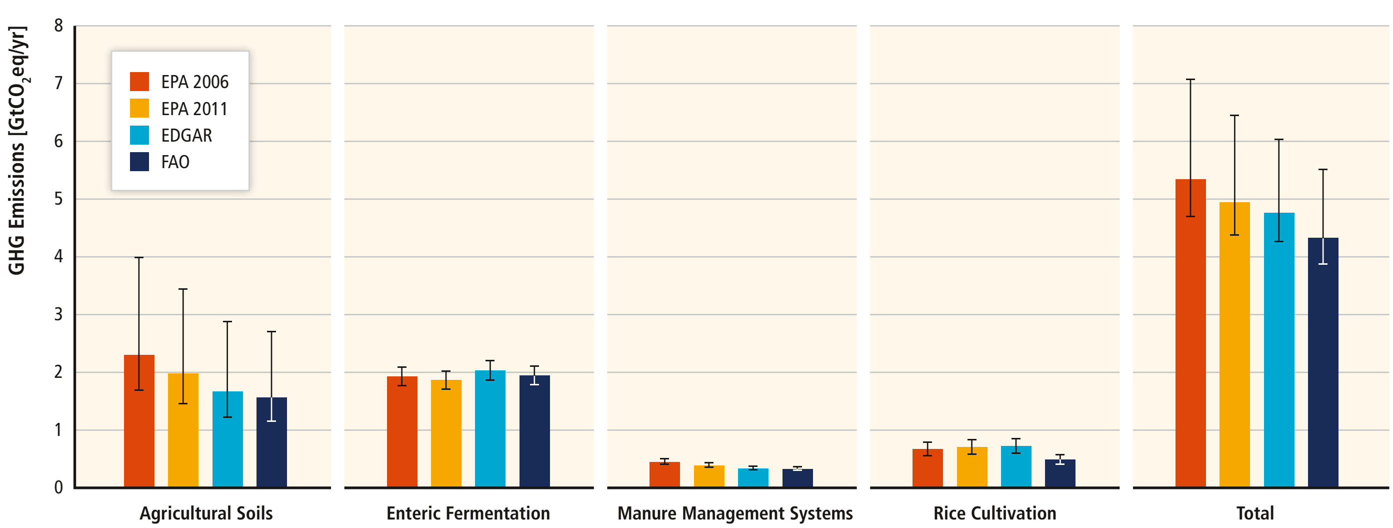


Figure 11.4 | Data comparison between FAOSTAT (2013), U.S. EPA (2006), and EDGAR (JRC/PBL, 2013) databases for key agricultural emission categories, grouped as agricultural soils, enteric fermentation, manure management systems, and rice cultivation, for 2005 | Whiskers represent 95 % confidence intervals of global aggregated categories, computed using IPCC guidelines (IPCC, 2006) for uncertainty estimation (from Tubiello et al., 2013).

0.4–0.6 $GtCO_2eq$/yr in 2010 from agricultural use in machinery, such as tractors, irrigation pumps, etc. (Ceschia et al., 2010; FAOSTAT, 2013), but these emissions are accounted for in the energy sector rather than the AFOLU sector. Between 1990 and 2010, agricultural non-CO_2 emissions grew by 0.9 %/yr, with a slight increase in growth rates after 2005 (Tubiello et al., 2013).

Three independent sources of disaggregated non-CO_2 GHG emissions estimates from agriculture at global, regional, and national levels are available. They are mostly based on FAOSTAT activity data and IPCC Tier 1 approaches (IPCC, 2006; FAOSTAT, 2012; JRC/PBL, 2013; U.S. EPA, 2013). EDGAR and FAOSTAT also provide data at country level. Estimates of global emissions for enteric fermentation, manure management and manure, estimated using IPCC Tier 2/3 approaches are also available (e.g., (Herrero et al., 2013). The FAOSTAT, EDGAR and U.S. EPA estimates are slightly different, although statistically consistent given the large uncertainties in IPCC default methodologies (Tubiello et al., 2013). They cover emissions from enteric fermentation, manure deposited on pasture, synthetic fertilizers, rice cultivation, manure management, crop residues, biomass burning, and manure applied to soils. Enteric fermentation, biomass burning, and rice cultivation are reported separately under IPCC inventory guidelines, with the remaining categories aggregated into 'agricultural soils'. According to EDGAR and FAOSTAT, emissions from enteric fermentation are the largest emission source, while US EPA lists emissions from agricultural soils as the dominant source (Figure 11.4).

The following analyses refer to annual total non-CO_2 emissions by all categories. All three databases agree that that enteric fermentation and agricultural soils represent together about 70 % of total emissions, followed by paddy rice cultivation (9–11 %), biomass burning (6–12 %) and manure management (7–8 %). If all emission categories are disaggregated, both EDGAR and FAOSTAT agree that the largest emitting categories after enteric fermentation (32–40 % of total agriculture emissions) are manure deposited on pasture (15 %) and synthetic fertilizer (12 %), both contributing to emissions from agricultural soils. Paddy rice cultivation (11 %) is a major source of global CH_4 emissions, which in 2010 were estimated to be 493–723 $MtCO_2eq$/yr. The lower end of the range corresponds to estimates by FAO (FAOSTAT, 2013), with EDGAR and US EPA data at the higher end. Independent analyses suggest that emissions from rice may be at the lower end of the estimated range (Yan et al., 2009).

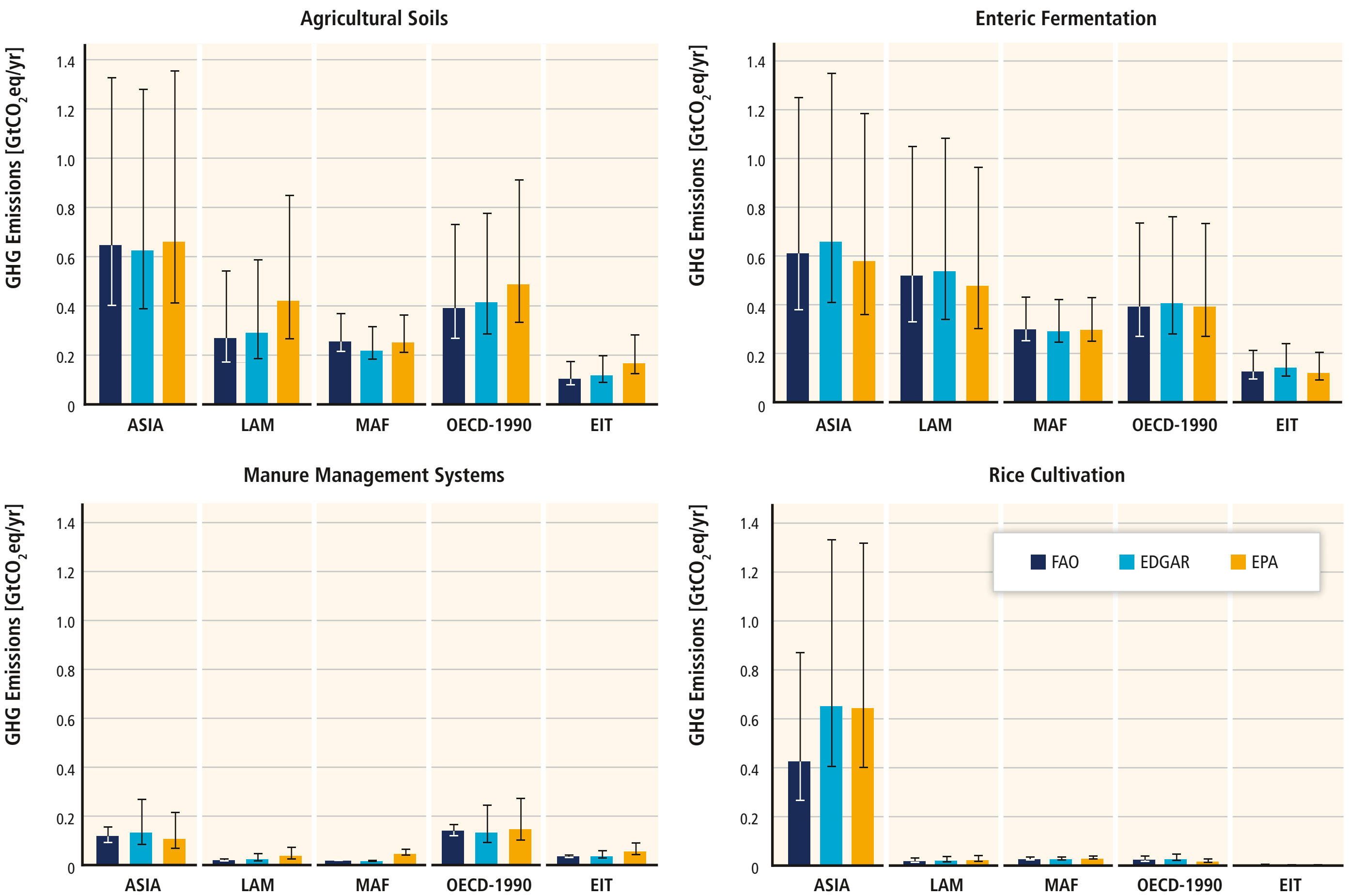


Figure 11.5 | Regional data comparisons for key agricultural emission categories in 2010 | Whiskers represent 95 % confidence intervals computed using IPCC guidelines (IPCC, 2006; Tubiello et al., 2013). The data show that most of the differences between regions and databases are of the same magnitude as the underlying emission uncertainties. [FAOSTAT, 2013; JRC/PBL, 2013; U.S. EPA, 2013]

Enteric Fermentation. Global emissions of this important category grew from 1.4 to 2.1 $GtCO_2eq/yr$ between 1961 and 2010, with average annual growth rates of 0.70 % (FAOSTAT, 2013). Emission growth slowed during the 1990s compared to the long-term average, but became faster again after the year 2000. In 2010, 1.0–1.5 $GtCO_2eq/yr$ (75 % of the total emissions), were estimated to come from developing countries (FAOSTAT, 2013). Over the period 2000–2010, Asia and the Americas contributed most, followed by Africa and Europe (FAOSTAT, 2013); see Figure 11.5). Emissions have grown most in Africa, on average 2.4 %/yr. In both Asia (2.0 %/yr) and the Americas (1.1 %/yr), emissions grew more slowly, and decreased in Europe (–1.7 %/yr). From 2000 to 2010, cattle contributed the largest share (75 % of the total), followed by buffalo, sheep and goats (FAOSTAT, 2013).

Manure. Global emissions from manure, as either organic fertilizer on cropland or manure deposited on pasture, grew between 1961 and 2010 from 0.57 to 0.99 $GtCO_2eq/yr$. Emissions grew by 1.1 %/yr on average. Manure deposited on pasture led to far larger emissions than manure applied to soils as organic fertilizer, with 80 % of emissions from deposited manures coming from developing countries (FAOSTAT, 2013; Herrero et al., 2013). The highest emitting regions from 2000–2010 were the Americas, Asia and Africa. Growth over the same period was most pronounced in Africa, with an average of 2.5 %/yr, followed by Asia (2.3 %/yr), and the Americas (1.2 %/yr), while there was a decrease in Europe of –1.2 %/yr. Two-thirds of the total came from grazing cattle, with smaller contributions from sheep and goats. In this decade, emissions from manure applied to soils as organic fertilizer were greatest in Asia, then in Europe and the Americas. Though the continent with the highest growth rates of 3.4 %/yr, Africa's share in total emissions remained small. In this sub-category, swine and cattle contributed more than three quarters (77 %) of the emissions. Emissions from manure management grew from 0.25 to 0.36 $GtCO_2eq/yr$, resulting in average annual growth rates of only 0.6 %/yr during the period 1961–2010. From 2000–2010 most emissions came from Asia, then Europe, and the Americas (Figure 11.5).

Synthetic Fertilizer. Emissions from synthetic fertilizers grew at an average rate of 3.9 %/yr from 1961 to 2010, with absolute values increasing more than 9-fold, from 0.07 to 0.68 $GtCO_2eq/yr$ (Tubiello et al., 2013). Considering current trends, synthetic fertilizers will become a larger source of emissions than manure deposited on pasture in less than 10 years and the second largest of all agricultural emission categories after enteric fermentation. Close to three quarters (70 %) of these emissions were from developing countries in 2010. In the decade 2000–2010, the largest emitter by far was Asia, then the Americas and then Europe (FAOSTAT, 2012). Emissions grew in Asia by 5.3 %/yr, in Africa by 2.0 %/yr, and in the Americas by 1.5 %/yr. Emissions decreased in Europe (–1.8 %/yr).

Rice. Emissions from rice are limited to paddy rice cultivation. From 1961 to 2010, global emissions increased with average annual growth rates of 0.4 %/yr (FAOSTAT, 2013) from 0.37 to 0.52 $GtCO_2eq/yr$. The growth in global emissions has slowed in recent decades, consistent with trends in rice cultivated area. During 2000–2010, the largest share of emissions (94 %) came from developing countries, with Asia being responsible for almost 90 % of the total (Figure 11.5). The largest growth of emissions took place in in Africa (2.7 %/yr), followed by Europe (1.4 %/yr). Growth rates in Asia and the Americas were much smaller over the same period (0.4–0.7 %/yr).

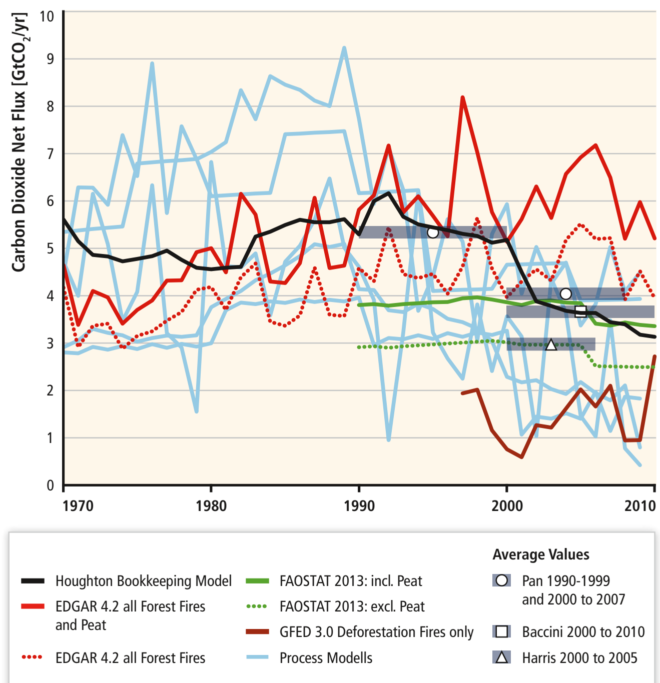


Figure 11.6 | Global net CO_2 emission estimates from FOLU including LUC. Black line: Houghton bookkeeping model approach updated to 2010 as in (Houghton et al., 2012), including LUC and forest management but no peatlands. Red lines: EDGAR 'LULUCF' emissions derived from the GFED 2.0 database (van der Werf et al., 2006) of emissions due to all forest fires (includes both FOLU and non-FOLU fires), with (solid line) and without (dotted line) peat fires and decay. Green lines: emissions from land-use change and management from FAO agricultural and forest inventory data (FAOSTAT, 2013), shown with (solid line) and without (dotted line) peat fires and peat degradation. Dark red line: deforestation and degradation fires only based on satellite fire data from GFED 3.0 database (van der Werf et al., 2010). Light blue lines: a selection of process-based vegetation model results, updated for WGI Chapter 6; (Le Quéré et al., 2013) include LUC, some include forest management, none include peatlands. LPJ-wsl: (Poulter et al., 2010); BernCC: (Stocker et al., 2011); VISIT: (Kato et al., 2011); ISAM: (Jain et al., 2013), IMAGE 2.4 (Van Minnen et al., 2009, deforestation only). The symbols and transparent rectangles represent mean values for the tropics only. Circles: tropical deforestation and forest management (Pan et al., 2011), using the Houghton (2003) bookkeeping model approach and FAO data. Triangle: tropical deforestation only, based on satellite forest area and biomass data (Baccini et al., 2012; Harris et al., 2012). Square: tropical deforestation and forest management, based on satellite forest area and biomass data and FAO data using bookkeeping model (Baccini et al., 2012; Harris et al., 2012).

Table 11.1 | Net global CO_2 flux from AFOLU.

	1750–2011			1980–1989			1990–1999			2000–2009		
	Cumulative $GtCO_2$			$GtCO_2$/yr			$GtCO_2$/yr			$GtCO_2$/yr		
IPCC WGI Carbon Budget, Table 6.1[a]:												
Net AFOLU CO_2 flux[b]	660	±	293	5.13	±	2.93	5.87	±	2.93	4.03	±	2.93
Residual terrestrial sink[c]	−550	±	330	−5.50	±	4.03	−9.90	±	4.40	−9.53	±	4.40
Fossil fuel combustions and cement production[d]	1338	±	110	20.17	±	1.47	23.47	±	1.83	28.60	±	2.20
Meta-analyses of net AFOLU CO_2 flux:												
WGI, Table 6.2[e]				4.77	±	2.57	4.40	±	2.20	2.93	±	2.20
Houghton et al., 2012[f]				4.18	±	1.83	4.14	±	1.83	4.03	±	1.83

Notes: Positive fluxes represent net emissions and negative fluxes represent net sinks.
(a) Selected components of the carbon budget in IPCC WGI AR5, Chapter 6, Table 6.1.
(b) From the bookkeeping model accounting method of Houghton (2003) updated in Houghton et al., (2012), uncertainty based on expert judgement; 90 % confidence uncertainty interval.
(c) Calculated as residual of other terms in the carbon budget.
(d) Fossil fuel flux shown for comparison (Boden et al., 2011).
(e) Average of estimates from 12 process models, only 5 were updated to 2009 and included in the 2000–2009 mean. Uncertainty based on standard deviation across models, 90 % confidence uncertainty interval (WGI Chapter 6).
(f) Average of 13 estimates including process models, bookkeeping model and satellite/model approaches, only four were updated to 2009 and included in the 2000–2009 mean. Uncertainty based on expert judgment.

11.2.3 Trends of GHG fluxes from forestry and other land use[3]

This section focuses on the most significant non-agricultural GHG fluxes to the atmosphere for which there are global trend data. Fluxes resulting directly from anthropogenic FOLU activity are dominated by CO_2 fluxes, primarily emissions due to deforestation, but also uptake due to reforestation/regrowth. Non-CO_2 greenhouse gas emissions from FOLU are small in comparison, and mainly arise from peat degradation through drainage and biomass fires (Box 11.1; Box 11.2).

FOLU accounted for about a third of anthropogenic CO_2 emissions from 1750 to 2011 and 12 % of emissions in 2000 to 2009 (Table 11.1). At the same time, atmospheric measurements indicate the land as a whole was a net sink for CO_2, implying a 'residual' terrestrial sink offsetting FOLU emissions (Table 11.1). This sink is confirmed by inventory measurements in both managed and unmanaged forests in temperate and tropical regions (Phillips et al., 1998; Luyssaert et al., 2008; Lewis et al., 2009; Pan et al., 2011). A sink of the right order of magnitude has been accounted for in models as a result of the indirect effects of human activity on ecosystems, i.e., the fertilizing effects of increased levels of CO_2 and N in the atmosphere and the effects of climate change (WGI Chapter 6; (Le Quéré et al., 2013), although some of it may be due to direct AFOLU activities not accounted for in current estimates (Erb et al., 2013). This sink capacity of forests is relevant to AFOLU mitigation through forest protection.

Global FOLU CO_2 flux estimates (Table 11.1 and Figure 11.6) are based on a wide range of data sources, and include different processes, definitions, and different approaches to calculating emissions (Houghton et al., 2012; Le Quéré et al., 2013; Pongratz et al., 2013). This leads to a large range across global FOLU flux estimates. Nonetheless, most approaches agree that there has been a decline in FOLU CO_2 emissions over the most recent years. This is largely due to a decrease in the rate of deforestation (FAO, 2010; FAOSTAT, 2013).

Regional trends in FOLU CO_2 emissions are shown in Figure 11.7. Model results indicate FOLU emissions peaked in the 1980s in Asia and LAM regions and declined thereafter. This is consistent with a reduced rate of deforestation, most notably in Brazil[4], and some areas of afforestation, the latter most notably in China, Vietnam and India (FAOSTAT, 2013). In MAF the picture is mixed, with the Houghton model (Houghton et al., 2012) showing a continuing increase from the 1970s to the 2000s, while the VISIT model (Kato et al., 2011) indicates a small sink in the 2000s. The results for temperate and boreal areas represented by OECD and EIT regions are very mixed ranging from large net sources (ISAM) to small net sinks. The general picture in temperate and boreal regions is of declining emissions and/or increasing sinks. These regions include large areas of managed forests subjected to harvest and regrowth, and areas of reforestation (e.g., following cropland abandonment in the United States and Europe). Thus results are sensitive to whether and how the models include forest management and environmental effects on regrowing forests.

3 The term 'forestry and other land use' used here, is consistent with AFOLU in the (IPCC, 2006) Guidelines and consistent with LULUCF (IPCC, 2003).

4 For annual deforestation rates in Brazil see http://www.obt.inpe.br/prodes/index.php

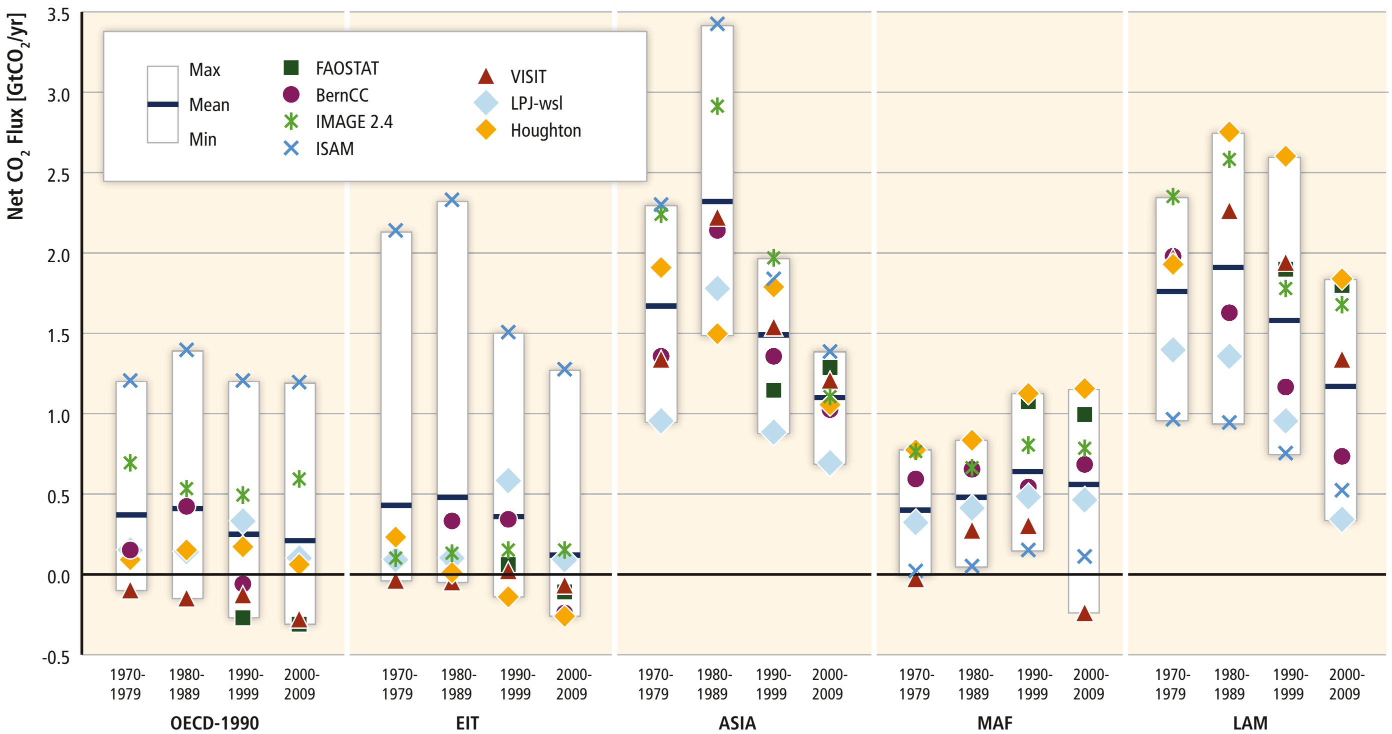


Figure 11.7 | Regional trends in net CO_2 fluxes from FOLU (including LUC). Houghton bookkeeping model approach updated to 2010 as in Houghton et al., (2012) and five process-based vegetation models updated to 2010 for WGI Chapter 6; (Le Quéré et al., 2013): LPJ-wsl: (Poulter et al., 2010); BernCC: (Stocker et al., 2011); VISIT: (Kato et al., 2011); ISAM: (Jain et al., 2013), IMAGE 2.4: ((Van Minnen et al., 2009), deforestation only). Only the FAO estimates (FAOSTAT, 2013) include peatlands.

The bookkeeping model method (Houghton, 2003; Houghton et al., 2012) uses regional biomass, growth and decay rates from the inventory literature that are not varied to account for changes in climate or CO_2. It includes forest management associated with shifting cultivation in tropical forest regions as well as global wood harvest and regrowth cycles. The primary source of data for the most recent decades is FAO forest area and wood harvest (FAO, 2010). FAOSTAT (2013) uses the default IPCC methodologies to compute stock-difference to estimate emissions and sinks from forest management, carbon loss associated with forest conversion to other land uses as a proxy for emissions from deforestation, GFED4 data on burned area to estimate emissions from peat fires, and spatial analyses to determine emissions from drained organic soils (IPCC, 2007b). The other models in Figures 11.6 and 11.7 are process-based terrestrial ecosystem models that simulate changing plant biomass and carbon fluxes, and include climate and CO_2 effects, with a few now including the nitrogen cycle (Zaehle et al., 2011; Jain et al., 2013). Inclusion of the nitrogen cycle results in much higher modelled net emissions in the ISAM model (Jain et al., 2013) as N limitation due to harvest removals limits forest regrowth rates, particularly in temperate and boreal forests. Change in land cover in the process models is from the HYDE dataset (Goldewijk et al., 2011; Hurtt et al., 2011), based on FAO cropland and pasture area change data. Only some process models include forest management in terms of shifting cultivation (VISIT) or wood harvest and forest degradation (ISAM); none account for emissions from peatlands (see Box 11.1).

Satellite estimates of change in land cover have been combined with model approaches to calculate tropical forest emissions (Hansen et al., 2010). The data is high resolution and verifiable, but only covers recent decades, and does not account for fluxes due to LUC that occurred prior to the start of the study period (e.g., decay or regrowth). Satellite data alone cannot distinguish the cause of change in land use (deforestation, natural disturbance, management), but can be used in conjunction with activity data for attribution (Baccini et al., 2012). A recent development is the use of satellite-based forest biomass estimates (Saatchi et al., 2011) together with satellite land cover change in the tropics to estimate 'gross deforestation' emissions (Harris et al., 2012) or further combining it with FAO and other activity data to estimate net fluxes from forest area change and forest management (Baccini et al., 2012).

A detailed breakdown of the component fluxes in (Baccini et al., 2012) is shown in Figure 11.8. Where there is temporary forest loss through management, 'gross' forest emissions can be as high as for permanent forest loss (deforestation), but are largely balanced by 'gross' uptake in regrowing forest, so net emissions are small. When regrowth does not balance removals, it leads to a degradation of forest carbon stocks. In Baccini et al. (2012) this degradation was responsible for 15 % of total net emissions from tropical forests (Houghton, 2013; Figure 11.8). Huang and Asner (2010) estimated that forest degradation in the Amazon, particularly from selective logging, is responsible for 15–19 % higher C emissions than reported from deforestation alone. Pan et al.

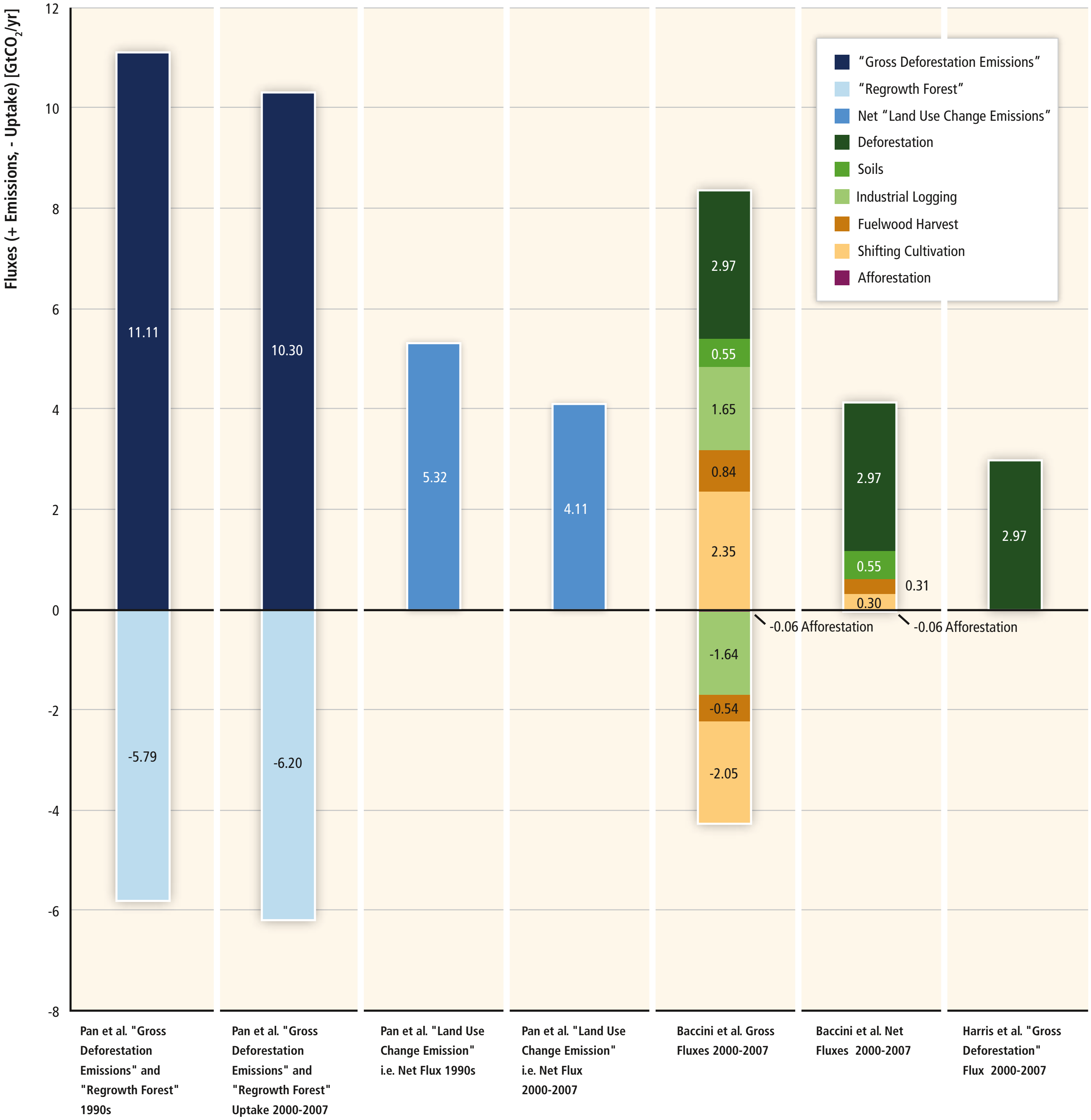


Figure 11.8 | Breakdown of mean annual CO_2 fluxes from deforestation and forest management in tropical countries ($GtCO_2$/yr). Pan et al. (2011) estimates are based on FAO data and the Houghton bookkeeping model (Houghton, 2003). Baccini et al. (2012) estimates are based on satellite land cover change and biomass data with FAO data, and the Houghton (2003) bookkeeping model, with the detailed breakdown of these results shown in Houghton, (2013). Harris et al. (2012) estimates are based on satellite land cover change and biomass data.

Box 11.1 | AFOLU GHG emissions from peatlands and mangroves

Undisturbed waterlogged peatlands (organic soils) store a large amount of carbon and act as small net sinks (Hooijer et al., 2010). Drainage of peatlands for agriculture and forestry results in a rapid increase in decomposition rates, leading to increased emissions of CO_2, and N_2O, and vulnerability to further GHG emissions through fire. The FAO emissions database estimates globally 250,000 km^2 of drained organic soils under cropland and grassland, with total GHG emissions of 0.9 $GtCO_2$eq/yr in 2010—with the largest contributions from Asia (0.44 $GtCO_2$eq/yr) and Europe (0.18 $GtCO_2$eq/yr) (FAOSTAT, 2013). Joosten (2010), estimated that there are > 500,000 km^2 of drained peatlands in the world including under forests, with CO_2 emissions having increased from 1.06 $GtCO_2$/yr in 1990 to 1.30 $GtCO_2$/yr in 2008, despite a decreasing trend in Annex I countries, from 0.65 to 0.49 $GtCO_2$/yr, primarily due to natural and artificial rewetting of peatlands. In Southeast Asia, CO_2 emissions from drained peatlands in 2006 were 0.61 ± 0.25 $GtCO_2$/yr (Hooijer et al., 2010). Satellite estimates indicate that peat fires in equatorial Asia emitted on average 0.39 $GtCO_2$ eq/yr over the period 1997–2009 (van der Werf et al., 2010), but only 0.2 $GtCO_2$ eq/yr over the period 1998–2009. This lower figure is consistent with recent independent FAO estimates over the same period and region. Mangrove ecosystems have declined in area by 20 % (36 Mha) since 1980, although the rate of loss has been slowing in recent years, reflecting an increased awareness of the value of these ecosystems (FAO, 2007). A recent study estimated that deforestation of mangroves released 0.07 to 0.42 $GtCO_2$/yr (Donato et al., 2011).

Box 11.2. | AFOLU GHG emissions from fires

Burning vegetation releases CO_2, CH_4, N_2O, ozone-precursors and aerosols (including black carbon) to the atmosphere. When vegetation regrows after a fire, it takes up CO_2 and nitrogen. Anthropogenic land management or land conversion fire activities leading to permanent clearance or increasing levels of disturbance result in net emissions to the atmosphere over time. Satellite-detection of fire occurrence and persistence has been used to estimate fire emissions (e.g., GFED 2.0 database; (van der Werf et al., 2006). It is hard to separate the causes of fire as natural or anthropogenic, especially as the drivers are often combined. An update of the GFED methodology now distinguishes FOLU deforestation and degradation fires from other management fires (GFED 3.0 database; (van der Werf et al., 2010); Figure 11.6). The estimated tropical deforestation and degradation fire emissions were 1.39 $GtCO_2$eq/yr during 1997 to 2009 (total carbon including CO_2, CH_4, CO and black carbon), 20 % of all fire emissions. Carbon dioxide FOLU fire emissions are already included as part of the global models results such as those presented in Table 1.1 and Figures 11.6 and 11.7. According to (FAOSTAT, 2013)[1], in 2010 the non-CO_2 component of deforestation and forest degradation fires totalled 0.1 $GtCO_2$eq/yr, with forest management and peatland fires (Box 11.1) responsible for an additional 0.2 $GtCO_2$eq/yr.

[1] FOLU GHG emissions by fires include, as per IPCC GHG guidelines, all fires on managed land. Most current FOLU estimates are limited however to fires associated to deforestation, forest management and peat fires. Emissions from prescribed burning of savannahs are reported under agriculture. Both CO_2 and non-CO_2 emissions are accounted under these FOLU components, but CO_2 emissions dominate.

(2011) separated 'gross emissions' from deforestation and forest management on the one hand, from uptake in regrowing vegetation on the other. Deforestation emissions decline from the 1990s to 2000–2007, and uptake in regrowing vegetation increases, both contributing to the decline in net tropical CO_2 emissions.

Satellite fire data have also been used to estimate FOLU emissions (van der Werf et al., 2006); Box 11.2). The EDGAR[5] database 'Land-Use Change and Forestry' emissions are based on forest and peat fire data from GFED 2.0 (van der Werf et al., 2006), with additional estimates of post-burn decay, and emissions from degraded peatlands based on (Joosten, 2010); Box 11.1). However, GFED 2.0 fire data does not distinguish anthropogenic AFOLU fires from other fires, unlike GFED 3.0 (van der Werf et al., 2010); Box 11.2). Fire data also does not capture significant additional AFOLU fluxes due to land clearing and forest management that is by harvest rather than fire (e.g., deforestation activities outside the humid tropics) or regrowth following clearing. Thus EDGAR data only approximates the FOLU flux.

[5] http://edgar.jrc.ec.europa.eu/index.php

FAO estimates AFOLU GHG emissions (FAOSTAT, 2013)[6] based on IPCC Tier 1 methodology[7]. With reference to the decade 2001–2010, total GHG FOLU emissions were 3.2 $GtCO_2eq/yr$ including deforestation (3.8 $GtCO_2eq/yr$), forest degradation and forest management (–1.8 $GtCO_2eq/yr$), biomass fires including peatland fires (0.3 $GtCO_2eq/yr$), and drained peatlands (0.9 $GtCO_2eq/yr$). The FAO estimated total mean net GHG FOLU flux to the atmosphere decreased from 3.9 $GtCO_2eq/yr$ in 1991–2000 to 3.2 $GtCO_2eq/yr$ in 2001–2010 (FAOSTAT, 2013).

11.3 Mitigation technology options and practices, and behavioural aspects

Greenhouse gases can be reduced by supply-side mitigation options (i.e., by reducing GHG emissions per unit of land/animal, or per unit of product), or by demand-side options (e.g., by changing demand for food and fibre products, reducing waste). In AR4, the forestry chapter (Nabuurs et al., 2007) considered some demand-side options, but the agriculture chapter focused on supply-side options only (Nabuurs et al., 2007; Smith et al., 2007). In this section, we discuss only supply-side options (Section 11.3.1). Demand-side options are discussed in Section 11.4.

Mitigation activities in the AFOLU sector can reduce climate forcing in different ways:

- Reductions in CH_4 or N_2O emissions from croplands, grazing lands, and livestock.
- Conservation of existing carbon stocks, e.g., conservation of forest biomass, peatlands, and soil carbon that would otherwise be lost.
- Reductions of carbon losses from biota and soils, e.g., through management changes within the same land-use type (e.g., reducing soil carbon loss by switching from tillage to no-till cropping) or by reducing losses of carbon-rich ecosystems, e.g., reduced deforestation, rewetting of drained peatlands.
- Enhancement of carbon sequestration in soils, biota, and long-lived products through increases in the area of carbon-rich ecosystems such as forests (afforestation, reforestation), increased carbon storage per unit area, e.g., increased stocking density in forests, carbon sequestration in soils, and wood use in construction activities.
- Changes in albedo resulting from land-use and land-cover change that increase reflection of visible light.
- Provision of products with low GHG emissions that can replace products with higher GHG emissions for delivering the same service (e.g., replacement of concrete and steel in buildings with wood, some bioenergy options; see Section 11.13).
- Reductions of direct (e.g., agricultural machinery, pumps, fishing craft) or indirect (e.g., production of fertilizers, emissions resulting from fossil energy use in agriculture, fisheries, aquaculture, and forestry or from production of inputs); though indirect emission reductions are accounted for in the energy end-use sectors (buildings, industry, energy generation, transport) so are not discussed further in detail in this chapter.

11.3.1 Supply-side mitigation options

Mitigation potentials for agricultural mitigation options were given on a 'per-area' and 'per-animal' in AR4 (Nabuurs et al., 2007; Smith et al., 2007). All options are summarized in Table 11.2 with impacts on each GHG noted, and a categorization of technical mitigation potential, ease of implementation, and availability (supported by recent references). These mitigation options can have additive positive effects, but can also work in opposition, e.g., zero tillage can reduce the effectiveness of residue incorporation. Most mitigation options were described in detail in AR4 so are not described further here; additional practices that were not considered in AR4, i.e., biochar, reduced emissions from aquaculture, and bioenergy are described in Boxes 11.3, 11.4, and 11.5, respectively.

In addition to the per-area and per-animal mitigation options described in AR4, more attention has recently been paid to options that reduce emissions intensity by improving the efficiency of production (i.e., less GHG emissions per unit of agricultural product; (Burney et al., 2010; Bennetzen et al., 2012); a reduction in emissions intensity has long been a feature of agricultural emissions reduction and is one component of a process more broadly referred to as sustainable intensification (Tilman et al., 2009; Godfray et al., 2010; Smith, 2013; Garnett et al., 2013). This process does not rely on reducing inputs *per se*, but relies on the implementation of new practices that result in an increase in product output that is larger than any associated increase in emissions (Smith, 2013). Even though per-area emissions could increase, there is a net benefit since less land is required for production of the same quantity of product. The scope to reduce emissions intensity appears considerable since there are very large differences in emissions intensity between different regions of the world (Herrero et al., 2013). Sustainable intensification is discussed further in Section 11.4.2, and trends in changes in emissions intensity are discussed further in Section 11.6.

6 http://faostat.fao.org/

7 Parties to the UNFCCC report net GHG emissions according to IPCC methodologies (IPCC, 2003, 2006). Reporting is based on a range of methods and approaches dependent on available data and national capacities, from default equations and emission factors applicable to global or regional cases and assuming instantaneous emissions of all carbon that will be eventually lost from the system following human action (Tier 1) to more complex approaches such as model-based spatial analyses (Tier 3).

Table 11.2 | Summary of supply-side mitigation options in the AFOLU sector. Technical Mitigation Potential: Area = (tCO_2eq/ha)/yr; Animal = percent reduction of enteric emissions. Low = < 1; < 5 % (white), Medium = 1–10; 5–15 % (light grey), High = > 10, > 15 % (grey); Ease of Implementation (acceptance or adoption by land manager): Difficult (white), Medium (light grey), Easy, i.e., universal applicability (grey); Timescale for Implementation: Long-term (at research and development stage; white), Mid-term (trials in place, within 5–10 years; light grey), Immediate (technology available now, grey).

Categories	Practices and Impacts	Technical Mitigation Potential	Ease of Implementation	Timescale for implementation	References
	Forestry				
Reducing deforestation	**C**: Conservation of existing C pools in forest vegetation and soil by controlling deforestation protecting forest in reserves, and controlling other anthropogenic disturbances such as fire and pest outbreaks. Reducing slash and burn agriculture, reducing forest fires.				1
	CH_4, N_2O: Protection of peatland forest, reduction of wildfires.				2
Afforestation/Reforestation	**C**: Improved biomass stocks by planting trees on non-forested agricultural lands. This can include either monocultures or mixed species plantings. These activities may also provide a range of other social, economic, and environmental benefits.				3, 4, 5
Forest management	**C:** Management of forests for sustainable timber production including extending rotation cycles, reducing damage to remaining trees, reducing logging waste, implementing soil conservation practices, fertilization, and using wood in a more efficient way, sustainable extortion of wood energy				6, 7, 8, 9
	CH_4, N_2O: Wildfire behaviour modification.				10, 11, 12
Forest restoration	**C**: Protecting secondary forests and other degraded forests whose biomass and soil C densities are less than their maximum value and allowing them to sequester C by natural or artificial regeneration, rehabilitation of degraded lands, long-term fallows.				13, 14
	CH_4, N_2O : Wildfire behaviour modification.				
	Land-based agriculture				
Cropland management					
Croplands—plant management	**C**: High input carbon practices, e.g., improved crop varieties, crop rotation, use of cover crops, perennial cropping systems, agricultural biotechnology.				15, 16, 17
	N_2O: Improved N use efficiency.				18
Croplands—nutrient management	**C**: Fertilizer input to increase yields and residue inputs (especially important in low-yielding agriculture).				19, 20
	N_2O: Changing N fertilizer application rate, fertilizer type, timing, precision application, inhibitors.				21, 22, 23, 24, 25, 105, 106
Croplands—tillage/residues management	**C**: Reduced tillage intensity; residue retention.				17, 24, 26, 27
	N_2O:				28, 96, 97
	CH_4:				96
Croplands—water management	**C**: Improved water availability in cropland including water harvesting and application.				29
	CH_4: Decomposition of plant residues.				
	N_2O: Drainage management to reduce emissions, reduce N runoff leaching.				
Croplands—rice management	**C**: Straw retention.				30
	CH_4: Water management, mid-season paddy drainage.				31, 32, 98
	N_2O: Water management, N fertilizer application rate, fertilizer type, timing, precision application.				32, 98, 99
Rewet peatlands drained for agriculture	**C**: Ongoing CO_2 emissions from reduced drainage (but CH_4 emissions may increase).				33
Croplands—set-aside and LUC	**C**: Replanting to native grasses and trees. Increase C sequestration.				34, 35, 36, 37, 38
	N_2O: N inputs decreased resulting in reduced N_2O.				
Biochar application	**C**: Soil amendment to increase biomass productivity, and sequester C (biochar was not covered in AR4 so is described in Box 11.3).				39, 40, 41
	N_2O: Reduced N inputs will reduce emissions.				39, 42

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Categories	Practices and Impacts	Technical Mitigation Potential	Ease of Implementation	Timescale for implementation	References
Grazing Land Management					
Grazing lands—plant management	**C:** Improved grass varieties/sward composition, e.g., deep rooting grasses, increased productivity, and nutrient management. Appropriate stocking densities, carrying capacity, fodder banks, and improved grazing management.				43, 44, 45
	N_2O				46
Grazing lands—animal management	**C:** Appropriate stocking densities, carrying capacity management, fodder banks and improved grazing management, fodder production, and fodder diversification.				43, 47
	CH_4				
	N_2O: Stocking density, animal waste management.				
Grazing land—fire management	**C:** Improved use of fire for sustainable grassland management. Fire prevention and improved prescribed burning.				
Revegetation					
Revegetation	**C:** The establishment of vegetation that does not meet the definitions of afforestation and reforestation (e.g., *Atriplex* spp.).				48
	CH_4: Increased grazing by ruminants may increase net emissions.				
	N_2O: Reduced N inputs will reduce emissions.				
Other					
Organic soils—restoration	**C:** Soil carbon restoration on peatlands; and avoided net soil carbon emissions using improved land management.				49
	CH_4: May increase.				
Degraded soils—restoration	Land reclamation (afforestation, soil fertility management, water conservation soil nutrients enhancement, improved fallow).				100, 101, 102, 103, 104
Biosolid applications	**C:** Use of animal manures and other biosolids for improved management of nitrogen; integrated livestock agriculture techniques.				26
	N_2O				
	Livestock				
Livestock—feeding	**CH_4**: Improved feed and dietary additives to reduce emissions from enteric fermentation; including improved forage, dietary additives (bioactive compounds, fats), ionophores/antibiotics, propionate enhancers, archaea inhibitors, nitrate and sulphate supplements.				50, 51, 52, 53, 54, 55, 56, 57, 58, 59
Livestock—breeding and other long-term management	**CH_4**: Improved breeds with higher productivity (so lower emissions per unit of product) or with reduced emissions from enteric fermentation; microbial technology such as archaeal vaccines, methanotrophs, acetogens, defaunation of the rumen, bacteriophages and probiotics; improved fertility.				54, 55, 56, 58, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71
Manure management	**CH_4**: Manipulate bedding and storage conditions, anaerobic digesters; biofilters, dietary additives.				56, 58, 72, 73
	N_2O: Manipulate livestock diets to reduce N excreta, soil applied and animal fed nitrification inhibitors, urease inhibitors, fertilizer type, rate and timing, manipulate manure application practices, grazing management.				56, 58, 72, 74, 75, 76, 77, 78
	Integrated systems				
Agroforestry (including agropastoral and agrosilvopastoral systems)	**C:** Mixed production systems can increase land productivity and efficiency in the use of water and other resources and protect against soil erosion as well as serve carbon sequestration objectives.				79, 80, 81, 82, 83, 84, 85, 86, 87, 88
	N_2O: Reduced N inputs will reduce emissions.				
Other mixed biomass production systems	**C:** Mixed production systems such as double-cropping systems and mixed crop-livestock systems can increase land productivity and efficiency in the use of water and other resources as well as serve carbon sequestration objectives. Perennial grasses (e.g., bamboo) can in the same way as woody plants be cultivated in shelter belts and riparian zones/buffer strips provide environmental services and supports C sequestration and biomass production.				82, 89, 90
	N_2O: Reduced N inputs will reduce emissions.				

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Categories	Practices and Impacts	Technical Mitigation Potential	Ease of Implementation	Timescale for implementation	References
Integration of biomass production with subsequent processing in food and bioenergy sectors	**C:** Integrating feedstock production with conversion, typically producing animal feed that can reduce demand for cultivated feed such as soy and corn and can also reduce grazing requirements. Using agricultural and forestry residues for energy production.				91, 92, 93, 94, 95
	N_2O: Reduced N inputs will reduce emissions.				
Bioenergy (see Box 11.5 and Section 11.13)					

[1]Van Bodegom et al., 2009; [2]Malmsheimer et al., 2008; [3]Reyer et al., 2009; [4]Sochacki et al., 2012; [5]IPCC, 2000; [6]DeFries and Rosenzweig, 2010; [7]Takimoto et al., 2008; [8]Masera et al., 2003; [9]Silver et al., 2000; [10]Dezzeo et al., 2005; [11]Ito, 2005; [12]Sow et al., 2013; [13]Reyer et al., 2009; [14]Palm et al., 2004; [15]Godfray et al., 2010; [16]Burney et al., 2010; [17]Conant et al., 2007; [18]Huang and Tang, 2010; [19]Lemke et al., 2010; [20]Eagle and Olander, 2012; [21]Snyder et al., 2007; [22]Akiyama et al., 2010; [23]Barton et al., 2011; [24]Powlson et al., 2011; [25]van Kessel et al., 2013; [26]Farage et al., 2007; [27]Smith, 2012; [28]Abdalla et al., 2013; [29]Bayala et al., 2008; [30]Yagi et al., 1997; [31]Tyagi et al., 2010; [32]Feng et al., 2013; [33]Lohila et al., 2004; [34]Seaquist et al., 2008; [35]Mbow, 2010; [36]Assogbadjo et al., 2012; [37]Laganiere et al., 2010; [38]Bayala et al., 2011; [39]Singh et al., 2010; [40]Woolf et al., 2010; [41]Lehmann et al., 2003; [42]Taghizadeh-Toosi et al., 2011; [43]Franzluebbers and Stuedemann, 2009; [44]Follett and Reed, 2010; [45]McSherry and Ritchie, 2013; [46]Saggar et al., 2004; [47]Thornton and Herrero, 2010; [48]Harper et al., 2007; [49]Smith and Wollenberg, 2012; [50]Beauchemin et al., 2008; [51]Beauchemin et al., 2009; [52]Martin et al., 2010; [53]Grainger and Beauchemin, 2011; [54]Clark, 2013; [55]Cottle et al., 2011; [56]Eckard et al., 2010; [57]Sauvant and Giger-Reverdin, 2007; [58]Hristov et al., 2013; [59]Bryan et al., 2013; [60]Attwood and McSweeney, 2008; [61]Attwood et al., 2011; [62]Hegarty et al., 2007; [63]Hook et al., 2010; [64]Janssen and Kirs, 2008; [65]Martin et al., 2010; [66]Morgavi et al., 2008; [67]Morgavi et al., 2010; [68]Place and Mitloehner, 2010; [69]Waghorn and Hegarty, 2011; [70]Wright and Klieve, 2011; [71]Yan et al., 2010 [72]Chadwick et al., 2011; [73]Petersen and Sommer, 2011; [74]de Klein et al., 2010; [75]de Klein and Eckard, 2008; [76]Dijkstra et al., 2011 [77]Schils et al., 2013; [78]VanderZaag et al., 2011; [79]Oke and Odebiyi, 2007; [80]Rice, 2008; [81]Takimoto et al., 2008; [82]Lott et al., 2009; [83]Sood and Mitchell, 2011; [84]Assogbadjo et al., 2012; [85]Wollenberg et al., 2012; [86]Semroc et al., 2012; [87]Souza et al. 2012; [88]Luedeling and Neufeldt, 2012; [89]Heggenstaller et al., 2008; [90]Herrero et al., 2010; [91]Dale et al., 2009; [92]Dale et al., 2010; [93]Sparovek et al. 2007; [94]Sood and Mitchell, 2011; [95]Vermeulen et al., 2012; [96]Metay et al., 2007 ; [97]Rochette, 2008; [98]Ma et al., 2009; [99]Yao et al., 2010; [100]Arnalds, 2004; [101]Batjes, 2004; [102]Hardner et al., 2000; [103]May et al., 2004; [104]Zhao et al., 2005; [105]Huang and Tang, 2010; [106]Kim et al., 2013.

11.3.2 Mitigation effectiveness (non-permanence: saturation, human and natural impacts, displacement)

Since carbon sequestration in soil and vegetation and the retention of existing carbon stocks forms a significant component of the mitigation potential in the AFOLU sector, this section considers the factors affecting this strategy compared to avoided GHG emissions.

Non-permanence/reversibility. Reversals are the release of previously sequestered carbon, which negates some or all of the benefits from sequestration that has occurred in previous years. This issue is sometimes referred to as 'non-permanence' (Smith, 2005). Various types of carbon sinks (e.g., afforestation/reforestation, agricultural soil C) have an inherent risk of future reversals.

Certain types of mitigation activities (e.g., avoided N_2O from fertilizer, emission reductions from changed diet patterns or reduced food-chain losses) are effectively permanent since the emissions, once avoided, cannot be re-emitted. The same applies to the use of bioenergy to displace fossil-fuel emissions (Section 11.13) or the use of biomass-based products to displace more emissions-intensive products (e.g., wood in place of concrete or steel) in construction.

Reversals may be caused by natural events that affect yields/growth. In some cases (e.g., frost damage, pest infestation, or fire; (Reichstein et al., 2013), these effects may be temporary or short-term. Although these events will affect the annual increment of C sequestration, they may not result in a permanent decline in carbon stocks. In other cases, such as stand replacing forest fires, insect or disease outbreaks, or drought, the declines may be more profound. Although a substantial loss of above-ground stored carbon could occur following a wildfire, whether this represents a loss depends on what happens following the fire and whether the forest recovers, or changes to a lower carbon-storage state (see Box 11.2). Similarly, some systems are naturally adapted to fire and carbon stocks will recover following fire, whereas in other cases the fire results in a change to a system with a lower carbon stock (e.g., Brown and Johnstone, 2011). For a period of time following fire (or other disruptive event), the stock of carbon will be less than that before the fire. Similarly, emissions of non-CO_2 gases also need to be considered.

The permanence of the AFOLU carbon stock relates to the longevity of the stock, i.e., how long the increased carbon stock remains in the soil or vegetation. This is linked to consideration of the reversibility of the increased carbon stock (Smith, 2005), as discussed in Section 11.5.2.

Saturation. Substitution of fossil fuel and material with biomass, and energy-intensive building materials with wood can continue in perpetuity. In contrast, it is often considered that carbon sequestration in soils (Guldea et al., 2008) or vegetation cannot continue indefinitely. The carbon stored in soils and vegetation reaches a new equilibrium (as the trees mature or as the soil carbon stock saturates). As the

Box 11.3 | Biochar

This box summarizes the mitigation potential for biochar technologies, which were not considered in AR4. Biomass C stabilization could be combined with (or substitute) bioenergy capture as part of a land-based mitigation strategy (Lehmann, 2007). Heating biomass with air excluded (pyrolysis) generates energy-containing volatiles and gases. Hydrogen and O are preferentially eliminated, creating a stable (biologically recalcitrant) C-rich co-product (char). By adding char to soil as 'biochar' a system can be established that may have a higher carbon abatement than typical bioenergy alternatives (Woolf et al., 2010). The gain is probably highest where efficient bioenergy is constrained by a remote, seasonal, or diffuse biomass resource (Shackley et al., 2012). The benefit of pyrolysis-biochar systems (PBS) is increased considerably if allowance is made for the indirect effects of using biochar *via* the soil. These effects include increased crop and biomass production and decreased N_2O and CH_4 emissions. Realizing the mitigation potential for biochar technologies will be constrained by the need for sustainable feedstock acquisition, competing biomass use options are an important influence of the production process on biochar properties. Considering sustainable feedstock production and targeting biochar deployment on less fertile land, Woolf et al. (2010) calculated maximum global abatement of 6.6 $GtCO_2eq$/yr from 2.27 Gt biomass C. Allowing for competition for virgin non-waste biomass the value was lower (3.67 $GtCO_2eq$/yr from 1.01 Gt biomass C), accruing 240–480 $GtCO_2eq$ abatement within 100 years.

Meta-analysis shows that in experimental situations crop productivity has, on average, been enhanced by circa 15 % near-term, but with a wide range of effects (Jeffery et al., 2011; Biederman and Harpole, 2013). This range is probably explained by the nature and extent of pre-existing soil constraints. The Woolf et al. (2010) analysis accordingly assumed crop yield increases of 0–90 % (relative). Relaxing this assumption by one-half decreased projected abatement by 10 %. Decreasing an assumed 25 % suppression on soil N_2O flux by the same proportion had a smaller impact. Beneficial interactions of biochar and the soil N cycle are beginning to be understood with effects on mineralization, nitrification, denitrification, immobilization and adsorption persisting at least for days and months after biochar addition (Nelissen et al., 2012; Clough et al., 2013). Although the often large suppression of soil N_2O flux observed under laboratory conditions can be increasingly explained (Cayuela et al., 2013), this effect is not yet predictable and there has been only limited validation of N_2O suppression by biochar in planted field soils (Liu et al., 2012; Van Zwieten et al., 2013) or over longer timeframes (Spokas, 2013). The potential to gain enhanced mitigation using biochar by tackling gaseous emissions from manures and fertilizers before and after application to soil are less well-explored (Steiner et al., 2010; Angst et al., 2013). The abatement potential for PBS remains most sensitive to the absolute stability of the C stored in biochar. Estimates of 'half-life' have been inferred from wildfire charcoal (Lehmann, 2007) or extrapolated from direct short-term observation. These give values that range from < 50 to > 10,000 years, but predominantly between 100–1000 years (Singh et al., 2012; Spokas, 2013). Nonetheless, the assumption made by Woolf et al. (2010) for the proportion of biochar C that is stable long-term (85 %) is subject to refinement and field validation.

Demonstration of the equipment and infrastructure required for effective use of energy products from biomass pyrolysis is still limited, especially across large and small unit scales. Preliminary analyses shows, however, that the break-even cost of biochar production is likely to be location- and feedstock-specific (Shackley et al., 2012; Field et al., 2013). Until economic incentives are established for the stabilization of C, biochar adoption will depend on predictable, positive effects on crop production. This requires more research on the use of biochar as a regular low-dose soil input, rather than single applications at rates > 10t/ha, which have so far been the norm (Sohi, 2012). Product standards are also required, to ensure that biochar is produced in a way that does not create or conserve problematic concentrations of toxic contaminants, and to support regulated deployment strategies (IBI Biochar, 2012; Downie et al., 2012).

soils/vegetation approach the new equilibrium, the annual removal (sometimes referred to as the sink strength) decreases until it becomes zero at equilibrium. This process is called saturation (Smith, 2005; Körner, 2006, 2009; Johnston et al., 2009b) , and the uncertainty associated with saturation has been estimated (Kim and McCarl, 2009). An alternative view is that saturation does not occur, with studies from old-growth forests, for example, showing that they can continue to sequester C in soil and dead organic matter even if net living biomass increment is near zero (e.g., Luyssaert et al., 2008). Peatlands are unlikely to saturate in carbon storage, but the rate of C uptake may be very slow (see Box 11.1).

Human and natural impacts. Soil and vegetation carbon sinks can be impacted upon by direct human-induced, indirect human-induced, and natural changes (Smith, 2005). All of the mitigation practices discussed in Section 11.3.1 arise from direct human-induced impacts (deliberate

Box 11.4 | Aquaculture

Aquaculture is defined as the farming of fish, shellfish, and aquatic plants (Hu et al., 2013). Although it is an ancient practice in some parts of world, this sector of the food system is growing rapidly. Since the mid-1970s, total aquaculture production has grown at an average rate of 8.3 % per year (1970–2008; (Hu et al., 2013). The estimated aquaculture production in 2009 was 55.10 Mt, which accounts for approximately 47 % of all the fish consumed by humans (Hu et al., 2013). The sector is diverse, being dominated by shellfish and herbivorous and omnivorous pond fish, either entirely or partly utilizing natural productivity, but globalizing trade and favourable economic conditions are driving intensive farming at larger scales (Bostock et al., 2010). Potential impacts of aquaculture, in terms emissions of N_2O, have recently been considered (Williams and Crutzen, 2010; Hu et al., 2012). Global N_2O emissions from aquaculture in 2009 were estimated to be 93 ktN_2O-N (~43 MtCO_2eq), and will increase to 383 ktN_2O-N (~178 MtCO_2eq) by 2030, which could account for 5.7 % of anthropogenic N_2O-N emissions if aquaculture continues to grow at the present growth rate (~7.1 %/yr; Hu et al., 2012).

Some studies have focused on rice-fish farming, which is a practice associated with wet rice cultivation in Southeast Asia, providing protein, especially for subsistence-oriented farmers (Bhattacharyya et al., 2013). Cultivation of fish along with rice increases emissions of CH_4 (Frei et al., 2007; Bhattacharyya et al., 2013), but decreases N_2O emissions, irrespective of the fish species used (Datta et al., 2009; Bhattacharyya et al., 2013). Although rice-fish farming systems might be globally important in terms of climate change, they are also relevant for local economy, food security, and efficient water use (shared water), which makes it difficult to design appropriate mitigation measures, because of the tradeoffs between mitigation measures and rice and fish production (Datta et al., 2009; Bhattacharyya et al., 2013). Feeding rate and dissolved oxygen (DO) concentration could affect N_2O emissions from aquaculture systems significantly, and nitrification and denitrification processes were equally responsible for the emissions of N_2O in these systems. Measures to control N_2O from aquaculture are described by Hu et al. (2012), and include the maintenance of optimal operating conditions of the system, such as appropriate pH and temperature, sufficient DO and good quality feed. Additionally, two potential ways to minimize N_2O emissions from aquaculture systems include 'Aquaponic Aquaculture' (polyculture consisting of fish tanks (aquaculture) and plants that are cultivated in the same water cycle (hydroponic)), and Bioflocs Technology (BFT) Aquaculture (which involves the development and control of heterotrophic bacteria in flocs within the fish culture component), where the growth of heterotrophic bacteria is stimulated, leading to nitrogen uptake (Hu et al., 2012).

management). Both sink processes and carbon stocks can be affected by natural factors such as soil and hydrological conditions. Indirect human-induced changes can impact carbon sinks and are influenced by human activity, but are not directly related to the management of that piece of land; examples include climate change and atmospheric nitrogen deposition. For some tree species, rising concentrations of tropospheric ozone caused by human activities may counteract the effects of increased atmospheric CO_2 or N deposition on tree growth (Sitch et al., 2008; Matyssek et al., 2010). Natural changes that threaten to impact the efficacy of mitigation measures are discussed in Section 11.5.

Displacement/leakage. Displacement/leakage arises from a change in land use or land management that causes a positive or negative change in emissions elsewhere. This can occur within or across national boundaries, and the efficacy of mitigation practices must consider the leakage implications. For example, if reducing emissions in one place leads to increased emissions elsewhere, no net reduction occurs; the emissions are simply displaced (Powlson et al., 2011; Kastner et al., 2011b; a). However, this assumes a one-to-one correspondence. Murray et al. (2004) estimated the leakage from different forest carbon programmes and this varied from $< 10\,\%$ to $> 90\,\%$ depending on the nature of the activity. West et al. (2010a) examined the impact of displaced activities in different geographic contexts; for example, land clearing in the tropics will release twice the carbon, but only produce half the crop yield of temperate areas. Indirect land-use change is an important component to consider for displaced emissions and assessments of this are an emerging area. Indirect land-use change is discussed further in Section 11.4 and in relation to bioenergy in Section 11.13.

The timing of mitigation benefits from actions (e.g., bioenergy, forest management, forest products use/storage) can vary as a result both of the nature of the activity itself (e.g., from the temporal pattern of soil or forest sequestration compared to biomass substitution), and rates of adoption. Timing thus needs to be considered when judging the effectiveness of a mitigation action. Cherubini et al. (2012) modelled the impact of timing of benefits for three different wood applications (fuel, non-structural panels, and housing construction materials) and showed that the options provide mitigation over different timeframes, and thus have different impacts on CO_2 concentrations and radiative forcing. The temporal pattern of emissions and removals is especially important in mitigating emissions of short-lived gases through carbon sequestration (Lauder et al., 2013).

Box 11.5 | Bioenergy

Bioenergy deployment offers significant potential for climate change mitigation, but also carries considerable risks. The SRREN (IPCC, 2011) suggested potential bioenergy deployment levels to be between 100–300 EJ. This assessment agrees on a technical bioenergy potential of around 100 EJ, and possibly 300 EJ and higher. Integrated models project between 15–245 EJ/yr deployment in 2050, excluding traditional bioenergy. Achieving high deployment levels would require, amongst others, extensive use of agricultural residues and second-generation biofuels to mitigate adverse impacts on land use and food production, and the co-processing of biomass with coal or natural gas with carbon dioxide capture and storage (CCS) to produce low net GHG-emitting transportation fuels and/or electricity. Integration of crucial sectoral research (albedo effects, evaporation, counterfactual land carbon sink assumptions) into transformation pathways research, and exploration of risks of imperfect policy settings (for example, in absence of a global CO_2 price on land carbon) is subject of further research (Sections 11.9, 11.13.2, 11.13.4). Small-scale bioenergy systems aimed at meeting rural energy needs synergistically provide mitigation and energy access benefits. Decentralized deployment of biomass for energy, in combination with improved cookstoves, biogas, and small-scale biopower, could improve livelihoods and health of around 2.6 billion people. Both mitigation potential and sustainability hinges crucially on the protection of land carbon (high-density carbon ecosystems), careful fertilizer application, interaction with food markets, and good land and water management. Sustainability and livelihood concerns might constrain beneficial deployment of dedicated biomass plantations to lower values (Sections 11.13.3, 11.13.5, 11.13.7).

Lifecycle assessments for bioenergy options demonstrate a plethora of pathways, site-specific conditions and technologies that produce a wide range of climate-relevant effects. Specifically, LUC emissions, N_2O emissions from soil and fertilizers, co-products, process design and process fuel use, end-use technology, and reference system can all influence the total attributional lifecycle emissions of bioenergy use. The large variance for specific pathways points to the importance of management decisions in reducing the lifecycle emissions of bioenergy use. The total marginal global warming impact of bioenergy can only be evaluated in a comprehensive setting that also addresses equilibrium effects, e.g., indirect land-use change (iLUC) emissions, actual fossil fuel substitution, and other effects. Structural uncertainty in modelling decisions renders such evaluation exercises uncertain. Available data suggest a differentiation between options that offer low lifecycle emissions under good land-use management (e.g., sugarcane, Miscanthus, and fast-growing tree species) and those that are unlikely to contribute to climate change mitigation (e.g., corn and soybean), pending new insights from more comprehensive consequential analyses (Sections 8.7, 11.13.4).

Coupling bioenergy and CCS (BECCS) has attracted particular attention since AR4 because it offers the prospect of negative emissions. Until 2050, the economic potential is estimated to be between 2–10 $GtCO_2$ per year. Some climate stabilization scenarios see considerable higher deployment towards the end of the century, even in some 580–650 ppm scenarios, operating under different time scales, socioeconomic assumptions, technology portfolios, CO_2 prices, and interpreting BECCS as part of an overall mitigation framework. Technological challenges and potential risks of BECCS include those associated with the provision of the biomass feedstock as well as with the capture, transport and long-term underground storage of CO_2. BECCS faces large challenges in financing and currently no such plants have been built and tested at scale (Sections 7.5.5, 7.9, 11.13.3).

Land demand and livelihoods are often affected by bioenergy deployment. Land demand for bioenergy depends on (1) the share of bioenergy derived from wastes and residues; (2) the extent to which bioenergy production can be integrated with food and fibre production, and conservation to minimize land-use competition; (3) the extent to which bioenergy can be grown on areas with little current production; and (4) the quantity of dedicated energy crops and their yields. Considerations of tradeoffs with water, land, and biodiversity are crucial to avoid adverse effects. The total impact on livelihood and distributional consequences depends on global market factors, impacting income and income-related food-security, and site-specific factors such as land tenure and social dimensions. The often site-specific effects of bioenergy deployment on livelihoods have not yet been comprehensively evaluated (Section 11.13.7).

Additionality: Another consideration for gauging the effectiveness of mitigation is determining whether the activity would have occurred anyway, with this encompassed in the concept of 'additionality' (see Glossary).

Impacts of climate change: An area of emerging activity is predicting the likely impacts of climate change on mitigation potential, both in terms of impacts on existing carbon stocks, but also on the rates of carbon sequestration. This is discussed further in Section 11.5.

11.4 Infrastructure and systemic perspectives

Only supply-side mitigation options are considered in Section 11.3. In this section, we consider infrastructure and systemic perspectives, which include potential demand-side mitigation options in the AFOLU sector. Since infrastructure is a minor issue in AFOLU compared to energy end-use sectors, this section focusses on systemic perspectives.

11.4.1 Land: a complex, integrated system

Mitigation in the AFOLU sector is embedded in the complex interactions between socioeconomic and natural factors simultaneously affecting land systems (Turner et al., 2007). Land is used for a variety of purposes, including housing and infrastructure (Chapter 12), production of goods and services through agriculture, aquaculture and forestry, and absorption or deposition of wastes and emissions (Dunlap and Catton, Jr., 2002). Agriculture and forestry are important for rural livelihoods and employment (Coelho et al., 2012), while aquaculture and fisheries can be regionally important (FAO, 2012). More than half of the planet's total land area

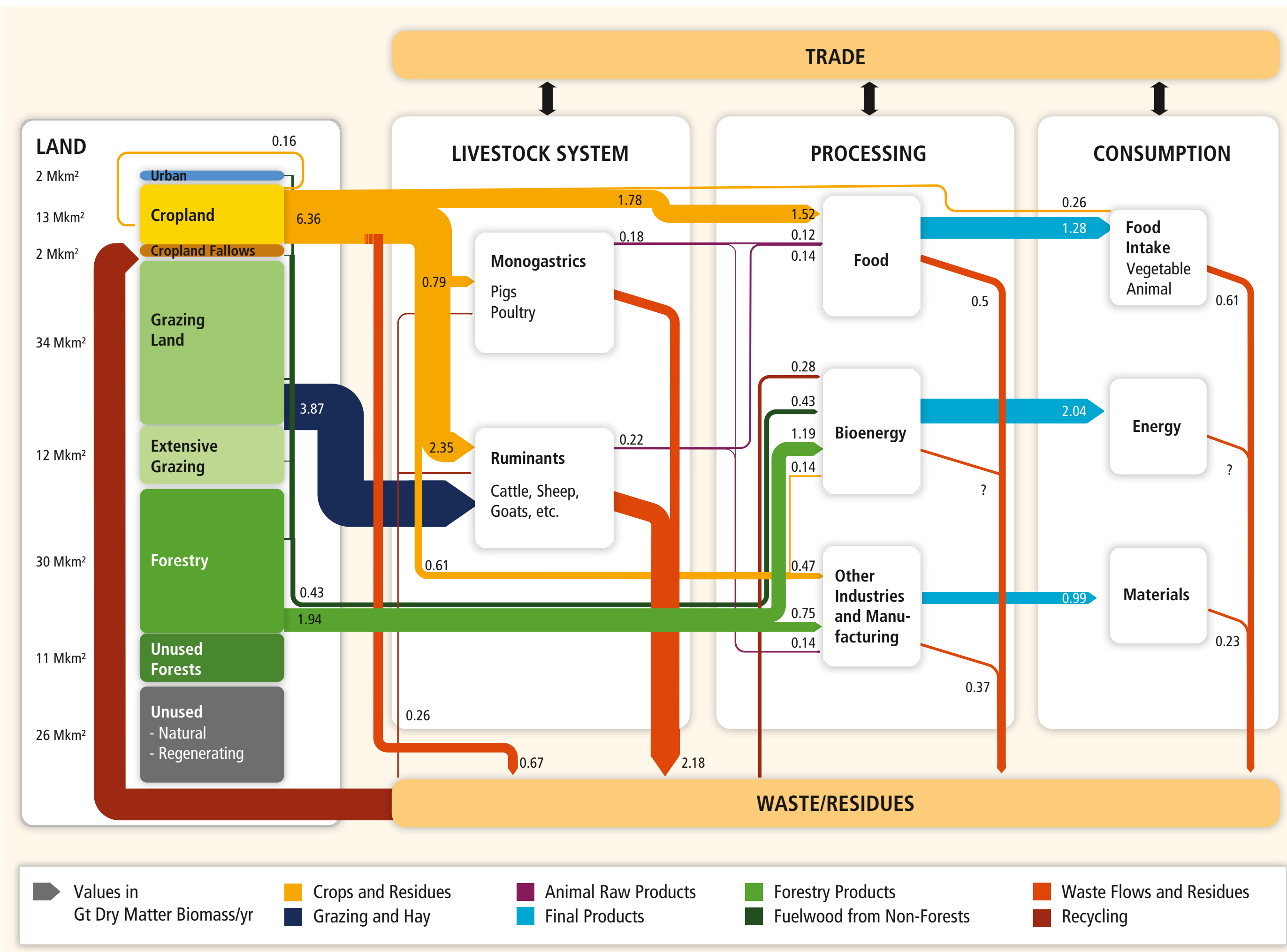


Figure 11.9 | Global land use and biomass flows arising from human economic activity in 2000 from the cradle to the grave. Values in Gt dry matter biomass/yr. Figure source: (Smith et al., 2013b). If a source reported biomass flows in energy units, the numbers were converted to dry matter assuming a gross energy value of 18.5 MJ/kg. The difference between inputs and outputs in the consumption compartment is assumed to be released to the atmosphere (respiration, combustion); small differences may result from rounding. Note that data sources a) area: (Erb et al., 2007; Schneider et al., 2009; FAO, 2010) ; b) biomass flows: (Wirsenius, 2003; Sims et al., 2006; Krausmann et al., 2008; FAOSTAT, 2012; Kummu et al., 2012) are incomplete; more research is needed to close data gaps between different statistical sources such as agricultural, forestry, and energy statistics (Section 11.11). 'Unused forests' are pristine forests not harvested or otherwise used.

(134 Mkm^2) is used for urban and infrastructure land, agriculture, and forestry. Less than one quarter shows relatively minor signs of direct human use (Erb et al., 2007; Ellis et al., 2010; Figure 11.9). Some of the latter areas are inhabited by indigenous populations, which depend on the land for the supply of vitally important resources (Read et al., 2010).

Land-use change is a pervasive driver of global environmental change (Foley et al., 2005, 2011) . From 1950 to 2005, farmland (cropland plus pasture) increased from 28 to 38 % of the global land area excluding ice sheets and inland waters (Hurtt et al., 2011). The growth of farmland area (+33 %) was lower than that of population, food production, and gross domestic product (GDP) due to increases in yields and biomass conversion efficiency (Krausmann et al., 2012). In the year 2000, almost one quarter of the global terrestrial net primary production (one third of the above-ground part) was 'appropriated' by humans. This means that it was either lost because the net primary productivity (the biomass production of green plants, net primary production, NPP) of agro-ecosystems or urban areas was lower than that of the vegetation they replaced or it was harvested for human purposes, destroyed during harvest or burned in human-induced fires (Imhoff et al., 2004; Haberl et al., 2007). The fraction of terrestrial NPP appropriated by humans doubled in the last century (Krausmann et al., 2013), exemplifying the increasing human domination of terrestrial ecosystems (Ellis et al., 2010). Growth trajectories of the use of food, energy, and other land-based resources, as well as patterns of urbanization and infrastructure development are influenced by increasing population and GDP, as well as the on-going agrarian-industrial transition (Haberl et al., 2011b; Kastner et al., 2012).

Growing resource use and land demand for biodiversity conservation and carbon sequestration (Soares-Filho et al., 2010), result in increasing competition for land (Harvey and Pilgrim, 2011; Section 11.4.2). Influencing ongoing transitions in resource use is a major challenge (WBGU, 2011; Fischer-Kowalski, 2011). Changes in cities, e. g., in terms of infrastructure, governance, and demand, can play a major role in this respect (Seto et al., 2012b; Seitzinger et al., 2012; Chapter 12).

Many mitigation activities in the AFOLU sector affect land use or land cover and, therefore, have socioeconomic as well as ecological consequences, e. g., on food security, livelihoods, ecosystem services or emissions (Sections 11.1; 11.4.5; 11.7). Feedbacks involved in implementing mitigation in AFOLU may influence different, sometimes conflicting, social, institutional, economic, and environmental goals (Madlener et al., 2006). Climate change mitigation in the AFOLU sector faces a complex set of interrelated challenges (Sections 11.4.5; 11.7):

- Full GHG impacts, including those from feedbacks (e. g., iLUC) or leakage, are often difficult to determine (Searchinger et al., 2008).
- Feedbacks between GHG reduction and other important objectives such as provision of livelihoods and sufficient food or the maintenance of ecosystem services and biodiversity are not completely understood.
- Maximizing synergies and minimizing negative effects involves multi-dimensional optimization problems involving various social, economic, and ecological criteria or conflicts of interest between different social groups (Martinez-Alier, 2002).
- Changes in land use and ecosystems are scale-dependent and may proceed at different speeds, or perhaps even move in different directions, at different scales.

11.4.2 Mitigation in AFOLU—feedbacks with land-use competition

Driven by economic and population growth, increased demand for food and bioenergy as well as land demand for conservation and urbanization (e. g., above-ground biomass carbon losses associated with land-clearing from new urban areas in the pan-tropics are estimated to be 5 % of the tropical deforestation and land-use change emissions, (Seto et al., 2012a; Section 12.2), competition for land is expected to intensify (Smith et al., 2010; Woods et al., 2010). Maximization of one output or service (e. g., crops) often excludes, or at least negatively affects, others (e. g., conservation; (Phalan et al., 2011). Mitigation in the AFOLU sector may affect land-use competition. Reduced demand for AFOLU products generally decreases inputs (fertilizer, energy, machinery) and land demand. The ecological feedbacks of demand-side options are mostly beneficial since they reduce competition for land and water (Smith et al., 2013b).

Some supply-side options, though not all, may intensify competition for land and other resources. Based on Figure 11.9 one may distinguish three cases:

- **Optimization of biomass-flow cascades;** that is, increased use of residues and by-products, recycling of biogenic materials and energetic use of wastes (WBGU, 2009). Such options increase resource use efficiency and may reduce competition, but there may also be tradeoffs. For example, using crop residues for bioenergy or roughage supply may leave less C and nutrients on cropland, reduce soil quality and C storage in soils, and increase the risk of losses of carbon through soil erosion. Residues are also often used as forage, particularly in the tropics. Forest residues are currently also used for other purposes, e. g., chipboard manufacture, pulp and paper production (González-Estrada et al., 2008; Blanco-Canqui and Lal, 2009; Muller, 2009; Ceschia et al., 2010).

- **Increases in yields** of cropland (Burney et al., 2010; Foley et al., 2011; Tilman et al., 2011; Mueller et al., 2012; Lobell et al., 2013), grazing land or forestry and improved livestock feeding efficiency (Steinfeld et al., 2010; Thornton and Herrero, 2010) can reduce land competition if yield increases relative to any additional inputs and the emission intensity (i. e., GHG emissions per unit of product) decreases. This may result in tradeoffs with other ecological, social, and economic costs (IAASTD, 2009) although these can to some extent be mitigated if intensification is sustainable (Tilman et al., 2011). Another caveat is that increases in yields may result in rebound effects that increase consumption (Lambin and Meyfroidt, 2011; Erb, 2012) or provide incentives to farm more land (Matson and Vitousek, 2006), and hence may fail to spare land (Section 11.10).

- **Land-demanding options** reduce GHG emissions by harnessing the potential of the land for either C sequestration or growing energy crops (including food crops used as feedstocks for bioenergy production). These options result in competition for land (and sometimes other resources such as water) that may have substantial social, economic, and ecological effects (positive or negative; (UNEP, 2009; WBGU, 2009; Chum et al., 2011; Coelho et al., 2012). Such options may increase pressures on ecosystems (e.g., forests) and GHG emissions related to direct and indirect LUC, contribute to price increases of agricultural products, or negatively affect livelihoods of rural populations. These possible impacts need to be balanced against possible positive effects such as GHG reduction, improved water quality (Townsend et al., 2012), restoration of degraded land (Harper et al., 2007), biodiversity protection (Swingland et al., 2002), and job creation (Chum et al., 2011; Coelho et al., 2012).

Therefore, an integrated energy/agriculture/land-use approach for mitigation in AFOLU can help to optimize synergies and mitigate negative effects (Popp et al., 2011; Smith, 2012; Creutzig et al., 2012a; Smith et al., 2013b).

11.4.3 Demand-side options for reducing GHG emissions from AFOLU

Some changes in demand for food and fibre can reduce GHG emissions in the production chain (Table 11.3) through (i) a switch to the consumption of products with higher GHG emissions in the process chain to products with lower GHG emissions and (ii) by making land available for other GHG reduction activities e.g., afforestation or bioenergy (Section 11.4.4). Food demand change is a sensitive issue due to the prevalence of hunger, malnutrition, and the lack of food security in many regions (Godfray et al., 2010). Sufficient production of, and equitable access to, food are both critical for food security (Misselhorn et al., 2012). GHG emissions may be reduced through changes in food demand without jeopardizing health and well-being by (1) reducing losses and wastes of food in the supply chain as well as during final consumption; (2) changing diets towards less GHG-intensive food, e.g., substitution of animal products with plant-based food, while quantitatively and qualitatively maintaining adequate protein content, in regions with high animal product consumption; and (3) reduction of overconsumption in regions where this is prevalent. Substituting plant-based diets for animal-based diets is complex since, in many circumstances, livestock can be fed on plants not suitable for human consumption or growing on land with high soil carbon stocks not suitable for cropping; hence, food production by grazing animals contributes to food security in many regions of the world (Wirsenius, 2003; Gill et al., 2010).

Reductions of losses in the food supply chain—Globally, rough estimates suggest that ~30–40 % of all food produced is lost in the supply chain from harvest to consumption (Godfray et al., 2010). Energy embodied in wasted food is estimated at ~36 EJ/yr (FAO, 2011). In developing countries, up to 40 % is lost on farm or during distribution due to poor storage, distribution, and conservation technologies and procedures. In developed countries, losses on farm or during distribution are smaller, but the same amount is lost or wasted in service sectors and at the consumer level (Foley et al., 2005; Parfitt et al., 2010; Godfray et al., 2010; Gustavsson et al., 2011; Hodges et al., 2011). However, uncertainties related to losses in the food supply chain are large and more research is needed.

Not all losses are (potentially) avoidable because losses in households also include parts of products normally not deemed edible (e.g., peels of some fruits and vegetables). According to Parfitt et al. (2010), in the UK, 18 % of the food waste is unavoidable, 18 % is potentially avoidable, and 64 % is avoidable. Data for Austria, Netherlands, Turkey, the United Kingdom, and the United States, derived with a variety of methods, show that food wastes at the household level in industrialized countries are 150–300 kg per household per year (Parfitt et al., 2010). According to a top-down mass-flow modelling study based on FAO commodity balances completely covering the food supply chain, but excluding non-edible fractions, food loss values range from 120–170 kg/cap/yr in Sub-Saharan Africa to 280–300 kg/cap/yr in Europe and North America.

Table 11.3 | Overview of demand-side mitigation options in the AFOLU sector.

Measure	Description	References
Reduced losses in the food supply chain	Reduced losses in the food supply chain and in final consumption reduces energy use and GHG emissions from agriculture, transport, storage and distribution, and reduce land demand.	(Godfray et al., 2010; Gustavsson et al., 2011), see text.
Changes in human diets towards less emission-intensive products	Where appropriate, reduced consumption of food items with high GHG emissions per unit of product, to those with low GHG products can reduce GHG emissions. Such demand changes can reduce energy inputs in the supply chain and reduces land demand.	(Stehfest et al., 2009; FAO, 2011), see text
Demand-side options related to wood and forestry	Wood harvest in forests releases GHG and at least temporarily reduces forest C stocks. Conservation of wood (products) through more efficient use or replacement with recycled materials and replacing wood from illegal logging or destructive harvest with wood from certified sustainable forestry (Section 11.10) can save GHG emissions. Substitution of wood for non-renewable resources can reduce GHG emissions, e.g., when wood is substituted for emission-intensive materials such as aluminium, steel, or concrete in buildings. Integrated optimization of C stocks in forests and in long-lived products, as well as the use of by-products and wastes for energy, can deliver the highest GHG benefits.	(Gustavsson et al., 2006; Werner et al., 2010; Ingerson, 2011), see text.

Losses ranging from 20 % in Sub-Saharan Africa to more than 30 % in the industrialized countries were calculated (Gustavsson et al., 2011).

A range of options exist to reduce wastes and losses in the supply chain: investments into harvesting, processing and storage technologies in the developing countries, awareness raising, taxation and other incentives to reduce retail and consumer-related losses primarily in the developed countries. Different options can help to reduce losses (i.e., increase efficiency) in the supply chain and at the household level. Substantial GHG savings could be realized by saving one quarter of the wasted food according to (Gustavsson et al., 2011); see Table 11.4.

Changes in human diets—Land use and GHG effects of changing diets require widespread behavioural changes to be effective; i.e., a strong deviation from current trajectories (increasing demand for food, in particular for animal products). Cultural, socioeconomic and behavioural aspects of implementation are discussed in Sections 11.4.5 and 11.7.

Studies based on Lifecycle Assessment (LCA) methods show substantially lower GHG emissions for most plant-based food than for animal products (Carlsson-Kanyama and González, 2009; Pathak et al., 2010; Bellarby et al., 2012; Berners-Lee et al., 2012), although there are exceptions, e.g., vegetables grown in heated greenhouses or transported by airfreight (Carlsson-Kanyama and González, 2009). A comparison of three meals served in Sweden with similar energy and protein content based on (1) soy, wheat, carrots, and apples, (2) pork, potatoes, green beans, and oranges, and (3) beef, rice, cooked frozen vegetables, and tropical fruits revealed GHG emissions of 0.42 $kgCO_2eq$ for the first option, 1.3 $kgCO_2eq$ for the second, and 4.7 $kgCO_2eq$ for the third, i.e., a factor of > 10 difference (Carlsson-Kanyama and González, 2009). Most LCA studies quoted here use attributional LCA; differences to results from consequential LCA (see Annex II) are generally not large enough to reverse the picture (Thomassen et al., 2008). The GHG benefits of plant-based food over animal products hold when compared per unit of protein (González et al., 2011). In addition to plant-based foods having lower emissions than animal-based ones, GHG emissions of livestock products also vary considerably; emissions per unit of protein are highest for beef and lower for pork, chicken meat, eggs and dairy products (de Vries and de Boer, 2010) due to their feed and land-use intensities. Figure 11.10 presents a comparison between milk and beef for different production systems and regions of the world (Herrero et al., 2013). Beef production can use up to five times more biomass for producing 1 kg of animal protein than dairy. Emissions intensities for the same livestock product also

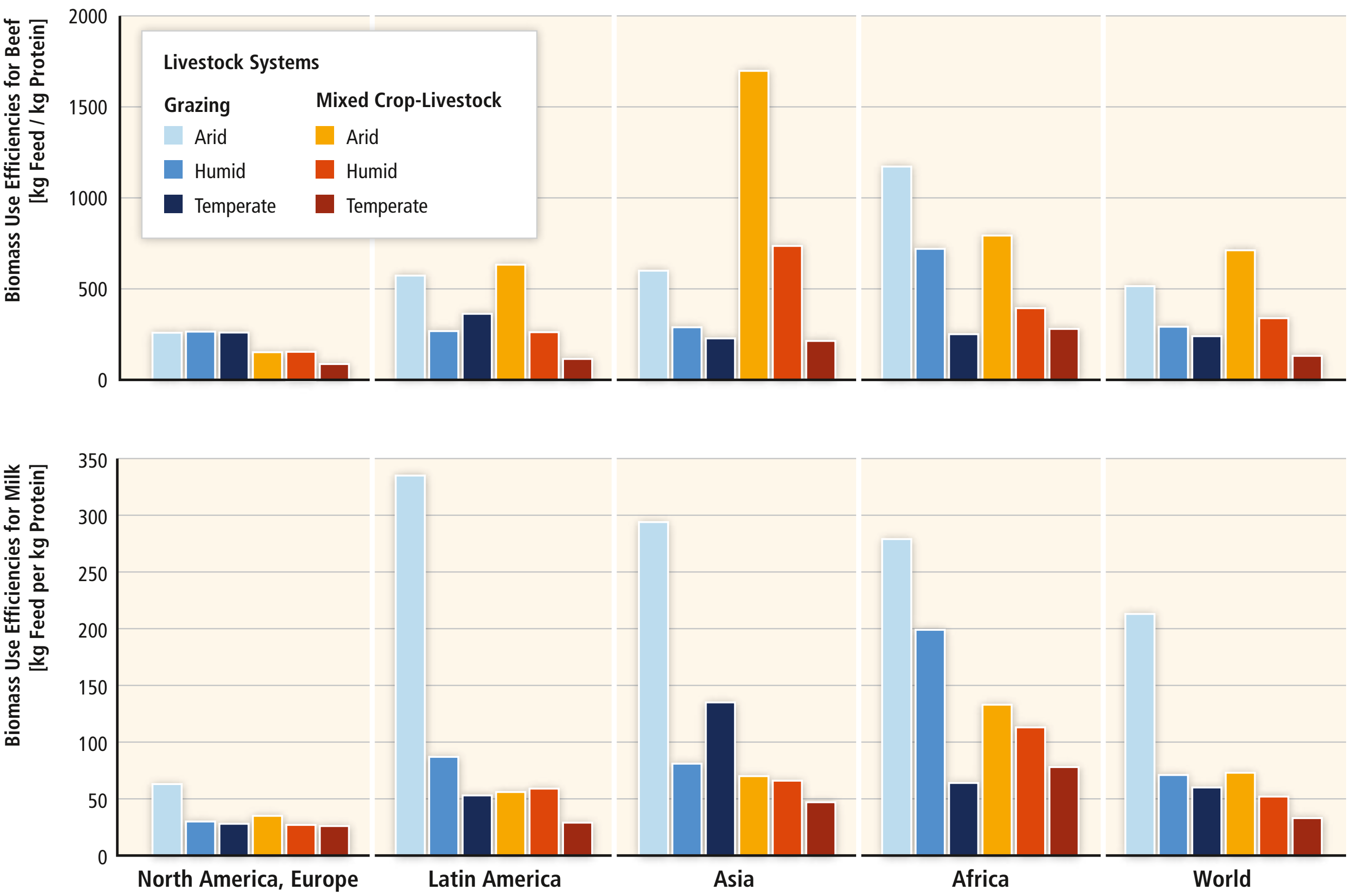


Figure 11.10 | Biomass use efficiencies for the production of edible protein from (top) beef and (bottom) milk for different production systems and regions of the world (Herrero et al., 2013).

Table 11.4 | Changes in global land use and related GHG reduction potentials in 2050 assuming the implementation of options to increase C sequestration on farmland, and use of spared land for either biomass production for energy or afforestation. Afforestation and biomass for bioenergy are both assumed to be implemented only on spare land and are mutually exclusive (Smith et al., 2013b).

Cases	Food crop area	Livestock grazing area	C sink on farmland[1]	Afforestation of spare land[2,3]	Biomass for bioenergy on spare land[2,4]	Total mitigation potential	Difference in mitigation from reference case
	[Gha]		GtCO$_2$eq/yr				
Reference	1.60	4.07	3.5	6.1	1.2–9.4	4.6–12.9	0
Diet change	1.38	3.87	3.2	11.0	2.1–17.0	5.3–20.2	0.7–7.3
Yield growth	1.49	4.06	3.4	7.3	1.4–11.4	4.8–14.8	0.2–1.9
Feeding efficiency	1.53	4.04	3.4	7.2	1.4–11.1	4.8–14.5	0.2–1.6
Waste reduction	1.50	3.82	3.3	10.1	1.9–15.6	5.2–18.9	0.6–6.0
Combined	1.21	3.58	2.9	16.5	3.2–25.6	6.1–28.5	1.5–15.6

Notes:

1 Potential for C sequestration on cropland for food production and livestock grazing land with improved soil C management. The potential C sequestration rate was derived from Smith et al., (2008).

2 Spare land is cropland or grazing land not required for food production, assuming increased but still sustainable stocking densities of livestock based on Haberl et al., (2011); Erb et al., (2012).

3 Assuming 11.8 (tCO$_2$eq/ha)/yr (Smith et al., 2000).

4 Assumptions were as follows. High bioenergy value: short-rotation coppice or energy grass directly replaces fossil fuels, energy return on investment 1:30, dry-matter biomass yield 190 GJ/ha/yr (WBGU, 2009). Low bioenergy value: ethanol from maize replaces gasoline and reduces GHG by 45 %, energy yield 75 GJ/ha/yr (Chum et al., 2011). Some energy crops may, under certain conditions, sequester C in addition to delivering bioenergy; the effect is context-specific and was not included. Whether bioenergy or afforestation is a better option to use spare land for mitigation needs to be decided on a case-by-case basis.

vary largely between different regions of the world due to differences in agro-ecology, diet quality, and intensity of production (Herrero et al., 2013). In overall terms, Europe and North America have lower emissions intensities per kg of protein than Africa, Asia, and Latin America. This shows that the highest potential for improving emissions intensities lies in developing countries, if intensification strategies can be matched to local resources and contexts.

Studies based on integrated modelling show that changes in diets strongly affect future GHG emissions from food production (Stehfest et al., 2009; Popp et al., 2010; Davidson, 2012). Popp et al. (2010) estimated that agricultural non-CO$_2$ emissions (CH$_4$ and N$_2$O) would triple by 2055 to 15.3 GtCO$_2$eq/yr if current dietary trends and population growth were to continue. Technical mitigation options on the supply side, such as improved cropland or livestock management, alone could reduce that value to 9.8 GtCO$_2$eq/yr, whereas emissions were reduced to 4.3 GtCO$_2$eq/yr in a 'decreased livestock product' scenario and to 2.5 GtCO$_2$eq/yr if both technical mitigation and dietary change were assumed. Hence, the potential to reduce GHG emissions through changes in consumption was found to be substantially higher than that of technical mitigation measures. Stehfest et al., (2009) evaluated effects of dietary changes on CO$_2$ (including C sources/sinks of ecosystems), CH$_4$, and N$_2$O emissions. In a 'business-as-usual' scenario largely based on FAO (2006), total GHG emissions were projected to reach 11.9 GtCO$_2$eq/yr in 2050. The following changes were evaluated: no ruminant meat, no meat, and a diet without any animal products. Changed diets resulted in GHG emission savings of 34–64 % compared to the 'business-as-usual' scenario; a switch to a 'healthy diet' recommended by the Harvard Medical School would save 4.3 GtCO$_2$eq/yr (–36 %). Adoption of the 'healthy diet' (which includes a meat, fish and egg consumption of 90 g/cap/day) would reduce global GHG abatement costs to reach a 450 ppm CO$_2$eq concentration target by ~50 % compared to the reference case (Stehfest et al., 2009). The analysis assumed nutritionally sufficient diets; reduced supply of animal protein was compensated by plant products (soy, pulses, etc.). Considerable cultural and social barriers against a widespread adoption of dietary changes to low-GHG food may be expected (Davidson, 2012; Smith et al., 2013, 11.4.5).

A limitation of food-related LCA studies is that they have so far seldom considered the emissions resulting from LUC induced by changing patterns of food production (Bellarby et al., 2012) . A recent study (Schmidinger and Stehfest, 2012) found that cropland and pastures required for the production of beef, lamb, calf, pork, chicken, and milk could annually sequester an amount of carbon equivalent to 30–470 % of the GHG emissions usually considered in LCA of food products if the land were to be reforested. Land-related GHG costs differ greatly between products and depend on the time horizon (30–100 yr) assumed (Schmidinger and Stehfest, 2012). If cattle production contributes to tropical deforestation (Zaks et al., 2009; Bustamante et al., 2012; Houghton et al., 2012), land-use related GHG emissions are particularly high (Cederberg et al., 2011). These findings underline the importance of diets for GHG emissions in the food supply chain (Garnett, 2011; Bellarby et al., 2012). A potential co-benefit is a reduction in diet-related health risks in regions where overconsumption of animal products is prevalent (McMichael et al., 2007).

Demand-side options related to wood and forestry—A comprehensive global, long-term dataset on carbon stocks in long-lived wood products in use (excluding landfills) shows an increase from approximately 2.2 GtC in 1900 to 6.9 GtC in 2008 (Lauk et al., 2012). Per capita, carbon stored in wood products amounted to ~1.4 tC/cap in 1900 and ~1.0 tC/cap in 2008. The net yearly accumulation of long-lived wood products in use varied between 35 and 91 MtC/yr in the period 1960–2008 (Lauk et al., 2012). The yearly accumulation of C in products and landfills was ~200 MtC/yr in the period 1990–2008 (Pan et al., 2011). If more long-lived wood products were used, C sequestration and mitigation could be enhanced.

Increased wood use does not reduce GHG emissions under all circumstances because wood harvest reduces the amount of carbon stored in the forest, at least temporarily, and increases in wood harvest levels may result in reduced long-term carbon storage in forests (Ingerson, 2011; Böttcher et al., 2012; Holtsmark, 2012; Lamers and Junginger, 2013). Reducing wood consumption, e.g., through paper recycling, can reduce GHG emissions (Acuff and Kaffine, 2013), as may the use of wood from sustainable forestry in place of emission-intensive materials such as concrete, steel, or aluminium. Recent studies suggest that, where technically possible, substitution of wood from sustainably managed forests for non-wood materials in the construction sector (concrete, steel, etc.) in single-family homes, apartment houses, and industrial buildings, reduces GHG emissions in most cases (Werner et al., 2010; Sathre and O'Connor, 2010; Ximenes and Grant, 2013). Most of the emission reduction results from reduced production emissions, whereas the role of carbon sequestration in products is relatively small (Sathre and O'Connor, 2010). Werner et al. (2010) show that GHG benefits are highest when wood is primarily used for long-lived products, the lifetime of products is maximized, and energy use of woody biomass is focused on by-products, wood wastes, and end-of-lifecycle use of long-lived wood products.

11.4.4 Feedbacks of changes in land demand

Mitigation options in the AFOLU sector, including options such as biomass production for energy, are highly interdependent due to their direct and indirect impacts on land demand. Indirect interrelationships, mediated *via* area demand for food production, which in turn affects the area available for other purposes, are difficult to quantify and require systemic approaches. Table 11.4 (Smith et al., 2013b) shows the magnitude of possible feedbacks in the land system in 2050. It first reports the effect of single mitigation options compared to a reference case, and then the combined effect of all options. The reference case is similar to the (FAO, 2006a) projections for 2050 and assumes a continuation of on-going trends towards richer diets, considerably higher cropland yields (+54 %) and moderately increased cropland areas (+9 %). The diet change case assumes a global contract-and-converge scenario towards a nutritionally sufficient low animal product diet (8 % of food calories from animal products). The yield growth case assumes that yields in 2050 are 9 % higher than those in the reference case, according to the 'Global Orchestration' scenario in (MEA, 2005). The feeding efficiency case assumes on average 17 % higher livestock feeding efficiencies than the reference case. The waste reduction case assumes a reduction of the losses in the food supply chain by 25 % (Section 11.4.3). The combination of all options results in a substantial reduction of cropland and grazing areas (Smith et al., 2013b), even though the individual options cannot simply be added up due to the interactions between the individual compartments.

Table 11.4 shows that demand-side options save GHG by freeing up land for bioenergy or afforestation and related carbon sequestration. The effect is strong and non-linear, and more than cancels out reduced C sequestration potentials on farmland. Demand-side potentials are substantial compared to supply-side mitigation potentials (Section 11.3), but implementation may be difficult (Sections 11.7; 11.8). Estimates of GHG savings from bioenergy are subject to large uncertainties related to the assumptions regarding power plants, utilization pathway, energy crop yields, and effectiveness of sustainability criteria (Sections 11.4.5; 11.7; 11.13).

The systemic effects of land-demanding mitigation options such as bioenergy or afforestation depend not only on their own area demand, but also on land demand for food and fibre supply (Chum et al., 2011; Coelho et al., 2012; Erb et al., 2012b). In 2007, energy crops for transport fuels covered about 26.6 Mha or 1.7 % of global cropland (UNEP, 2009). Assumptions on energy crop yields (Section 11.13) are the main reason for the large differences in estimates of future area demand of energy crops in the next decades, which vary from < 100 Mha to > 1000 Mha, i.e., 7–70 % of current cropland (Sims et al., 2006; Smeets et al., 2007; Pacca and Moreira, 2011; Coelho et al., 2012). Increased pressure on land systems may also emerge when afforestation claims land, or forest conservation restricts farmland expansion (Murtaugh and Schlax, 2009; Popp et al., 2011).

Land-demanding mitigation options may result in feedbacks such as GHG emissions from land expansion or agricultural intensification, higher yields of food crops, higher prices of agricultural products, reduced food consumption, displacement of food production to other regions and consequent land clearing, as well as impacts on biodiversity and non-provisioning ecosystem services (Plevin et al., 2010; Popp et al., 2012).

Restrictions to agricultural expansion due to forest conservation, increased energy crop area, afforestation and reforestation may increase costs of agricultural production and food prices. In a modelling study, conserving C-rich natural vegetation such as tropical forests was found to increase food prices by a factor of 1.75 until 2100, due to restrictions of cropland expansion, even if no growth of energy crop area was assumed (Wise et al., 2009). Food price indices (weighted average of crop and livestock products) are estimated to increase until 2100 by 82 % in Africa, 73 % in Latin America, and 52 % in Pacific Asia if large-scale bioenergy deployment is combined with strict forest conservation, compared to a reference scenario without forest conservation and bioenergy (Popp et al., 2011). Further trade liberalization can lead to lower costs of food, but also increases the pressure on land, especially on tropical forests (Schmitz et al., 2011).

Increased land demand for GHG mitigation can be partially compensated by higher agricultural yield per unit area (Popp et al., 2011). While yield increases can lead to improvements in output from less land, generate better economic returns for farmers, help to reduce competition for land, and alleviate environmental pressures (Burney et al., 2010; Smith et al., 2010), agricultural intensification if poorly implemented incurs economic costs (Lotze-Campen et al., 2010) and may also create social and environmental problems such as nutrient leaching, soil degradation, pesticide pollution, impact on animal welfare, and many more (IAASTD, 2009). Maintaining yield growth while reducing negative environmental and social effects of agricultural intensification is, therefore, a central challenge, requiring sustainable management of natural resources as well as the increase of resource efficiency (DeFries and Rosenzweig, 2010), two components of sustainable intensification (Garnett et al., 2013).

Additional land demand may put pressures on biodiversity, as LUC is one of the most important drivers of biodiversity loss (Sala et al., 2000). Improperly managed large-scale agriculture (or bioenergy) may negatively affect biodiversity (Groom et al., 2008), which is a key prerequisite for the resilience of ecosystems, i.e., their ability to adapt to changes such as climate change, and to continue to deliver ecosystem services in the future (Díaz et al., 2006; Landis et al., 2008). However, implementing appropriate management, such as establishing bioenergy crops or plantations for carbon sequestration in already degraded ecosystems areas represents an opportunity where bioenergy can be used to achieve positive environmental outcomes (e.g., Hill et al., 2006; Semere and Slater, 2007; Campbell et al., 2008; Nijsen et al., 2012). Because climate change is also an important driver of biodiversity loss (Sala et al., 2000), bioenergy for climate change mitigation may also be beneficial for biodiversity if it is planned with biodiversity conservation in mind (Heller and Zavaleta, 2009; Dawson et al., 2011; Section 11.13).

Tradeoffs related to land demand may be reduced through multifunctional land use, i.e., the optimization of land to generate more than one product or service such as food, animal feed, energy or materials, soil protection, wastewater treatment, recreation, or nature protection (de Groot, 2006; DeFries and Rosenzweig, 2010; Section 11.7). This also applies to the potential use of ponds and other small water bodies for raising fish fed with agricultural waste (Pullin et al., 2007).

11.4.5 Sustainable development and behavioural aspects

The assessment of impacts of AFOLU mitigation options on sustainable development requires an understanding of a complex multilevel system where social actors make land-use decisions aimed at various development goals, one of them being climate change mitigation. Depending on the specific objectives, the beneficiaries of a particular land-use choice may differ. Thus tradeoffs between global, national, and local concerns and various stakeholders need to be considered (see also Section 4.3.7 and WGII Chapter 20). The development context provides opportunities or barriers for AFOLU (May et al., 2005; Madlener et al., 2006; Smith and Trines, 2006; Smith et al., 2007; Angelsen, 2008; Howden et al., 2008; Corbera and Brown, 2008; Cotula et al., 2009; Cattaneo et al., 2010; Junginger et al., 2011; Section 11.8 and Figure 11.11).

Further, AFOLU measures have additional effects on development, beyond improving the GHG balance (Foley et al., 2005; Alig et al., 2010; Calfapietra et al., 2010; Busch et al., 2011; Smith et al., 2013b; Branca et al., 2013; Albers and Robinson, 2013). These effects can be positive (co-benefits) or negative (adverse side-effects) and do not necessarily overlap geographically, socially or in time (Section 11.7 and Figure 11.11). This creates the possibility of tradeoffs, because an AFOLU measure can bring co-benefits to one social group in one area (e.g., increasing income), while bringing adverse side-effects to others somewhere else (e.g., reducing food availability).

Table 11.5 summarizes the issues commonly considered when assessing the above-mentioned interactions at various levels between sustainable development and AFOLU.

Social complexity: Social actors in the AFOLU sector include individuals (farmers, forest users), social groups (communities, indigenous groups), private companies (e.g., concessionaires, food-producer multinationals), subnational authorities, and national states (see Table 11.6).

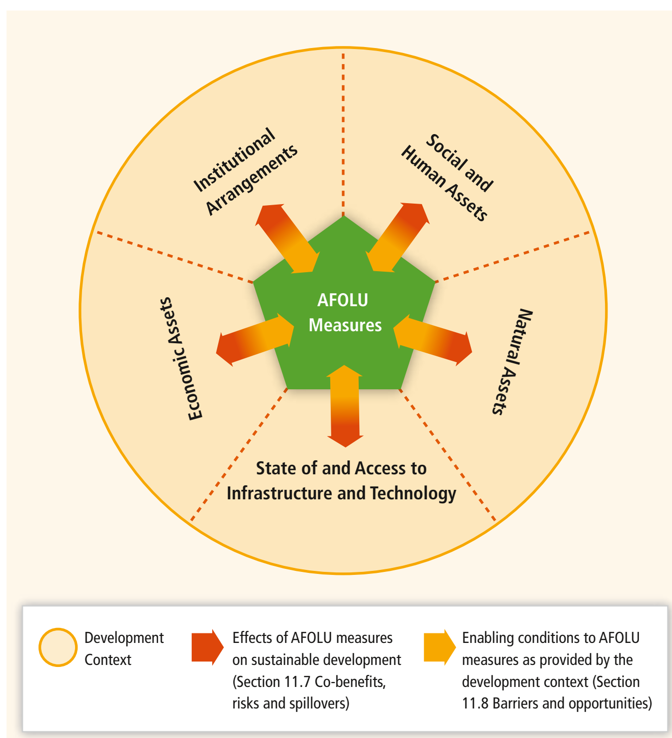


Figure 11.11 | Dynamic interactions between the development context and AFOLU.

Spatial scale refers on the one hand to the size of an intervention (e.g., in number of hectares) and on the other hand to the biophysical characterization of the specific land (e.g., soil type, water availability, slope). Social interactions tend to become more complex the bigger the area of an AFOLU intervention, on a social-biophysical continuum: family/farm—neighbourhood—community—village—city—province—country—region—globe. Impacts from AFOLU measures on sustainable development are different along this spatial-scale continuum (Table 11.6). The challenge is to provide landscape governance that responds to societal needs as well as biophysical capacity at different spatial scales (Görg, 2007; Moilanen and Arponen, 2011; van der Horst and Vermeylen, 2011).

Temporal scale: As the concept of sustainable development includes current and future generations, the impacts of AFOLU over time need to be considered (see Chapter 4). Positive and negative impacts of AFOLU measures can be realized at different times. For instance, while reducing deforestation has an immediate positive impact on reducing GHG emissions, reforestation will have a positive impact on C sequestration over time. Further, in some circumstances, there is the risk of reversing current emission reductions in the future (see Section 11.3.2 on non-permanence).

Behavioural aspects: Level of education, cultural values and tradition, as well as access to markets and technology, and the decision power of individuals and social groups, all influence the perception of potential impacts and opportunities from AFOLU measures, and consequently have a great impact on local land management decisions (see Chapters 2, 3, and 4; Guthinga, 2008; Durand and Lazos, 2008; Gilg, 2009; Bhuiyan et al., 2010; Primmer and Karppinen, 2010; Durand and Vázquez, 2011). When decisions are taken at a higher administrative level (e.g., international corporations, regional authorities or national states), other factors or values play an important role, including national and international development goals and priorities, policies and commitments, international markets or corporate image (see Chapters 3 and 4). Table 11.7 summarizes the emerging behavioural aspects regarding AFOLU mitigation measures.

Land-use policies (Section 11.10) have the challenge of balancing impacts considering these parameters: social complexity, spatial scale, temporal scale, and behavioural aspects. Vlek and Keren (1992) and Vlek (2004) indicate the following dilemmas relevant to land-management decisions: Who should take the risks, when (this generation or future generations) and where (specific place) co-benefits and potential adverse effects will take place, and how to mediate between individual *vs*. social benefits. Addressing these dilemmas is context-specific. Nevertheless, the fact that a wide range of social actors need to face these dilemmas explains, to a certain extent, disagreements about environmental decision making in general, and land-management decisions in particular (Villamor et al., 2011; Le et al., 2012; see Section 11.10) .

11.5 Climate change feedback and interaction with adaptation (includes vulnerability)

When reviewing the inter-linkages between climate change mitigation and adaptation within the AFOLU sector the following issues need to be considered: (i) the impact of climate change on the mitigation potential of a particular activity (e.g., forestry and agricultural soils) over time, (ii) potential synergies/tradeoffs within a land-use sector between mitigation and adaptation objectives, and (iii) potential tradeoffs across sectors between mitigation and adaptation objectives.

Mitigation and adaptation in land-based ecosystems are closely interlinked through a web of feedbacks, synergies, and tradeoffs (Section 11.8). The mitigation options themselves may be vulnerable to climatic change (Section 11.3.2) or there may be possible synergies or tradeoffs between mitigation and adaptation options within or across AFOLU sectors.

Table 11.5 | Issues related to AFOLU measures and sustainable development.

Dimensions	Issues
Social and human assets	Population growth and migration, level of education, human capacity, individual skills, indigenous and traditional knowledge, cultural values, equity and health, animal welfare, organizational capacity
Natural assets	Availability of natural resources (land, forest, water, agricultural land, minerals, fauna), GHG balance, ecosystem integrity, biodiversity conservation, ecosystem services, the productive capacity of ecosystems, ecosystem health and resilience
State of infrastructure and technology	Availability of infrastructure and technology and industrial capacity, technology development, appropriateness, acceptance
Economic factors	Credit capacity, employment creation, income, wealth distribution/distribution mechanisms, carbon finance, available capital/investments, market access
Institutional arrangements	Land tenure and land-use rights, participation and decision making mechanisms (e.g., through Free, Prior and Informed Consent), sectoral and cross-sectoral policies, investment in research, trade agreements and incentives, benefit sharing mechanisms, existence and forms of social organization

Based on Madlener et al. (2006), Sneddon et al. (2006), Pretty (2008), Corbera and Brown (2008), Macauley and Sedjo (2011), and de Boer et al. (2011).

Table 11.6 | Characterization of social actors in AFOLU.

Social actors	Characterization
Individuals (legal and illegal forest users, farmers)	Rather small-scale interventions, although some can be medium-scale Decisions taken rather at the local level
Social groups (communities, indigenous peoples)	Small to medium interventions Decisions taken at the local or regional levels
Sub-national authorities (provinces, states)	Medium to large interventions Decisions taken at the national or sub-national level, depending on the governance structure
State (national level)	Rather large interventions Decisions taken at the national level, often in line with international agreements
Corporate (at the national or multinational levels)	Rather large interventions. Decisions can be taken within a specific region/country, in another country, or at global level (e.g., for multinational companies). National and international markets play a key role in decision making

Table 11.7 | Emerging behavioural aspects relevant for AFOLU mitigation measures.

Change in	Emerging behavioural aspects in AFOLU
Consumption patterns	**Dietary change:** Several changes in diet can potentially reduce GHG emissions, including reduction of food waste and reduction of or changes in meat consumption (especially in industrialized countries). On the other hand, increasing income and evolving lifestyles with increasing consumption of animal protein in developing countries are projected to increase food-related GHG emissions. The potential of reducing GHG emissions in the food sector needs to be understood in a wider and changing socio-cultural context that determines nutrition. Potential drivers of change: Health awareness and information, income increase, lifestyle References 1, 2,3, 4, 5
Production patterns	**Large-scale land acquisition:** The acquisition of (long-term rights) of large areas of farmland in lower-income countries, by transnational companies, agribusiness, investments funds or government agencies. There are various links between these acquisitions and GHG emissions in the AFOLU sector. On one hand because some acquisitions are aimed at producing energy crops (through non-food or 'flex-crops'), on the other because these can cause the displacement of peoples and activity, increasing GHG leakage. Impacts on livelihood, local users rights, local employment, economic activity, or on biodiversity conservation are of concern. Potential drivers of change: International markets and their mechanisms, national and international policies References 6, 7, 8
Production and consumption patterns	**Switching to low-carbon products:** Land managers are sensitive to market changes. The promotion of low-carbon products as a means for reducing GHG emissions can increase the land area dedicated to these products. Side-effects from this changes in land management (positive and negative), and acceptability of products and technologies at the production and consumption sides are context-related and cannot be generalized Potential drivers of change: International agreements and markets, accessibility to rural energy, changes in energy demand References 9, 10, 11
Relation between producers and consumers	**Certification:** Labelling, certification, or other information-based instruments have been developed for promoting behavioural changes towards more sustainable products (Section 11.10). Recently, the role of certification in reducing GHG while improving sustainability has been explored, especially for bioenergy (Section 11.13). Potential drivers of change: Consumer awareness, international agreements, cross-national sector policies and initiatives. References 11, 12, 13, 14
Management priorities	**Increasing interest in conservation and sustainable (land) management:** Changing management practices towards more sustainable ones as alternative for gaining both environmental and social co-benefits, including climate change mitigation, is gaining recognition. Concerns about specific management practices, accountability methods of co-benefits, and sharing mechanisms seem to be elements of concerns when promoting a more sustainable management of natural resources. Potential drivers of change: Policies and international agreements and their incentive mechanisms, schemes for payments for environmental services. References 15, 16, 17, 18, 19

[1] Stehfest et al. (2009); [2]Roy et al. (2012); [3]González et al. (2011); [4]Popp et al. (2010); [5]Schneider et al. (2011); [6]Cotula (2012); [7]Messerli et al. (2013); [8]German et al. (2013); [9]Muys et al. (2014); [10]MacMillan Uribe et al. (2012); [11]Chakrabarti (2010); [12]Karipidis et al. (2010); [13]Auld et al. (2008); [14]Diaz-Chavez (2011); [15]Calegari et al. (2008); [16]Deal et al. (2012); [17]DeFries and Rosenzweig (2010); [18]Hein and van der Meer (2012);[19] Lippke et al. (2003).

The IPCC WGI presents feedbacks between climate change and the carbon cycle (WGI Chapter 6; Le Quéré et al., 2013), while WGII assesses the impacts of climate change on terrestrial ecosystems (WGII Chapter 4) and crop production systems (WGII Chapter 7), including vulnerability and adaptation. This section focuses particularly on the impacts of climate change on mitigation potential of land-use sectors and interactions that arise with adaptation, linking to the relevant chapters of WGI and WGII reports.

11.5.1 Feedbacks between ALOFU and climate change

AFOLU activities can either reduce or accelerate climate change by affecting biophysical processes (e.g., evapotranspiration, albedo) and change in GHG fluxes to and from the atmosphere (WGI). Whether a particular ecosystem is functioning as sink or source of GHG emission may change over time, depending on its vulnerability to climate change and other stressors and disturbances. Hence, mitigation options available today (Section 11.3) in the AFOLU sectors may no longer be available in the future.

There is *robust evidence* that human-induced land-use changes have led to an increased surface albedo (WGI Chapter 8; Myhre and Shindell, 2013). Changes in evapotranspiration and surface roughness may counteract the effect of changes in albedo. Land-use changes affect latent heat flux and influence the hydrological cycle. Biophysical climate feedbacks of forest ecosystems differ depending on regional climate regime and forest types. For example, a decrease in tropical forests has a positive climate forcing through a decrease in evaporative cooling (Bala et al., 2007; Bonan, 2008). An increase in coniferous-boreal forests compared to grass and snow provides a positive climate forcing through lowering albedo (Bala et al., 2007; Bonan, 2008; Swann et al., 2010). There is currently *low agreement* on the net biophysical effect of land-use changes on the global mean temperature (WGI Chapter 8; Myhre and Shindell, 2013). By contrast, the biogeochemical effects of LUC on radiative forcing through emissions of GHG is positive (WGI Chapter 8; Sections 11.2.2; 11.2.3).

11.5.2 Implications of climate change on terrestrial carbon pools and mitigation potential of forests

Projections of the global carbon cycle to 2100 using 'Coupled Model Intercomparison Project Phase 5 (CMIP5) Earth System Models' (WGI Chapter 6; Le Quéré et al., 2013) that represent a wider range of complex interactions between the carbon cycle and the physical climate system consistently estimate a positive feedback between climate and the carbon cycle, i.e., reduced natural sinks or increased natural CO_2 sources in response to future climate change. Implications of climate change on terrestrial carbon pools biomes and mitigation potential of forests.

Rising temperatures, drought, and fires may lead to forests becoming a weaker sink or a net carbon source before the end of the century (Sitch et al., 2008). Pervasive droughts, disturbances such as fire and insect outbreaks, exacerbated by climate extremes and climate change put the mitigation benefits of the forests at risk (Canadell and Raupach, 2008; Phillips et al., 2009; Herawati and Santoso, 2011). Forest disturbances and climate extremes have associated carbon balance implications (Millar et al., 2007; Kurz et al., 2008; Zhao and Running, 2010; Potter et al., 2011; Davidson, 2012; Reichstein et al., 2013). Allen et al. (2010) suggest that at least some of the world's forested ecosystems may already be responding to climate change.

Experimental studies and observations suggest that predicted changes in temperature, rainfall regimes, and hydrology may promote the die-back of tropical forests (e.g., Nepstad et al., 2007). The prolonged drought conditions in the Amazon region during 2005 contributed to a decline in above-ground biomass and triggered a release of 4.40 to 5.87 $GtCO_2$ (Phillips et al., 2009). Earlier model studies suggested Amazon die-back in the future (Cox et al., 2013; Huntingford et al., 2013). However, recent model estimates suggest that rainforests may be more resilient to climate change, projecting a moderate risk of tropical forest reduction in South America and even lower risk for African and Asian tropical forests (Gumpenberger et al., 2010; Cox et al., 2013; Huntingford et al., 2013).

Arcidiacono-Bársony et al., (2011) suggest that the mitigation benefits from deforestation reduction under REDD+ (Section 11.10.1) could be reversed due to increased fire events, and climate-induced feedbacks, while Gumpenberger et al., (2010) conclude that the protection of forests under the forest conservation (including REDD) programmes could increase carbon uptake in many tropical countries, mainly due to CO_2 fertilization effects, even under climate change conditions.

11.5.3 Implications of climate change on peatlands, grasslands, and croplands

Peatlands: Wetlands, peatlands, and permafrost soils contain higher carbon densities relative to mineral soils, and together they comprise extremely large stocks of carbon globally (Davidson and Janssens, 2006). Peatlands cover approximately 3 % of the Earth's land area and are estimated to contain 350–550 Gt of carbon, roughly between 20 to 25 % of the world's soil organic carbon stock (Gorham, 1991; Fenner et al., 2011). Peatlands can lose CO_2 through plant respiration and aerobic peat decomposition (Clair et al., 2002) and with the onset of climate change, may become a source of CO_2 (Koehler et al., 2010). Large carbon losses are likely from deep burning fires in boreal peatlands under future projections of climate warming and drying (Flannigan et al., 2009). A study by Fenner et al. (2011) suggests that climate change is expected to increase the frequency and severity of drought in many of the world's peatlands which, in turn, will release far more GHG emissions than thought previously. Climate change is projected to have a severe impact on the peatlands in northern regions where most of the perennially frozen peatlands are found (Tarnocai, 2006). According to Schuur et al. (2008), the thawing permafrost and consequent microbial decomposition of previously frozen organic carbon, is one of the most significant potential feedbacks from terrestrial ecosystems to the atmosphere in a changing climate. Large areas of permafrost will experience thawing (WGI Chapter 12), but uncertainty over the magnitude of frozen carbon losses through CO_2 or CH_4 emissions to the atmosphere is large, ranging between 180 and 920 $GtCO_2$ by the end of the 21st century under the Representative Concentration Pathways (RCP) 8.5 scenario (WGI Chapter 6; Le Quéré et al., 2013).

Grasslands: Tree cover and biomass in savannah has increased over the past century (Angassa and Oba, 2008; Witt et al., 2009; Lunt et al., 2010; Rohde and Hoffman, 2012) leading to increased carbon storage per hectare (Hughes et al., 2006; Liao et al., 2006; Throop and Archer, 2008; Boutton et al., 2009), which has been attributed to land management, rising CO_2, climate variability, and climate change. Climate change and CO_2 may affect grazing systems by altering species composition; for example, warming will favour tropical (C4) species over temperate (C3) species but CO_2 increase would favour C3 grasses (Howden et al., 2008).

Croplands: Climate change impacts on agriculture will affect not only crop yields, but also soil organic carbon (SOC) levels in agricultural soils (Rosenzweig and Tubiello, 2007). Such impacts can be either positive or negative, depending on the particular effect considered, which highlights the uncertainty of the impacts. Elevated CO_2 concentrations alone are expected to have positive effects on soil carbon storage, because of increased above- and below-ground biomass production in agro-ecosystems. Similarly, the lengthening of the growing season under future climate will allow for increased carbon inputs into soils. Warmer temperatures could have negative impacts on SOC, by speeding decomposition and by reducing inputs by shortening crop lifecycles (Rosenzweig and Tubiello, 2007), but increased productivity could increase SOC stocks (Gottschalk et al., 2012).

11.5.4 Potential adaptation options to minimize the impact of climate change on carbon stocks in forests and agricultural soils

Forests: Forest ecosystems require a longer response time to adapt. The development and implementation of adaptation strategies is also lengthy (Leemans and Eickhout, 2004; Ravindranath, 2007). Some examples of the adaptation practices (Murthy et al., 2011) are as follows: anticipatory planting of species along latitude and altitude, assisted natural regeneration, mixed-species forestry, species mix adapted to different temperature tolerance regimes, fire protection and management practices, thinning, sanitation and other silvicultural practices, *in situ* and *ex situ* conservation of genetic diversity, drought and pest resistance in commercial tree species, adoption of sustainable forest management practices, increase in Protected Areas and linking them wherever possible to promote migration of species, forests conservation and reduced forest fragmentation enabling species migration, and energy-efficient fuel-wood cooking devices to reduce pressure on forests.

Agricultural soils: On current agricultural land, mitigation and adaptation interaction can be mutually re-enforcing, particularly for improving resilience to increased climate variability under climate change (Rosenzweig and Tubiello, 2007). Many mitigation practices implemented locally for soil carbon sequestration will increase the ability of soils to hold soil moisture and to better withstand erosion and will enrich ecosystem biodiversity by establishing more diversified cropping systems, and may also help cropping systems to better withstand droughts and floods, both of which are projected to increase in frequency and severity under a future warmer climate (Rosenzweig and Tubiello, 2007).

11.5.5 Mitigation and adaptation synergies and tradeoffs

Mitigation choices taken in a particular land-use sector may further enhance or reduce resilience to climate variability and change within or across sectors, in light of the multiple, and often competing, pressures on land (Section 11.4), and shifting demographics and consumption patterns (e.g., (O'Brien et al., 2004; Sperling et al., 2008; Hunsberger and Evans, 2012). Land-use choices driven by mitigation concerns (e.g., forest conservation, afforestation) may have consequences for adaptive responses and/or development objectives of other sectors (e.g., expansion of agricultural land). For example, reducing emissions from deforestation and degradation may also yield co-benefits for adaptation by maintaining biodiversity and other ecosystem goods and services, while plantations, if they reduce biological diversity may diminish adaptive capacity to climate change (e.g., Chum et al., 2011). Primary forests tend to be more resilient to climate change and other human-induced environmental changes than secondary forests and plantations (Thompson et al., 2009). The impact of plantations on the carbon balance is dependent on the land-use system they replace. While plantation forests are often monospecies stands, they may be more vulnerable to climatic change (see IPCC WGII Chapter 4). Smith and Olesen (2010) identified a number of synergies between options that deliver mitigation in agriculture while also enhancing resilience to future climate change, the most prominent of which was enhancement of soil carbon stocks.

Adaptation measures in return may help maintain the mitigation potential of land-use systems. For example, projects that prevent fires and restore degraded forest ecosystems also prevent release of GHGs and enhance carbon stocks (CBD and GiZ, 2011). Mitigation and adaptation benefits can also be achieved within broader-level objectives of AFOLU measures, which are linked to sustainable development considerations. Given the exposure of many livelihoods and communities to multiple stressors, recommendations from case studies suggest that climate risk-management strategies need to appreciate the full hazard risk envelope, as well as the compounding socio-economic stressors (O'Brien et al., 2004; Sperling et al., 2008). Within this broad context, the potential tradeoffs and synergies between mitigation, adaptation, and development strategies and measures need to be considered. Forest and biodiversity conservation, protected area formation, and mixed-species forestry-based afforestation are practices that can help to maintain or enhance carbon stocks, while also providing adaptation options to enhance resilience of forest ecosystems to climate change (Ravindranath, 2007). Use of organic soil amendments as a source of fertility could potentially increase soil carbon (Gattinger et al., 2012). Most categories of adaptation options for climate change have positive impacts on mitigation. In the agriculture sector, cropland adaptation options that also contribute to mitigation are 'soil management practices that reduce fertilizer use and increase crop diversification; promotion of legumes in crop rotations; increasing biodiversity, the availability of quality seeds and integrated crop/livestock systems; promotion of low energy production systems; improving the control of wildfires and avoiding burning of crop residues; and promoting efficient energy use by commercial agriculture and agro-industries' (FAO, 2008, 2009a). Agroforestry is an example of mitigation-adaptation synergy in the agriculture sector, since trees planted sequester carbon and tree products provide livelihood to communities, especially during drought years (Verchot et al., 2007).

11.6 Costs and potentials

This section deals with economic costs and potentials of climate change mitigation (emission reduction or sequestration of carbon) within the AFOLU sector. Economic mitigation potentials are distinguished from technical or market mitigation potentials (Smith, 2012). Technical mitigation potentials represent the full biophysical potential of a mitigation option, without accounting for economic or other constraints. These estimates account for constraints and factors such as land availability and suitability (Smith, 2012), but not any associated costs (at least explicitly). By comparison, economic potential refers to mitigation that could be realized at a given carbon price over a specific period, but does not take into consideration any socio-cultural (for example, lifestyle choices) or institutional (for example, political, policy, and informational) barriers to practice or technology adoption. Economic potentials are expected to be lower than the corresponding technical potentials. Also, policy incentives (e.g., a carbon price; see also Section 11.10) and competition for resources across various mitigation options, tend to affect the size of economic mitigation potentials in the AFOLU sector (McCarl and Schneider, 2001). Finally, market potential is the realized mitigation outcome under current or forecast market conditions encompassing biophysical, economic, socio-cultural, and institutional barriers to, as well as policy incentives for, technological and/or practice adoption, specific to a sub-national, national or supra-national market for carbon. Figure 11.12 (Smith, 2012) provides a schematic view of the three types of mitigation potentials.

Economic (as well as market) mitigation potentials tend to be context-specific and are likely to vary across spatial and temporal scales. Unless otherwise stated, in the rest of this section, economic potentials are expressed in million tonnes (Mt) of mitigation in carbon dioxide equivalent (CO_2eq) terms, that can arise from an individual mitigation option or from an AFOLU sub-sector at a given cost per tonne of CO_2eq. (USD/tCO_2eq) over a given period to 2030, which is 'additional' to the corresponding baseline or reference case levels.

Various supply-side mitigation options within the AFOLU sector are described in Section 11.3, and Section 11.4 considers a number of potential demand-side options. Estimates for costs and potentials are not always available for the individual options described. Also, aggregate estimates covering both the supply- and demand-side options for mitigation within the AFOLU sector are lacking, so this section mostly focuses on the supply-side options. Key uncertainties and sensitivities around mitigation costs and potentials in the AFOLU sector are (1) carbon price, (2) prevailing biophysical and climatic conditions, (3) existing management heterogeneity (or differences in the baselines), (4) management interdependencies (arising from competition or co-benefits across tradition production, environmental outcomes and mitigation strategies or competition/co-benefits across mitigation options), (5) the extent of leakage, (6) differential impact on different GHGs associated with a particular mitigation option, and (7) timeframe for abatement activities and the discount rate. In this section, we (a) provide aggregate mitigation potentials for the AFOLU sector (because these wereprovided separately for agriculture and forestry in AR4), (b) provide estimates of

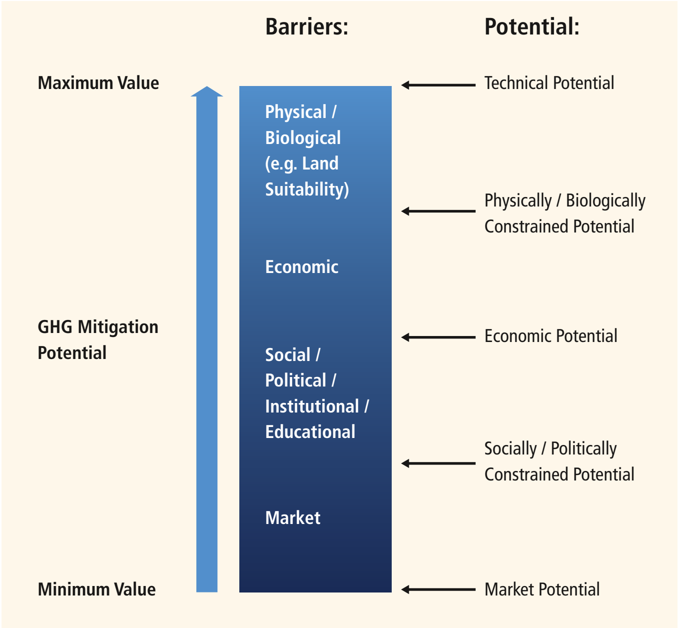


Figure 11.12 | Relationship between technical, economic, and market potential (based on Smith, 2012).

global mitigation costs and potentials published since AR4, and (c) provide a regional disaggregation of the potentials to show how potential, and the portfolio of available options, varies in different world regions.

11.6.1 Approaches to estimating economic mitigation potentials

Bottom-up and top-down modelling approaches are used to estimate AFOLU mitigation potentials and costs. While both approaches provide useful estimates for mitigation costs and potentials, comparing bottom-up and top-down estimates is not straightforward.

Bottom-up estimates are typically derived for discrete abatement options in agriculture at a specific location or time, and are often based on detailed technological, engineering and process information, and data on individual technologies (DeAngelo et al., 2006). These studies provide estimates of how much technical potential of particular AFOLU mitigation options will become economically viable at certain carbon dioxide-equivalent prices. Bottom-up mitigation responses are typically restricted to input management (for example, changing practices with fertilizer application and livestock feeding) and mitigation costs estimates are considered 'partial equilibrium' in that the relevant input-output prices (and, sometimes, quantities such as area or production levels) are held fixed. As such, unless adjusted for potential overlaps and tradeoffs across individual mitigation options, adding up various individual estimates to arrive at an aggregate for a particular landscape or at a particular point in time could be misleading.

With a 'systems' approach, top-down models (described in Chapter 6; Section 11.9) typically take into account possible interactions between individual mitigation options. These models can be sector-specific or economy-wide, and can vary across geographical scales: sub-national, national, regional, and global. Mitigation strategies in top-down models may include a broad range of management responses and practice changes (for example, moving from cropping to grazing or grazing to forestry) as well as changes in input-output prices (for example, land and commodity prices). Such models can be used to assess the cost competitiveness of various mitigation options and implications across input-output markets, sectors, and regions over time for large-scale domestic or global adoption of mitigation strategies. In top-down modelling, dynamic cost-effective portfolios of abatement strategies are identified incorporating the lowest cost combination of mitigation strategies over time from across sectors, including agricultural, forestry, and other land-based sectors across the world that achieve the climate stabilization target (see Chapter 6). Top-down estimates for 2030 are included in this section, and are revisited in Section 11.9 when considering the role of the AFOLU sector in transformation pathways.

Providing consolidated estimates of economic potentials for mitigation within the AFOLU sector as a whole is complicated because of complex interdependencies, largely stemming from competing demands on land for various agricultural and forestry (production and mitigation) activities, as well as for the provision of many ecosystem services (Smith et al., 2013a). These interactions are discussed in more detail in Section 11.4.

11.6.2 Global estimates of costs and potentials in the AFOLU sector

Through combination of forestry and agriculture potentials from AR4, total mitigation potentials for the AFOLU sector are estimated to be ~3 to ~7.2 $GtCO_2eq/yr$ in 2030 at 20 and 100 USD/tCO_2eq, respectively (Figure 11.13), including only supply-side options in agriculture (Smith et al., 2007) and a combination of supply- and demand-side options for forestry (Nabuurs et al., 2007).

Estimates of global economic mitigation potentials in the AFOLU sector published since AR4 are shown in Figure 11.14, with AR4 estimates shown for comparison (IPCC, 2007a).

Table 11.8 summarizes the ranges of global economic mitigation potentials from AR4 (Nabuurs et al., 2007; Smith et al., 2007), and studies published since AR4 that are shown in full in Figure 11.14, for agriculture, forestry, and AFOLU combined.

As described in Section 11.3, since AR4, more attention has been paid to options that reduce emissions intensity by improving the efficiency of production (i.e., less GHG emissions per unit of agricultural product; Burney et al., 2010; Bennetzen et al., 2012). As agricultural and silvicultural efficiency have improved over recent decades, emissions intensities have declined (Figure 11.15). Whilst emissions intensity has increased (1960s to 2000s) by 45 % for cereals, emissions intensities have decreased by 38 % for milk, 50 % for rice, 45 % for pig meat, 76 % for chicken, and 57 % for eggs.

The implementation of mitigation measures can contribute to further decrease emission intensities of AFOLU commodities (Figure 11.16; which shows changes of emissions intensities when a commodity-specific mix of mitigation measures is applied). For cereal production, mitigation measures considered include improved cropland agronomy, nutrient and fertilizer management, tillage and residue management, and the establishment of agro-forestry systems. Improved rice management practices were considered for paddy rice cultivation. Mitigation measures applied in the livestock sector include improved feeding and dietary additives. Countries can improve emission intensities of AFOLU commodities through increasing production at the same level of input, the implementation of mitigation measures, or a combination of both. In some regions, increasing current yields is still an option with a significant potential to improve emission intensities of agricultural production. Foley et al. (2011) analyzed current and potential yields that could be achieved for 16 staple crops using available agricultural practices and technologies and identified large 'yield gaps', especially across many parts of Africa, Latin America, and Eastern Europe. Better crop management practices can help to close yield gaps and improve emission intensities if measures are selected that also have a mitigation potential.

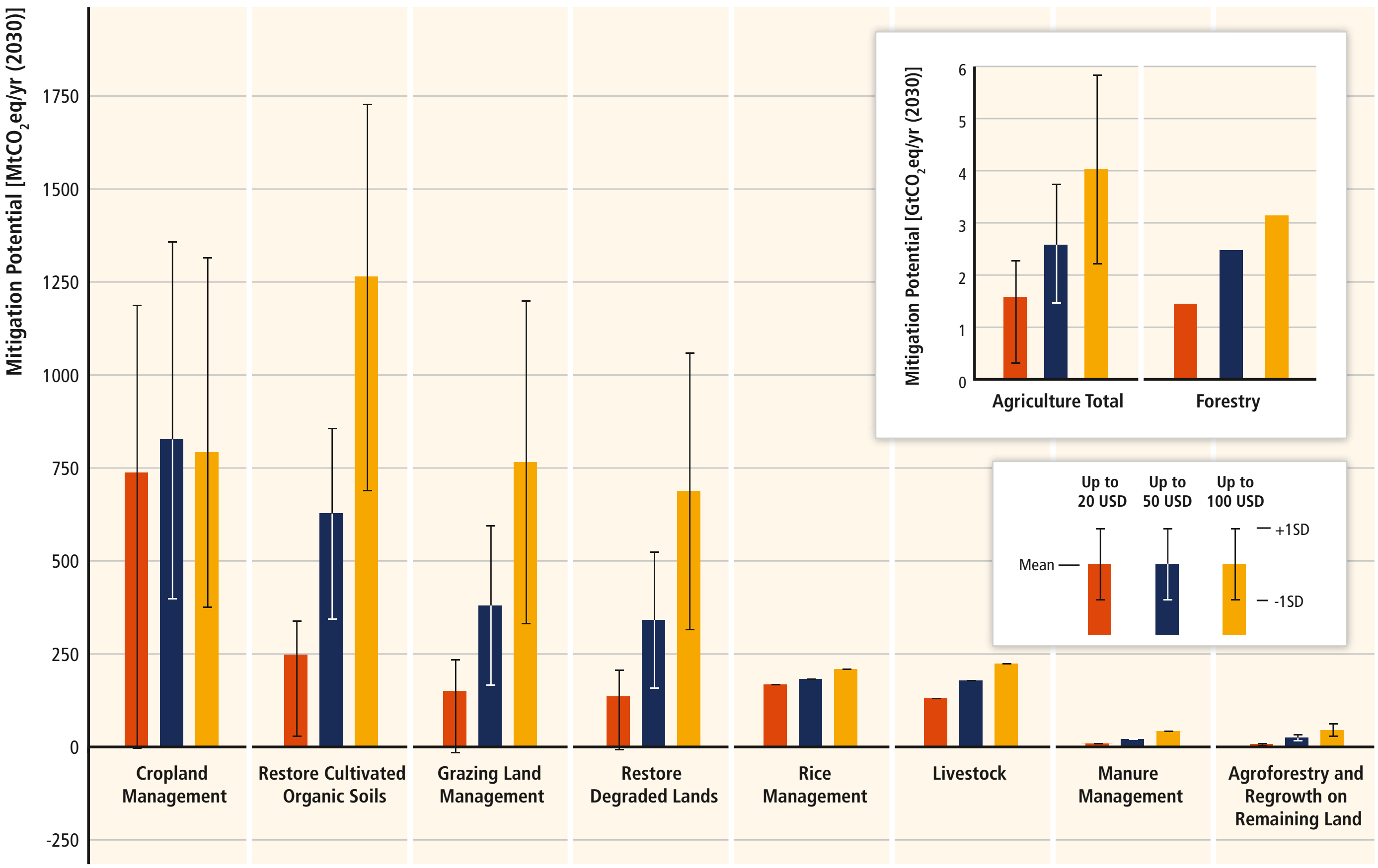


Figure 11.13 | Mitigation potential for the AFOLU sector, plotted using data from AR4 (Nabuurs et al., 2007; Smith et al., 2007). Whiskers show the range of estimates (+/- 1 standard deviation) for agricultural options for which estimates are available.

Mitigation potentials and costs differ largely between AFOLU commodities (Figure 11.16). While average abatement costs are low for roundwood production under the assumption of perpetual rotation, costs of mitigation options applied in meat and dairy production systems have a wide range (1:3 quartile range: 58–856 USD/tCO_2eq). Calculations of emission intensities are based on the conservative assumption that production levels stay the same after the application of the mitigation option. However, some mitigation options can increase production. This would not only improve food security but could also increase the cost-effectiveness of mitigation actions in the agricultural sector.

Agriculture and forestry-related mitigation could cost-effectively contribute to transformation pathways associated with long-run climate change management (Sections 11.9 and 6.3.5). Transformation pathway modelling includes LUC, as well as land-management options that reduce emissions intensities and increase sequestration intensities. However, the resulting transformation pathway emissions (sequestration) intensities are not comparable to those discussed here. Transformation pathways are the result of integrated modelling and the resulting intensities are the net result of many effects. The intensities capture mitigation technology adoption, but also changes in levels of production, land-cover change, mitigation technology competition, and model-specific definitions for sectors/regions/and assigned emissions inventories. Mitigation technology competition, in particular, can lead to intensification (and increases in agricultural emissions intensities) that support cost-effective adoption of other mitigation strategies, such as afforestation or bioenergy (Sections 11.9 and 6.3.5).

11.6.3 Regional disaggregation of global costs and potentials in the AFOLU sector

Figure 11.17 shows the economically viable mitigation opportunities in AFOLU in 2030 by region and by main mitigation option at carbon prices of up to 20, 50, and 100 USD/tCO_2eq. The composition of the agricultural mitigation portfolio varies greatly with the carbon price (Smith, 2012), with low cost options such as cropland management being favoured at low carbon prices, but higher cost options such as restoration of cultivated organic soils being more cost-effective at higher prices. Figure 11.17 also reveals some very large differences in mitigation potential, and different ranking of most effective options, between regions. Across all AFOLU options, Asia has the largest mitigation potential, with the largest mitigation in both forestry and agriculture, followed by LAM, OECD-1990, MAF, and EIT.

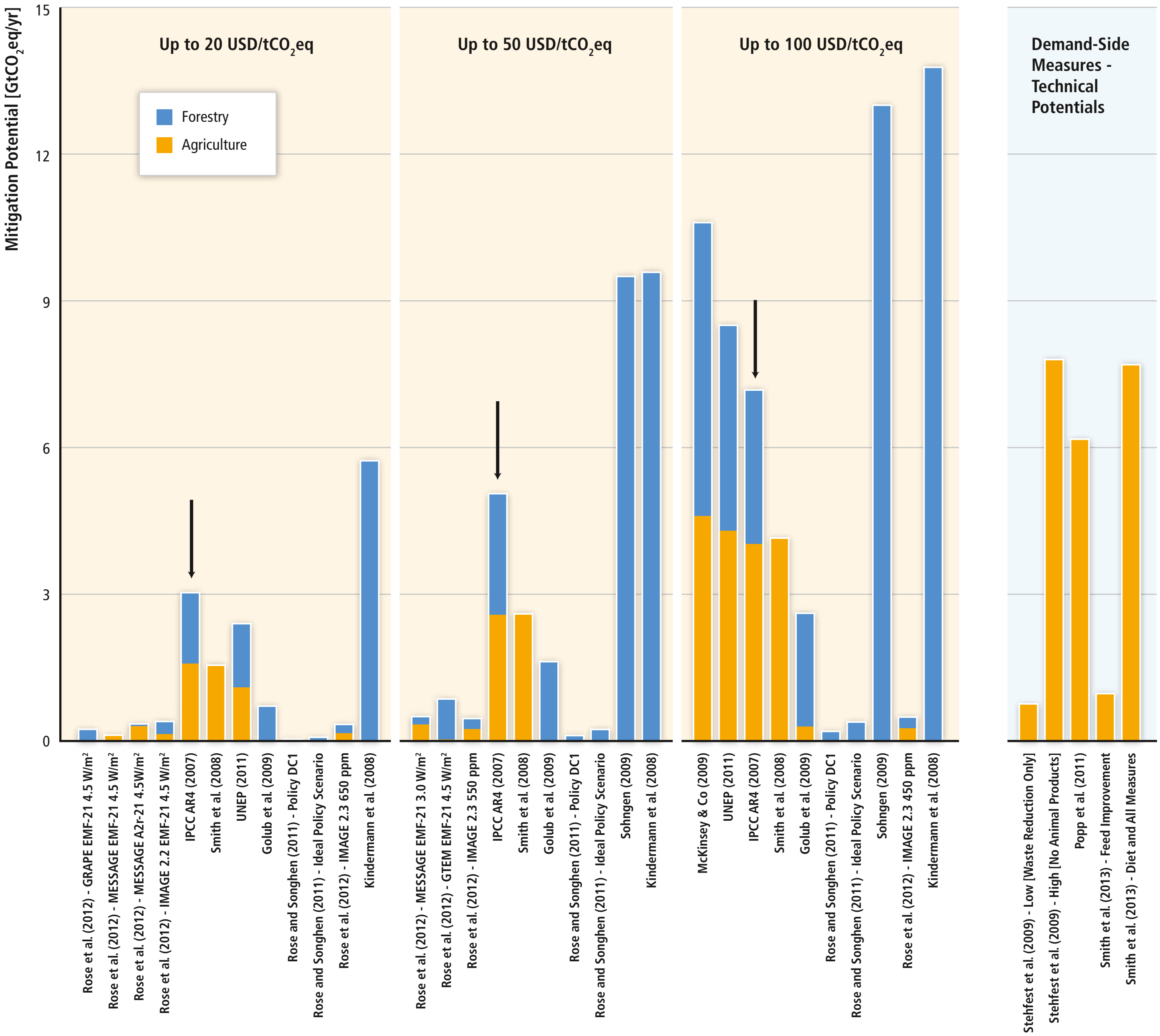


Figure 11.14 | Estimates of economic mitigation potentials in the AFOLU sector published since AR4, (AR4 estimates shown for comparison, denoted by arrows), including bottom-up, sectoral studies, and top-down, multi-sector studies. Some studies estimate potential for agriculture and forestry, others for one or other sector. Supply-side mitigation potentials are estimated for around 2030, but studies range from estimates for 2025 (Rose et al., 2012) to 2035 (Rose and Sohngen, 2011). Studies are collated for those reporting potentials at carbon prices of up to ~20 USD/tCO_2eq (actual range 1.64–21.45), up to ~50 USD/tCO_2eq (actual range 31.39–50.00), and up to ~100 USD/tCO_2eq (actual range 70.0–120.91). Demand-side options (shown on the right-hand side of the figure) are for ~2050 and are not assessed at a specific carbon price, and should be regarded as technical potentials. Smith et al. (2013) values are mean of the range. Not all studies consider the same options or the same GHGs; further details are given in the text.

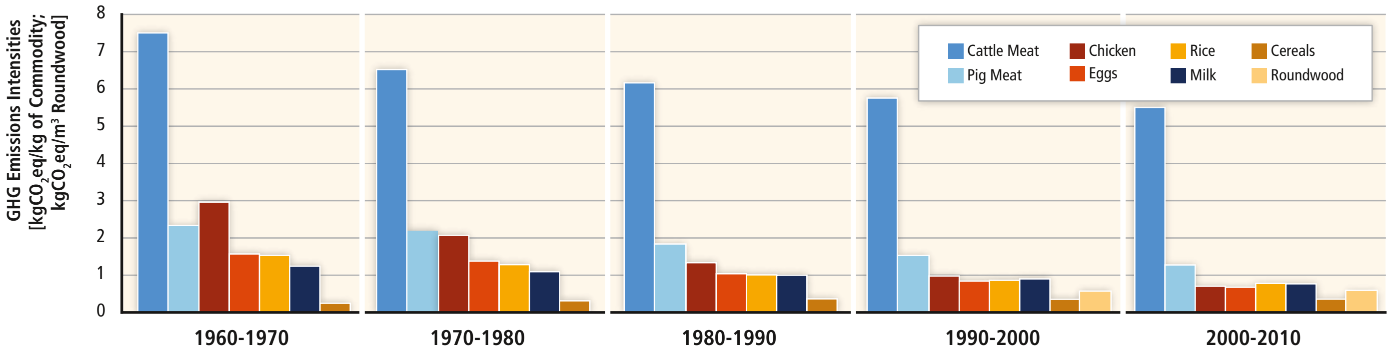


Figure 11.15 | GHG emissions intensities of selected major AFOLU commodities for decades 1960s–2000s, based on (Tubiello et al., 2012). i) Cattle meat, defined as GHG (enteric fermentation + manure management of cattle, dairy and non-dairy)/meat produced; ii) Pig meat, defined as GHG (enteric fermentation + manure management of swine, market and breeding)/meat produced; iii) Chicken meat, defined as GHG (manure management of chickens)/meat produced; iv) Milk, defined as GHG (enteric fermentation + manure management of cattle, dairy)/milk produced; v) Eggs, defined as GHG (manure management of chickens, layers)/egg produced; vi) Rice, defined as GHG (rice cultivation)/rice produced; vii) Cereals, defined as GHG (synthetic fertilizers)/cereals produced; viii) Wood, defined as GHG (carbon loss from harvest)/roundwood produced. Data Source: (FAOSTAT, 2013).

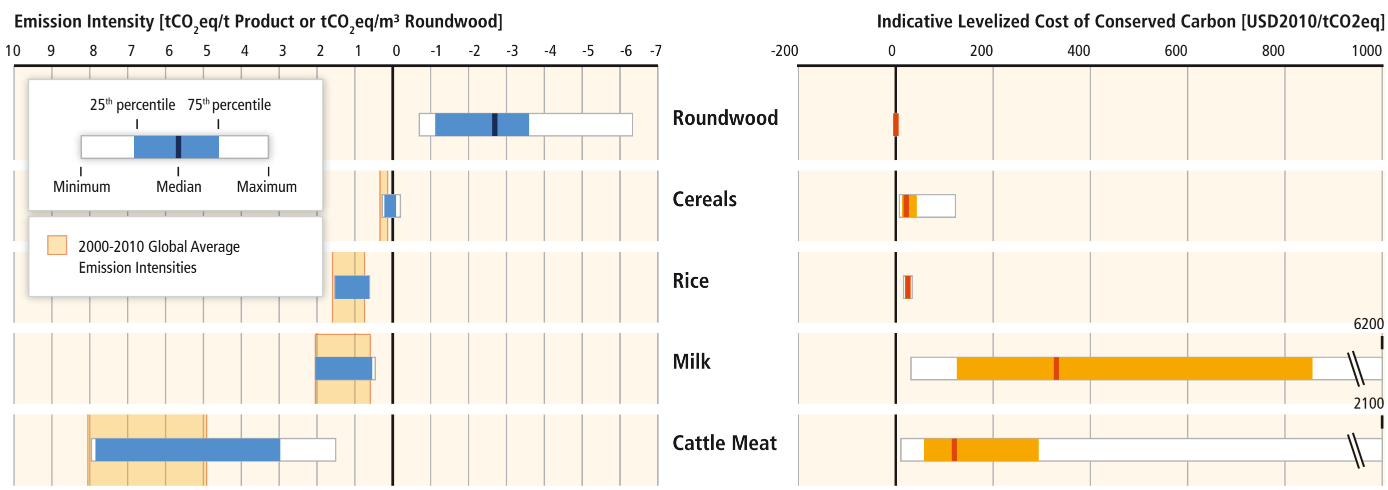


Figure 11.16 | Potential changes of emission intensities of major AFOLU commodities through implementation of commodity-specific mitigation measures (left panel) and related mitigation costs (right panel). Commodities and GHG emission sources are defined as in Figure 11.15, except for roundwood, expressed as the amount of carbon sequestered per unit roundwood from reforestation and afforestation within dedicated plantation cycles. Agricultural emission intensities represent regional averages, calculated based on 2000–2010 data (FAOSTAT, 2013) for selected commodities. Data on mitigation potentials and costs of measures are calculated using the mean values reported by (Smith et al., 2008) and the maximum and minimum are defined by the highest and lowest values for four climate zones for cereals and rice, or five geographical regions for milk and cattle meat. Emission intensities and mitigation potentials of roundwood production are calculated using data from Sathaye et al. (2005; 2006), FAO (2006), and IPCC (2006); maximum and minimum values are defined by the highest and lowest values for 10 geographical regions. The right panel shows the mitigation costs (in USD/tCO_2eq) of commodity-specific mitigation measures (25th to 75th percentile range).

Table 11.8 | Ranges of global mitigation potential (GtCO_2eq/yr) reported since AR4 | All values are for 2030 except demand-side options that are for ~2050 (full data shown in Figure 11.14).

	up to 20 USD/tCO_2eq	up to 50 USD/tCO_2eq	up to 100 USD/tCO_2eq	Technical potential only
Agriculture only[1]	0–1.59	0.03–2.6	0.26–4.6	-
Forestry only	0.01–1.45	0.11–9.5	0.2–13.8	-
AFOLU total[1,2]	0.12–3.03	0.5–5.06	0.49–10.6	-
Demand-side options	-	-	-	0.76–8.55

Notes:

1 All lower range values for agriculture are for non-CO_2 GHG mitigation only and do not include soil C sequestration

2 AFOLU total includes only estimates where both agriculture and forestry have been considered together.

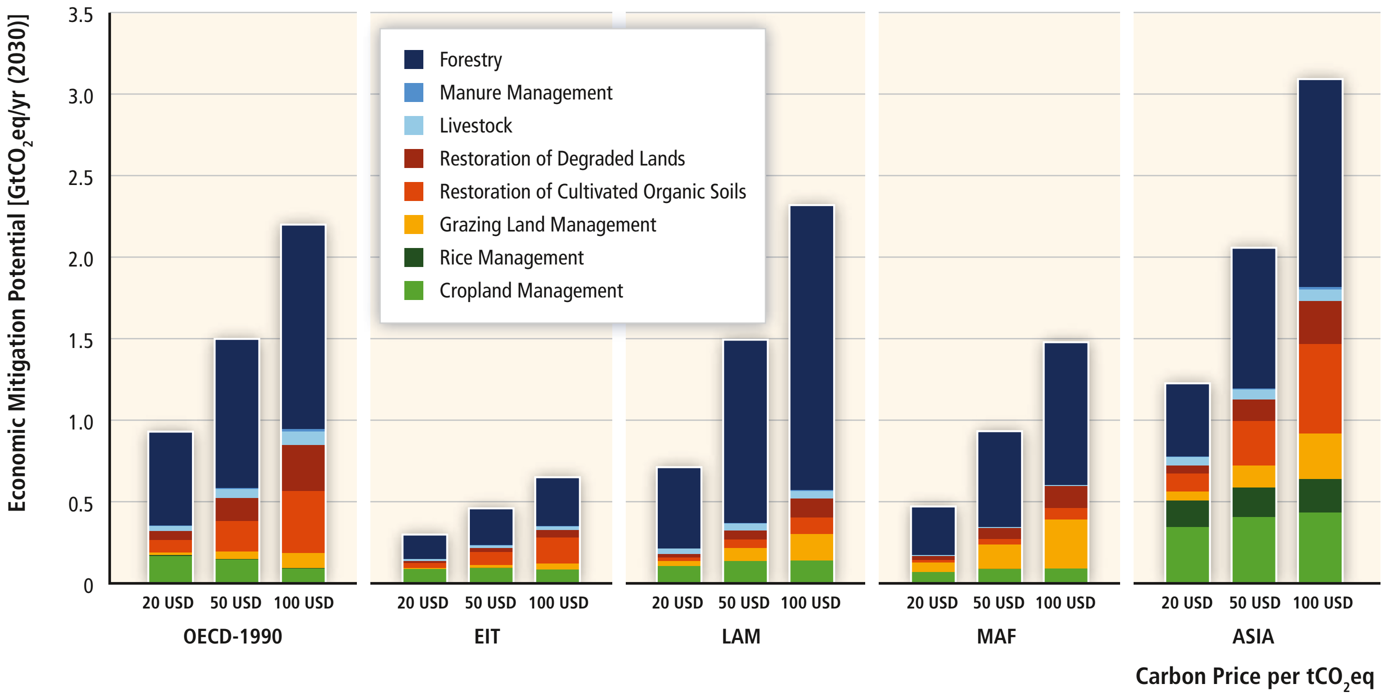


Figure 11.17 | Economic mitigation potentials in the AFOLU sector by region. Agriculture values are from Smith et al. (2007). Forestry values are from Nabuurs et al. (2007). For forestry, 20 USD values correspond to 'low', and 100 USD values correspond to 'high' values from Nabuurs et al. (2007). Values of 50 USD represent the mean of the 'high' and 'low' values from Nabuurs et al. (2007).

Differences between the most effective forestry options in each region (Figure 11.18) are particularly striking, with reduced deforestation dominating the forestry mitigation potential LAM and MAF, but very little potential in OECD-1990 and EIT. Forest management, followed by afforestation, dominate in OECD-1990, EIT, and Asia (Figure 11.18). Among agricultural options, among the most striking of regional differences are the rice management practices for which almost all of the global potential is in Asia, and the large potential for restoration of organic soils also in Asia (due to cultivated Southeast Asian peats), and OECD-1990 (due to cultivated northern peatlands; Figure 11.18).

11.7 Co-benefits, risks, and spillovers

Implementation of AFOLU mitigation measures (Section 11.3) will result in a range of outcomes beyond changes in GHG balances with respect to institutional, economic, social, and environmental objectives. To the extent these effects are positive, they can be deemed 'co-benefits'; if adverse and uncertain, they imply risks.[8] A global assessment of the co-benefits and adverse side-effects of AFOLU mitigation measures is challenging for a number of reasons. First, co-benefits and adverse side-effects depend on the development context and the scale of the intervention (size), i.e., implementing the same AFOLU mitigation measure in two different areas (different countries or different regions within a country) can have different socio-economic, institutional, or environmental effects (Forner et al., 2006; Koh and Ghazoul, 2008; Trabucco et al., 2008; Zomer et al., 2008; Alves Finco and Doppler, 2010; Alig et al., 2010, p. 201; Colfer, 2011; Davis et al., 2013; Albers and Robinson, 2013; Muys et al., 2014). Thus the effects are site-specific and generalizations are difficult. Second, these effects do not necessarily overlap geographically, socially, or over the same time scales (Section 11.4.5). Third, there is no general agreement on attribution of co-benefits and adverse side-effects to specific AFOLU mitigation measures; and fourth there are no standardized metrics for quantifying many of these effects. Modelling frameworks are being developed that allow an integrated assessment of multiple outcomes at landscape (Bryant et al., 2011), project (Townsend et al., 2012), and smaller (Smith et al., 2013a) scales. Table 11.9 presents an overview of the potential effects from AFOLU mitigation measures, while the text presents the most relevant co-benefits and potential adverse side-effects from the recent literature.

Maximizing co-benefits of AFOLU mitigation measures can increase efficiency in achieving the objectives of other international agreements, including the United Nations Convention to Combat Desertification (UNCCD, 2011), or the Convention on Biological Diversity (CBD), and mitigation actions may also contribute to a broader global sus-

8 Co-benefits and adverse side-effects describe effects in non-monetary units without yet evaluating the net effect on overall social welfare. Please refer to the respective sections in the framing chapters as well as to the glossary in Annex I for concepts and definitions—particularly Sections 2.4, 3.6.3, and 4.8.

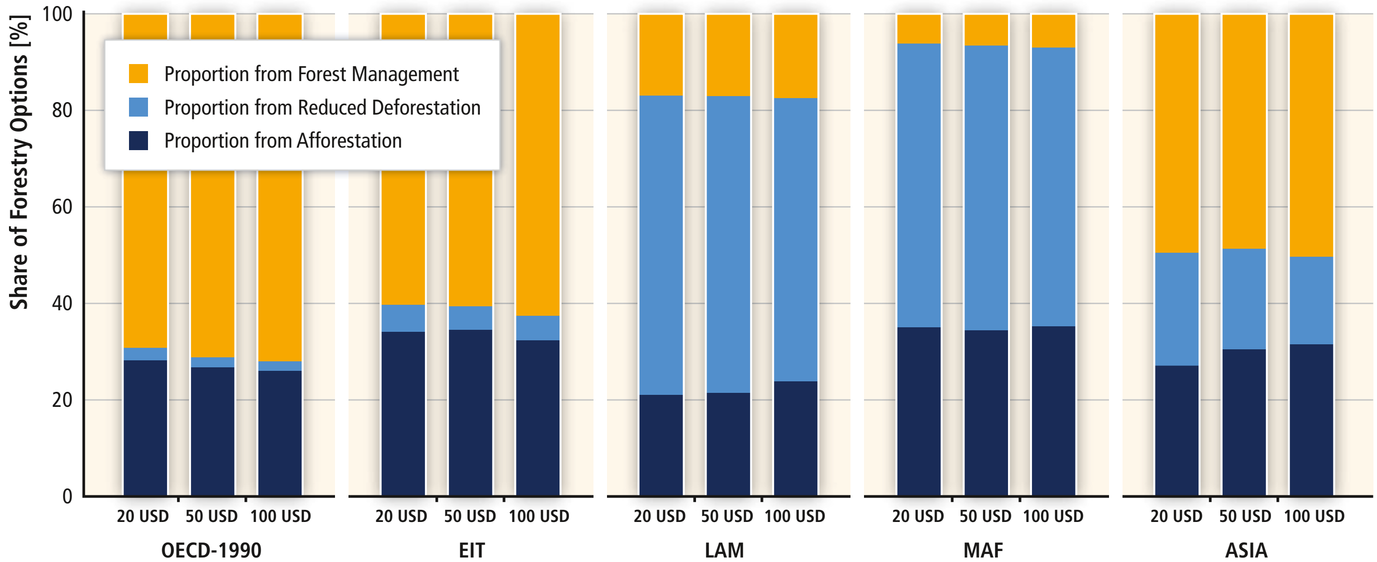


Figure 11.18 | Regional differences in forestry options, shown as a proportion of total potential available in forestry in each region. Global forestry activities (annual amount sequestered or emissions avoided above the baseline for forest management, reduced deforestation and afforestation), at carbon prices up to 100 USD/tCO_2 are aggregated to regions from results from three models of global forestry and land use: the Global Timber Model (GTM; Sohngen and Sedjo, 2006), the Generalized Comprehensive Mitigation Assessment Process (Sathaye et al., 2006), and the Dynamic Integrated Model of Forestry and Alternative Land Use (Benítez et al., 2007).

tainability agenda (Harvey et al., 2010; Gardner et al., 2012; see Chapter 4). In many cases, implementation of these agendas is limited by capital, and mitigation may provide a new source of finance (Tubiello et al., 2009).

11.7.1 Socio-economic effects

AFOLU mitigation measures can affect institutions and living conditions of the various social groups involved. This section includes potential effects of AFOLU mitigation measures on three dimensions of sustainable development: institutional, social, and economic (Section 11.4.5).

AFOLU mitigation measures may have impacts on *land tenure and land-use rights* for several social groups including indigenous peoples, local communities and other social groups, dependant on natural assets. Co-benefits from AFOLU mitigation measures can be clarification of land tenure and harmonization of rights, while adverse side-effects can be lack of recognition of customary rights, loss of tenure or possession rights, and even displacement of social groups (Sunderlin et al., 2005; Chhatre and Agrawal, 2009; Blom et al., 2010; Sikor et al., 2010; Robinson et al., 2011; Rosemary, 2011; Larson, 2011; Rosendal and Andresen, 2011). Whether an impact on land tenure and use rights is positive or negative depends upon two factors: (a) the institutions regulating land tenure and land-use rights (e.g., laws, policies), and (b) the level of enforcement by such institutions (Corbera and Brown, 2008; Araujo et al., 2009; Rosemary, 2011; Larson et al., 2013; Albers and Robinson, 2013). More research is needed on specific tenure forms (e.g., individual property, state ownership or community rights), and on the specific effects from tenure and rights options, on enabling AFOLU mitigation measures and co-benefits in different regions under specific circumstances (Sunderlin et al., 2005; Katila, 2008; Chhatre and Agrawal, 2009; Blom et al., 2010; Sikor et al., 2010; Robinson et al., 2011; Rosemary, 2011; Larson, 2011; Rosendal and Andresen, 2011).

AFOLU mitigation measures can support *enforcement of sectoral policies* (e.g., conservation policies) as well as *cross-sectoral coordination* (e.g., facilitating a landscape view for policies in the agriculture, energy, and forestry sectors (Brockhaus et al., 2013). However, AFOLU mitigation activities can also introduce or reduce clashes with existing policies in other sectors (e.g., if a conservation policy covers a forest area, where agricultural land is promoted by another policy (Madlener et al., 2006; Halsnæs and Verhagen, 2007; Smith et al., 2007; Beach et al., 2009; Alig et al., 2010; Jackson and Baker, 2010; DeFries and Rosenzweig, 2010; Pettenella and Brotto, 2011; Section 11.10).

An area of increasing concern since AR4 is the potential impact of AFOLU mitigation measures on *food security.* Efforts to reduce hunger and malnutrition will increase individual food demand in many developing countries, and population growth will increase the number of individuals requiring secure and nutritionally sufficient food production. Thus, a net increase in food production is an essential component for securing sustainable development (Ericksen et al., 2009; FAO, WFP, and IFAD, 2012). AFOLU mitigation measures linked to increases in food production (e.g., agroforestry, intensification of agricultural production, or integrated systems) can increase food availability and access especially at the local level, while other measures (e.g., forest or energy crop plantations) can reduce food production at least locally (Foley et al., 2005; McMichael et al., 2007;

Pretty, 2008; Godfray et al., 2010; Jackson and Baker, 2010; Graham-Rowe, 2011; Jeffery et al., 2011).

Regarding *human health* reduced emissions from agriculture and forestry may also improve air, soil, and water quality (Smith et al., 2013a), thereby indirectly providing benefits to human health and well-being. Demand-side measures aimed at reducing the proportion of livestock products in human diets that are high in animal products are also associated with multiple health benefits (McMichael et al., 2007; Stehfest et al., 2009; Marlow et al., 2009). AFOLU mitigation measures, particularly in the livestock sector, can have an impact on *animal welfare* (Sundrum, 2001; Lund and Algers, 2003; Keeling et al., 2011; Kehlbacher et al., 2012; Koknaroglu and Akunal, 2013).

A major area of concern is related to the potential impacts of AFOLU mitigation measures on *equity* (Sections 3.3; 4.2; 4.7;

Box 11.6 | Challenges for mitigation in developing countries in the AFOLU sector

Mitigation challenges related to the AFOLU sector

The contribution of developing countries to future GHG emissions is expected to be very significant due to projected increases in food production by 2030 driving short-term land conversion in these countries. Mitigation efforts in the AFOLU sector rely mainly on reduction of GHG emissions and an increase in carbon sequestration (Table 11.2). Potential activities include reducing deforestation, increasing forest cover, agroforestry, agriculture and livestock management, and production of sustainable renewable energy (Sathaye et al., 2005; Smith et al., 2013b). Although agriculture and forestry are important sectors for GHG abatement (Section 11.2.3), it is likely that technology alone will not be sufficient to deliver the necessary transitions to a low-GHG future (Alig et al., 2010; Section 11.3.2). Other barriers include access to market and credits, technical capacities to implement mitigation options, including accurate reporting of emission levels and emission factors based on activity data, and institutional frameworks and regulations (Corbera and Schroeder, 2011; Mbow et al., 2012; Sections 11.7; 11.8). Additionally, the diversity of circumstances among developing countries makes it difficult to establish the modelled relationships between GDP and CO_2 emissions per capita found by using the Kaya identity. This partly arises from the wide gap between rural and urban communities, and the difference in livelihoods (e.g., the use of fuel wood, farming practices in various agro-ecological conditions, dietary preferences with a rising middle class in developing countries, development of infrastructure, and behavioural change, etc.; Lambin and Meyfroidt, 2011). Also, some mitigation pathways raise the issue of non-permanence and leakage that can lead to the transfer activities to non-protected areas, which may threaten conservation areas in countries with low capacities (Lippke et al., 2003; Jackson and Baker, 2010; Section 11.3.2).

Critical issues to address are the co-benefits and adverse side-effects associated with changed agricultural production, the necessary link between mitigation and adaptation, and how to manage incentives for a substantial GHG abatement initiative without compromising food security (Smith and Wollenberg, 2012; Sections 11.5; 11.7). The challenge is to strike a balance between emissions reductions/adaptation and development/poverty alleviation priorities, or to find policies that co-deliver. Mitigation pathways in developing countries should address the dual need for mitigation and adaptation through clear guidelines to manage multiple options (Section 11.5.4). Prerequisites for the successful implementation of AFOLU mitigation projects are ensuring that (a) communities are fully engaged in implementing mitigation strategies, (b) any new strategy is consistent with ongoing policies or programmes, and (c) *a priori* consent of small holders is given. Extra effort is required to address equity issues including gender, challenges, and prospects (Mbow et al., 2012).

Mitigation challenges related to the bioenergy sector

Bioenergy has a significant mitigation potential, provided that the resources are developed sustainably and that bioenergy systems are efficient (Chum et al., 2011; Section 11.9.1). Bioenergy production can be integrated with food production in developing countries, e.g., through suitable crop rotation schemes, or use of by-products and residues (Berndes et al., 2013). If implemented sustainably this can result in higher food and energy outcomes and hence reduce land-use competition. Some bioenergy options in developing countries include perennial cropping systems, use of biomass residues and wastes, and advanced conversion systems (Beringer et al., 2011; Popp et al., 2011; Box 7.1). Agricultural and forestry residues can provide low-carbon and low-cost feedstock for bioenergy. Biomass from cellulosic bioenergy crops feature substantially in future energy systems, especially in the framework of global climate policy that aims at stabilizing CO_2 concentration at low levels (Popp et al., 2011; Section 11.13). The large-scale use of bioenergy is controversial in the context of developing countries because of the risk of reducing carbon stocks and releasing carbon to the atmosphere (Bailis and McCarthy, 2011), threats to food security in Africa (Mbow, 2010), and threats to biodiversity *via* the conversion of forests to biofuel (e.g., palm oil) plantations. Several studies underline the inconsistency between the need for bioenergy and the requirement for, e.g., Africa, to use its productive lands for sustainable food production (Cotula et al., 2009). Efficient biomass production for bioenergy requires a range of sustainability requirements to safeguard food production, biodiversity, and terrestrial carbon storage.

4.8). Depending on the actual and perceived distribution of socio-economic benefits, responsibilities (burden sharing), as well the access to decision making, financing mechanisms, and technology, AFOLU mitigation measures can promote inter- and intra-generational equity (Di Gregorio et al., 2013). Conversely, depending on the policy instruments and the implementation schemes of these mitigation measures, they can increase inequity and land conflicts, or marginalize small-scale farm/forest owners or users (Robinson et al., 2011; Kiptot and Franzel, 2012; Huettner, 2012; Mattoo and Subramanian, 2012). Potential impacts on equity and benefit-sharing mechanisms arise for AFOLU activities using forestry measures in developing countries including conservation, restoration, reduced deforestation and degradation, as well as sustainable management and afforestation/reforestation (Combes Motel et al., 2009; Cattaneo et al., 2010; Rosemary, 2011).

Large-scale land acquisition (often referred to as 'land grabbing') related to the promotion of AFOLU mitigation measures (especially for production of bioenergy crops) and its links to sustainable development in general, and equity in particular, are emerging issues in the literature (Cotula et al., 2009; Scheidel and Sorman, 2012; Mwakaje, 2012; Messerli et al., 2013; German et al., 2013).

In many cases, the implementation of agricultural and forestry systems with positive impacts mitigating climate change are limited by capital, and *carbon payments or compensation mechanisms* may provide a new source of finance (Tubiello et al., 2009). For instance, in some cases, mitigation payments can help to make production of non-timber forest products (NTFP) economically viable, further *diversifying income* at the local level (Singh, 2008). However, depending on the accessibility of the financing mechanisms (payments, compensation, or other) economic benefits can become concentrated, marginalizing many local stakeholders (Combes Motel et al., 2009; Alig et al., 2010; Asante et al., 2011; Asante and Armstrong, 2012; Section 11.8). The realization of economic co-benefits is related to the design of the specific mechanisms and depends upon three main variables: (a) the amount and coverage of these payments, (b) the recipient of the payments, and (c) timing of payments (*ex-ante* or *ex-post*; Corbera and Brown, 2008; Skutsch et al., 2011). Further considerations on financial mechanisms and carbon payments, both within and outside UNFCCC agreements, are described in Section 11.10.

Financial flows supporting AFOLU mitigation measures (e.g., those resulting from the REDD+) can have positive effects on conserving biodiversity, but could eventually create conflicts with conservation of biodiversity hotspots, when their respective carbon stocks are low (Gardner et al., 2012; Section 11.10). Some authors propose that carbon payments can be complemented with biodiversity payments as an option for reducing tradeoffs with biodiversity conservation (Phelps et al., 2010a). Bundling of ecosystem service payments, and links to carbon payments, is an emerging area of research (Deal and White, 2012).

11.7.2 Environmental effects

Availability of land and land competition can be affected by AFOLU mitigation measures. Different stakeholders may have different views on what land is available, and when considering several AFOLU mitigation measures for the same area, there can be different views on the importance of the goods and ecosystem services provided by the land, e.g., some AFOLU measures can increase food production but reduce water availability or other environmental services. Thus decision makers need to be aware of potential site-specific tradeoffs within the sector. A further potential adverse side-effect is that of increasing land rents and food prices due to a reduction in land availability for agriculture in developing countries (Muller, 2009; Smith et al., 2010, 2013b; Rathmann et al., 2010; Godfray et al., 2010; de Vries and de Boer, 2010; Harvey and Pilgrim, 2011; Amigun et al., 2011; Janzen, 2011; Cotula, 2012; Scheidel and Sorman, 2012; Haberl et al., 2013a).

AFOLU mitigation options can promote conservation of *biological diversity* (Smith et al., 2013a) both by reducing deforestation (Chhatre et al., 2012; Murdiyarso et al., 2012; Putz and Romero, 2012; Visseren-Hamakers et al., 2012), and by using reforestation/afforestation to restore biodiverse communities on previously developed farmland (Harper et al., 2007). However, promoting land-use changes (e.g., through planting monocultures on biodiversity hot spots) can have adverse side-effects, reducing biodiversity (Koh and Wilcove, 2008; Beringer et al., 2011; Pandit and Grumbine, 2012; Ziv et al., 2012; Hertwich, 2012; Gardner et al., 2012).

In addition to potential climate impacts, land-use intensity drives the three main N loss pathways (nitrate leaching, denitrification, and ammonia volatilization) and typical *N balances* for each land use indicate that total N losses also increase with increasing land-use intensity (Stevenson et al., 2010). Leakages from the N cycle can cause air (e.g., ammonia (NH_3^+), nitrogen oxides (NO_x))[9], soil nitrate (NO_3^-) and water pollution (e.g., eutrophication), and agricultural intensification can lead to a variety of other adverse environmental impacts (Smith et al., 2013a). Combined strategies (e.g., diversified crop rotations and organic N sources) or single-process strategies (e.g., reduced N rates, nitrification inhibitors, and changing chemical forms of fertilizer) can reduce N losses (Bambo et al., 2009; Gardner and Drinkwater, 2009). Integrated systems may be an alternative approach to reduce leaching (Section 11.10).

AFOLU mitigation measures can have either positive or negative *impacts on water resources*, with responses dependant on the mitigation measure used, site conditions (e.g., soil thickness and slope, hydrological setting, climate; Yu et al., 2013) and how the particular mitigation measure is managed. There are two main components: water yield and water quality. Water yields can be manipulated with forest management, through afforestation, reforestation, for-

9 Please see Section 7.9.2 and WGII Section 11.9 for a discussion of health effects related to air pollution.

Table 11.9 | Summary of potential co-benefits (green arrows) and adverse side-effects (orange arrows) from AFOLU mitigation measures; arrows pointing up/down denote positive/negative effect on the respective issue. These effects depend on the specific context (including bio-physical, institutional, and socio-economic aspects) as well as on the scale of implementation. For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see Sections 3.9, 6.3.6, 13.2.2.3, and 14.4.2. Note: Co-benefits/adverse side-effects of bioenergy are discussed in Section 11.13.

	Issue	Potential co-benefit or adverse side-effect	Scale	AFOLU mitigation measure
Institutional	Land tenure and use rights	Improving (↑) or diminishing (↓) tenure and use rights for local communities and indigenous peoples, including harmonization of land tenure and use regimes (e.g., with customary rights)	Local to national	Forestry (4, 5, 6, 8, 9, 12, 20)
	Sectoral policies	Promoting (↑) or contradicting (↓) the enforcement of sectoral (forest and/or agriculture) policies	National	Forestry (2, 5, 6, 9, 20); land-based agriculture (7, 11, 20)
	Cross-sectoral policies	Cross-sectoral coordination (↑) or clashes (↓) between forestry, agriculture, energy, and/or mining policies	Local to national	Forestry (7, 20); agriculture (7, 11, 20)
	Participative mechanisms	Creation/use of participative mechanisms (↑) for decision making regarding land management (including participation of various social groups, e.g., indigenous peoples or local communities)	Local to national	Forestry (4, 5, 6, 8, 9, 14, 20); agriculture (20, 32); integrated systems (20, 34)
	Benefit sharing mechanisms	Creation/use of benefits-sharing mechanisms (↑) from AFOLU mitigation measures	Local to national	Forestry (4, 5, 6, 8, 20)
Social	Food security	Increase (↑) or decrease (↓) on food availability and access	Local to national	Forestry (18, 19); agriculture (7, 15, 18, 19, 23, 28, 30); livestock (2, 3, 19, 35, 36); integrated systems (18, 19); biochar (17, 26)
	Local/traditional knowledge	Recognition (↑) or denial (↓) of indigenous and local knowledge in managing (forest/agricultural) land	Local/sub-national	Forestry (4, 5, 6, 8, 20); agriculture (20, 28); integrated systems (2); livestock (2, 3, 35); biochar (2)
	Animal welfare	Changes in perceived or measured animal welfare (perceived due to cultural values or measured, e.g., through amount of stress hormones)	Local to national	Livestock (2, 31, 35, 37, 38)
	Cultural values	Respect and value cultural habitat and traditions (↑), reduce (↓), or increase (↑) existing conflicts or social discomfort (4, 5, 6, 20, 8)	Local to trans-boundary	Forestry (4, 5, 6, 9, 20)
	Human health	Impacts on health due to dietary changes, especially in societies with a high consumption of animal protein (↓)	Local to global	Changes in demand patterns (31, 36)
	Equity	Promote (↑) or not (↓) equal access to land, decision making, value chain, and markets as well as to knowledge- and benefit-sharing mechanisms	Local to global	Forestry (4, 5, 6, 8, 9, 10, 20); agriculture (11, 23, 32)
Economic	Income	Increase (↑) or decrease (↓) in income. There are concerns regarding income distribution (↑)	Local	Forestry (6, 7, 8, 16, 20, 21, 22); agriculture (16, 19, 20, 23, 28); livestock (2, 3); integrated systems (7, 20); biochar (24); changes in demand patterns (2)
	Employment	Employment creation (↑) or reduction of employment (especially for small farmers or local communities) (↓)	Local	Forestry (8, 20); agriculture (20, 23); livestock (2, 3); integrated systems (7, 20)
	Financing mechanisms	Access (↑) or lack of access (↓) to new financing schemes	Local to global	Forestry (6, 8, 16, 20); agriculture (16, 20); livestock (2, 3)
	Economic activity	Diversification and increase in economic activity (↑) while concerns on equity (↑)	Local	Forestry (6, 7, 8, 20); land-based agriculture (16, 19, 20, 23, 28); livestock (2, 3)
Environmental	Land availability	Competition between land uses and risk of activity or community displacement (↑)	Local to trans-boundary	Forestry and land-based-agriculture (5, 6, 15, 18, 20, 29, 30); livestock (2, 3, 29, 40)
	Biodiversity	Monocultures can reduce biodiversity (↓). Ecological restoration increases biodiversity and ecosystem services (↑) by 44 and 25% respectively (28). Conservation, forest management, and integrated systems can keep biodiversity (↑) and/or slow desertification (↓)	Local to trans-boundary	Forestry (1, 19, 20, 27); on conservation and forest management (1, 19, 21, 27, 30); agriculture and integrated systems (15, 19, 20, 28, 30)
	Albedo	Positive impacts (↑) on albedo and evaporation and interactions with ozone	Local to global	See Section 11.5
	N and P cycles	Impacts on N and P cycles in water (↓/↑) especially from monocultures or large agricultural areas	Local to trans-boundary	Agriculture (19, 23, 30, 35); livestock (2, 3, 30)
	Water resources	Monocultures and /or short rotations can have negative impacts on water availability (↓). Potential water depletion due to irrigation (↓). Some management practices can support regulation of the hydrological cycle and protection of watersheds (↑)	Local to trans-boundary	Forestry (1, 19, 20, 27); land-based agriculture (30, 44); integrated systems (2, 30, 44)
	Soil	Soil conservation (↑) and improvement of soil quality and fertility (↑). Reduction of erosion. Positive or negative carbon mineralization priming effect (↑/↓)	Local	Forestry (44, 45); land-based agriculture (13, 19, 23, 28, 30); integrated systems biochar (39, 40)
	New products	Increase (↑) or decrease (↓) on fibre availability as well as non-timber/non-wood products output	Local to national	Forestry (18, 19, 41, 42); agriculture (7, 15, 18, 19, 23, 28, 30); integrated systems (18, 19)
	Ecosystem resilience	Increase (↑) or reduction (↓) of resilience, reduction of disaster risks (↓)	Local to trans-boundary	Forestry, integrated systems (11, 33; see Section 11.5)

	Issue	Potential co-benefit or adverse side-effect	Scale	AFOLU mitigation measure
Technology	Infrastructure	Increase (↑) or decrease (↓) in availability of and access to infrastructure. Competition for infrastructure for agriculture (↑), can increase social conflicts	Local	Agriculture (20, 46, 47)
	Technology innovation and transfer	Promote (↑) or delay (↓) technology development and transfer	Local to global	Forestry (7, 13, 25); agriculture (23); livestock (2, 3)
	Technology Acceptance	Can facilitate acceptance of sustainable technologies (↑)	Local to national	Forestry (7, 13, 25); livestock (2, 3, 35)

Notes: AFOLU mitigation measures are grouped following the structure given in Table 11.2

Sources: [1]Trabucco et al., 2008; [2]Steinfeld et al., 2010; [3]Gerber et al., 2010; [4]Sikor et al., 2010; [5]Rosemary, 2011; [6]Pettenella and Brotto, 2011; [7]Jackson and Baker, 2010; [8]Corbera and Schroeder, 2011; [9]Colfer, 2011; [10]Blom et al., 2010; [11]Halsnæs and Verhagen, 2007; [12]Larson, 2011; [13]Lichtfouse et al., 2009; [14]Thompson et al., 2011; [15]Graham-Rowe, 2011; [16]Tubiello et al., 2009; [17]Barrow, 2012; [18]Godfray et al., 2010; [19]Foley et al., 2005 ; [20]Madlener et al., 2006; [21]Strassburg et al., 2012; [22]Canadell and Raupach, 2008; [23]Pretty, 2008; [24]Galinato et al., 2011; [25]Macauley and Sedjo, 2011; [26]Jeffery et al., 2011; [27]Benayas et al., 2009; [28]Foley et al., 2011; [29]Haberl et al., 2013; [30]Smith et al., 2013; [31]Stehfest et al., 2009; [32]Chhatre et al., 2012; [33]Seppälä et al., 2009; [34]Murdiyarso et al., 2012; [35]de Boer et al., 2011; [36]McMichael et al., 2007; [37]Koknaroglu and Akunal, 2013; [38]Kehlbacher et al., 2012; [39]Zimmerman et al., 2011; [40]Luo et al., 2011; [41]Mirle, 2012; [42]Albers and Robinson, 2013; [43]Smith et al., 2013a; [44]Chatterjee and Lal, 2009; [45]Smith, 2008; [46]Ziv et al., 2012; [47]Beringer et al., 2011; [48]Douglas et al., 2009

est thinning, or deforestation. In general, reduction in water yields in afforestation/reforestation projects has been reported in both groundwater or surface catchments (Jackson et al., 2005), or where irrigation water is used to produce bioenergy crops. For water supply security, it is important to consider the relative yield reduction and this can have severe consequences in dry regions with inherent water shortages (Wang et al., 2011c). Where there is a water imbalance, however, this additional water use can be beneficial by reducing the efflux of salts (Jackson et al., 2005). Another aspect of water yield is the reduction of flood peaks, and also prolonged periods of water flow, because discharge is stabilized (Jackson et al., 2005), however low flows can be reduced because of increased forest water use. Water quality can be affected by AFOLU in several ways. For example, minimum tillage systems have been reported to reduce water erosion and thus sedimentation of water courses (Lal, 2011). Deforestation is well known to increase erosion and thus efflux of silt; avoiding deforestation will prevent this. In other situations, watershed scale reforestation can result in the restoration of water quality (e. g., Townsend et al., 2012). Furthermore, strategic placement of tree belts in lands affected by dryland salinity can remediate the affected lands by lowering the water table (Robinson et al., 2004) . Various types of AFOLU mitigation can result in degradation of water sources through the losses of pesticides and nutrients to water (Smith et al., 2013a).

AFOLU mitigation measures can have several *impacts on soil*. Increasing or maintaining carbon stocks in living biomass (e. g., through forest or agroforestry systems) will reduce wind erosion by acting as wind breaks and may increase crop production; and reforestation, conservation, forest management, agricultural systems, or bioenergy systems can be used to restore degraded or abandoned land (Smith et al., 2008; Stickler et al., 2009; Chatterjee and Lal, 2009; Wicke et al., 2011b; Sochacki et al., 2012). Silvo-pastoral systems can help to reverse land degradation while providing food (Steinfeld et al., 2008, 2010; Janzen, 2011). Depending on the soil type, production temperature regimes, the specific placement and the feedstock tree species, biochar can have positive or negative carbon mineralization priming effects over time (Zimmerman et al., 2011; Luo et al., 2011).

AFOLU mitigation options can promote innovation, and many technological supply-side mitigation options outlined in Section 11.3 also increase agricultural and silvicultural efficiency. At any given level of demand for agricultural products, intensification increases output per unit area and would therefore, if all else were equal, allow the reduction in farmland area, which would in turn free land for C sequestration and/or bioenergy production (Section 11.4). For example, a recent study calculated potentially large GHG reductions from global agricultural intensification by comparing the past trajectory of agriculture (with substantial yield improvements), with a hypothetical trajectory with constant technology (Burney et al., 2010). However, in real-world situations increases in yield may result in feedbacks such as increased consumption ('rebound effects'; see Section 11.4; Lambin and Meyfroidt, 2011; Erb, 2012).

11.7.3 Public perception

Mitigation measures that support sustainable development are likely to be viewed positively in terms of public perception, but a large-scale drive towards mitigation without inclusion of key stakeholder communities involved would likely not be greeted favourably (Smith and Wollenberg, 2012). However, there are concerns about competition between food and AFOLU outcomes, either because of an increasing use of land for biofuel plantations (Fargione et al., 2008; Alves Finco and Doppler, 2010), or afforestation/reforestation (Mitchell et al., 2012), or by blocking the transformation of forest land into agricultural land (Harvey and Pilgrim, 2011).

Further, lack of clarity regarding the architecture of the future international climate regime and the role of AFOLU mitigation measures is perceived as a potential threat for long-term planning and long-term investments (Streck, 2012; Visseren-Hamakers et al., 2012). Certain technologies, such as animal feed additives and genetically modified organisms are banned in some jurisdictions due to perceived health and/or environmental risks. Public perception is often as important as scientific evidence of hazard/risk in considering government policy regarding such technologies (Royal Society, 2009; Smith and Wollenberg, 2012).

11.7.4 Spillovers

Emerging knowledge on the importance of ecosystems services as a means for addressing climate change mitigation and adaptation have brought attention to the role of ecosystem management for achieving several development goals, beyond climate change adaptation and mitigation. This knowledge has enhanced the creation of ecosystem markets (Section 11.10). In some jurisdictions ecosystem markets are developing (MEA, 2005; Engel et al., 2008; Deal and White, 2012; Wünscher and Engel, 2012)and these allow valuation of various components of land-use changes, in addition to mitigation (Mayrand and Paquin, 2004; Barbier, 2007). Different approaches are used; in some cases the individual components (both co-benefits and adverse side-effects) are considered singly (bundled), in other situations they are considered together (stacked) (Deal and White, 2012). Ecosystem market approaches can serve as a framework to assess the benefits of mitigation actions from project, to regional and national level (Farley and Costanza, 2010). Furthermore, designing ecosystem market approaches yields methodologies for the evaluation of individual components (e.g., water quality response to reforestation, timber yield), and other types of ecosystem service (e.g., biodiversity, social amenity; Bryan et al., 2013).

11.8 Barriers and opportunities

Barriers and opportunities refer to the conditions provided by the development context (Section 11.4.5). These conditions can enable and facilitate (opportunities) or hinder (barriers) the full use of AFOLU mitigation measures. AFOLU programmes and policies can help to overcome barriers, but countries being affected by many barriers will need time, financing, and capacity support. In some cases, international negotiations have recognized these different circumstances among countries and have proposed corresponding approaches (e.g., a phased approach in the REDD+, Green Climate Fund; Section 11.10). Corresponding to the development framework presented in Section 11.4.5, the following types of barriers and benefits are discussed: socio-economic, environmental, institutional, technological, and infrastructural.

11.8.1 Socio-economic barriers and opportunities

The *design and coverage of the financing mechanisms* is key to successful use of the AFOLU mitigation potential (Section 11.10; Chapter 16). Questions remain over which costs will be covered by such mechanisms. If financing mechanisms fail to cover at least transaction and monitoring costs, they will become a barrier to the full implementation of AFOLU mitigation. According to some studies, opportunity costs also need to be fully covered by any financing mechanism for the AFOLU sector, especially in developing countries, as otherwise AFOLU mitigation measures would be less attractive compared to returns from other land uses (Angelsen, 2008; Cattaneo et al., 2010; Böttcher et al., 2012). Conversely, if financing mechanisms are designed to modify economic activity, they could provide an opportunity to leverage a larger proportion of AFOLU mitigation potential.

*Scale of financing s*ources can become either a barrier (if a relevant financial volume is not secured) or create an opportunity (if financial sources for AFOLU suffice) for using AFOLU mitigation potential (Streck, 2012; Chapter 16). Another element is the *accessibility to AFOLU financing* for farmers and forest stakeholders (Tubiello et al., 2009, p. 200; Havemann, 2011; Colfer, 2011). Financial concerns, including reduced access to loan and credits, high transaction costs or reduced income due to price changes of carbon credits over the project duration, are potential risks for AFOLU measures, especially in developing countries, and when land holders use market mechanisms (e.g., Afforestation and Reforestation (A/R) Clean Development Mechanism (CDM); Madlener et al., 2006).

Poverty is characterized not only by low income, but also by insufficient food availability in terms of quantity and/or quality, limited access to decision making and social organization, low levels of education and reduced access to resources (e.g., land or technology; UNDP International Poverty Centre, 2006). High levels of poverty can limit the possibilities for using AFOLU mitigation options, because of short-term priorities and lacking resources. In addition, poor communities have limited skills and sometimes lack of social organization that can limit the use and scaling up of AFOLU mitigation options, and can increase the risk of displacement, with other potential adverse side-effects (Smith and Wollenberg, 2012; Huettner, 2012). This is especially relevant when forest land sparing competes with other development needs e.g., increasing land for agriculture or promoting some types of mining (Forner et al., 2006), or when large-scale bioenergy compromises food security (Nonhebel, 2005; Section 11.13).

Cultural values and social acceptance can determine the feasibility of AFOLU measures, becoming a barrier or an opportunity depending of the specific circumstances (de Boer et al., 2011).

11.8.2 Institutional barriers and opportunities

Transparent and accountable governance and swift institutional establishment are very important for a sustainable implementation of AFOLU mitigation measures. This includes the need to have *clear land tenure and land-use rights* regulations and a certain level of enforcement, as well as clarity about carbon ownership (Palmer, 2011; Thompson et al., 2011; Markus, 2011; Rosendal and Andresen, 2011; Murdiyarso et al., 2012 Sections 11.4.5; 11.10; Chapters 14; 15).

Lack of institutional capacity (as a means for securing creation of equal institutions among social groups and individuals) can reduce feasibility of AFOLU mitigation measures in the near future, especially in areas where small-scale farmers or forest users are the main stakeholders (Laitner et al., 2000; Madlener et al., 2006; Thompson et al., 2011a). *Lack of an international agreement* that supports a wide implementation of AFOLU measures can become a major barrier for realizing the mitigation potential from the sector globally (Section 11.10; Chapter 13).

11.8.3 Ecological barriers and opportunities

Mitigation potential in the agricultural sector is highly site-specific, even within the same region or cropping system (Baker et al., 2007; Chatterjee and Lal, 2009). *Availability of land and water* for different uses need to be balanced, considering short- and long-term priorities, and global differences in resource use. Consequently, limited resources can become an ecological barrier and the decision of how to use them needs to balance ecological integrity and societal needs (Jackson, 2009).

At the local level, the *specific soil conditions, water availability, GHG emission-reduction potential as well as natural variability and resilience* to specific systems will determine the level of realization of mitigation potential of each AFOLU measure (Baker et al., 2007; Halvorson et al., 2011). Frequent droughts in Africa and changes in the hydrometeorological events in Asia and Central and South America are important in defining the specific regional potential (Bradley et al., 2006; Rotenberg and Yakir, 2010). Ecological saturation (e.g., soil carbon or yield) means that some AFOLU mitigation options have their own limits (Section 11.5). The fact that many *AFOLU measures can provide adaptation benefits* provides an opportunity for increasing ecological efficiency (Guariguata et al., 2008; van Vuuren et al., 2009; Robledo et al., 2011; Section 11.5).

11.8.4 Technological barriers and opportunities

Technological barriers refer to the limitations in generating, procuring, and applying science and technology to identify and solve an environmental problem. Some mitigation technologies are already applied now (e.g., afforestation, cropland, and grazing land management, improved livestock breeds and diets) so there are no technological barriers for these options, but others (e.g., some livestock dietary additives, crop trait manipulation) are still at the development stage (see Table 11.2).

The *ability to manage and re-use knowledge assets* for scientific communication, technical documentation and learning is lacking in many areas where mitigation could take place. Future developments present opportunities for additional mitigation to be realized if efforts to deliver ease-of-use and range-of-use are guaranteed. There is also a need to adapt technology to local needs by focusing on existing local opportunities (Kandji et al., 2006), as proposed in Nationally Appropriate Mitigation Actions (NAMAs) (Section 11.10).

Barriers and opportunities related to *monitoring, reporting, and verification* of the progress of AFOLU mitigation measures also need be considered. Monitoring activities, aimed at reducing uncertainties, provide the opportunity of increasing credibility in the AFOLU sector. However there are technical challenges. For instance, monitoring carbon in forests with high spatial variability in species composition and tree density can pose a technical barrier to the implementation of some AFOLU activities (e.g., REDD+; Baker et al., 2010; Section 11.10). The IPCC National Greenhouse Gas Inventory Guidelines (Paustian et al., 2006) also provide an opportunity, because they offer standard scientific methods that countries already use to report AFOLU emissions and removals under the UNFCCC. Also, field research in high-biomass forests (Gonzalez et al., 2010) shows that remote sensing data and Monte Carlo quantification of uncertainty offer a technical opportunity for implementing REDD+ (Section 11.10). Exploiting the existing *human skills* within a country is essential for realizing full AFOLU potential. A lack of trained people can therefore become a barrier to implementation of appropriate technologies (Herold and Johns, 2007).

Technology improvement and technology transfer are two crucial components for the sustainable increase of agricultural production in developed and developing regions with positive impacts in terms of mitigation, soil, and biodiversity conservation (Tilman et al., 2011). International and national policy instruments are relevant to foster technology transfer and to support research and development (Section 11.10.4), overcoming technological barriers.

11.9 Sectoral implications of transformation pathways and sustainable development

Some climate change management objectives require large-scale transformations in human societies, in particular in the production and consumption of energy and the use of the land resource. Chapter 6 describes alternative 'transformation pathways' of societies over time from now into the future, consistent with different climate change outcomes. Many pathways that foresee large efforts in mitigation will have implications for sustainable development, and corrective actions to move toward sustainability may be possible. However, impacts on development are context specific and depend upon scale and institutional agreements of the AFOLU options, and not merely on the type of option (see Sections 11.4 for development context and systemic view, 11.7 for potential co-benefits and adverse effects, and 11.8 for opportunities and challenges). To evaluate sectoral implications of transformation pathways, it is useful to first characterize the pathways in terms of mitigation technologies and policy assumptions.

11.9.1 Characterization of transformation pathways

Uncertainty about reference AFOLU emissions is significant both historically (Section 11.2) and in projections (Section 6.3.1.3). The transformation projections of the energy system, AFOLU emissions and land-use are characterized by the reference scenario, as well as the abatement policy assumptions regarding eligible abatement options, regions covered, and technology costs over time. Many mitigation scenarios suggest a substantial cost-effective mitigation role for land related mitigation assuming idealized policy implementation, with immediate, global, and comprehensive availability of land-related mitigation options. However, policy implementation of large-scale land-based mitigation will be challenging. In addition, the transformation pathways often ignore, or only partially cover, important mitigation risks, costs, and benefits (e.g., transaction costs or Monitoring Reporting and Verification (MRV) costs), and other developmental issues including intergenerational debt or non-monetary benefits (Ackerman et al., 2009; Lubowski and Rose, 2013).

In recent idealized implementation scenarios from a model comparison study, land-related changes can represent a significant share of emissions reductions (Table 11.10). In these scenarios, models assume an explicit terrestrial carbon stock incentive, or a global forest protection policy, as well as an immediate global mitigation policy in general. Bioenergy is consistently deployed (because it is considered to reduce net GHG emissions over time; see Section 6.3.5), and agricultural emissions are priced. Note that bioenergy related mitigation is not captured in Table 11.10. The largest land emission reductions occur in net CO_2 emissions, which also have the greatest variability across models. Some models exhibit increasing land CO_2 emissions under mitigation, as bioenergy feedstock production leads to LUC, while other models exhibit significant reductions with protection of existing terrestrial carbon stocks and planting of new trees to increase carbon stocks. Land-related CO_2 and N_2O mitigation is more important in the nearer-term

Table 11.10 | Cumulative land-related emissions reductions, land reduction share of global reductions, and percent of baseline land emissions reduced for CH_4, CO_2, and N_2O in idealized implementation 550 and 450 ppm CO_2eq scenarios. The number of scenarios is indicated for each GHG and atmospheric concentration goal. Negative values represent increases in emissions (Kriegler et al., 2013). Bioenergy-related mitigation is not captured in the table.

			550 ppm			450 ppm		
			2010–2030	2010–2050	2010–2100	2010–2030	2010–2050	2010–2100
Cumulative global land-related emissions reductions ($GtCO_2$eq)	CH_4	min	3.5	17.5	51.4	0.0	4.5	52.3
	(n = 5/5)	max	9.8	46.0	201.7	12.7	50.5	208.6
	CO_2	min	–20.2	–43.2	–129.8	–20.3	–50.8	–153.9
	(n = 11/10)	max	280.9	543.0	733.4	286.6	550.5	744.6
	N_2O	min	3.1	8.4	25.5	3.1	8.4	25.5
	(n = 4/4)	max	8.2	27.7	96.6	9.7	29.3	96.8
	Sum	min	–8.7	2.5	53.9	–3.7	5.6	69.7
	(n = 4/4)	max	295.2	587.7	903.5	301.4	596.9	940.3
Land reductions share of total global emissions reductions	CH_4	min	25 %	20 %	20 %	22 %	20 %	16 %
		max	37 %	40 %	42 %	30 %	31 %	36 %
	CO_2	min	–43 %	–12 %	–4 %	–20 %	-8 %	-4 %
		max	74 %	48 %	17 %	73 %	47 %	15 %
	N_2O	min	52 %	61 %	65 %	53 %	61 %	65 %
		max	95 %	90 %	87 %	78 %	83 %	85 %
	Sum	min	-11 %	0 %	1 %	-2 %	1 %	1 %
		max	70 %	47 %	19 %	69 %	46 %	17 %
Percent of baseline land emissions reduced	CH_4	min	3 %	8 %	10 %	0 %	2 %	10 %
		max	8 %	16 %	28 %	10 %	18 %	30 %
	CO_2	min	-42 %	-89 %	0 %	-42 %	-104 %	0 %
		max	373 %	417 %	504 %	381 %	423 %	512 %
	N_2O	min	4 %	6 %	8 %	4 %	6 %	8 %
		max	10 %	16 %	22 %	12 %	17 %	22 %
	Sum	min	-4 %	1 %	7 %	-2 %	1 %	8 %
		max	97 %	100 %	73 %	99 %	101 %	76 %

for some models. Land-related N_2O and CH_4 reductions are a significant part of total N_2O and CH_4 reductions, but only a small fraction of baseline emissions, suggesting that models have cost-effective reasons to keep N_2O and CH_4 emissions. Emissions reductions from land increase only slightly with the stringency of the atmospheric concentration goal, as energy and industry emission reductions increase faster with target stringency. This result is consistent with previous studies (Rose et al., 2012). Land-based CO_2 reductions can be over 100 % of baseline emissions, from the expansion of managed and unmanaged forests for sequestration.

Emissions reductions from individual land-related technologies, especially bioenergy, are not generally reported in transformation pathway studies. In part, this is due to emphasis on the energy system, but also other factors that make it difficult to uniquely quantify mitigation by technology. An exception is Rose et al. (2012) who reported agriculture, forest carbon, and bioenergy abatement levels for various atmospheric concentration goals. Cumulatively, over the century, bioenergy was the dominant strategy, followed by forestry, and then agriculture. Bioenergy cumulatively generated approximately 5 to 52 $GtCO_2eq$ and 113 to 749 $GtCO_2eq$ mitigation by 2050 and 2100, respectively. In total, land-related strategies contributed 20 to 60 % of total cumulative abatement to 2030, 15 to 70 % to 2050, and 15 to 40 % to 2100.

Within models, there is a positive correlation between emissions reductions and GHG prices. However, across models, it is less clear, as some estimate large reductions with a low GHG price, while others estimate low reductions despite a high GHG price (Rose et al., 2012). For the most part, these divergent views are due to differences in model assumptions and are difficult to disentangle. Overall, while a tighter target and higher carbon price results in a decrease in land-use emissions, emissions decline at a decreasing rate. This is indicative of the rising relative cost of land mitigation, the increasing demand for bioenergy, and subsequent increasing need for overall energy system GHG abatement and energy consumption reductions. For additional discussion of land's potential role in transformation pathways, especially regarding physical land-use and bioenergy, see sections 6.3.2.4 and 6.3.5.

Models project increased deployment of, and dependence on, modern bioenergy (i.e., non-traditional bioenergy that is produced centrally to service communities rather than individual household production for heat and cooking), with some models projecting up to 95 EJ per year by 2030, and up to 245 EJ per year by 2050. Models universally project that the majority of agriculture and forestry mitigation, and bioenergy primary energy, will occur in developing and transitional economies (Section 6.3.5).

More recently, the literature has begun analyzing more realistic policy contexts. This work has identified a number of policy coordination and implementation issues. There are many dimensions to policy coordination: technologies, sectors, regions, climate and non-climate policies, and timing. There are three prominent issues. First, there is coordination between mitigation activities. For instance, increased bioenergy incentives without global terrestrial carbon stock incentives or global forest protection policy, could result in substantial land conversion and emissions with large-scale deployment of energy crops. The projected emissions come primarily from the displacement of pasture, grassland, and natural forest (Sections 6.3.5 and 11.4.3). Energy cropland expansion also results in non-energy cropland conversion. These studies find that ignoring land conversion emissions with energy crop expansion, results in the need for deeper emissions reductions in the fossil and industrial sectors, and increased total mitigation costs. However, illustrative scenarios by (Calvin et al., 2013a) suggest that extensive forest protection policies may be needed for managing bioenergy driven deforestation. Note that providing energy crops, especially while protecting terrestrial carbon stocks, could result in a significant increase in food prices, potentially further exacerbated if also expanding forests (Wise et al., 2009; Popp et al., 2011; Reilly et al., 2012; Calvin et al., 2013a; see also Sections 11.4.3 and 11.13.7). In addition to competition between energy crops and forest carbon strategies, there is also competition between avoided deforestation and afforestation mitigation strategies, but synergies between forest management and afforestation (Rose and Sohngen, 2011). Bioenergy sustainability policies across sectors also need to be coordinated (Frank et al., 2013).

The second major concern is coordination of mitigation activity over time. The analyses noted in the previous paragraph assume the ability to globally protect or incentivize all, or a portion, of forest carbon stocks. A few studies to date have evaluated the implications of staggered forest carbon incentives—across regions and forest carbon activities. For instance, (Calvin et al., 2009) estimate land CO_2 emissions increases of 4 and 6 $GtCO_2/yr$ in 2030 and 2050, respectively, from scenarios with staggered global regional climate policies that include forest carbon incentives. And, Rose and Sohngen (2011) find that fragmented or delayed forest carbon policy could accelerate deforestation. They project 60–100 $GtCO_2$ of leakage by 2025 with a carbon price of 15 USD_{2010}/tCO_2 that rises at 5 % per year. Regional agriculture and forestry mitigation supply costs are also affected by regional participation/non-participation, with non-participating regions potentially increasing the mitigation costs for participating regions (Golub et al., 2009). Staggered adoption of land-mitigation policies will likely have institutional and socioeconomic implications as well (Madlener et al., 2006). Institutional issues, especially clarification of land tenure and property rights and equity issues (Section 11.7), will also be critical for successful land mitigation in forestry over time (Palmer, 2011; Gupta, 2012; Karsenty et al., 2014).

Finally, the type of incentive structure has implications. International land-related mitigation projects are currently regarded as high risk carbon market investments, which may affect market appeal. Also, mitigation scenarios assume that all emissions and sequestration changes are priced (similar to capping all emissions). However, mitigation, especially in agriculture and forestry, may be sought through voluntary markets, where mitigation suppliers choose whether to participate (Section 11.10). For instance, Rose et al. (2013) estimate reduced mitigation potential, as well as over-crediting, for United States agriculture and forestry with voluntary mitigation supply incentives, e.g., mitigation decreased 25–55 % at 15 USD_{2010}/tCO_2eq due to non-participant leakage and non-additional crediting.

11.9.2 Implications of transformation pathways for the AFOLU sector

Transformation pathways indicate that a combination of forces can result in very different projected landscapes relative to today, even in baseline scenarios (Section 6.3.5). For instance, Popp et al. (2013) evaluate three models, and show that projected 2030 baseline changes from today alone vary sharply across models in all regions (Figure 11.19). See Section 6.3.5 for global land cover change results for a broader set of studies and policy contexts. In the examples in Figure 11.19, projections exhibit growth and reductions in both non-energy cropland (e.g., ASIA), and energy cropland (e.g., ASIA, OECD-1990, EIT). Furthermore, different kinds of land are converted when baseline cropland expands (e.g., MAF). Mitigation generally induces greater land cover changes than in baseline scenarios, but there are very different potential transformation visions. Overall, it is difficult to generalize on regional land cover effects of mitigation. For the same atmospheric concentration goal, some models convert significant area, some do not. There is energy cropland expansion in many regions that supports the production of bioenergy. Less consistent is the response of forest land, primarily due to differences in the land carbon options/policies modelled (Section 6.3.5). Finally, there is relatively modest additional land conversion in the 450 ppm, compared to the 550 ppm, scenarios, which is consistent with the declining role of land-related mitigation with policy stringency.

The implications of transformation pathway scenarios with large regional expansion of forest cover for carbon sequestration, depends in part on how the forest area increases (Figure 11.19; Popp et al., 2013). If forest areas increase through the expansion of natural vegetation, biodiversity and a range of other ecosystem services provided by forests could be enhanced. If afforestation occurs through large-scale plantation, however, some negative impacts on biodiversity, water, and other ecosystem services could arise, depending on what land cover the plantation replaces and the rotation time (Section 11.7). Similar issues arise with large-scale bioenergy, and environmental impacts of energy crop plantations, which largely depend upon where, how, and at what scale they are implemented, and how they are managed (Davis et al., 2013; see Section 11.13.6). Not surprisingly, the realistic policy coordination and implementation issues discussed in Section 11.9.1 could have significant land-use consequences, and additional policy design research is essential to better characterize mitigation costs, net emissions, and other social implications.

11.9.3 Implications of transformation pathways for sustainable development

The implications of the transformation pathways on sustainable development are context- and time-specific. A detailed discussion of the implications of large-scale LUC, competition between different demands for land, and the feedbacks between LUC and other services provided by land is provided in Section 11.4, potential co-benefits and adverse side-effects are discussed in Section 11.7, and Section 6.6 compares potential co-benefits and adverse side-effects across sectors, while Section 11.8 presents the opportunities and barriers for promoting AFOLU mitigation activities in the future. Finally, Section 11.13 discusses the specific implications of increasing bioenergy crops.

11.10 Sectoral policies

Climate change and different policy and management choices interact. The interrelations are particularly strong in agriculture and forestry: climate has a strong influence on these sectors that also constitute sources of GHG as well as sinks (Golub et al., 2009). The land provides a multitude of ecosystem services, climate change mitigation being just one of many services that are vital to human well-being. The nature of the sector means that there are, potentially, many barriers and opportunities as well as a wide range of potential impacts related to the implementation of AFOLU mitigation options (Sections 11.7 and 11.8). Successful mitigation policies need to consider how to address the multi-functionality of the sector. Furthermore, physical environmental limitations are central for the implementation of mitigation options and associated policies (Pretty, 2013). The cost-effectiveness of different measures is hampered by regional variability. National and international agricultural and forest climate policies have the potential to redefine the opportunity costs of international land-use in ways that either complement or hinder the attainment of climate change mitigation goals (Golub et al., 2009). Policy interactions could be synergistic (e.g., research and development investments and economic incentives for integrated production systems) or conflicting (e.g., policies promoting land conversion *vs*. conservation policies) across the sector (see Table 11.11). Additionally, adequate policies are needed to orient practices in agriculture and in forestry toward global sharing of innovative technologies for the efficient use of land resources to support effective mitigation options (see Table 11.2).

Forty-three countries in total (as of December 2010) have proposed NAMAs to the UNFCCC. Agriculture and forestry activities were considered as ways to reduce their GHG emissions in 59 and 94 % of the proposed NAMAs. For the least developed countries, the forestry sector was quoted in all the NAMAs, while the agricul-

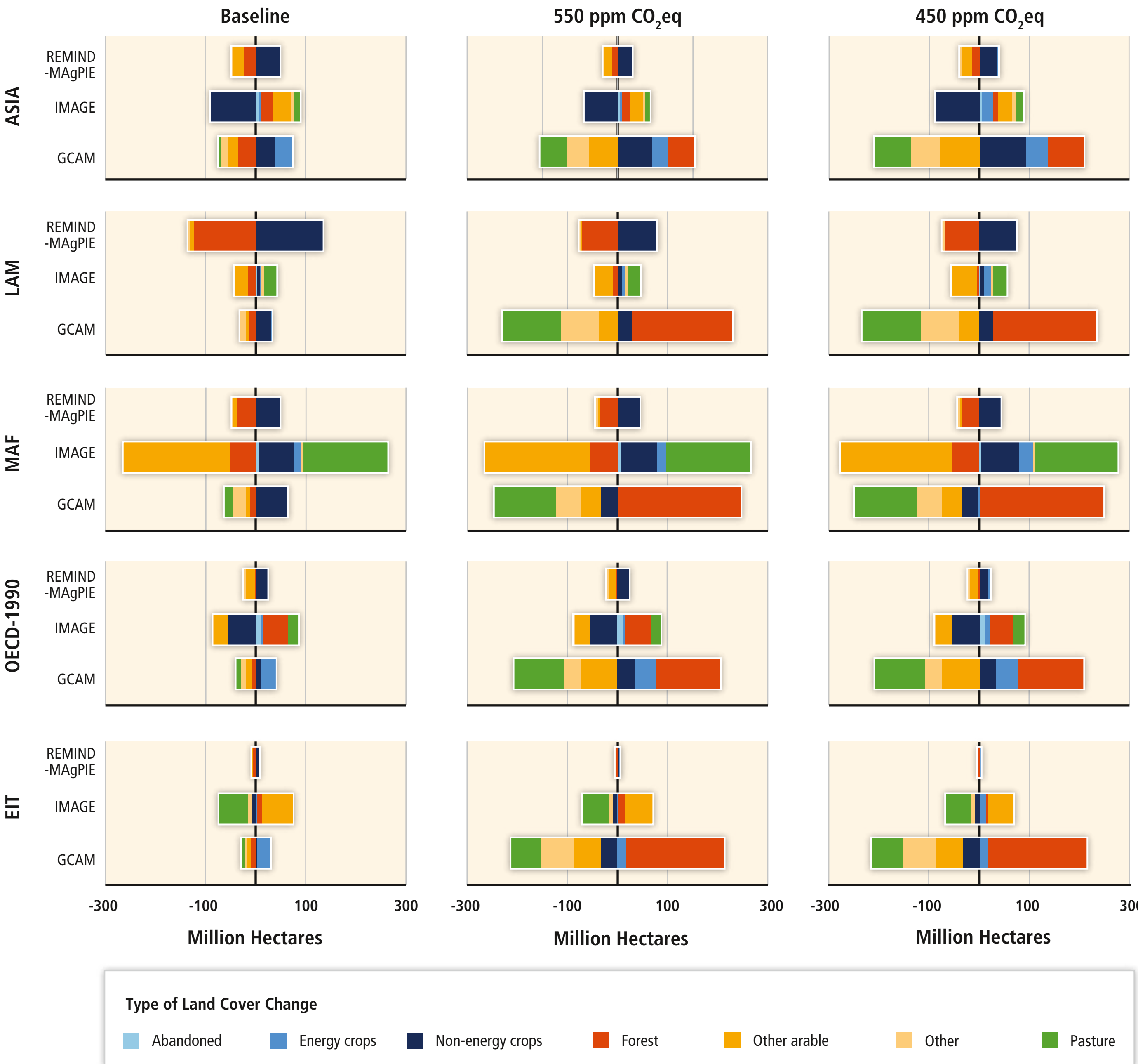


Figure 11.19 | Regional land cover change by 2030 from 2005 from three models for baseline (left) and idealized policy implementation 550 ppm CO_2eq (centre) and 450 ppm CO_2eq (right) scenarios. (Popp et al., 2013).

tural sector was represented in 70 % of the NAMAs (Bockel et al., 2010). Policies related to the AFOLU sector that affect mitigation are discussed below according to the instruments through which they may be implemented (economic incentives, regulatory and control approaches, information, communication and outreach, research and development). Economic incentives (e.g., special credit lines for low-carbon agriculture, sustainable agriculture and forestry practices, tradable credits, payment for ecosystem services) and regulatory approaches (e.g., enforcement of environmental law to reduce deforestation, set-aside policies, air and water pollution control reducing nitrate load and N_2O emissions) have been effective in different cases. Investments in research, development, and diffusion (e.g., improved fertilizer use efficiency, livestock improvement, better forestry management practices) could result in positive and synergistic impacts for adaptation and mitigation (Section 11.5). Emphasis is given to REDD+, considering its development in recent years, and relevance for the discussion of mitigation policies in the forestry sector.

Table 11.11 | Some regional and global programs and partnerships related to illegal logging, forest management and conservation and REDD+.

Programme/Institution/Source	Context	Objectives and Strategies
Forest Law Enforcement and Governance (FLEG)/ World Bank/ www.worldbank.org/eapfleg	Illegal logging and lack of appropriate forest governance are major obstacle to countries to alleviate poverty, to develop their natural resources and to protect global and local environmental services and values	Support regional forest law enforcement and governance (FLEG)
Improving Forest Law Enforcement and Governance in the European Neighbourhood Policy East Countries and Russia (ENPI-FLEG)/EU/ www.enpi-fleg.org	Regional cooperation in the European Neighbourhood Policy Initiative East Countries (Armenia, Azerbaijan, Belarus, Georgia, Moldova, and Ukraine), and Russia following up on the St. Petersburg Declaration	Support governments, civil society, and the private sector in participating countries in the development of sound and sustainable forest management practices, including reducing the incidence of illegal forestry activities.
Forest Law Enforcement, Governance and Trade (FLEGT)/European Union/ www.euflegt.efi.int/	Illegal logging has a devastating impact on some of the world's most valuable forests. It can have not only serious environmental, but also economic and social consequences.	Exclude illegal timber from markets, to improve the supply of legal timber and to increase the demand for responsible wood products. Central elements are trade accords to ensure legal timber trade and support good forest governance in the partner countries. There are a number of countries in Africa, Asia, South and Central America currently negotiating FLEGT Voluntary Partnership Agreements (VPAs) with the European Union.
Program on Forests (PROFOR)/multiple donors including the European Union, European countries, Japan and the World Bank/ www.profor.info	Well-managed forests have the potential to reduce poverty, spur economic development, and contribute to a healthy local and global environment	Provide in-depth analysis and technical assistance on key forest questions related to livelihoods, governance, financing, and cross-sectoral issues. PROFOR activities comprise analytical and knowledge generating work that support the strategy's objectives of enhancing forests' contribution to poverty reduction, sustainable development and the protection of environmental services.
UN-REDD Programme/United Nations/ www.un-redd.org	The UN collaborative initiative on Reducing Emissions from Deforestation and forest Degradation (REDD) in developing countries was launched in 2008 and builds on the convening role and technical expertise of the FAO, UNDP, and the UNEP.	The Programme supports national REDD+ readiness efforts in 46 partner countries (Africa, Asia-Pacific, and Latin America) through (i) direct support to the design and implementation of REDD+ National Programmes; and (ii) complementary support to national REDD+ action (common approaches, analyses, methodologies, tools, data, and best practices).
REDD+ Partnership/International effort (50 different countries)/ www.reddpluspartnership.org	The UNFCCC has encouraged the Parties to coordinate their efforts to reduce emissions from deforestation and forest degradation. As a response, countries attending the March 2010 International Conference on the Major Forest Basins, hosted by the Government of France, agreed on the need to forge a strong international partnership on REDD+.	The REDD+ Partnership serves as an interim platform for its partner countries to scale up actions and finance for REDD+ initiatives in developing countries (including improving the effectiveness, efficiency, transparency, and coordination of REDD+ and financial instruments), to facilitate knowledge transfer, capacity enhancement, mitigation actions and technology development, and transfer among others.
Forest Investment Program (FIP)/Strategic Climate Fund (a multi-donor Trust Fund within the Climate Investment Funds) www.climateinvestmentfunds.org/cif/	Reduction of deforestation and forest degradation and promotion of sustainable forest management, leading to emission reductions and the protection of carbon terrestrial sinks.	Support developing countries' efforts to REDD and promote sustainable forest management by providing scaled-up financing to developing countries for readiness reforms and public and private investments, identified through national REDD readiness or equivalent strategies.
Forest Carbon Partnership (FCPF)/World Bank/ www.forestcarbonpartnership.org	Assistance to developing countries to implement REDD+ by providing value to standing forests.	Builds the capacity of developing countries to reduce emissions from deforestation and forest degradation and to tap into any future system of REDD+.
Indonesia-Australia Forest Carbon Partnership/ www.iafcp.or.id	Australia's assistance on climate change and builds on long-term practical cooperation between Indonesia and Australia.	The Partnership supports strategic policy dialogue on climate change, the development of Indonesia's National Carbon Accounting System, and implementing demonstration activities in Central Kalimantan.

11.10.1 Economic incentives

Emissions trading: Carbon markets occur under both compliance schemes and as voluntary programmes. A review of existing offset programmes was provided by Kollmuss et al. (2010). More details are also presented in Section 15.5.3. Compliance markets (Kyoto offset mechanisms, mandatory cap-and-trade systems, and other mandatory GHG systems) are created and regulated by mandatory national, regional, or international carbon reduction regimes (Kollmuss et al., 2010). The three Kyoto Protocol mechanisms are very important for the regulatory market: CDM, Joint Implementation (JI) and the Emissions Trading System (ETS). Currently, AFOLU projects in CDM only include specific types of projects: for agriculture—methane avoidance (manure management), biogas projects, agricultural residues for biomass energy; for forestry—reforestation and afforestation. By June 2013, the total number of registered CDM projects was 6989, 0.6 and 2.5 % of this total being related to afforestation/reforestation and agriculture, respectively (UNFCCC—CDM); therefore, finance streams coming from A/R CDM Projects are marginal from the global perspective. An analysis of A/R CDM projects suggests crucial factors for the performance of these projects are initial funding support, design, and implementation guided by large organizations with technical expertise, occurrence on private land (land with secured property rights attached), and that most revenue from Certified Emission Reductions (CERs) is directed back to local communities (Thomas et al., 2010).

There are compliance schemes outside the scope of the Kyoto Protocol, but these are carried out exclusively at the national level, with no relation to the Protocol. In 2011, Australia started the Carbon Farming Initiative (CFI) that allows farmers and investors to generate tradable carbon offsets from farmland and forestry projects. This followed several years of state-based and voluntary activity that resulted in 65,000 ha of A/R projects (Mitchell et al., 2012). Another example is The Western Arnhem Land Fire Abatement Project (WALFA), a fire management project in Australia initiated in 2006 that produces a tradable carbon offset through the application of improved fire management using traditional management practices of indigenous land owners (Whitehead et al., 2008; Bradstock et al., 2012). Alberta's offset credit system is a compliance mechanism for entities regulated under the province's mandatory GHG emission intensity-based regulatory system (Kollmuss et al., 2010). In the case of N_2O emissions from agriculture, the Alberta Quantification Protocol for Agricultural N_2O Emissions Reductions issues C offset credits for on-farm reductions of N_2O emissions and fuel use associated with the management of fertilizer, manure, and crop residues for each crop type grown. Other N_2O emission reduction protocols (e.g., Millar et al., 2010) are being considered for the Verified Carbon Standard, the American Carbon Registry, and the Climate Action Reserve (Robertson et al., 2013).

Agriculture and Forestry activities are not covered by the European Union Emissions Trading Scheme (EU ETS), which is by far the largest existing carbon market. Forestry entered the New Zealand Kyoto Protocol compliant ETS in 2008, and mandatory reporting for agriculture began in 2012, although full entry of agriculture into the scheme has been delayed indefinitely. Agricultural participants include meat processors, dairy processors, nitrogen fertilizer manufacturers and importers, and live animal exporters, although some exemptions apply (Government of New Zealand). California's Cap-and-Trade Regulation took effect on January 1, 2012, with amendments to the Regulation effective September 1, 2012. The enforceable compliance obligation began on January 1, 2013. Four types of projects were approved as eligible to generate carbon credits to regulated emitters in California: avoidance of methane emissions from installation of anaerobic digesters on farms, carbon sequestration in urban and rural forestry, and destruction of ozone depleting substances (California Environmental Protection Agency).

Voluntary carbon markets operate outside of the compliance markets. By enabling businesses, governments, non-governmental organizations (NGOs), and individuals to purchase offsets that were created either in the voluntary market or through the CDM, they can offset their emissions (Verified or Voluntary Emissions Reductions (VERs)). The voluntary offset market includes a wide range of programmes, entities, standards, and protocols (e.g., Community & Biodiversity Standards, Gold Standard, Plan Vivo among others) to improve the quality and credibility of voluntary offsets. The most common incentives for the quantity buyers of carbon credits in the private sector are corporate social responsibility and public relations. Forest projects are increasing in the voluntary markets. Transactions of carbon credits from this sector totalled 133 million USD in 2010, 95 % of them in voluntary markets (Peters-Stanley et al., 2011).

Reducing emissions from deforestation; reducing emissions from forest degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks (REDD+): REDD+ consists of forest-related activities implemented voluntarily by developing countries that may, in isolation or jointly lead to significant climate change mitigation[10]. REDD+ was introduced in the agenda of the UNFCCC in 2005, and has since evolved to an improved understanding of the potential positive and negative impacts, methodological issues, safeguards, and financial aspects associated with REDD+ implementation. Here, we first address the REDD+ discussions under the UNFCCC, but also introduce other REDD+-related initiatives. The novel aspects of REDD+ under the Convention, relative to previous forest-related mitigation efforts by developing countries under the UNFCCC are its national and broader coverage, in contrast to project-based mitigation activities[11] (e.g., under the CDM of the Kyoto Protocol). Its main innovation is its results-based approach, in which payments are done *ex post* in relation to a mitigation outcome already achieved, as opposed to project-based activities, where financing is provided *ex ante* in relation to expected outcomes. A phased approach to REDD+ was agreed at the UNFCCC, building from the development of national strategies or action plans, policies and measures, and evolving into results-based actions that should be fully measured, reported, and verified—MRV (UNFCCC Dec. 1/16). REDD+ payments are expected for results-based actions, and although the UNFCCC has already identified potential ways to pay for these[12], the financing architecture for the REDD+ mechanism is still under negotiation under the UNFCCC.

Meanwhile, and as a result to the explicit request from the UNFCCC for early actions in REDD+, different regional and global programmes and partnerships address forest management and conservation and readiness for REDD+ (Table 11.11), while some REDD+ strategies have started in countries with significant forest cover (see Box 11.7 for examples). Initiatives include multilateral activities (e.g., UN-REDD

[10] Decision 1/CP.16 (FCCC/CP/2010/7/Add.1 , paragraph 70) "Encourages developing countries to contribute to mitigation actions in the forest sector by undertaking the following activities, as deemed appropriate by each Party and in accordance with their respective capabilities and national circumstances—reducing emissions from deforestation; reducing emissions from forest degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks".

[11] Decision 1/CP.16 (FCCC/CP/2010/7/Add.1 , paragraph 73) "*Decides* that the activities undertaken by Parties referred to in paragraph 70 above should be implemented in phases, beginning with the development of national strategies or action plans, policies and measures, and capacity-building, followed by the implementation of national policies and measures and national strategies or action plans that could involve further capacity-building, technology development and transfer and results-based demonstration activities, and evolving into results-based actions that should be fully measured, reported and verified".

[12] Decision 2/CP.17 (FCCC/CP/2011/9/Add.1, paragraph 65) "*Agrees* that results-based finance provided to developing country Parties that is new, additional and predictable may come from a wide variety of sources, public and private, bilateral and multilateral, including alternative sources".

Programme, Forest Carbon Partnership Facility, Forest Investment Program), bilateral activities (e.g., Tanzania-Norway, Indonesia-Norway), country driven initiatives (in addition to 16 UN-REDD Programme countries, the Programme also supports 31 other partner countries across Africa, Asia-Pacific, and Latin America and the Caribbean; UN-REDD Programme—Support to Partner Countries).

REDD+ can be a very cost-effective option for mitigating climate change and could supply a large share of global abatement of emissions from the AFOLU sector from the extensive margin of forestry, especially through reducing deforestation in tropical regions (Golub et al., 2009). Issues of concern for REDD+ implementation have been captured under REDD+ safeguards in line with the UNFCCC Cancun Agreement. To respond to the requirements outlined in the UNFCCC agreement, a number of steps need to be considered in the development of country-level safeguard information systems for REDD+ including defining social and environmental objectives, assessing potential benefits and risks from REDD+, assessing current safeguard systems, drafting a strategic plan or policy, and establishing a governance system.

A growing body of literature has analyzed different aspects related to the implementation, effectiveness, and scale of REDD+, as well as the interactions with other social and environmental co-benefits (e.g., Angelsen et al., 2008; Levin et al., 2008; Larson, 2011; Gardner et al., 2012). Results-based REDD+ actions, which are entitled to results-based finance, require internationally agreed rules for MRV. Measuring and monitoring the results will most likely rely on a combination of remotely-sensed data with ground-based inventories. The design of a REDD policy framework (and specifically its rules) can have a significant impact on monitoring costs (Angelsen et al., 2008; Böttcher et al., 2009). Forest governance is another central aspect in recent studies, including debate on decentralization of forest management, logging concessions in public-owned commercially valuable forests, and timber certification, primarily in temperate forests (Agrawal et al., 2008). Although the majority of forests continue to be formally owned by governments, there are indications that the effectiveness of forest governance is increasingly independent of formal ownership (Agrawal et al., 2008). However, there are widespread concerns that REDD+ will increase costs on forest-dependent peoples and in this context, stakeholders rights, including rights to continue sustainable traditional land-use practices, appear as a precondition for REDD development (Phelps et al., 2010b).

Some studies have addressed the potential displacement of emissions, i.e., a reduction of emissions in one place resulting in an increase of emissions elsewhere (or leakage) (Santilli et al., 2005; Forner et al., 2006; Nabuurs et al., 2007; Strassburg et al., 2008, 2009; Section 11.3.2). The national coverage of REDD+ might ameliorate the issue of emissions displacement, a major drawback of project-based approaches (Herold and Skutsch, 2011). To minimize transnational displacement of emissions, REDD+ needs to stimulate the largest number of developing countries to engage voluntarily. There are also concerns about the impacts of REDD+ design and implementation options on biodiversity conservation, as areas of high C content and high biodiversity are not necessarily coincident. Some aspects of REDD+ implementation that might affect biodiversity include site selection, management strategies, and stakeholder engagement (Harvey et al., 2010). From a conservation biology perspective, it is also relevant where the displacement occurs, as deforestation and exploitation of natural

Box 11.7 | Examples of REDD+ initiatives at national scale in different regions with significant extension of forest cover

Amazon Fund: The Amazon Fund in Brazil was officially created in 2008 by a presidential decree. The Brazilian Development Bank (BNDES) was given the responsibility of managing it. The Norwegian government played a key role in creating the fund by donating funds to the initiative in 2009. Since then, the Amazon Fund has received funds from two more donors: the Federal Republic of Germany and Petrobrás, Brazil's largest oil company. As of February 2013, 1.03 billion USD has been pledged, with 227 million USD approved for activities (Amazon Fund).

UN-REDD Democratic Republic of Congo: The Congo Basin rainforests are the second largest after Amazonia. In 2009, Democratic Republic of the Congo (DRC), with support of UN-REDD Programme and Forest Carbon Partnership Facility (FCPC), started planning the implementation stages of REDD+ readiness. The initial DRC National Programme transitioned into the full National Programme (Readiness Plan) after it was approved by the UN-REDD Programme Policy Board in 2010 (UN-REDD Programme). The budget comprises 5.5 million USD_{2010} and timeframe is 2010–2013.

Indonesia-Norway REDD+ Partnership: In 2010, the Indonesia-Norway REDD+ Partnership was established through an agreement between governments of the two countries. The objective was to 'support Indonesia's efforts to reduce emissions from deforestation and degradation of forests and peatlands. Indonesia agreed to take systematic and decisive action to reduce its forest and peat-related GHG emissions, whereas Norway agreed to support those efforts by making available up to 1 billion USD_{2010}, exclusively on a payment-for-results basis over the next few years' (UN-REDD Programme). In 2013, Indonesia's government has extended the moratorium on new forest concessions for a further two years, protecting an additional 14.5 Mha of forest.

resources could move from areas of low conservation value to those of higher conservation value, or to other natural ecosystems, threatening species native to these ecosystems (Harvey et al., 2010). Additionally, transnational displacement could cause deforestation to move into relatively intact areas of high biodiversity value, or into countries that currently have little deforestation (Putz and Redford, 2009).

Taxes, charges, subsidies: Financial regulations are another approach to pollution control. A range of instruments can be used: pollution charges, taxes on emission, taxes on inputs, and subsidies (Jakobsson et al., 2002). Nitrogen taxes are one possible instrument, since agricultural emissions of N_2O mainly derive from the use of nitrogenous fertilizers. An analysis of the tax on the nitrogen content of synthetic fertilizers in Sweden indicated that direct N_2O emissions from agricultural soils in Sweden (the tax abolished in 2010) would have been on average 160 tons or 2 % higher without the tax (Mohlin, 2013). Additionally, the study showed that removal of the N tax could completely counteract the decreases in CO_2 emissions expected from the future tax increase on agricultural CO_2. The mitigation potential of GHG-weighted consumption taxes on animal food products was estimated for the EU using a model of food consumption (Wirsenius et al., 2011). A 7 % reduction of current GHG emission in European Union (EU) agriculture was estimated with a GHG-weighted tax on animal food products of 79 USD_{2010}/tCO_2eq (60 EUR_{2010}/tCO_2eq). Low-interest loans can also support the transition to sustainable agricultural practices as currently implemented in Brazil, the second largest food exporter, through the national programme (launched in 2010; Plano ABC).

11.10.2 Regulatory and control approaches

Deforestation control and land planning (protected areas and land sparing/set-aside policies): The rate of deforestation in the tropics and relative contribution to anthropogenic carbon emissions has been declining (Houghton, 2012; see Section 11.2 for details). Public policies have had a significant impact by reducing deforestation rates in some tropical countries (see, e.g., Box 11.8).

Since agricultural expansion is one of the drivers of deforestation (especially in tropical regions), one central question is if intensification of agriculture reduces cultivated areas and results in land sparing by concentrating production on other land. Land sparing would allow released lands to sequester carbon, provide other environmental services, and protect biodiversity (Fischer et al., 2008). In the United States, over 13 Mha of former cropland are enrolled in the US Conservation Reserve Program (CRP), with biodiversity, water quality, and carbon sequestration benefits (Gelfand et al., 2011). In 1999, China launched the Grain for Green Program or Sloping Land Conversion Program as a national measure to increase vegetation cover and reduce erosion. Cropland and barren land were targeted and over 20 Mha of land were converted into mostly tree-based plantations. Over its first 10 years between ~800 to 1700 $MtCO_2eq$ (Moberg, 2011) were sequestered.

Environmental regulation (GHG and their precursors emissions control): In many developed countries, environmental concerns related to water and air pollution since the mid-1990s led to the adoption of laws and regulations that now mandate improved agricultural nutrient management planning (Jakobsson et al., 2002). Some policy initiatives deal indirectly with N leakages and thus promote the reduction of N_2O emissions. The EU Nitrates Directive (1991) sets limits on the use of fertilizer N and animal manure N in nitrate-vulnerable zones. Across the 27 EU Member States, 39.6 % of territory is subject to related action programmes. However, in terms of the effectiveness of environmental policies and agriculture, there has been considerable progress in controlling point pollution, but efforts to control non-point pollution of nutrients have been less successful, and potential synergies from various soil-management strategies could be better exploited. Emission targets for the AFOLU sector were also introduced by different countries (e.g., Climate Change Acts in UK and Scotland; European Union).

Bioenergy targets: Many countries worldwide, by 2012, have set targets or mandates or both for bioenergy, to deliver to multiple policy objectives, such as climate change mitigation, energy security, and rural development. The bulk of mandates continue to come from the EU-27 but 13 countries in the Americas, 12 in Asia-Pacific, and 8 in Africa have mandates or targets in place (Petersen, 2008; www.biofuelsdigest.com). For the sustainability of biofuels implementation, land-use planning and governance are central (Tilman et al., 2009), as related policy and legislation, e.g., in agriculture, forestry, environment and trade, can strongly influence the development of bioenergy programmes (Jull et al., 2007). A recent study analyzed the consequences of renewable targets of EU member states on the CO_2 sink of EU forests, and indicated a decrease in the forest sink by 4–11 % (Böttcher et al., 2012). Another possible tradeoff of biofuel targets is related to international trade. Global trade in biofuels might have a major impact on other commodity markets (e.g., vegetable oils or animal fodder) and has already caused a number of trade disputes, because of subsidies and non-tariff barriers (Oosterveer and Mol, 2010).

Box 11.8 | Deforestation control in Brazil

The Brazilian Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) includes coordinated efforts among federal, state, and municipal governments, and civil organizations, remote-sensing monitoring, significant increase of new protected areas (Soares-Filho et al., 2010), and combination of economic and regulatory approaches. For example, since 2008 federal government imposed sanctions to municipalities with very high deforestation rates, subsidies were cut and new credit policies made rural credit dependent on compliance with environmental legislation (Macedo et al., 2012; Nolte et al., 2013).

11.10.3 Information schemes

Acceptability by land managers and practicability of mitigation measures (Table 11.2) need to be considered, because the efficiency of a policy is determined by the cost of achieving a given goal (Sections 11.4.5; 11.7). Therefore, costs related to education and communication of policies should be taken into account (Jakobsson et al., 2002). Organizations created to foster the use of science in environmental policy, management, and education can facilitate the flow of information from science to society, increasing awareness of environmental problems (Osmond et al., 2010). In the agriculture sector, non-profit conservation organizations (e.g., The Sustainable Agriculture Network (SAN)) and governments (e.g., Farming for a Better Climate, Scotland) promote the social and environmental sustainability of activities by developing standards and educational campaigns.

Certification schemes also support sustainable agricultural practices (Sections 11.4.5; 11.7). Climate-friendly criteria reinforce existing certification criteria and provide additional value. Different certification systems also consider improvements in forest management, reduced deforestation and carbon uptake by regrowth, reforestation, agroforestry, and sustainable agriculture. In the last 20 years, forest certification has been developed as an instrument for promoting sustainable forest management. Certification schemes encompass all forest types, but there is a concentration in temperate forests (Durst et al., 2006). Approximately 8% of global forest area has been certified under a variety of schemes and 25% of global industrial roundwood comes from certified forests (FAO, 2009b). Less than 2% of forest area in African, Asian, and tropical American forests are certified, and most certified forests (82%) are large and managed by the private sector (ITTO, 2008). In the forestry sector, many governments have worked towards a common understanding of sustainable forest management (Auld et al., 2008). Certification bodies certify that farms or groups comply with standards and policies (e.g., Rainforest Alliance Certified). In some, specific voluntary climate change adaptation and mitigation criteria are included.

Forest certification as an instrument to promote sustainable forest management (SFM) and biodiversity maintenance was evaluated by (Rametsteiner and Simula, 2003) they indicated that standards used for issuing certificates upon compliance are diverse, but often include elements that set higher than minimum standards.

Further, independent audits are an incentive for improving forest management. In spite of many difficulties, forest certification was considered successful in raising awareness, disseminating knowledge on the SFM concept worldwide, and providing a tool for a range of applications other than the assessment of sustainability, e.g., verifying carbon sinks. Another evaluation of certification schemes for conserving biodiversity (Harvey et al., 2008) indicated some constraints that probably also apply to climate-friendly certification: weakness of compliance or enforcement of standards, transaction costs and paperwork often limit participation, and incentives are insufficient to attract high levels of participation. Biofuel certification is a specific case as there are multiple actors and several successive segments of biofuel production pathways: feedstock production, conversion of the feedstock to biofuels, wholesale trade, retail, and use of biofuels in engines (Gnansounou, 2011). Because of the length and the complexity of biofuel supply chains assessing sustainability is challenging (Kaphengst et al., 2009).

11.10.4 Voluntary actions and agreements

Innovative agricultural practices and technologies can play a central role in climate change mitigation and adaptation, with policy and institutional changes needed to encourage the innovation and diffusion of these practices and technologies to developing countries. Under the UNFCCC, the 2007 Bali Action Plan identified technology development and transfer as a priority area. A Technology Mechanism was established by Parties at the COP16 in 2010 "to facilitate the implementation of enhanced action on technology development and transfer, to support action on mitigation and adaptation, in order to achieve the full implementation of the Convention" (UNFCCC). For agriculture, Burney et al., (2010) indicated that investment in yield improvements compared favourably with other commonly proposed mitigation strategies.

Additionally, adaptation measures in agriculture can also generate significant mitigation effects. Lobell et al. (2013) investigated the co-benefits of adaptation measures on farm level that reduced GHG emissions from LUC. The study focused on investments in research for developing and deploying new technologies (e.g., disease-resistant or drought-tolerant crops, or soil-management techniques). It concluded that broad-based efforts to adapt agriculture to climate change have mitigation co-benefits that are associated with lower costs than many activities focusing on mitigation, especially in developed countries.

11.11 Gaps in knowledge and data

Data and knowledge gaps include:

- Improved global high-resolution data sets of crop production systems (including crop rotations, variety selection, fertilization practices, and tillage practices), grazing areas (including quality, intensity of use, management), and freshwater fisheries and aquaculture, also comprising subsistence farming.
- Globally standardized and homogenized data on soil as well as forest degradation and a better understanding of the effects of degradation on carbon balances and productivity.

- Improved understanding of the mitigation potential, interplay, and costs as well as environmental and socio-economic consequences of land use-based mitigation options such as improved agricultural management, forest conservation, bioenergy production, and afforestation on the national, regional, and global scale.

- Better understanding of the effect of changes in climate parameters, rising CO_2 concentrations and N deposition on productivity and carbon stocks of different types of ecosystems, and the related consequences for land-based climate change mitigation potentials.

11.12 Frequently Asked Questions

FAQ 11.1 How much does AFOLU contribute to GHG emissions and how is this changing?

Agriculture and land-use change, mainly deforestation of tropical forests, contribute greatly to anthropogenic greenhouse gas emissions and are expected to remain important during the 21st century. Annual GHG emissions (mainly CH_4 and N_2O) from agricultural production in 2000–2010 were estimated at 5.0–5.8 $GtCO_2eq/yr$, comprising about 10–12 % of global anthropogenic emissions. Annual GHG flux from land use and land-use change activities accounted for approximately 4.3–5.5 $GtCO_2eq/yr$, or about 9–11 % of total anthropogenic greenhouse gas emissions. The total contribution of the AFOLU sector to anthropogenic emissions is therefore around one quarter of the global anthropogenic total.

FAQ 11.2 How will mitigation actions in AFOLU affect GHG emissions over different timescales?

There are many mitigation options in the AFOLU sector that are already being implemented, e.g., afforestation, reducing deforestation, cropland and grazing land management, fire management, and improved livestock breeds and diets. These can be implemented now. Others (such as some forms of biotechnology and livestock dietary additives) are still in development and may not be applicable for a number of years. In terms of the mode of action of the options, in common with other sectors, non-CO_2 greenhouse gas emission reduction is immediate and permanent. However, a large portion of the mitigation potential in the AFOLU sector is carbon sequestration in soils and vegetation. This mitigation potential differs, in that the options are time-limited (the potential saturates), and the enhanced carbon stocks created are reversible and non-permanent. There is, therefore, a significant time component in the realization and the duration of much of the mitigation potential available in the AFOLU sector.

FAQ 11.3 What is the potential of the main mitigation options in AFOLU for reducing GHG emissions?

In general, available top-down estimates of costs and potentials suggest that AFOLU mitigation will be an important part of a global cost-effective abatement strategy. However, potentials and costs of these mitigation options differ greatly by activity, regions, system boundaries, and the time horizon. Especially, forestry mitigation options—including reduced deforestation, forest management, afforestation, and agro-forestry—are estimated to contribute 0.2–13.8 $GtCO_2/yr$ of economically viable abatement in 2030 at carbon prices up to 100 USD/tCO_2eq. Global economic mitigation potentials in agriculture in 2030 are estimated to be up to 0.5–10.6 $GtCO_2eq/yr$. Besides supply-side-based mitigation, demand-side mitigation options can have a significant impact on GHG emissions from food production. Changes in diet towards plant-based and hence less GHG-intensive food can result in GHG emission savings of 0.7–7.3 $GtCO_2eq/yr$ in 2050, depending on which GHGs and diets are considered. Reducing food losses and waste in the supply chain from harvest to consumption can reduce GHG emissions by 0.6–6.0 $GtCO_2eq/yr$.

FAQ 11.4 Are there any co-benefits associated with mitigation actions in AFOLU?

In several cases, the implementation of AFOLU mitigation measures may result in an improvement in land management and therefore have socio-economic, health, and environmental benefits: For example, reducing deforestation, reforestation, and afforestation can improve local climatic conditions, water quality, biodiversity conservation, and help to restore degraded or abandoned land. Soil management to increase soil carbon sequestration may also reduce the amount of wind and water erosion due to an increase in surface cover. Further considerations on economic co-benefits are related to the access to carbon payments either within or outside the UNFCCC agreements and new income opportunities especially in developing countries (particularly for labour-intensive mitigation options such as afforestation).

FAQ 11.5 What are the barriers to reducing emissions in AFOLU and how can these be overcome?

There are many barriers to emission reduction. Firstly, mitigation practices may not be implemented for economic reasons (e.g., market failures, need for capital investment to realize recurrent savings), or a range of factors including risk-related, political/bureaucratic, logistical, and educational/societal barriers. Technological barriers can be overcome by research and development; logistical and political/bureaucratic barriers can be overcome by better governance and institutions; education barriers can be overcome through better education and extension networks; and risk-related barriers can be overcome, for example, through clarification of land tenure uncertainties.

11.13 Appendix Bioenergy: Climate effects, mitigation options, potential and sustainability implications

11.13.1 Introduction

SRREN (IPCC, 2011) provided a comprehensive overview on bioenergy (Chum et al., 2011). However, a specific bioenergy Appendix in the context of the WGIII AR5 contribution is necessary because (1) many of the more stringent mitigation scenarios (resulting in 450 ppm, but also 550 ppm CO_2eq concentration by 2100, see Section 11.9.1) heavily rely on a large-scale deployment of bioenergy with carbon dioxide capture and storage (BECCS); (2) there has been a large body of literature published since SRREN, which complements and updates the analysis presented in this last report; (3) bioenergy is important for many chapters (Chapters 6; 7; 8; 10; 11), which makes it more useful to treat it in a single section instead of in many scattered chapter sections throughout the report. Chapter 11 is the appropriate location for the Appendix, as bioenergy analysis relies crucially on land-use assessments.

Bioenergy is energy derived from biomass, which can be deployed as solid, liquid, and gaseous fuels for a wide range of uses, including transport, heating, electricity production, and cooking (Chum et al., 2011). Bioenergy has a significant mitigation potential, but there are issues to consider, such as the sustainability of practices and the efficiency of bioenergy systems (Chum et al., 2011). Bioenergy systems can cause both positive and negative effects and their deployment needs to balance a range of environmental, social, and economic objectives that are not always fully compatible. The consequences of bioenergy implementation depend on (1) the technology used; (2) the location, scales, and pace of implementation; (3) the land category used (forest, grassland, marginal lands, and crop lands); and (4) the business models and practices adopted—including how these integrate with or displace the existing land use.

As an update to the SRREN, this report presents (1) a more fine-grained assessment of the technical bioenergy potential reflecting diverse perspectives in the literature; (2) recent potential estimates on technological solutions such as BECCS; (3) an in-depth description of different lifecycle emission accounting methods and their results; (4) a small increase in uncertainty on the future economic bioenergy potential; (5) a comprehensive assessment of diverse livelihood and sustainability effects of bioenergy deployment, identifying the need for systematic aggregation.

11.13.2 Technical bioenergy potential

The technical bioenergy potential, also known as the technical primary biomass potential for bioenergy, is the amount of the theoretical bioenergy output obtainable by full implementation of demonstrated technologies or practices (IPCC, 2011). Unfortunately there is no standard methodology to estimate the technical bioenergy potential, which leads to diverging estimates. Most of the recent studies estimating technical bioenergy potentials assume a 'food/fibre first principle' and exclude deforestation, eventually resulting in an estimate of the 'environmentally sustainable bioenergy potential' when a comprehensive range of environmental constraints is considered (Batidzirai et al., 2012).

Recently published estimates that are based in this extended definition of global technical bioenergy potentials in 2050 span a range of almost three orders of magnitude, from < 50 EJ/yr to > 1,000 EJ/yr (Smeets et al., 2007; Field et al., 2008; Haberl et al., 2010; Batidzirai et al., 2012). For example, Chum et al. reported global technical bioenergy potentials of 50–500 EJ/yr for the year 2050 (IPCC, 2011), and the Global Energy Assessment gave a range of 160–270 EJ/yr (Johansson et al., 2012). The discussion following the publication of these global reports has not resulted in a consensus on the magnitude of the future global technical bioenergy potential, but has helped to better understand some of its many structural determinants (Wirsenius et al., 2011; Berndes, 2012; Erb et al., 2012a). How much biomass for energy is technically available in the future depends on the evolution of a multitude of social, political, and economic factors, e.g., land tenure and regulation, trade, and technology (Dornburg et al., 2010).

Figure 11.20 shows estimates of the global technical bioenergy potential in 2050 by resource categories. Ranges were obtained from assessing a large number of studies based on a food/fibre first principle and various restrictions regarding resource limitations and environmental concerns but no explicit cost considerations (Hoogwijk et al., 2005; Smeets et al., 2007; Smeets and Faaij, 2007; van Vuuren et al., 2009; Hakala et al., 2009; Dornburg et al., 2010; Haberl et al., 2010, 2011a; Gregg and Smith, 2010; Chum et al., 2011; GEA, 2012; Rogner et al., 2012). Most studies agree that the technical bioenergy potential in 2050 is at least approximately 100 EJ/yr with some modelling assumptions leading to estimates exceeding 500 EJ/yr (Smeets et al., 2007). As stated, different views about sustainability and socio-ecological constraints lead to very different estimates, with some studies reporting much lower figures.

As shown in Figure 11.20, the total technical bioenergy potential is composed of several resource categories that differ in terms of their absolute potential, the span of the ranges—which also reflect the relative agreement/disagreement in the literature—and the implications of utilizing them. Regional differences—which are not addressed here—are also important as the relative size of each biomass resource within the total potential and its absolute magnitude vary widely across countries and world regions.

Forest and Agriculture residues. Forest residues (Smeets and Faaij, 2007; Smeets et al., 2007; Dornburg et al., 2010; Haberl et al., 2010; Gregg and Smith, 2010; Rogner et al., 2012) include residues from silvicultural thinning and logging; wood processing residues such as sawdust, bark, and black liquor; and dead wood from natural disturbances, such as storms and insect outbreaks (irregular source). The use of these resources is in general beneficial and any adverse side-effects can be mitigated by controlling residue removal rates considering biodiversity, climate, topography, and soil factors. There is a near-term tradeoff, particularly within temperate and boreal regions, in that organic matter retains organic C for longer if residues are left to decompose slowly instead of being used for energy. Agricultural residues (Smeets et al., 2007; Hakala et al., 2009; Haberl et al., 2010, 2011a; Gregg and Smith, 2010; Chum et al., 2011; Rogner et al., 2012) include manure, harvest residues (e.g., straw), and processing residues (e.g., rice husks from rice milling) and are also in general beneficial. However, mitigating

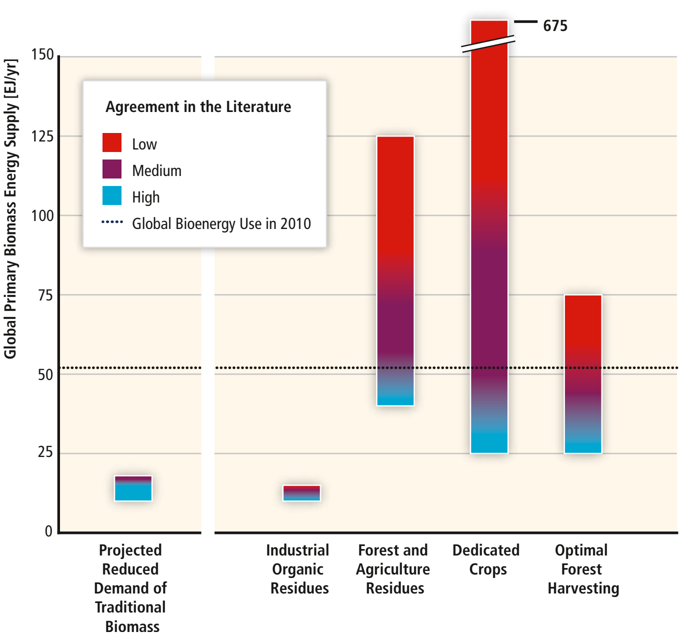


Figure 11.20 | Global Technical Bioenergy Potential by main resource category for the year 2050 | The figure shows the ranges in the estimates by major resource category of the global technical bioenergy potential. The color grading is intended to show qualitatively the degree of agreement in the estimates, from blue (large agreement in the literature) to purple (medium agreement) to red (small agreement). In addition, reducing traditional biomass demand by increasing its use efficiency could release the saved biomass for other energy purposes with large benefits from a sustainable development perspective.

potential adverse side-effects—such as the loss of soil C—associated to harvesting agriculture residues is more complex as they depend on the different crops, climate, and soil conditions (Kochsiek and Knops, 2012; Repo et al., 2012). Alternative uses of residues (bedding, use as fertilizer) need to be considered. Residues have varying collection and processing costs (in both agriculture and forestry) depending on residue quality and dispersal, with secondary residues often having the benefits of not being dispersed and having relatively constant quality. Densification and storage technologies would enable cost-effective collections over larger areas. Optimization of crop rotation for food and bioenergy output and the use of residues in biogas plants may result in higher bioenergy yields from residues without food-energy competition.

Optimal forest harvesting is defined as the fraction of sustainable harvest levels (often set equal to net annual increment) in forests available for wood extraction, which is additional to the projected biomass demand for producing other forest products. This includes both biomass suitable for other uses (e.g., pulp and paper production) and biomass that is not used commercially (Smeets and Faaij, 2007; Chum et al., 2011). The resource potential depends on both environmental and socio-economic factors. For example, the change in forest management and harvesting regimes due to bioenergy demand depends on forest ownership and the structure of the associated forest industry. Also, the forest productivity—and C stock—response to changes in forest management and harvesting depends on the character of the forest ecosystem, as shaped by historic forest management and events such as fires, storms, and insect outbreaks, but also on the management scheme (e.g., including replanting after harvest, soil protection, recycling of nutrients, and soil types (Jonker et al., 2013; Lamers et al., 2013). In particular, optimizing forest management for mitigation is a complex issue with many uncertainties and still subject to scientific debate. Intensive forest management activities of the early- to mid-twentieth century as well as other factors such as recovery from past overuse, have led to strong forest C sinks in many OECD regions (Pan et al., 2011; Loudermilk et al., 2013; Nabuurs et al., 2013; Erb et al., 2013). However, the capacity of these sinks is being reduced as forests approach saturation (Smith, 2005; Körner, 2006; Guldea et al., 2008; Nabuurs et al., 2013; Sections 11.2.3, 11.3.2). Active forest management, including management for bioenergy, is therefore important for sustaining the strength of the forest carbon sink well into the future (Nabuurs et al., 2007, 2013; Canadell and Raupach, 2008; Ciais et al., 2008), although countries should realize that for some old forest areas, conserving carbon stocks may be preferential, and that the actively managed forests may for some time (decades) act as sources.

Organic wastes include waste from households and restaurants, discarded wood products such as paper, construction, and demolition wood waste, and waste waters suitable for anaerobic biogas production (Haberl et al., 2010; Gregg and Smith, 2010). Organic waste may be dispersed and also heterogeneous in quality but the health and environmental gains from collection and proper management through

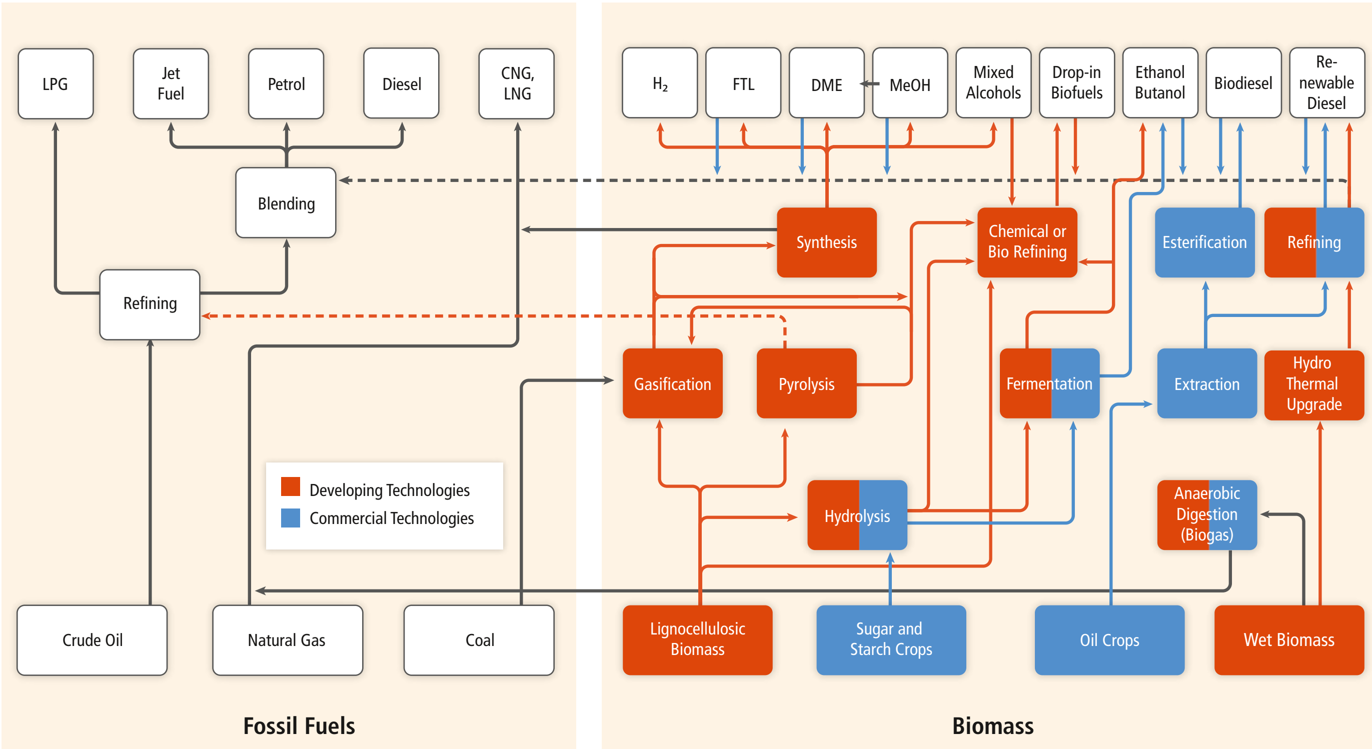


Figure 11.21 | Production pathways to liquid and gaseous fuels from biomass and, for comparison from fossil fuels (adapted from GEA, 2012; Turkenburg et al., 2012).

combustion or anaerobic digestion can be significant. Competition with alternative uses of the wastes may limit this resource potential.

Dedicated biomass plantations include annual (cereals, oil, and sugar crops) and perennial plants (e.g., switchgrass, Miscanthus) and tree plantations (both coppice and single-stem plantations (e.g., willow, poplar, eucalyptus, pine; (Hoogwijk et al., 2005, 2009; Smeets et al., 2007; van Vuuren et al., 2009; Dornburg et al., 2010; Wicke et al., 2011b; Haberl et al., 2011a). The range of estimates of technical bioenergy potentials from that resource in 2050 is particularly large (< 50 to > 500 EJ/yr). Technical bioenergy potentials from dedicated biomass plantations are generally calculated by multiplying (1) the area deemed available for energy crops by (2) the yield per unit area and year (Batidzirai et al., 2012; Coelho et al., 2012). Some studies have identified a sizable technical potential (up to 100 EJ) for bioenergy production using marginal and degraded lands (e.g., saline land) that are currently not in use for food production or grazing (Nijsen et al., 2012). However, how much land is really unused and available is contested (Erb et al., 2007; Haberl et al., 2010; Coelho et al., 2012). Contrasting views on future technical bioenergy potentials from dedicated biomass plantations can be explained by differences in assumptions regarding feasible future agricultural crop yields, livestock feeding efficiency, land availability for energy crops and yields of energy crops (Dornburg et al., 2010; Batidzirai et al., 2012; Erb et al., 2012a). Most scientists agree that increases in food crop yields and higher feeding efficiencies and lower consumption of animal products results in higher technical bioenergy potential. Also, there is a large agreement that careful policies for implementation focused on land-use zoning approaches (including nature conservation and biodiversity protection), multifunctional land use, integration of food and energy production, avoidance of detrimental livelihood impacts, e.g., on livestock grazing and subsistence farming, and consideration of equity issues, and sound management of impacts on water systems are crucial for sustainable solutions.

Reduced traditional biomass demand. A substantial quantity of biomass will become available for modern applications by improving the end-use efficiency of traditional biomass consumption for energy, mostly in households but also within small industries (such as charcoal kilns, brick kilns, etc.). Traditional bioenergy represents approximately 15 % of total global energy use and 80 % of current bioenergy use (≈35 EJ/yr) and helps meeting the cooking needs of ~2.6 billion people (Chum et al., 2011; IEA, 2012b). Traditional bioenergy use covers several end-uses including cooking, water, and space heating, and small-industries (such as brick and pottery kilns, bakeries, and many others). Cooking is the dominant end use; it is mostly done in open fires and rudimentary stoves, with approximately 10–20 % conversion efficiency, leading to very high primary energy consumption. Advanced woodburning and biogas stoves can potentially reduce biomass fuel consumption by 60 % or more (Jetter et al., 2012) and further lower the atmospheric radiative forcing, reducing CO_2 emissions, and in many cases black carbon emissions, by up to 90 % (Anenberg et al., 2013). Assuming that actual savings reach on average 30–60 % of current consumption, the total bioenergy potential from reducing traditional bioenergy demand can be estimated at 8–18 EJ/yr. An unknown fraction of global traditional biomass is consumed in a non-environmentally sustainable way, leading to forest degradation and deforestation.

Detailed country studies have estimated the fraction of non-renewable biomass from traditional bioenergy use to vary widely, e.g., from 1.6 % for the Democratic Republic of Congo to 73 % for Burundi (CDM-SSC WG, 2011) with most countries in the range between 10–30 % (i.e., meaning that 70–90 % of total traditional bioenergy use is managed sustainably). Thus a fraction of the traditional biomass saved through better technology, should not be used for other energy purposes but simply not consumed to help restore the local ecosystems.

11.13.3 Bioenergy conversion: technologies and management practices

Numerous conversion technologies can transform biomass to heat, power, liquid, and gaseous fuels for use in the residential, industrial, transport, and power sectors (see Chum et al., 2011; GEA, 2012) for a comprehensive coverage of each alternative, and Figure 11.21 for the pathways concerning liquid and gaseous fuels). Since SRREN, the major advances in the large-scale production of bioenergy include the increasing use of hybrid biomass-fossil fuel systems. For example, current commercial coal and biomass co-combustion technologies are the lowest-cost technologies for implementing renewable energy policies, enabled by the large-scale pelletized feedstocks trade (REN21, 2013; Junginger et al., 2014). Direct biopower use is also increasing commercially on a global scale (REN21, 2013, p. 21). In fact, using biomass for electricity and heat, for example, co-firing of woody biomass with coal in the near term and large heating systems coupled with networks for district heating, and biochemical processing of waste biomass, are among the most cost-efficient and effective biomass applications for GHG emission reduction in modern pathways (Sterner and Fritsche, 2011).

Integrated gasification combined cycle (IGCC) technologies for co-production of electricity and liquid fuels from coal and biomass with higher efficiency than current commercial processes are in demonstration phase to reduce cost (Williams et al., 2011; GEA, 2012; Larson et al., 2012). Coupling of biomass and natural gas for fuels is another option for liquid fuels (Baliban et al., 2013) as the biomass gasification technology development progresses. Simulations suggest that integrated gasification facilities are technically feasible (with up to 50 % biomass input; Meerman et al., 2011), and economically attractive with a CO_2 price of about 66 USD_{2010}/tCO_2 (50 EUR_{2010}/tCO_2) (Meerman et al., 2012). Many gasification technology developments around the world are in pilot, demonstration, operating first commercial scale for a variety of applications (see examples in Bacovsky et al., 2013; Balan et al., 2013).

Many pathways and feedstocks (Figure 11.21) can lead to biofuels for aviation. The development of biofuel standards started and enabled testing of 50 % biofuel in jet fuel for commercial domestic and transatlantic flights by consortia of governments, aviation industry, and associations (IEA, 2010; REN21, 2013). Advanced 'drop in' fuels, such as iso-butanol, synthetic aviation kerosene from biomass gasification or upgrading of pyrolysis liquids, can be derived through a number of possible conversion routes such as hydro treatment of vegetable oils, iso-butanol, and Fischer-Tropsch synthesis from gasification of biomass (Hamelinck and Faaij, 2006; Bacovsky et al., 2010; Meerman et al., 2011, 2012; Rosillo-Calle et al., 2012); see also Chapter 8). In specific cases, powering electric cars with electricity from biomass has higher land-use efficiency and lower global-warming potential (GWP) effects than the usage of bioethanol from biofuel crops for road transport across a range of feedstocks, conversion technologies, and vehicle classes (Campbell et al., 2009; Schmidt et al., 2011)[13], though costs are likely to remain prohibitive for considerable time (van Vliet et al., 2011a; b; Schmidt et al., 2011).

The number of routes from biomass to a broad range of biofuels, shown in Figure 11.21, includes hydrocarbons connecting today's fossil fuels industry in familiar thermal/catalytic routes such as gasification (Williams et al., 2011; Larson et al., 2012) and pyrolysis (Brown et al., 2011; Bridgwater, 2012; Elliott, 2013; Meier et al., 2013). In addition, advances in genomic technology, the emphasis in systems approach, and the integration between engineering, physics, chemistry, and biology bring together many new approaches to biomass conversion (Liao and Messing, 2012) such as (1) biomolecular engineering (Li et al., 2010; Favaro et al., 2012; Peralta-Yahya et al., 2012; Lee et al., 2013; Yoon et al., 2013); (2) deconstruction of lignocellulosic biomass through combinations of mild thermal and biochemical routes in multiple sequential or consolidated steps using similar biomolecular engineering tools (Rubin, 2008; Chundawat et al., 2011; Beckham et al., 2012; Olson et al., 2012; Tracy et al., 2012; Saddler and Kumar, 2013; Kataeva et al., 2013); and (3) advances in (bio)catalysis and basic understanding of the synthesis of cellulose are leading to routes for many fuels and chemicals under mild conditions (Serrano-Ruiz et al., 2010; Carpita, 2012; Shen et al., 2013; Triantafyllidis et al., 2013; Yoon et al., 2013). Fundamental understanding of biofuel production increased for microbial genomes by forward engineering of cyanobacteria, microalgae, aiming to arrive at minimum genomes for synthesis of biofuels or chemicals (Chen and Blankenship, 2011; Eckert et al., 2012; Ungerer et al., 2012; Jones and Mayfield, 2012; Kontur et al., 2012; Lee et al., 2013).

Bioenergy coupled with CCS (Spath and Mann, 2004; Liu et al., 2010) is seen as an option to mitigate climate change through negative emissions if CCS can be successfully deployed (Cao and Caldeira 2010; Lenton and Vaughan 2009). BECCS features prominently in long-run mitigation scenarios (Sections 6.3.2 and 6.3.5) for two reasons: (1) The potential for negative emissions may allow shifting emissions in time; and (2) in scenarios, negative emissions from BECCS compensate for residual emissions in other sectors (most importantly transport) in the second half of the 21st century. As illustrated in Figure 11.22, BECCS is markedly different than fossil CCS because it not only reduces CO_2 emissions by storing C in long-term geological sinks, but it continu-

[13] Biomass can be used for electric transport and biofuels within one pathway (Macedo et al., 2008)

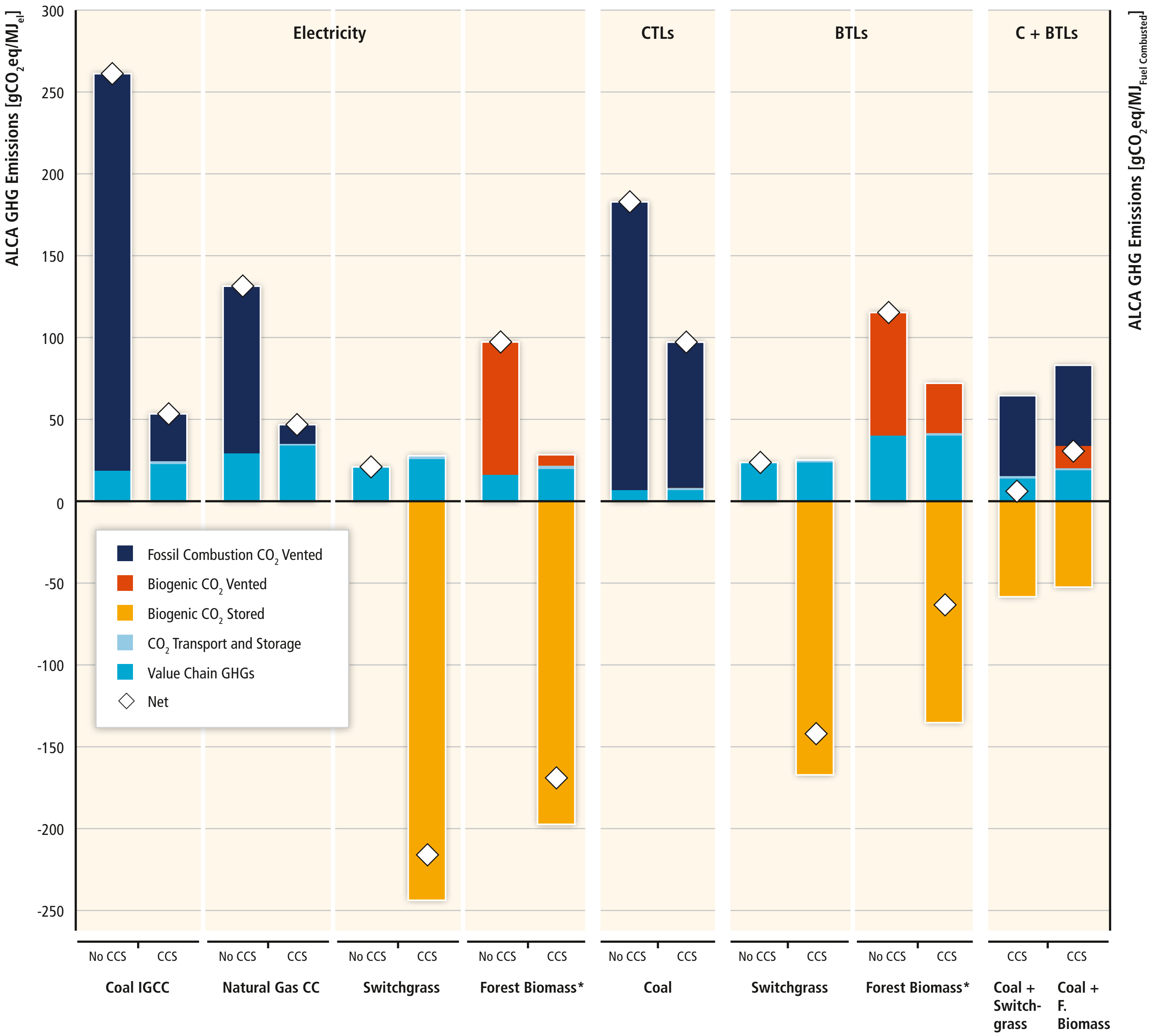


Figure 11.22 | Illustration of the sum of CO_2eq (GWP_{100})* emissions from the process chain of alternative transport and power generation technologies both with and without CCS. (*Differences in C-density between forest biomass and switchgrass are taken into account but not calorific values (balance-of-plant data are for switchgrass, ref. Larson et al., 2012). Specific emissions vary with biomass feedstock and conversion technology combinations, as well as lifecycle GHG calculation boundaries. For policy relevant purposes, counterfactual and market-mediated aspects (e.g., iLUC), changes in soil organic carbon, or changes in surface albedo need also to be considered, possibly leading to significantly different outcomes, quantitatively (Section 11.13.4, Figures 11.23 and 11.24). Unit: gCO_2eq/MJ_{El} (left y-axis, electricity); gCO_2eq/MJ combusted (right y-axis, transport fuels). Direct CO_2 emissions from energy conversion ('vented' and 'stored') are adapted from the mean values in Tables 12.7, 12.8, and 12.15 of ref. [1], which are based on the work of refs. [2, 3], and characterized with the emission metrics in ref. [4]. Impacts upstream in the supply chain associated with feedstock procurement (i.e., sum of GHGs from mining/cultivation, transport, etc.) are adapted from refs. [5, 6] and Figure 11.23 (median values).

[1]Larson, et al. (2012); [2]Woods, et al., (2007) ; [3]Liu et al. (2010); [4]Guest et al. (2013); [5]Turconi et al. (2013); [6]Jaramillo et al. (2008)

Notes:
* Global Warming Potential over 100 years. See Glossary and Section 1.2.5.

ally sequesters CO_2 from the air through regeneration of the biomass resource feedstock.

BECCS deployment is in the development and exploration stages. The most relevant BECCS project is the 'Illinois Basin—Decatur Project' that is projected to inject 1 $MtCO_2$/yr (Gollakota and McDonald, 2012; Senel and Chugunov, 2013). In the United States, two ethanol fuel production by fermentation facilities are currently integrated commercially with carbon dioxide capture, pipeline transport, and use in enhanced oil recovery in nearby facilities at a rate of about 0.2 $MtCO_2$/yr (DiPietro et al., 2012). Altogether, there are 16 global BECCS projects in exploration stage (Karlsson and Byström, 2011).

Critical to overall CO_2 storage is the realization of a lignocellulosic biomass supply infrastructure for large-scale commodity feedstock production and efficient advanced conversion technologies at scale; both benefit from cost reductions and technological learning as does the integrated system with CCS, with financial and institutional conditions that minimize the risks of investment and facilitate dissemination (Eranki and Dale, 2011; IEA, 2012c, 2013). Integrated analysis is needed to capture system and knock-on effects for bioenergy potentials. A nascent feedstock infrastructure for densified biomass trading globally could indicate decreased pressure on the need for closely co-located storage and production (IEA, 2011; Junginger et al., 2014).

The overall technical potential is estimated to be around 10 $GtCO_2$ storage per year for both Integrated Gasification Combined Cycle (IGCC)-CCS co-firing (IGCC with co-gasification of biomass), and Biomass Integrated Gasification Combined Cycle (BIGCC)-CCS dedicated, and around 6 $GtCO_2$ storage for biodiesel based on gasification and Fischer-Tropsch synthesis (FT diesel), and 2.7 $GtCO_2$ for biomethane production (Koornneef et al., 2012, 2013). Another study estimates the potential capacity (similar to technical potential) to be between 2.4 and 10 $GtCO_2$ per year for 2030–2050 (McLaren, 2012). The economic potential, at a CO_2 price of around 70 USD/t is estimated to be around 3.3 $GtCO_2$, 3.5 $GtCO_2$, 3.1 $GtCO_2$ and 0.8 $GtCO_2$ in the corresponding four cases, judged to be those with highest economic potential (Koornneef et al., 2012, 2013). Potentials are assessed on a route-by-route basis and cannot simply be added, as they may compete and substitute each other. Practical figures might be not much higher than 2.4 $GtCO_2$ per year at 70–250 USD/tCO_2 (McLaren, 2012). Altogether, until 2050, the economic potential is anywhere between 2–10 $GtCO_2$ per year. Some climate stabilization scenarios see considerable higher deployment towards the end of the century, even in some 580–650 ppm scenarios, operating under different time scales, socioeconomic assumptions, technology portfolios, CO_2 prices, and interpreting BECCS as part of an overall mitigation framework (e.g., Rose et al., 2012; Kriegler et al., 2013; Tavoni and Socolow, 2013).

Possible climate risks of BECCS relate to reduction of land carbon stock, feasible scales of biomass production and increased N_2O emissions, and potential leakage of CO_2, which has been stored in deep geologic reservoirs (Rhodes and Keith, 2008). The assumptions of sufficient spatially appropriate CCS capture, pipeline, and storage infrastructure are uncertain. The literature highlights that BECCS as well as CCS deployment is dependent on strong financial incentives, as they are not cost competitive otherwise (Sections 7.5.5; 7.6.4; 7.9; 7.12).

Figure 11.22 illustrates some GHG effects associated with BECCS pathways. Tradeoffs between CO_2 capture rate and feedstock conversion efficiency are possible. Depicted are pathways with the highest removal rate but not necessarily with the highest feedstock conversion rate. Among all BECCS pathways, those based on integrated gasification combined cycle produce most significant geologic storage potential from biomass, alone (shown in Figure 11.23, electricity) or coupled with coal. Fischer-Tropsch diesel fuel production with biomass as feedstock and CCS attached to plant facilities could enable BECCS for transport; uncertainties in input factors, and output metrics warrant further research (van Vliet et al., 2009). Fischer-Tropsch diesel would also allow net removal but at lower rates than BIGCC.

Economics of scale in power plant size are crucial to improve economic viability of envisaged BECCS projects. Increasing power plant size requires higher logistic challenges in delivering biomass.

Scales of 4,000 to 10,000 Mg/day needed for > 600 MW power plants could become feasible as the biomass feedstock supply logistic development with manageable logistic costs if biomass is derived from high-yield monocrops; logistical costs are more challenging when biomass is derived from residues (e.g., Argo et al., 2013; Junginger et al., 2014). Large-scale biomass production with flexible integrated polygeneration facilities for fuels and/or power can improve the techno-economic performance, currently above market prices to become more economically competitive over time (Meerman et al., 2011). In the future, increased operating experience of BECCS IGCC-CCS through technological improvements and learning could enable carbon neutral electricity and, in combination with CCS, could result in net removal of CO_2 (Figure 11.22). BECCS is among the lowest cost CCS options for a number of key industrial sectors (Meerman et al., 2013). It should be noted that primary empiric cost and performance data for dedicated bioenergy plants are not yet available and needed for comprehensively assessing BECCS. The current status of CCS and on-going research issues are discussed in Sections 7.5.5 and 7.6.4. Social concerns constitute a major barrier for implement demonstration and deployment projects.

Integrated bio-refineries continue to be developed; for instance, 10 % of the ethanol or corresponding sugar stream goes into bio-products in Brazil (REN21, 2012) including making ethylene for polymers (IEA-ETSAP and IRENA, 2013). Multi product bio-refineries could produce a wider variety of co-products to enhance the economics of the overall process, facilitating learning in the new industry (IEA, 2011); Lifecycle Analyses (LCAs) for these systems are complex (Pawelzik et al., 2013).

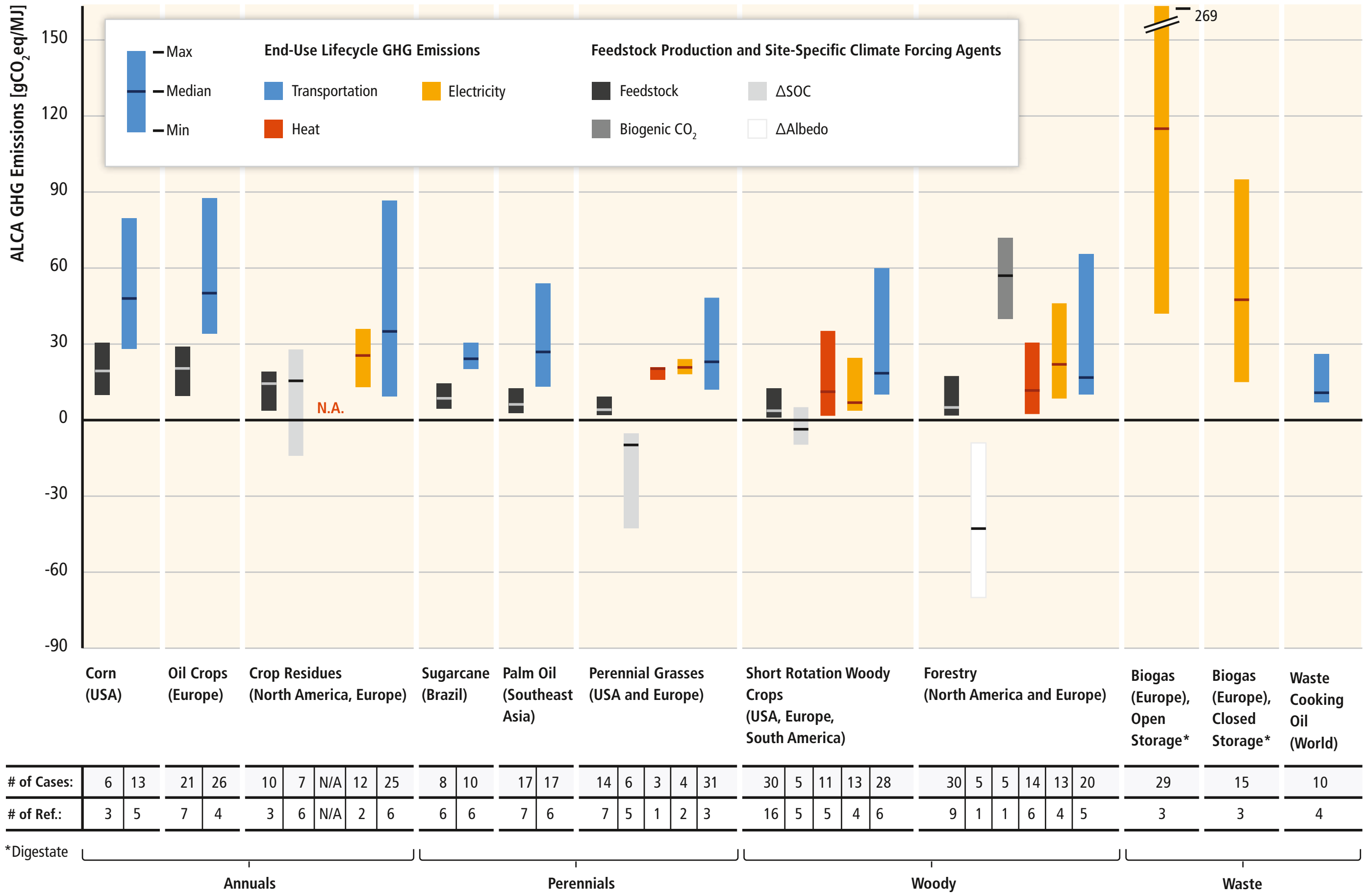


Figure 11.23 | Direct CO_2eq (GWP_{100}) emissions from the process chain or land-use disturbances of major bioenergy product systems, not including impacts from LUC (see Figure 11.24). The interpretation of values depends also on baseline assumption about the land carbon sink when appropriate and the intertemporal accounting frame chosen, and should also consider information from Figure 11.24. The lower and upper bounds of the bars represent the minimum and the maximum value reported in the literature. Whenever possible, peer-reviewed scientific literature published post SRREN is used (but results are comparable). Note that narrow ranges may be an artefact of the number of studies for a given case. Results are disaggregated in a manner showing the impact of *Feedstock* production (in gCO_2eq/MJ lower heating value (LHV) of feedstock) and the contributions from end product/conversion technology. Results from conversion into final energy products *Heat*, *Power*, and *Transport fuels* include the contribution from *Feedstock* production and are shown in gCO_2eq/MJ of final product. For some pathways, additional site-specific climate forcing agents apply and are presented as separate values to be added or subtracted from the value indicated by the median in the *Feedstock* bar (dark grey). Final products are also affected by these factors, but this is not displayed here. References: Corn 1–7; Oil crops 1, 8, 8–12; Crop residues 1, 4, 13–24; Sugarcane 2, 3, 5, 6, 25–27; Palm Oil 2, 3, 10, 28–31; Perennial grasses 1, 3, 11, 18, 22, 32–40; Short Rotation Woody Crops 1, 3, 6, 12, 22, 33, 35, 37, 38, 41–53; Forestry 5, 6, 38, 49, 54–66; Biogas, open storage: 67–69; Biogas, closed storage 69–71; Waste cooking oil: 22, 72–74. Note that the biofuels technologies for transport from lignocellulosic feedstocks, short rotation woody crops, and crop residues, including collection and delivery, are developing so larger ranges are expected than for more mature commercial technologies such as sugarcane ethanol and waste cooking oil (WCO) biodiesel. The biogas electricity bar represents scenarios using LCAs to explore treating mixtures of a variety of lignocellulosic feedstocks (e.g., ensiled grain or agricultural residues or perennial grasses) with more easily biodegradable wastes (e.g., from animal husbandry), to optimize multiple outputs. Some of the scenarios assume CH_4 leakage, which leads to very high lifecycle emissions.

[1]Gelfand et al. (2013); [2]Nemecek et al. (2012); [3]Hoefnagels et al. (2010); [4]Kaufman et al. (2010); [5]Cherubini et al. (2009); [6] Cherubini (2012); [7]Wang et al. (2011b); [8]Milazzo et al. (2013); [9]Goglio et al. (2012); [10]Stratton et al. (2011); [11]Fazio and Monti (2011); [12]Börjesson and Tufvesson (2011); [13]Cherubini and Ulgiati (2010); [14]Li et al. (2012); [15]Luo et al. (2009); [16]Gabrielle and Gagnaire (2008); [17]Smith et al. (2012b); [18]Anderson-Teixeira et al. (2009); [19]Nguyen et al. (2013); [20]Searcy and Flynn (2008); [21]Giuntoli et al. (2013); [22]Whitaker et al. (2010); [23]Wang et al. (2013a); [24]Patrizi et al. (2013); [25]Souza et al. (2012a); [26]Seabra et al. (2011); [27]Walter et al. (2011); [28]Choo et al. (2011); [29]Harsono et al. (2012); [30]Siangjaeo et al. (2011); [31]Silalertruksa and Gheewala (2012); [32]Smeets et al. (2009b); [33]Tiwary and Colls (2010); [34]Wilson et al. (2011); [35]Brandão et al. (2011); [36]Cherubini and Jungmeier (2010); [37]Don et al. (2012); [38]Pucker et al. (2012); [39]Monti et al. (2012); [40]Bai et al. (2010); [41]Bacenetti et al. (2012); [42]Budsberg et al. (2012); [43]González-García et al. (2012a); [44]González-García (2012b) ; [45]Stephenson et al. (2010); [46]Hennig and Gawor (2012);[47]Buonocore et al. (2012); [48]Gabrielle et al. (2013); [49]Dias and Arroja (2012); [50]González-García et al. (2012b); [51]Roedl (2010); [52]Djomo et al. (2011); [53]Njakou Djomo et al. (2013); [54]McKechnie et al. (2011); [55]Pa et al. (2012); [56]Puettmann et al. (2010); [57]Guest et al. (2011); [58]Valente et al. (2011); [59]Whittaker et al. (2011); [60]Bright and Strømman (2009); [61]Felder and Dones (2007); [62]Solli et al. (2009); [63]Lindholm et al. (2011); [64]Mallia and Lewis (2013); [65]Bright et al. (2010); [66]Bright and Strømman (2010); [67]Rehl et al. (2012); [68]Blengini et al. (2011); [69]Boulamanti et al. (2013); [70]Lansche and Müller (2012); [71]De Meester et al. (2012); [72]Sunde et al. (2011); [73]Thamsiriroj and Murphy (2011); [74]Talens Peiró et al. (2010)

There are alternatives to land-based bioenergy. Microalgae, for example, offer a high-end technical potential. However, it might be compromised by water supply, if produced in arid land, or by impacts on ocean ecosystems. To make microalgae cost competitive, maximizing algal lipid content (and then maximizing growth rate) requires technological breakthroughs (Davis et al., 2011a; Sun et al., 2011; Jonker and Faaij, 2013). The market potential depends on the co-use of products for food, fodder, higher value products, and fuel markets (Chum et al., 2011).

Similarly, lignocellulosic feedstocks produced from waste or residues, or grown on land unsupportive of food production (e.g., contaminated land for remediation as in previously mined land) have been suggested to reduce socio-environmental impact. In addition, lignocellulosic feedstocks can be bred specifically for energy purposes, and can be harvested by coupling collection and pre-processing (densification and others) in depots prior to final conversion, which could enable delivery of more uniform feedstocks throughout the year (Eranki and Dale, 2011; U.S. DOE, 2011; Argo et al., 2013).

Various conversion pathways are in research and development (R&D), near commercialization, or in early deployment stages in several countries (see Section 2.6.3 in Chum et al., 2011). More productive land is also more economically attractive for cellulosic feedstocks, in which case competition with food production is more likely. Depending on the feedstock, conversion process, prior land use, and land demand, lignocellulosic bioenergy can be associated with high or low GHG emissions (e.g., Davis et al., 2011b). Improving agricultural lands and reducing non-point pollution emissions to watersheds remediate nitrogen run off and increase overall ecosystems' health (Van Dam et al., 2009a; b; Gopalakrishnan et al., 2012). Also regeneration of saline lands by salt-tolerant tree and grass species can have a large potential on global scale as demonstrated by Wicke et al. (2011).

A range of agro-ecological options to improve agricultural practices such as no/low tillage conservation, agroforestry, etc., have potential to increase yields (e.g., in sub-Saharan Africa), while also providing a range of co-benefits such as increased soil organic matter. Such options require a much lower level of investment and inputs and are thus more readily applicable in developing countries, while also holding a low risk of increased GHG emissions (Keating et al., 2013).

Substantial progress has also been achieved in the last four years in small-scale bioenergy applications in the areas of technology innovation, impact evaluation and monitoring, and in large-scale implementation programmes. For example, advanced combustion biomass cookstoves, which reduce fuel use by more than 60 % and hazardous pollutant as well as short-lived climate pollutants by up to 90 %, are now in the last demonstration stages or commercial (Kar et al., 2012; Anenberg et al., 2013). Innovative designs include micro-gasifiers, stoves with thermoelectric generators to improve combustion efficiency and provide electricity to charge LED lamps while cooking, stoves with advanced combustion chamber designs, and multi-use stoves (e.g., cooking and water heating for bathing (Ürge-Vorsatz et al., 2012; Anenberg et al., 2013). Biogas stoves, in addition to providing clean combustion, help reduce the health risks associated with the disposal of organic wastes. There has also been a boost in cookstove dissemination efforts ranging from regional (multi-country) initiatives (Wang et al., 2013b) to national, and project-level interventions. In total, more than 200 large-scale cookstove projects are in place worldwide, with several million efficient cookstoves installed each year (Cordes, 2011). A Global Alliance for Clean Cookstoves has been launched that is promoting the adoption of 100 million clean and efficient cookstoves per year by 2030 and several countries have launched National Cookstove Programs in recent years (e.g., Mexico, Peru, Honduras, and others). Many cookstove models are now manufactured in large-scale industrial facilities using state-of-the-art materials and combustion design technology. Significant efforts are also in place to develop international standards and regional stove testing facilities. In addition to providing tangible local health and other sustainable benefits, replacing traditional open fires with efficient biomass cookstoves has a global mitigation potential estimated to be between 0.6 and 2.4 $GtCO_2eq/yr$ (Ürge-Vorsatz et al., 2012).

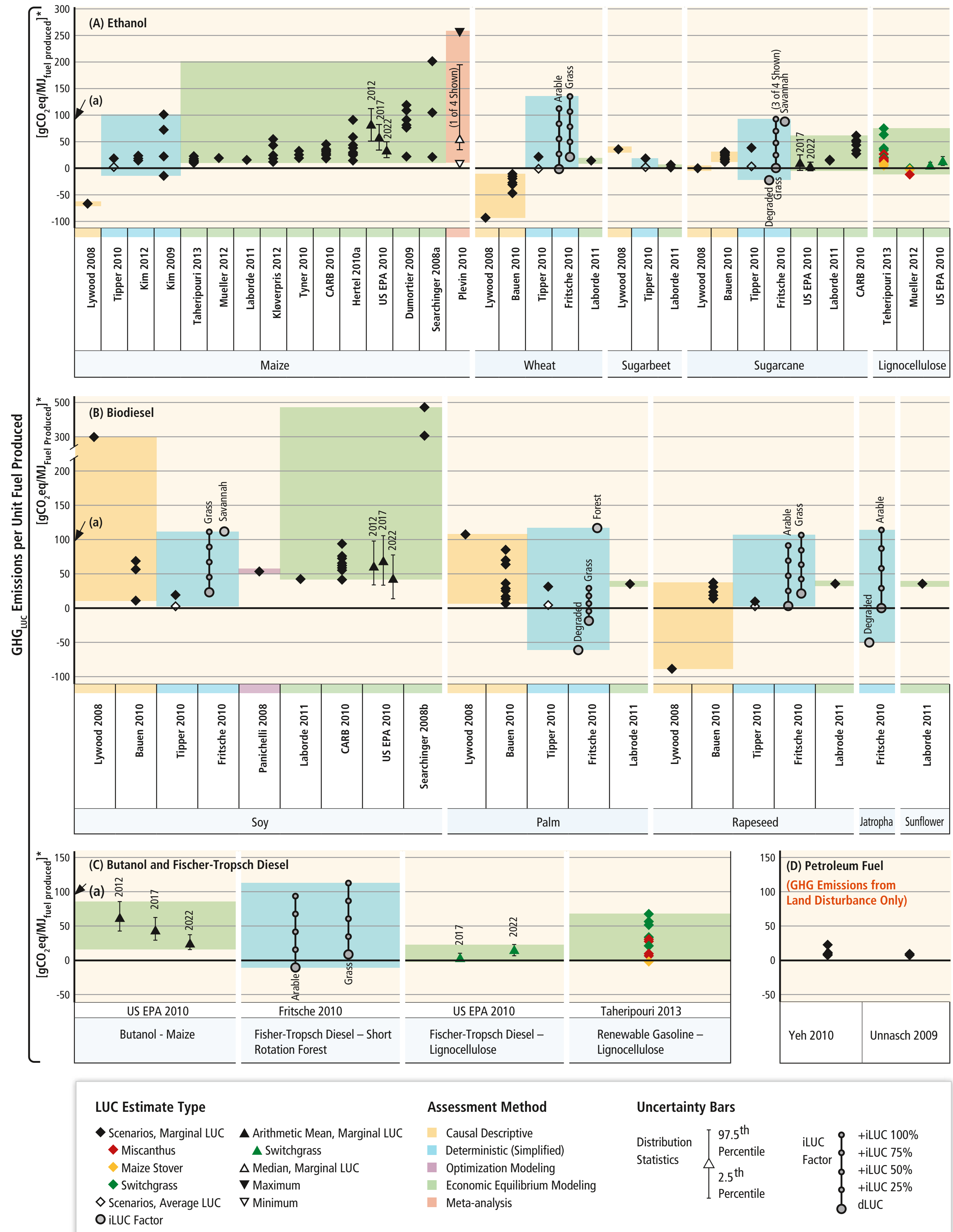
Small-scale decentralized biomass power generation systems based on biomass combustion and gasification and biogas production systems have the potential to meet the electricity needs of rural communities in the developing countries. The biomass feedstocks for these small-scale systems could come from residues of crops and forests, wastes from livestock production, and/or from small-scale energy plantations (Faaij, 2006).

11.13.4 GHG emission estimates of bioenergy production systems

The combustion of biomass generates gross GHG emissions roughly equivalent to the combustion of fossil fuels. If bioenergy production is to generate a net reduction in emissions, it must do so by offsetting those emissions through increased net carbon uptake of biota and soils. The appropriate comparison is then between the net biosphere flux in the absence of bioenergy compared to the net biosphere flux in the presence of bioenergy production. Direct and indirect effects need to be considered in calculating these fluxes.

Bioenergy systems directly influence local and global climate through (i) GHG emissions from fossil fuels associated with biomass production, harvest, transport, and conversion to secondary energy carriers (von Blottnitz and Curran, 2007; van der Voet et al., 2010); (ii) CO_2 and other GHG emissions from biomass or biofuel combustion (Cherubini et al., 2011); (iii) atmosphere-ecosystem exchanges of CO_2 following land disturbance (Berndes et al., 2013; Haberl, 2013); (iv) climate forcing resulting from emissions of short-lived GHGs like black carbon and other chemically active gases (NO_x, CO, etc.) (Tsao et al., 2012; Jetter et al., 2012); (v) climate forcing resulting from alteration of biophysical properties of the land surface affecting the surface energy balance

11



GHG_LUC Emissions per Unit Fuel Produced
[gCO2eq/MJfuel produced]*
(A) Ethanol
(a)
(1 of 4 Shown)
2012
2017
2022
Arable
Grass
(3 of 4 Shown)
Savannah
Degraded
Grass
Lywood 2008
Tipper 2010
Kim 2012
Kim 2009
Taheripouri 2013
Mueller 2012
Laborde 2011
Kløverpris 2012
Tyner 2010
CARB 2010
Hertel 2010a
US EPA 2010
Dumortier 2009
Searchinger 2008a
Plevin 2010
Bauen 2010
Fritsche 2010
Maize
Wheat
Sugarbeet
Sugarcane
Lignocellulose
(B) Biodiesel
Savannah
Forest
Degraded
Arable
Panichelli 2008
Searchinger 2008b
Labrode 2011
Soy
Palm
Rapeseed
Jatropha
Sunflower
(C) Butanol and Fischer-Tropsch Diesel
US EPA 2010
Fritsche 2010
Taheripouri 2013
Butanol - Maize
Fisher-Tropsch Diesel – Short Rotation Forest
Fischer-Tropsch Diesel – Lignocellulose
Renewable Gasoline – Lignocellulose
(D) Petroleum Fuel
(GHG Emissions from Land Disturbance Only)
Yeh 2010
Unnasch 2009
LUC Estimate Type
Scenarios, Marginal LUC
Miscanthus
Maize Stover
Switchgrass
Scenarios, Average LUC
iLUC Factor
Arithmetic Mean, Marginal LUC
Switchgrass
Median, Marginal LUC
Maximum
Minimum
Assessment Method
Causal Descriptive
Deterministic (Simplified)
Optimization Modeling
Economic Equilibrium Modeling
Meta-analysis
Uncertainty Bars
Distribution Statistics
97.5th Percentile
2.5th Percentile
iLUC Factor
+iLUC 100%
+iLUC 75%
+iLUC 50%
+iLUC 25%
dLUC

⟹

Figure 11.24 | Estimates of GHG_{LUC} emissions—GHG emissions from biofuel production-induced LUC (as $gCO_2eq/MJ_{fuel\ produced}$) over a 30-year time horizon organized by fuel(s), feedstock, and study. Assessment methods, LUC estimate types and uncertainty metrics are portrayed to demonstrate the diversity in approaches and differences in results within and across any given category. Points labeled 'a' on the Y-axis represent a commonly used estimate of lifecycle GHG emissions associated with the direct supply chain of petroleum gasoline (frame A) and diesel (frame B). These emissions are not directly comparable to GHG_{LUC} because the emission sources considered are different, but are potentially of interest for scaling comparison. Based on Warner et al. (2013). Please note: These estimates of global LUC are highly uncertain, unobservable, unverifiable, and dependent on assumed policy, economic contexts, and inputs used in the modelling. All entries are not equally valid nor do they attempt to measure the same metric despite the use of similar naming conventions (e.g., iLUC). In addition, many different approaches to estimating GHG_{LUC} have been used. Therefore, each paper has its own interpretation and any comparisons should be made only after careful consideration. *CO_2eq includes studies both with and without CH_4 and N_2O accounting.

(e.g., from changes in surface albedo, heat and water fluxes, surface roughness, etc.; (Bonan, 2008; West et al., 2010a; Pielke Sr. et al., 2011); and (vi) GHGs from land management and perturbations to soil biogeochemistry, e.g., N_2O from fertilizers, CH_4, etc. (Cai, 2001; Allen et al., 2009). Indirect effects include the partial or complete substitution of fossil fuels and the indirect transformation of land use by equilibrium effects. Hence, the total climate forcing of bioenergy depends on feedstock, site-specific climate and ecosystems, management conditions, production pathways, end use, and on the interdependencies with energy and land markets.

In contrast, bioenergy systems have often been assessed (e.g., in LCA studies, integrated models, policy directives, etc.) under the assumption that the CO_2 emitted from biomass combustion is climate neutral[14] because the carbon that was previously sequestered from the atmosphere will be re-sequestered if the bioenergy system is managed sustainably (Chum et al., 2011; Creutzig et al., 2012a; b). The shortcomings of this assumption have been extensively discussed in environmental impact studies and emission accounting mechanisms (Searchinger et al., 2009; Searchinger, 2010; Cherubini et al., 2011; Haberl, 2013).

Studies also call for a consistent and case-specific carbon stock/flux change accounting that integrates the biomass system with the global carbon cycle (Mackey et al., 2013). As shown in Chapter 8 of WGI (Myhre and Shindell, 2013) and (Plattner et al., 2009; Fuglestvedt et al., 2010), the climate impacts can be quantified at different points along a cause-effect chain, from emissions to changes in temperature and sea level rise. While a simple sum of the net CO_2 fluxes over time can inform about the skewed time distribution between sources and sinks ('C debt'; Marland and Schlamadinger, 1995; Fargione et al., 2008; Bernier and Paré, 2013), understanding the climate implication as it relates to policy targets (e.g., limiting warming to 2 °C) requires models and/or metrics that also include temperature effects and climate consequence (Smith et al., 2012c; Tanaka et al., 2013). While the warming from fossil fuels is nearly permanent as it persists for thousands of years, direct impacts from renewable bioenergy systems cause a perturbation in global temperature that is temporary and even at times cooling if terrestrial carbon stocks are not depleted (House et al., 2002; Cherubini et al., 2013; Joos et al., 2013; Mackey et al., 2013). The direct, physical climate effects at various end-points need to be fully understood and characterized—despite the measurement challenges that some climate forcing mechanisms can entail (West et al., 2010b; Anderson-Teixeira et al., 2012), and coherently embedded in mitigation policy scenarios along with the possible counterfactual effects. For example, in the specific case of existing forests that may continue to grow if not used for bioenergy, some studies employing counterfactual baselines show that forest bioenergy systems can temporarily have higher cumulative CO_2 emissions than a fossil reference system (for a time period ranging from a few decades up to several centuries; (Repo et al., 2011; Mitchell et al., 2012; Pingoud et al., 2012; Bernier and Paré, 2013; Guest et al., 2013; Helin et al., 2013; Holtsmark, 2013).

In some cases, cooling contributions from changes in surface albedo can mitigate or offset these effects (Arora and Montenegro, 2011; O'Halloran et al., 2012; Anderson-Teixeira et al., 2012; Hallgren et al., 2013).

Accounting always depends on the time horizon adopted when assessing climate change impacts, and the assumed baseline, and hence includes value judgements (Schwietzke et al., 2011; Cherubini et al., 2013; Kløverpris and Mueller, 2013).

Two specific contributions to the climate forcing of bioenergy, not addressed in detail in SRREN include N_2O and biogeophysical factors.

Nitrous oxide emissions: For first-generation crop-based biofuels, as with food crops (see Chapter 11), emissions of N_2O from agricultural soils is the single largest contributor to direct lifecycle GHG emissions, and one of the largest contributors across many biofuel production cycles (Smeets et al., 2009a; Hsu et al., 2010). Emission rates can vary by as much as 700 % between different crop types for the same site, fertilization rate, and measurement period (Kaiser and Ruser, 2000; Don et al., 2012; Yang et al., 2012). Increased estimates of N_2O emissions alone can convert some biofuel systems from apparent net sinks to net sources (Crutzen et al., 2007; Smith et al., 2012c). Improvements in nitrogen use efficiency and nitrogen inhibitors can substantially reduce emissions of N_2O (Robertson and Vitousek, 2009). For some specific crops, such as sugarcane, N_2O emissions can be low (Macedo et al., 2008; Seabra et al., 2011) or high (Lisboa et al., 2011). Other bioenergy crops require minimal or zero N fertilization and can reduce GHG emissions relative to the former land use where they replace conventional food crops (Clair et al., 2008).

14 The neutrality perception is linked to a misunderstanding of the guidelines for GHG inventories, e.g., IPCC—Land Use, Land-Use Change and Forestry (2000) states "Biomass fuels are included in the national energy and carbon dioxide emissions accounts for informational purposes only. Within the energy module biomass consumption is assumed to equal its regrowth. Any departures from this hypothesis are counted within the Land Use Change and Forestry Model." Carbon neutrality is valid if the countries account for LUC in their inventories for self-produced bioenergy.

Biogeophysical factors: Land cover changes or land-use disturbances of the surface energy balance, such as surface albedo, surface roughness, and evapotranspiration influence the climate system (Betts, 2001; Marland et al., 2003; Betts et al., 2007; Bonan, 2008; Jackson et al., 2008; Mahmood et al., 2013). Perturbations to these can lead to both direct and indirect climate forcings whose impacts can differ in spatial extent (global and/or local) (Bala et al., 2007; Davin et al., 2007). Surface albedo is found to be the dominant direct biogeophysical climate impact mechanism linked to land cover change at the global scale, especially in areas with seasonal snow cover (Claussen et al., 2001; Bathiany et al., 2010), with radiative forcing effects possibly stronger than those of the co-occuring C-cycle changes (Randerson et al., 2006; Lohila et al., 2010; Bright et al., 2011; Cherubini et al., 2012; O'Halloran et al., 2012). Land cover changes can also affect other biogeophysical factors like evapotranspiration and surface roughness, which can have important local (Loarie et al., 2011; Georgescu et al., 2011) and global climatic consequences (Bala et al., 2007; Swann et al., 2010, 2011). Biogeophysical climate impacts from changes in land use are site-specific and show variations in magnitude across different geographic regions and biomes (Bonan, 2008; Anderson, 2010; Pielke Sr. et al., 2011; Anderson-Teixeira et al., 2012). Biogeophysical impacts should be considered in climate impact assessments and in the design of land-use policies to adequately assess the net impacts of land-use mitigation options (Jackson et al., 2008; Betts, 2011; Arora and Montenegro, 2011) as their size may be comparable to impacts from changes to the C cycle.

Figure 11.23 illustrates the range of lifecycle global direct climate impact (in g CO_2 equivalents per MJ, after characterization with GWP time horizon=100 years) attributed to major global bioenergy products reported in the peer-reviewed literature after 2010. Results are broadly comparable to those of Chapter 2 in SRREN (Figures 2.10 and 2.11 in SRREN; Chum et al., 2011) Those figures displayed negative emissions, resulting from crediting emission reduction due to substitution effects. This appendix refrains from allocating credits to feedstocks to avoid double accounting.

Significant variation in the results reflects the wide range of conversion technologies and the reported performances in addition to analyst assumptions affecting system boundary completeness, emission inventory completeness, and choice of allocation method (among others). Additional 'site-specific' land-use considerations such as changes in soil organic carbon stocks (ΔSOC), changes in surface albedo (Δalbedo), and the skewed time distribution of terrestrial biogenic CO_2 fluxes can either reduce or compound land-use impacts and are presented to exemplify that, for some bioenergy systems, these impacts can be greater in magnitude than lifecycle impacts from feedstock cultivation and bioenergy product conversion. 'Site-specific' land-use considerations are geographically explicit and highly sensitive to background climate conditions, soil properties, biomass yields, and land management regimes. The figure reveals that studies find very different values depending on the boundaries of analysis chosen, site-specific effects, and management methods. Nonetheless, it is clear that fuels from sugarcane, perennial grasses, crop residues, and waste cooking oil are more beneficial than other fuels (LUC emissions can still be relevant, see Figure 11.23). Another important result is that albedo effects and site-specific CO_2 fluxes are highly variable for different forest systems and environmental conditions and determine the total climate forcing of bioenergy from forestry.

Direct and indirect land-use change: Direct land-use change occurs when bioenergy crops displace other crops or pastures or forests, while iLUC results from bioenergy deployment triggering the conversion to cropland of lands, somewhere on the globe, to replace some portion of the displaced crops (Searchinger et al., 2008; Kløverpris et al., 2008; Delucchi, 2010; Hertel et al., 2010). Direct LUC to establish biomass cropping systems can increase the net GHG emissions, for example, if carbon-rich ecosystems such as wetlands, forests, or natural grasslands are brought into cultivation (Gibbs et al., 2008; UNEP, 2009, p. 2009; Chum et al., 2011). Biospheric C losses associated with LUC from some bioenergy schemes can be, in some cases, more than hundred times larger than the annual GHG savings from the assumed fossil fuel replacement (Gibbs et al., 2008; Chum et al., 2011). Impacts have been shown to be significantly reduced when a dynamic baseline includes future trends in global agricultural land use (Kløverpris and Mueller, 2013). Albeit at lower magnitude, beneficial LUC effects can also be observed, for example, when some semi-perennial crops, perennial grasses or woody plants replace annual crops grown with high fertilizer levels, or where such plants are produced on lands with carbon-poor soils (Tilman et al., 2006; Harper et al., 2010; Sterner and Fritsche, 2011; Sochacki et al., 2012). In particular, Miscanthus improves soil organic carbon reducing overall GHG emissions (Brandão et al., 2011); degraded USA Midwest land for economic agriculture, over a 20-year period, shows successional perennial crops without the initial carbon debt and indirect land-use costs associated with food-based biofuels (Gelfand et al., 2013). Palm oil, when grown on more marginal grasslands, can deliver a good GHG balance and net carbon storage in soil (Wicke et al., 2008). Such lands represent a substantial potential for palm oil expansion in Indonesia without deforestation and draining peat lands (Wicke et al., 2011a).

In long-term rotation forests, the increased removal of biomass for bioenergy may be beneficial or not depending on the site-specific forest conditions (Cherubini et al., 2012b). For long-term rotation biomass, the carbon debt (increased cumulative CO_2 emissions for a duration in the order of a rotation cycle or longer) becomes increasingly important (Schlamadinger and Marland, 1996; Marland and Schlamadinger, 1997; Fargione et al., 2008; McKechnie et al., 2011; Hudiburg et al., 2011). Calculations of specific GHG emissions from long-term rotation forests need to account for the foregone CO_2-accumulation (Searchinger, 2010; Holtsmark, 2012; Pingoud et al., 2012; Haberl et al., 2012).

If part of a larger forest is used as a feedstock for bioenergy while the overall forest carbon stock increases (the so-called landscape perspective), then the overall mitigation effects are positive, in particular over several harvesting cycles making use of the faster carbon sequestration rates of younger forests (Daigneault et al., 2012; Ximenes et al., 2012; Lamers and Junginger, 2013; Latta et al., 2013). Nabuurs et al. (2013) observe first signs of a carbon sink saturation in European forest biomass and suggest to focus less on the forest biomass sink strength but to consider a mitigation strategy that maximizes the sum of all the possible components: (1) carbon sequestration in forest biomass; (2) soil and wood products; and (3) the effects of material and energy substitution of woody biomass. In general, the use of easily decomposable residues and wastes for bioenergy can produce GHG benefits (Zanchi et al., 2012), similarly to increasing the biomass outtake from forests affected by high mortality rates (Lamers et al., 2013), whereas the removal of slowly decomposing residues reduces soil carbon accumulation at a site and results in net emissions (Repo et al., 2011). The anticipation of future bioenergy markets may promote optimized forest management practices or afforestation of marginal land areas to establish managed plantations, thus contributing to increased forest carbon stocks (Sedjo and Tian, 2012). Rather than leading to wide-scale loss of forest lands, growing markets for tree products can provide incentives for maintaining or increasing forest stocks and land covers, and improving forest health through management (Eisenbies et al., 2009; Dale et al., 2013). If managed to maximize CO_2 storage rate over the long-term, long-term rotation forests offer low-cost mitigation options, in particular, when woody products keep carbon within the human-built environment over long time-scales (e.g., wood substituting for steel joist; (Lippke et al., 2011).

Indirect land-use change is difficult to ascertain because the magnitude of these effects must be modelled (Nassar et al., 2011) raising important questions about model validity and uncertainty (Liska and Perrin, 2009; Plevin et al., 2010; Khanna et al., 2011; Gawel and Ludwig, 2011; Wicke et al., 2012) and policy implications (DeCicco, 2013; Finkbeiner, 2013; Plevin et al., 2013). Available model-based studies have consistently found positive and, in some cases, high emissions from LUC and iLUC, mostly of first-generation biofuels (Figure 11.23), albeit with high variability and uncertainty in results (Hertel et al., 2010; Taheripour et al., 2011; Dumortier et al., 2011; Havlík et al., 2011; Chen et al., 2012; Timilsina et al., 2012; Warner et al., 2014). Causes of the great uncertainty include: incomplete knowledge on global economic dynamics (trade patterns, land-use productivity, diets, use of by-products, fuel prices, and elasticities); selection of specific policies modelled; and the treatment of emissions over time (O'Hare et al., 2009; Khanna et al., 2011; Wicke et al., 2012). In addition, LUC modelling philosophies and model structures and features (e.g., dynamic *vs*. static model) differ among studies. Variations in estimated GHG emissions from biofuel-induced LUC are also driven by differences in scenarios assessed, varying assumptions, inconsistent definitions across models (e.g., LUC, land type), specific selection of reference scenarios against which (marginal) LUC is quantified, and disparities in data availability and quality. The general lack of thorough sensitivity and uncertainty analysis hampers the evaluation of plausible ranges of estimates of GHG emissions from LUC.

Wicke et al. (2012) identified the need to incorporate the impacts of iLUC prevention or mitigation strategies in future modelling efforts, including the impact of zoning and protection of carbon stocks, selective sourcing from low risk-areas, policies and investments to improve agricultural productivity, double cropping, agroforestry schemes, and the (improved) use of degraded and marginal lands (see Box 7.1). Indirect land-use change is mostly avoided in the modelled mitigation pathways in Chapter 6. The relatively limited fuel coverage in the literature precludes a complete set of direct comparisons across alternative and conventional fuels sought by regulatory bodies and researchers.

GHG emissions from LUC can be reduced, for instance through production of bioenergy co-products that displace additional feedstock requirements, thus decreasing the net area needed (e.g., for corn, Wang et al., 2011a; for wheat, Berndes et al., 2011). Proper management of livestock and agriculture can lead to improved resource efficiency, lower GHG emissions, and lower land use while releasing land for bioenergy production as demonstrated for Europe (de Wit et al., 2013) and Mozambique (van der Hilst et al., 2012b). For land transport, cellulosic biomass, such as Miscanthus, has been suggested as a relatively low-carbon source for bioethanol that could be produced at scale, but only if iLUC can be avoided by not displacing food and other commodities and if comprehensive national land management strategies are developed (e.g., Dornburg et al., 2010; Scown et al., 2012). Negative iLUC values are theoretically possible (RFA, 2008). Producing biofuels from wastes and sustainably harvested residues, and replacing first-generation biofuel feedstocks with lignocellulosic crops (e.g., grasses) would induce little or no iLUC (Davis et al., 2011b; Scown et al., 2012). While iLUC quantifications remain uncertain, lower agricultural yields, land-intensive diets, and livestock feeding efficiencies, stronger climate impacts and higher energy crop production levels can result in higher LUC-related GHG emissions. Strong global and regional governance (forest protection, zoning), technological change in agriculture and biobased options, and high-yield bioenergy crops and use of residues and degraded land (if available) could all reduce iLUC (Van Dam et al., 2009a; b; Wicke et al., 2009; Fischer et al., 2010; de Wit et al., 2011, 2013; van der Hilst et al., 2012a; Rose et al., 2013). As with any other renewable fuel, bioenergy can replace or complement fossil fuel. The fossil fuel replacement effect, relevant when a global cap on CO_2 emissions is absent, is discussed in Chapter 8.7. Indirect effects are not restricted to indirect GHG effects of production of biomass in agricultural systems; there are also indirect (market-mediated) effects of wood energy, but also effects in terms of biodiversity threats, environmental degradation, and external social costs, which are not considered here.

11.13.5 Aggregate future potential deployment in integrated models

In SRREN scenarios (IPCC, 2011), bioenergy is projected to contribute 80–190 EJ/yr to global primary energy supply by 2050 for 50 % of the scenarios in the two mitigation levels modelled. The min to max ranges were 20–265 EJ/yr for the less stringent scenarios and 25–300 EJ for the tight mitigation scenarios (< 440 ppm). Many of these scenarios coupled bioenergy with CCS. The Global Energy Assessment (GEA, 2012) scenarios project 80–140 EJ by 2050, including extensive use of agricultural residues and second-generation bioenergy to try to reduce the adverse impacts on land use and food production, and the co-processing of biomass with coal or natural gas with CCS to make low net GHG-emitting transport fuels and or electricity.

Traditional biomass demand is steady or declines in most scenarios from 34 EJ/yr. The transport sector increases nearly ten-fold from 2008 to 18–20 EJ/yr while modern uses for heat, power, combinations, and industry increase by factors of 2–4 from 18 EJ in 2008 (Fischedick et al., 2011). The 2010 International Energy Agency (IEA) model projects a contribution of 12 EJ/yr (11 %) by 2035 to the transport sector, including 60 % of advanced biofuels for road and aviation. Bioenergy supplies 5 % of global power generation in 2035, up from 1 % in 2008. Modern heat and industry doubles their contributions from 2008 (IEA, 2010). The future potential deployment level varies at the global and national level depending on the technological developments, land availability, financial viability, and mitigation policies.

The WGIII AR5 transformation pathway studies suggest that modern bioenergy could play a significant role within the energy system (Section 6.3.5) providing 5 to 95 EJ/yr in 2030, 10 to 245 EJ/yr in 2050, and 105 to 325 EJ/yr in 2100 under idealized full implementation scenarios (see also Figure 7.12), with immediate, global, and comprehensive incentives for land-related mitigation options. The scenarios project increasing deployment of bioenergy with tighter climate change targets, both in a given year as well as earlier in time (see Figure 6.20). Models project increased dependence, as well as increased deployment, of modern bioenergy, with some models projecting 35 % of total primary energy from bioenergy in 2050, and as much as 50 % of total primary energy from modern bioenergy in 2100. Bioenergy's share of regional total electricity and liquid fuels could be significant—up to 35 % of global regional electricity from biopower by 2050, and up to 70 % of global regional liquid fuels from biofuels by 2050. However, the cost-effective allocation of bioenergy within the energy system varies across models. Several sectoral studies, focusing on biophysical constraints, model assumptions (e. g., estimated increase in crop yields over large areas) and current observations, suggest to focus on the lower half of the ranges reported above (Field et al., 2008; Campbell et al., 2008; Johnston et al., 2009a, 2011; Haberl et al., 2013b).

BECCS features prominently in many mitigation scenarios. BECCS is deployed in greater quantities and earlier in time the more stringent the climate policy (Section 6.3.5). Whether BECCS is essential for mitigation, or even sufficient, is unclear. In addition, the likelihood of BECCS deployment is difficult to evaluate and depends on safety con-

Box 11.9 | Examples of co-benefits from biofuel production

Brazilian sugar cane ethanol production provides six times more jobs than the Brazilian petroleum sector and spreads income benefits across numerous municipalities (de Moraes et al., 2010). Worker income is higher than in nearly all other agricultural sectors (de Moraes et al., 2010; Satolo and Bacchi, 2013) and several sustainability standards have been adopted (Viana and Perez, 2013). When substituting gasoline, ethanol from sugar cane also eliminates lead compounds and reduces noxious emissions (Goldemberg et al., 2008). Broader strategic planning, understanding of cumulative impacts, and credible and collaborative decision making processes can help to enhance biodiversity and reverse ecological fragmentation, address direct and iLUC, improve the quality and durability of livelihoods, and other sustainability issues (Duarte et al., 2013).

Co-benefits of palm oil production have been reported in the major producer countries, Malaysia and Indonesia (Sumathi et al., 2008; Lam et al., 2009) as well as from new producer countries (Garcia-Ulloa et al., 2012). Palm oil production results in employment creation as well as in increment state and individual income (Sumathi et al., 2008; Tan et al., 2009; Lam et al., 2009; Sayer et al., 2012; von Geibler, 2013). When combined with agroforestry, palm oil plantations can increase food production locally and have a positive impact on biodiversity (Lam et al., 2009; Garcia-Ulloa et al., 2012) and when palm oil plantations are installed on degraded land further co-benefits on biodiversity and carbon enhancement (Sumathi et al., 2008; Garcia-Ulloa et al., 2012; Sayer et al., 2012). Further, due to its high productivity, palm oil plantations can produce the same bioenergy input using less land than other bio-energy crops (Sumathi et al., 2008; Tan et al., 2009). Certification in palm oil production can become a means for increasing sustainable production of biofuels (Tan et al., 2009; Edser, 2012; von Geibler, 2013).

Similarly, co-benefits from the production of Jatropha as a biofuel crop in developing countries have been reported, mainly when Jatropha is planted on degraded land. These include increases in individuals' incomes (Garg et al., 2011; Arndt et al., 2012), improvement in energy security at the local level (von Maltitz and Setzkorn, 2013; Muys et al., 2014), and reducing soil erosion (Garg et al., 2011).

firmations, affordability and public acceptance (see Section 11.13.3 for details). BECCS may also affect the cost-effective emissions trajectory (Richels et al., In Review; Rose et al., 2013).

Some integrated models are cost-effectively trading off lower land carbon stocks and increased land N_2O emissions for the long-run mitigation benefits of bioenergy (Rose et al., 2013; Popp et al., 2013). The models find that bioenergy could contribute effectively to climate change mitigation despite land conversion and intensification emissions. However, as discussed below and in Section 11.9, policy implementation and coordination are factors to consider. In these models, constraining bioenergy has a cost. For instance, limiting global bioenergy availability to 100 EJ/year tripled marginal abatement costs and doubled consumption losses associated with transformation pathways (Rose et al., 2013). Overall outcomes may depend strongly on governance of land use and deployment of best practices in agricultural production (see sections above). Progressive developments in governance of land and modernization of agriculture and livestock and effective sustainability frameworks can help realize large parts of the technical bioenergy potential with low associated GHG emissions.

With increasing scarcity of productive land, the growing demand for food and bioenergy could induce substantial LUC causing high GHG emissions and/or increased agricultural intensification and higher N_2O emissions unless wise integration of bioenergy into agriculture and forestry landscapes occurs (Delucchi, 2010). Consideration of LUC emissions in integrated models show that valuing or protecting global terrestrial carbon stocks reduces the potential LUC-related GHG emissions of energy crop deployment, and could lower the cost of achieving climate change objectives, but could exacerbate increases in agricultural commodity prices (Popp et al., 2011; Reilly et al., 2012). Many integrated models are investigating idealized policy implementation pathways, assuming global prices on GHG (including the terrestrial land carbon stock); if such conditions cannot be realized, certain types of bioenergy could lead to additional GHG emissions. More specifically, if the global terrestrial land carbon stock remains unprotected, large GHG emissions from bioenergy-related LUC alone are possible (Melillo et al., 2009; Wise et al., 2009; Creutzig et al., 2012a; Calvin et al., 2013b).

In summary, recent integrated model scenarios project between 10–245 EJ/yr modern bioenergy deployment in 2050. Good governance and favourable conditions for bioenergy development may facilitate higher bioenergy deployment while sustainability and livelihood concerns might constrain deployment of bioenergy scenarios to low values (see Section 11.13.6).

11.13.6 Bioenergy and sustainable development

The nature and extent of the impacts of implementing bioenergy depend on the specific system, the development context, and on the size of the intervention (Section 11.4.5). The effects on livelihoods have not yet been systematically evaluated in integrated models (Davis et al., 2013; Creutzig et al., 2012b; Creutzig et al., 2013; Muys et al., 2014), even if human geography studies have shown that bioenergy deployment can have strong distributional impacts (Davis et al., 2013; Muys et al., 2014). The total effects on livelihoods will be mediated by global market dynamics, including policy regulations and incentives, the production model and deployment scale, and place-specific factors such as governance, land tenure security, labour and financial capabilities, among others (Creutzig et al., 2013).

Bioenergy projects can be economically beneficial, e.g., by raising and diversifying farm incomes and increasing rural employment through the production of biofuels for domestic use (Gohin, 2008) or export markets (Wicke et al., 2009; Arndt et al., 2011).

The establishment of large-scale biofuels feedstock production can also cause smallholders, tenants, and herders to lose access to productive land, while other social groups such as workers, investors, company owners, biofuels consumers, and populations who are more responsible for GHG emission reductions enjoy the benefits of this production (van der Horst and Vermeylen, 2011). This is particularly relevant where large areas of land are still unregistered or are being claimed and under dispute by several users and ethnic groups (Dauvergne and Neville, 2010). Furthermore, increasing demand for first-generation biofuels is partly driving the expansion of crops like soy and oil palm, which in turn contribute to promote large-scale agribusinesses at the expense of family and community-based agriculture, in some cases (Wilkinson and Herrera, 2010). Biofuels deployment can also translate into reductions of time invested in on-farm subsistence and community-based activities, thus translating into lower productivity rates of subsistence crops and an increase in intra-community conflicts as a result of the uneven share of collective responsibilities (Mingorría et al., 2010).

Bioenergy deployment is more beneficial when it is not an additional land-use activity expanding over the landscape, but rather integrates into existing land uses and influences the way farmers and forest owners use their land. Various studies indicate the ecosystem services and values that perennial crops have in restoring degraded lands, via agroforestry systems, controlling erosion, and even in regional climate effects such as improved water retention and precipitation (Faaij, 2006; Wicke et al., 2011c; Immerzeel et al., 2013). Examples include adjustments in agriculture practices where farmers, for instance, change their manure treatment to produce biogas, reduce methane and N losses. Changes in management practice may swing the net GHG balance of options and also have clear sustainable development implications (Davis et al., 2013).

Small-scale bioenergy options can provide cost-effective alternatives for mitigating climate change, at the same time helping advance sustainable development priorities, particularly in rural areas of developing countries. IEA (2012b) estimates that 2.6 billion people world-

Table 11.12 | Potential institutional, social, environmental, economic and technological implications of bioenergy options at local to global scale.

Institutional		Scale
May contribute to energy independence (+), especially at the local level (reduce dependency on fossil fuels) (2, 20, 32, 39,50)	+	Local to national
Can improve (+) or decrease (–) land tenure and use rights for local stakeholders (2, 17, 38, 50)	+/–	Local
Cross-sectoral coordination (+) or conflicts (–) between forestry, agriculture, energy, and/or mining (2, 13, 26, 31, 60)	+/–	Local to national
Impacts on labor rights among the value chain (2, 6, 17)	+/–	Local to national
Promoting of participative mechanisms for small-scale producers (14, 15)	+	Local to national
Social		**Scale**
Competition with food security including food availability (through reduced food production at the local level), food access (due to price volatility), usage (as food crops can be diverted towards biofuel production), and consequently to food stability. Bio-energy derived from residues, wastes, or by-products is an exception (1,2, 7, 9, 12, 18, 23)	–	Local to global
Integrated systems (including agroforestry) can improve food production at the local level creating a positive impact towards food security (51, 52, 53, 69, 73, 74). Further, biomass production combined with improved agricultural management can avoid such competition and bring investment in agricultural production systems with overall improvements of management as a result (as observed in Brazil) (60, 63 66, 67, 70, 71)	+	Local
Increasing (+) or decreasing (–) existing conflicts or social tension (9, 14, 19, 26)	+/–	Local to national
Impacts on traditional practices: using local knowledge in production and treatment of bioenergy crops (+) or discouraging local knowledge and practices (–) (2, 50)	+/–	Local
Displacement of small-scale farmers (14, 15, 19). Bioenergy alternatives can also empower local farmers by creating local income opportunities	+/–	Local
Promote capacity building and new skills (3, 15, 50)	+	Local
Gender impacts (2, 4, 14, 15, 27)	+/–	Local to national
Efficient biomass techniques for cooking (e. g., biomass cookstoves) can have positive impacts on health, especially for women and children in developing countries (42, 43, 44)	+	Local to national
Environmental		**Scale**
Biofuel plantations can promote deforestation and/or forest degradation, under weak or no regulation (1, 8, 22)	–	Local to global
When used on degraded lands, perennial crops offer large-scale potential to improve soil carbon and structure, abate erosion and salinity problems. Agroforestry schemes can have multiple benefits including increased overall biomass production, increase biodiversity and higher resilience to climate changes. (59, 64, 65, 69, 73)	+	Local to global
Some large-scale bio-energy crops can have negative impacts on soil quality, water pollution, and biodiversity. Similarly potential adverse side-effects can be a consequence of increments in use of fertilizers for increasing productivity (7, 12, 26, 30). Experience with sugarcane plantations has shown that they can maintain soil structure (56) and application of pesticides can be substituted by the use of natural predators and parasitoids (57, 71)	–/+	Local to transboundary
Can displace activities or other land uses (8, 26)	–	Local to global
Smart modernization and intensification can lead to lower environmental impacts and more efficient land use (75, 76)	+	Local to transboundary
Creating bio-energy plantations on degraded land can have positive impacts on soil and biodiversity (12)	+	Local to transboundary
There can be tradeoffs between different land uses, reducing land availability for local stakeholders (45, 46, 47,48, 49). Multicropping system provide bioenergy while better maintaining ecological diversity and reducing land-use competition (58)	–/+	Local to national
Ethanol utilization leads to the phaseout of lead addititives and methyl tertiary-butyl ether (MBTE) and reduces sulfur, particulate matter, and carbon monoxide emissions (55)	+	Local to global
Economic		**Scale**
Increase in economic activity, income generation, and income diversification (1, 2, 3, 12, 20, 21, 27, 54)	+	Local
Increase (+) or decrease (–) market opportunities (16, 27, 31)	+/–	Local to national
Contribute to the changes in prices of feedstock (2, 3, 5, 21)	+/–	Local to global
May promote concentration of income and/or increase poverty if sustainability criteria and strong governance is not in place (2, 16, 26)	–	Local to regional
Using waste and residues may create socio-economic benefits with little environmental risks (2, 41, 36)	+	Local to regional
Uncertainty about mid- and long-term revenues (6, 30)	–	National
Employment creation (3, 14, 15)	+	Local to regional
Technological		**Scale**
Can promote technology development and/or facilitate technology transfer (2, 27, 31)	+	Local to global
Increasing infrastructure coverage (+). However if access to infrastructure and/or technology is reduced to few social groups it can increase marginalization (–) (27, 28, 29)	+/–	Local
Bioenergy options for generating local power or to use residues may increase labor demand, creating new job opportunities. Participatory technology development also increases acceptance and appropriation (6, 8, 10, 37, 40)	+	Local
Technology might reduce labor demand (–). High dependent of tech. transfer and/or acceptance	–	Local

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[1]Alves Finco and Doppler (2010); [2]Amigun et al. (2011); [3]Arndt et al. (2012); [4]Arndt et al. (2011); [5]Arndt et al.(2012); [6]Awudu and Zhang (2012); [7]Beringer et al. (2011); [8]Borzoni (2012); [9]Bringezu et al. (2012); [10]Cacciatore et al. (2012); [11]Cançado et al. (2006); [12]Danielsen et al. (2009); [13]Diaz-Chavez (2011); [14]Duvenage et al. (2013); [15]Ewing and Msangi (2009); [16]Gasparatos et al. (2011); [17]German and Schoneveld (2012); [18]Haberl et al. (2011a); [19]Hall et al. (2009); [20]Hanff et al. (2011); [21]Huang et al. (2012); [22]Koh and Wilcove (2008); [23]Koizumi (2013); [24]Kyu et al. (2010); [25]Madlener et al. (2006); [26]Martinelli and Filoso (2008); [27]Mwakaje (2012); [28]Oberling et al. (2012); [29]Schut et al. (2010); [30]Selfa et al. (2011); [31]Steenblik (2007); [32]Stromberg and Gasparatos (2012); [33]Searchinger et al. (2009); [34]Searchinger et al. (2008); [35]Smith and Searchinger (2012); [36]Tilman et al. (2009); [37]Van de Velde et al. (2009); [38]von Maltitz and Setzkorn (2013); [39]Wu and Lin (2009); [40]Zhang et al. (2011); [41]Fargione et al. (2008); [42]Jerneck and Olsson (2013); [43]Gurung and Oh (2013); [44]O'Shaughnessy et al. (2013); [45]German et al. (2013); [46]Cotula (2012); [47]Mwakaje (2012); [48]Scheidel and Sorman (2012); [49]Haberl et al.(2013b); [50]Muys et al. (2014); [51]Egeskog et al. (2011); [52]Diaz-Chavez (2012); [53]Ewing and Msangi (2009); [54]de Moraes et al. (2010); [55]Goldemberg (2007); [56]Walter et al. (2011); [57]Macedo (2005); [58]Langeveld et al. (2013); [59]Van Dam et al. (2009a; b); [60]van Dam et al. (2010); [61]van Eijck et al. (2012); [62]van Eijck et al. (2014); [63]Martínez et al. (2013); [64]van der Hilst et al. (2010); [65]van der Hilst et al. (2012); [66]van der Hilst and Faaij (2012); [67]van der Hilst et al. (2012b); [68]Hoefnagels et al. (2013); [69]Immerzeel et al. (2013); [70]Lynd et al. (2011); [71]Smeets et al. (2008); [72]Smeets and Faaij (2010); [73]Wicke et al. (2013); [74]Wiskerke et al. (2010); [75]De Wit et al. (2011); [76]de Wit et al. (2013)

wide depend on traditional biomass for cooking, while 84 % of these belong to rural communities. Use of low-quality fuels and inefficient cooking and heating devices leads to pollution resulting in nearly 4 million premature deaths every year, and a range of chronic illnesses and other health problems (Lim et al., 2012; see Section 9.7.3.1). Modern small-scale bioenergy technologies such as advanced/efficient cook stoves, biogas for cooking and village electrification, biomass gasifiers, and bagasse-based co-generation systems for decentralized power generation, can provide energy for rural communities with energy services that also promote rural development (IEA, 2011). Such bioenergy systems reduce CO_2 emissions from unsustainable biomass harvesting and short-lived climate pollutants, e.g., black carbon, from cleaner combustion (Chung et al., 2012). Scaling up clean cookstove initiatives could not only save 2 million lives a year, but also significantly reduce GHG emissions (Section 11.13.3). Efficient biomass cook stoves and biogas stoves at the same time provide multiple benefits: They reduce the pressure on forests and biodiversity; they reduce exposure to smoke-related health hazards; they reduce drudgery for women in collection fuelwood; and they save money if fuel needs to be purchased (Martin et al., 2011). Benefits from the dissemination of improved cookstoves outweigh their costs by sevenfold, when their health, economic, and environmental benefits are accounted for (Garcia-Frapolli et al., 2010).

Table 11.12 presents the implications of bioenergy options in the light of social, institutional, environmental, economic, and technological conditions. The relationship between bioenergy and these conditions is complex and there could be negative or positive implications, depending on the type of bioenergy option, the scale of the production system and the local context. While biofuels can allow the reduction of fossil fuel use and of GHG emissions, they often shift environmental burdens towards land use-related impacts (i.e., eutrophication, acidification, water depletion, ecotoxicity; EMPA, 2012; Smith and Torn, 2013; Tavoni and Socolow, 2013). Co-benefits and adverse side-effects do not necessarily overlap, neither geographically nor socially (Dauvergne and Neville, 2010; Wilkinson and Herrera, 2010; van der Horst and Vermeylen, 2011). The main potential co-benefits are related to access to energy and impacts on the economy and well-being, jobs creation, and improvement of local resilience (Walter et al., 2011; Creutzig et al., 2013). Main risks of crop-based bioenergy for sustainable development and livelihoods include competition for arable land (Haberl et al., 2013b) and consequent impact on food security, tenure arrangements, displacement of communities and economic activities, creation of a driver of deforestation, impacts on biodiversity, water, and soil, or increment in vulnerability to climate change, and unequal distribution of benefits (Sala et al., 2000; Hall et al., 2009; German et al., 2011; Thompson et al., 2011b; IPCC, 2012).

Good governance is an essential component of a sustainable energy system. Integrated studies that compare impacts of bioenergy production between different crops and land management strategies show that the overall impact (both ecological and socio-economic) depends strongly on the governance of land use and design of the bioenergy system see van der Hilst et al. (2012) in the European context, and Van Dam et al. (2009a; b) for different crops and scenarios in Argentina). Van Eijck et al. (2012) show similar differences in impacts between the production and use of Jatropha based on smallholder production versus plantation models. This implies that governance and planning have a strong impact on the ultimate result and impact of large-scale bioenergy deployment. Legislation and regulation of bioenergy as well as voluntary certification schemes are required to guide bioenergy production system deployment so that the resources and feedstocks be put to best use, and that (positive and negative) socioeconomic and environmental issues are addressed as production grows (van Dam et al., 2010). There are different options, from voluntary to legal and global agreements, to improve governance of biomass markets and land use that still require much further attention (Verdonk et al., 2007). The integration of bioenergy systems into agriculture and forest landscapes can improve land and water use efficiency and help address concerns about environmental impacts of present land use (Berndes et al., 2004, 2008; Börjesson and Berndes, 2006; Sparovek et al., 2007; Gopalakrishnan et al., 2009, 2011a; b, 2012; Dimitriou et al., 2009, 2011; Dornburg et al., 2010; Batidzirai et al., 2012; Parish et al., 2012; Baum et al., 2012; Busch, 2012), but the global potentials of such systems are difficult to determine (Berndes and Börjesson, 2007; Dale and Kline, 2013). Similarly, existing and emerging guiding principles and governance systems influence biomass resources availability (Stupak et al., 2011). Certification approaches can be useful, but they should be accompanied by effective territorial policy frameworks (Hunsberger et al., 2012).

11.13.7 Tradeoffs and synergies with land, water, food, and biodiversity

This section summarizes results from integrated models (models that have a global aggregate view, but cannot disaggregate place-specific effects in biodiversity and livelihoods discussed above) on land, water, food, and biodiversity. In these models, at any level of future bioenergy supply, land demand for bioenergy depends on (1) the share of bioenergy derived from wastes and residues (Rogner et al., 2012); (2) the extent to which bioenergy production can be integrated with food or fiber production, which ideally results in synergies (Garg et al., 2011; Sochacki et al., 2013) or at least mitigates land-use competition (Berndes et al., 2013); (3) the extent to which bioenergy can be grown on areas with little current or future production, taking into account growing land demand for food (Nijsen et al., 2012); and (4) the volume of dedicated energy crops and their yields (Haberl et al., 2010; Batidzirai et al., 2012; Smith et al., 2012d). Energy crop yields per unit area may differ by factors of > 10 depending on differences in natural fertility (soils, climate), energy crop plants, previous land use, management and technology (Johnston et al., 2009a; Lal, 2010; Beringer et al., 2011; Pacca and Moreira, 2011; Smith et al., 2012a; Erb et al., 2012a). Assumptions on energy crop yields are one of the main reasons for the large differences in estimates of future area demand of energy crops (Popp et al., 2013). Likewise, assumptions on yields, strategies, and governance on future food/feed crops have large implications for assessments of the degree of land competition between biofuels and these land uses (Batidzirai et al., 2012; de Wit et al., 2013).

However, across models, there are very different potential landscape transformation visions in all regions (Sections 6.3.5 and 11.9.). Overall, it is difficult to generalize on regional land cover effects of mitigation. Some models assume significant land conversion while other models do not. In idealized implementation scenarios, there is expansion of energy cropland and forest land in many regions, with some models exhibiting very strong forest land expansion and others very little by 2030. Land conversion is increased in the 450 ppm scenarios compared to the 550 ppm scenarios, but at a declining share, a result consistent with a declining land-related mitigation rate with policy stringency. The results of these integrated model studies need to be interpreted with caution, as not all GHG emissions and biogeophysical or socio-economic effects of bioenergy deployment are incorporated into these models, and as not all relevant technologies are represented (e.g., cascade utilization).

Large-scale bioenergy production from dedicated crops may affect water availability and quality (see Section 6.6.2.6), which are highly dependent on (1) type and quantity of local freshwater resources; (2) necessary water quality; (3) competition for multiple uses (agricultural, urban, industrial, power generation), and (4) efficiency in all sector end uses (Gerbens-Leenes et al., 2009; Coelho et al., 2012). In many regions, additional irrigation of energy crops could further intensify existing pressures on water resources (Popp et al., 2011). Studies indicate that an exclusion of severe water scarce areas for bioenergy production (mainly to be found in the Middle East, parts of Asia, and western United States) would reduce global technical bioenergy potentials by 17 % until 2050 (van Vuuren et al., 2009). A model comparison study with five global economic models shows that the aggregate food price effect of large-scale lignocellulosic bioenergy deployment (i.e., 100 EJ globally by the year 2050) is significantly lower (+5 % on average across models) than the potential price effects induced by climate impacts on crop yields (+25 % on average across models (Lotze-Campen et al., 2013). Possibly hence, ambitious climate change mitigation need not drive up global food prices much, if the extra land required for bioenergy production is accessible or if the feedstock, e.g., from forests, does not directly compete for agricultural land. Effective land-use planning and strict adherence to sustainability criteria need to be integrated into large-scale bioenergy projects to minimize competitions for water (for example, by excluding the establishment of biofuel projects in irrigated areas). If bioenergy is not managed properly, additional land demand and associated LUC may put pressures on biodiversity (Groom et al., 2008; see Section 6.6.2.5). However, implementing appropriate management, such as establishing bioenergy crops in degraded areas represents an opportunity where bioenergy can be used to achieve positive environmental outcomes (Nijsen et al., 2012).

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12

Human Settlements, Infrastructure, and Spatial Planning

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Executive Summary

The shift from rural to more urban societies is a global trend with significant consequences for greenhouse gas (GHG) emissions and climate change mitigation. Across multiple dimensions, the scale and speed of urbanization is unprecedented: more than half of the world population live in urban areas and each week the global urban population increases by 1.3 million. Today there are nearly 1000 urban agglomerations with populations of 500,000 or greater; by 2050, the global urban population is expected to increase by between 2.5 to 3 billion, corresponding to 64 % to 69 % of the world population (*robust evidence, high agreement*). Expansion of urban areas is on average twice as fast as urban population growth, and the expected increase in urban land cover during the first three decades of the 21st century will be greater than the cumulative urban expansion in all of human history (*medium evidence, high agreement*). Urban areas generate around 80 % of global Gross Domestic Product (GDP) (*medium evidence, medium agreement*). Urbanization is associated with increases in income, and higher urban incomes are correlated with higher consumption of energy use and GHG emissions (*medium evidence, high agreement*) [Sections 12.1, 12.2, 12.3].

Current and future urbanization trends are significantly different from the past (*robust evidence, high agreement*). Urbanization is taking place at lower levels of economic development and the majority of future urban population growth will take place in small- to medium-sized urban areas in developing countries. Expansion of urban areas is on average twice as fast as urban population growth, and the expected increase in urban land cover during the first three decades of the 21st century will be greater than the cumulative urban expansion in all of human history (*robust evidence, high agreement*). [12.1, 12.2]

Urban areas account for between 71 % and 76 % of CO_2 emissions from global final energy use and between 67–76 % of global energy use (*medium evidence, medium agreement*). There are very few studies that have examined the contribution of all urban areas to global GHG emissions. The fraction of global CO_2 emissions from urban areas depends on the spatial and functional boundary definitions of urban and the choice of emissions accounting method. Estimates for urban energy related CO_2 emissions range from 71 % for 2006 to between 53 % and 87 % (central estimate, 76 %) of CO_2 emissions from global final energy use (*medium evidence, medium agreement*). There is only one attempt in the literature that examines the total GHG (CO_2, CH_4, N_2O and SF_6) contribution of urban areas globally, estimated at between 37 % and 49 % of global GHG emissions for the year 2000. Using Scope1 accounting, urban share of global CO_2 emissions is about 44 % (*limited evidence, medium agreement*). [12.2]

No single factor explains variations in per-capita emissions across cities, and there are significant differences in per capita GHG emissions between cities within a single country (*robust evidence, high agreement*). Urban GHG emissions are influenced by a variety of physical, economic and social factors, development levels, and urbanization histories specific to each city. Key influences on urban GHG emissions include income, population dynamics, urban form, locational factors, economic structure, and market failures. There is a prevalence for cities in Annex I countries to have lower per capita final energy use and GHG emissions than national averages, and for per capita final energy use and GHG emissions of cities in non-Annex I countries tend to be higher than national averages (*robust evidence, high agreement*) [12.3].

The anticipated growth in urban population will require a massive build-up of urban infrastructure, which is a key driver of emissions across multiple sectors (*limited evidence, high agreement*). If the global population increases to 9.3 billion by 2050 and developing countries expand their built environment and infrastructure to current global average levels using available technology of today, the production of infrastructure materials alone would generate approximately 470 Gt of CO_2 emissions. Currently, average per capita CO_2 emissions embodied in the infrastructure of industrialized countries is five times larger than those in developing countries. The continued expansion of fossil fuel-based infrastructure would produce cumulative emissions of 2,986–7,402 $GtCO_2$ during the remainder of the 21st century (*limited evidence, high agreement*). [12.2, 12.3]

The existing infrastructure stock of the average Annex I resident is three times that of the world average and about five times higher than that of the average non-Annex I resident (*medium evidence, medium agreement*). The long life of infrastructure and the built environment, make them particularly prone to lock-in of energy and emissions pathways, lifestyles and consumption patterns that are difficult to change. The committed emissions from energy and transportation infrastructures are especially high, with respective ranges of 127–336 and 63–132 Gt, respectively (*medium evidence, medium agreement*). [12.3, 12.4]

Infrastructure and urban form are strongly linked, especially among transportation infrastructure provision, travel demand and vehicle kilometres travelled (*robust evidence, high agreement*). In developing countries in particular, the growth of transport infrastructure and ensuing urban forms will play important roles in affecting long-run emissions trajectories. Urban form and structure significantly affect direct (operational) and indirect (embodied) GHG emissions, and are strongly linked to the throughput of materials and energy in a city, the wastes that it generates, and system efficiencies of a city. (*robust evidence, high agreement*) [12.4, 12.5]

Key urban form drivers of energy and GHG emissions are density, land use mix, connectivity, and accessibility (*medium evidence, high agreement*). These factors are interrelated and interdependent. Pursuing one of them in isolation is insufficient for lower emissions. Connectivity and accessibility are tightly related: highly connected places are accessible. While individual measures of urban form

have relatively small effects on vehicle miles travelled, they become more effective when combined. There is consistent evidence that co-locating higher residential densities with higher employment densities, coupled with significant public transit improvements, higher land use mixes, and other supportive demand management measures can lead to greater emissions savings in the long run. Highly accessible communities are typically characterized by low daily commuting distances and travel times, enabled by multiple modes of transportation (*robust evidence, high agreement*). [12.5]

Urban mitigation options vary across urbanization trajectories and are expected to be most effective when policy instruments are bundled (*robust evidence, high agreement*). For rapidly developing cities, options include shaping their urbanization and infrastructure development towards more sustainable and low carbon pathways. In mature or established cities, options are constrained by existing urban forms and infrastructure and the potential for refurbishing existing systems and infrastructures. Key mitigation strategies include co-locating high residential with high employment densities, achieving high land use mixes, increasing accessibility and investing in public transit and other supportive demand management measures. Bundling these strategies can reduce emissions in the short term and generate even higher emissions savings in the long term (*robust evidence, high agreement*). [12.5]

Successful implementation of mitigation strategies at local scales requires that there be in place the institutional capacity and political will to align the right policy instruments to specific spatial planning strategies (*robust evidence, high agreement*). Integrated land-use and transportation planning provides the opportunity to envision and articulate future settlement patterns, backed by zoning ordinances, subdivision regulations, and capital improvements programmes to implement the vision. While smaller scale spatial planning may not have the energy conservation or emissions reduction benefits of larger scale ones, development tends to occur parcel by parcel and urbanized areas are ultimately the products of thousands of individual site-level development and design decisions (*robust evidence, high agreement*). [12.5, 12.6]

The largest opportunities for future urban GHG emissions reduction are in rapidly urbanizing areas where urban form and infrastructure are not locked-in, but where there are often limited governance, technical, financial, and institutional capacities (*robust evidence, high agreement*). The bulk of future infrastructure and urban growth is expected in small- to medium-size cities in developing countries, where these capacities are often limited or weak (*robust evidence, high agreement*). [12.4, 12.5, 12.6, 12.7]

Thousands of cities are undertaking climate action plans, but their aggregate impact on urban emissions is uncertain (*robust evidence, high agreement*). Local governments and institutions possess unique opportunities to engage in urban mitigation activities and local mitigation efforts have expanded rapidly. However, there has been little systematic assessment regarding the overall extent to which cities are implementing mitigation policies and emission reduction targets are being achieved, or emissions reduced. Climate action plans include a range of measures across sectors, largely focused on energy efficiency rather than broader land-use planning strategies and cross-sectoral measures to reduce sprawl and promote transit-oriented development. The majority of these targets have been developed for Annex I countries and reflect neither their mitigation potential nor implementation. Few targets have been established for non-Annex I country cities, and it is in these places where reliable city-level GHG emissions inventory may not exist (*robust evidence, high agreement*). [12.6, 12.7, 12.9]

The feasibility of spatial planning instruments for climate change mitigation is highly dependent on a city's financial and governance capability (*robust evidence, high agreement*). Drivers of urban GHG emissions are interrelated and can be addressed by a number of regulatory, management, and market-based instruments. Many of these instruments are applicable to cities in both developed and developing countries, but the degree to which they can be implemented varies. In addition, each instrument varies in its potential to generate public revenues or require government expenditures, and the administrative scale at which it can be applied. A bundling of instruments and a high level of coordination across institutions can increase the likelihood of achieving emissions reductions and avoiding unintended outcomes (*robust evidence, high agreement*). [12.6, 12.7]

For designing and implementing climate policies effectively, institutional arrangements, governance mechanisms, and financial resources should be aligned with the goals of reducing urban GHG emissions (*robust evidence, high agreement*). These goals will reflect the specific challenges facing individual cities and local governments. The following have been identified as key factors: (1) institutional arrangements that facilitate the integration of mitigation with other high-priority urban agendas; (2) a multilevel governance context that empowers cities to promote urban transformations; (3) spatial planning competencies and political will to support integrated land-use and transportation planning; and (4) sufficient financial flows and incentives to adequately support mitigation strategies (*robust evidence, high agreement*). [12.6, 12.7]

Successful implementation of urban climate change mitigation strategies can provide co-benefits (*robust evidence, high agreement*). Urban areas throughout the world continue to struggle with challenges, including ensuring access to energy, limiting air and water pollution, and maintaining employment opportunities and competitiveness. Action on urban-scale mitigation often depends on the ability to relate climate change mitigation efforts to local co-benefits. The co-benefits of local climate change mitigation can include public savings, air quality and associated health benefits, and productivity increases in urban centres, providing additional motivation for undertaking mitigation activities (*robust evidence, high agreement*). [12.5, 12.6, 12.7, 12.8]

This assessment highlights a number of key knowledge gaps. First, there is lack of consistent and comparable emissions data at local scales, making it particularly challenging to assess the urban share of global GHG emissions as well as develop urbanization typologies and their emissions pathways. Second, there is little scientific understanding of the magnitude of the emissions reduction from altering urban form, and the emissions savings from integrated infrastructure and land use planning. Third, there is a lack of consistency and thus comparability on local emissions accounting methods, making cross-city comparisons of emissions or climate action plans difficult. Fourth, there are few evaluations of urban climate action plans and their effectiveness. Fifth, there is lack of scientific understanding of how cities can prioritize mitigation strategies, local actions, investments, and policy responses that are locally relevant. Sixth, there are large uncertainties about future urbanization trajectories, although urban form and infrastructure will play large roles in determining emissions pathways. [12.9]

12.1 Introduction

Urbanization is a global phenomenon that is transforming human settlements. The shift from primarily rural to more urban societies is evident through the transformation of places, populations, economies, and the built environment. In each of these dimensions, urbanization is unprecedented for its speed and scale: massive urbanization is a megatrend of the 21st century. With disorienting speed, villages and towns are being absorbed by, or coalescing into, larger urban conurbations and agglomerations. This rapid transformation is occurring throughout the world, and in many places it is accelerating.

Today, more than half of the global population is urban, compared to only 13 % in 1900 (UN DESA, 2012). There are nearly 1,000 urban agglomerations with populations of 500,000 or more, three-quarters of which are in developing countries (UN DESA, 2012). By 2050, the global urban population is expected to increase between 2.5 to 3 billion, corresponding to 64 % to 69 % of the world population (Grubler et al., 2007; IIASA, 2009; UN DESA, 2012). Put differently, each week the urban population is increasing by approximately 1.3 million.

Future trends in the levels, patterns, and regional variation of urbanization will be significantly different from those of the past. Most of the urban population growth will take place in small- to medium-sized urban areas. Nearly all of the future population growth will be absorbed by urban areas in developing countries (IIASA, 2009; UN DESA, 2012). In many developing countries, infrastructure and urban growth will be greatest, but technical capacities are limited, and governance, financial, and economic institutional capacities are weak (Bräutigam and Knack, 2004; Rodrik et al., 2004). The kinds of towns, cities, and urban agglomerations that ultimately emerge over the coming decades will have a critical impact on energy use and carbon emissions.

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) did not have a chapter on human settlements or urban areas. Urban areas were addressed through the lens of individual sector chapters. Since the publication of AR4, there has been a growing recognition of the significant contribution of urban areas to GHG emissions, their potential role in mitigating them, and a multi-fold increase in the corresponding scientific literature. This chapter provides an assessment of this literature and the key mitigation options that are available at the local level. The majority of this literature has focused on urban areas and cities in developed countries. With the exception of China, there are few studies on the mitigation potential or GHG emissions of urban areas in developing countries. This assessment reflects these geographic limitations in the published literature.

Urbanization is a process that involves simultaneous transitions and transformations across multiple dimensions, including demographic, economic, and physical changes in the landscape. Each of these dimensions presents different indicators and definitions of urbanization. The chapter begins with a brief discussion of the multiple dimensions and definitions of urbanization, including implications for GHG emissions accounting, and then continues with an assessment of historical, current, and future trends across different dimensions of urbanization in the context of GHG emissions (12.2). It then discusses GHG accounting approaches and challenges specific to urban areas and human settlements.

In Section 12.3, the chapter assesses the drivers of urban GHG emissions in a systemic fashion, and examines the impacts of drivers on individuals sectors as well as the interaction and interdependence of drivers. In this section, the relative magnitude of each driver's impact on urban GHG emissions is discussed both qualitatively and quantitatively, and provides the context for a more detailed assessment of how urban form and infrastructure affect urban GHG emissions (12.4). Here, the section discusses the individual urban form drivers such as density, connectivity, and land use mix, as well as their interactions with each other. Section 12.4 also examines the links between infrastructure and urban form, as well as their combined and interacting effects on GHG emissions.

Section 12.5 identifies spatial planning strategies and policy instruments that can affect multiple drivers, and Section 12.6 examines the institutional, governance, and financial requirements to implement such policies. Of particular importance with regard to mitigation potential at the urban or local scale is a discussion of the geographic and administrative scales for which policies are implemented, overlapping, and/or in conflict. The chapter then identifies the scale and range of mitigation actions currently planned and/or implemented by local governments, and assesses the evidence of successful implementation of the plans, as well as barriers to further implementation (12.7). Next, the chapter discusses major co-benefits and adverse side-effects of mitigation at the local scale, including opportunities for sustainable development (12.8). The chapter concludes with a discussion of the major gaps in knowledge with respect to mitigation of climate change in urban areas (12.9).

12

12.2 Human settlements and GHG emissions

This section assesses past, current, and future trends in human settlements in the context of GHG emissions. It aims to provide a multi-dimensional perspective on the scale of the urbanization process. This section includes a discussion of the development trends of urban areas, including population size, land use, and density. Section 12.2.1 outlines historic urbanization dynamics in multiple dimensions as drivers of GHG emissions. Section 12.2.2 focuses on current GHG emissions. Finally, Section 12.2.3 assesses future scenarios of urbanization in order to frame the GHG emissions challenges to come.

12.2.1 The role of cities and urban areas in energy use and GHG emissions

Worldwide, 3.3 billion people live in rural areas, the majority of whom, about 92 %, live in rural areas in developing countries (UN DESA, 2012). In general, rural populations have lower per capita energy consumption compared with urban populations in developing countries (IEA, 2008). Globally, 32 % of the rural population lack access to electricity and other modern energy sources, compared to only 5.3 % of the urban population (IEA, 2010). Hence, energy use and GHG emissions from human settlements is mainly from urban areas rather than rural areas, and the role of cities and urban areas in global climate change has become increasingly important over time.

Table 12.1 | Arithmetic growth of human settlement classes for five periods between 1950–2050. Number of human settlements by size class at four points in time.

Population	Average annual growth [%]					Number of cities			
	1950–1970	1970–1990	1990–2010	1950–2010	2010–2050	1950	1970	1990	2010
10,000,000 and more	2.60	6.72	4.11	4.46	2.13	2	2	10	23
5,000,000—10,000,000	7.55	1.34	2.53	3.77	1.22	4	15	19	38
1,000,000—5,000,000	3.27	3.17	2.70	3.05	1.36	69	128	237	388
100,000–1,000,000	2.86	2.48	1.87	2.40	0.70	Not Available			
Less than 100,000	2.54	2.37	1.71	2.21	1.95				
Rural	1.38	1.23	0.61	1.07	-0.50				

Source: (UN DESA, 2012).

Box 12.1 | What is urban? The system boundary problem

Any empirical analysis of urban and rural areas, as well as human settlements, requires clear delineation of physical boundaries. However, it is not a trivial or unambiguous task to determine where a city, an urban area, or human settlement physically begins and ends. In the literature, there are a number of methods to establish the boundaries of a city or urban area (Elliot, 1987; Buisseret, 1998; Churchill, 2004). Three common types of boundaries include:

1. **Administrative boundaries**, which refer to the territorial or political boundaries of a city (Hartshorne, 1933; Aguilar and Ward, 2003).
2. **Functional boundaries**, which are delineated according to connections or interactions between areas, such as economic activity, per capita income, or commuting zone (Brown and Holmes, 1971; Douglass, 2000; Hidle et al., 2009).
3. **Morphological boundaries**, which are based on the form or structure of land use, land cover, or the built environment. This is the dominant approach when satellite images are used to delineate urban areas (Benediktsson et al., 2003; Rashed et al., 2003).

What approach is chosen will often depend on the particular research question under consideration. The choice of the physical boundaries can have a substantial influence on the results of the analysis. For example, the Global Energy Assessment (GEA) (GEA, 2012) estimates global urban energy consumption between 180–250 EJ/yr depending on the particular choice of the physical delineation between rural and urban areas. Similarly, depending on the choice of different administrative, morphological, and functional boundaries, between 37 % and 86 % in buildings and industry, and 37 % to 77 % of mobile diesel and gasoline consumption can be attributed in urban areas (Parshall et al., 2010). Thus any empirical evidence presented in this chapter is dependent on the particular boundary choice made in the respective analysis.

Urbanization involves change across multiple dimensions and accordingly is defined differently by different disciplines. Demographers define urbanization as a demographic transition that involves a population becoming urbanized through the increase in the urban proportion of the total population (Montgomery, 2008; Dorélien et al., 2013). Geographers and planners describe urbanization as a land change process that includes the expansion of the urban land cover and growth in built-up areas and infrastructure (Berry et al., 1970; Blanco et al., 2011; Seto et al., 2011). Economists characterize urbanization as a structural shift from primary economic activities such as agriculture and forestry to manufacturing and services (Davis and Henderson, 2003; Henderson, 2003). Sociologists, political scientists, and other social scientists describe urbanization as cultural change, including change in social interactions and the growing complexity of political, social, and economic institutions (Weber, 1966; Berry, 1973). The next sections describe urbanization trends across the first three of these four dimensions and point to the increasing and unprecedented speed and scale of urbanization.

12.2.1.1 Urban population dynamics

In the absence of any other independent data source with global coverage, assessments of historic urban and rural population are commonly based on statistics provided by the United Nations Department for Economic and Social Affairs (UN DESA). The *World Urbanization Prospects* is published every two years by UN DESA and provides projections of key demographic and urbanization indicators for all countries in the world. Even within this dataset, there is no single definition of urban or rural areas that is uniformly applied across the data. Rather, each country develops its own definition of urban, often based on a combination of population size or density, and other criteria such as the percentage of population not employed in agriculture; the availability of electricity, piped water, or other infrastructure; and characteristics of the built environment such as dwellings and built structures (UN DESA, 2012). The large variation in criteria gives rise to significant differences in national definitions. However, the underlying variations in the data do not seriously affect an assessment of urbanization dynamics as long as the national definitions are sufficiently consistent over time (GEA, 2012; UN DESA, 2012). Irrespective of definition, the underlying assumption in all the definitions is that urban areas provide a higher standard of living than rural areas (UN DESA, 2013). A comprehensive assessment of urban and rural population dynamics is provided in the Global Energy Assessment (2012). Here, only key developments are briefly summarized.

For most of human history, the world population mostly lived in rural areas and in small urban settlements, and growth in global urban population occurred slowly. In 1800, when the world population was around one billion, only 3 % of the total population lived in urban areas and only one city—Beijing—had had a population greater than one million (Davis, 1955; Chandler, 1987; Satterthwaite, 2007). Over the next one hundred years, the global share of urban population

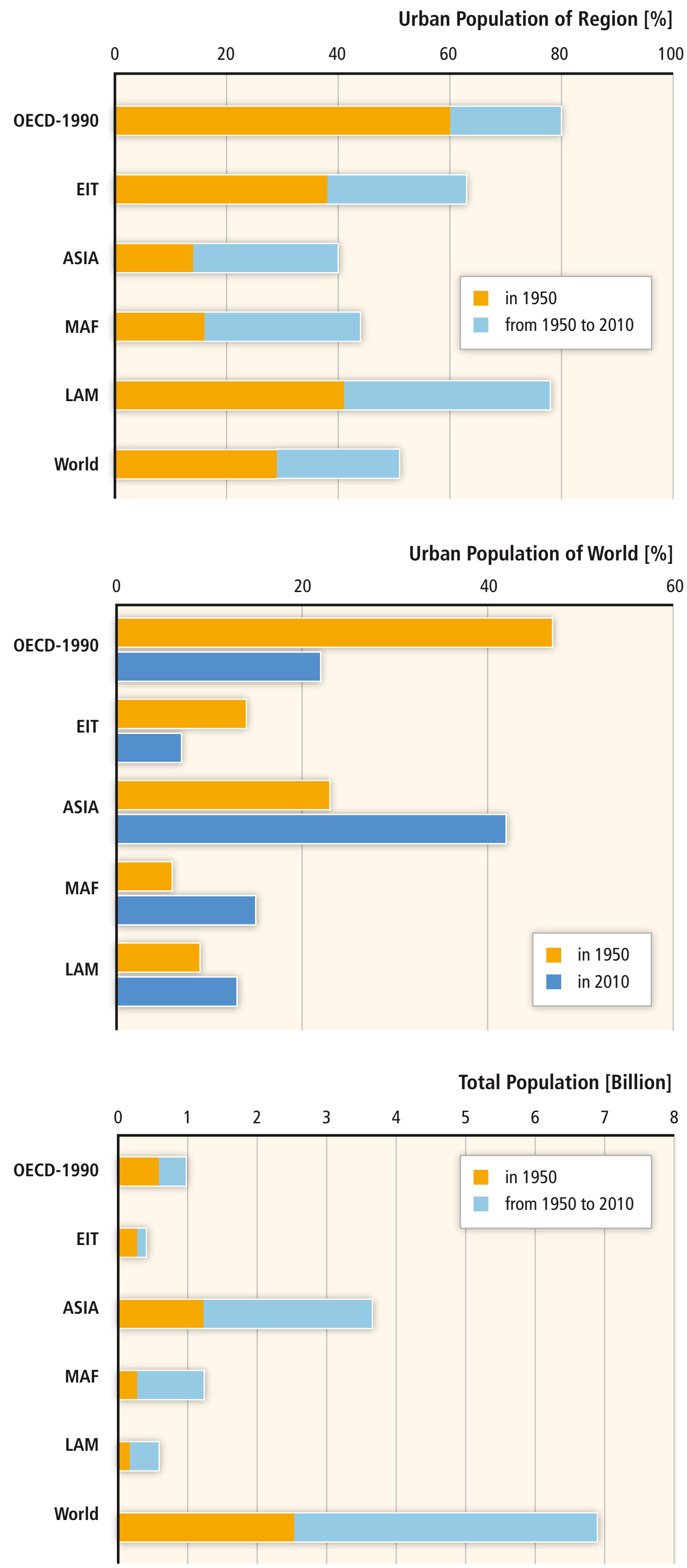

Figure 12.1 | Urban population as percentage of regional and world populations and in absolute numbers for RC5 regions (see Annex II.2), 1950–2010 Source: UN DESA (2012).

increased to 13 % in 1900. The second half of the 20th century experienced rapid urbanization. The proportion of world urban population increased from 13 % in 1900, to 29 % in 1950, and to 52 % in 2011 (UN DESA, 2012). In 1960, the world reached a milestone when global urban population surpassed one billion (UN DESA, 2012). Although it took all previous human history to 1960 to reach one billion urban dwellers, it took only additional 26 years to reach two billion (Seto et al., 2010). Since then, the time interval to add an additional one billion urban dwellers is decreasing, and by approximately 2030, the world urban population will increase by one billion every 13 years (Seto et al., 2010). Today, approximately 52 % of the global population, or 3.6 billion, are estimated to live in urban areas (UN DESA, 2012).

While urbanization has been occurring in all major regions of the world (Table 12.1) since 1950, there is great variability in urban transitions across regions and settlement types. This variability is shaped by multiple factors, including history (Melosi, 2000), migration patterns (Harris and Todaro, 1970; Keyfitz, 1980; Chen et al., 1998), technological development (Tarr, 1984), culture (Wirth, 1938; Inglehart, 1997), governance institutions (National Research Council, 2003), as well as environmental factors such as the availability of energy (Jones, 2004; Dredge, 2008). Together, these factors partially account for the large variations in urbanization levels across regions.

Urbanization rates in developed regions are high, between 73 % in Europe to 89 % in North America, compared to 45 % in Asia and 40 % in Africa (UN DESA, 2012).The majority of urbanization in the future is expected to take place primarily in Africa and Asia, and will occur at lower levels of economic development than the urban transitions that occurred in Europe and North America. While its urbanization rate is still lower than that of Europe and the Americas, the urban population in Asia increased by 2.3 billion between 1950 and 2010 (Figure 12.1).

Overall, urbanization has led to the growth of cities of all sizes (Figure 12.2). Although mega-cities (those with populations of 10 million or greater) receive a lot of attention in the literature, urban population growth has been dominated by cities of smaller sizes. About one-third of the growth in urban population between 1950 and 2010 (1.16 billion) occurred in settlements with populations fewer than 100 thousand. Currently, approximately 10 % of the 3.6 billion urban dwellers live in mega-cities of 10 million or greater (UN DESA, 2012). Within regions and countries, there are large variations in development levels, urbanization processes, and urban transitions. While the dominant global urbanization trend is growth, some regions are experiencing significant urban population declines. Urban shrinkage is not a new phenomenon, and most cities undergo cycles of growth and decline, which is argued to correspond to waves of economic growth and recession (Kondratieff and Stolper, 1935). There are few systematic analyses on the scale and prevalence of shrinking cities (UN-Habitat, 2008). A recent assessment by the United Nations (UN) (UN DESA, 2012) indicates that about 11 % of 3,552 cities with populations of 100,000 or more in 2005 experienced total population declines of 10.4 million between 1990 and 2005. These 'shrinking cities' are distributed globally but concentrated mainly in Eastern Europe (Bontje, 2005; Bernt, 2009) and the rust belt in the United States (Martinez-Fernandez et al., 2012), where de-urbanization is strongly tied with de-industrialization.

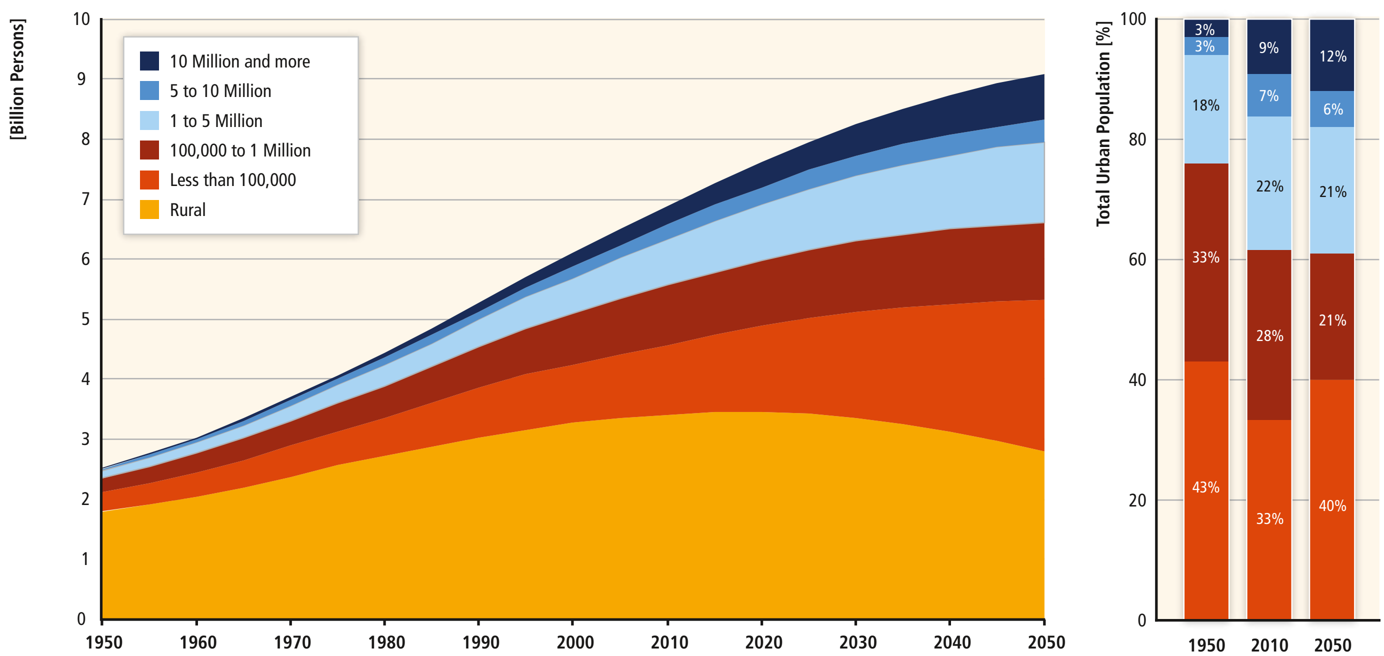

Figure 12.2 | Population by settlement size using historical (1950–2010) and projected data to 2050. Source: UN DESA (2010), Grubler et al. (2012). Note: rounded population percentages displayed across size classes sum do not sum to 100 % for year 2010 due to rounding. Urbanization results in not only in growth in urban population, but also changes in household structures and dynamics. As societies industrialize and urbanize, there is often a decline in household size, as traditional complex households become more simple and less extended (Bongaarts, 2001; Jiang and O'Neill, 2007; O'Neill et al., 2010). This trend has been observed in Europe and North America, where household size has declined from between four to six in the mid 1800s to between two and three today (Bongaarts, 2001).

12.2.1.2 Urban land use

Another key dimension of urbanization is the increase in built-up area and urban land cover. Worldwide, urban land cover occupies a small fraction of global land surface, with estimates ranging between 0.28 to 3.5 million km^2, or between 0.2 % to 2.7 % of ice free terrestrial land (Schneider et al., 2009). Although the urban share of global land cover is negligible, urban land use at the local scale shows trends of declining densities and outward expansion.

Analyses of 120 global cities show significant variation in densities across world regions, but the dominant trend is one of declining built-up and population densities across all income levels and city sizes (Figure 12.3) (Angel et al., 2010). For this sample of cities, built-up area densities have declined significantly between 1990 and 2000, at an average annual rate of 2.0±0.4 % (Angel et al., 2010). On average, urban population densities are four times higher in low-income countries (11,850 persons/km^2 in 2000) than in high-income countries (2,855 persons/km^2 in 2000). Urban areas in Asia experienced the largest decline in population densities during the 1990s. Urban population densities in East Asia and Southeast Asia declined 4.9 % and 4.2 %, respectively, between 1990 and 2000 (World Bank, 2005). These urban population densities are still higher than those in Europe, North America, and Australia, where densities are on average 2,835 persons/km^2. As the urban transition continues in Asia and Africa, it is expected that their urban population densities will continue to decline. Although urban population densities are decreasing, the amount of built-up area per person is increasing (Seto et al., 2010; Angel et al., 2011). A meta-analysis of 326 studies using satellite data shows a minimum global increase in urban land area of 58,000km^2 between 1970 and 2000, or roughly 9 % of the 2000 urban extent (Seto et al., 2011). At current rates of declining densities among developing country cities, a doubling of the urban population over the next 30 years will require a tripling of built-up areas (Angel et al., 2010). For a discussion on drivers of declining densities, see Box 12.4.

12.2.1.3 Urban economies and GDP

Urban areas are engines of economic activities and growth. Further, the transition from a largely agrarian and rural society to an industrial and consumption-based society is largely coincident with a country's level of industrialization and economic development (Tisdale, 1942; Jones, 2004), and reflects changes in the relative share of GDP by both sector and the proportion of the labour force employed in these sectors (Satterthwaite, 2007; World Bank, 2009). The concentration and scale of people, activities, and resources in urban areas fosters economic growth (Henderson et al., 1995; Fujita and Thisse, 1996; Duranton and Puga, 2004; Puga, 2010), innovation (Feldman and Audretsch, 1999; Bettencourt et al., 2007; Arbesman et al., 2009), and an increase of economic and resource use efficiencies (Kahn, 2009; Glaeser and Kahn, 2010). The agglomeration economies made possible by the concentration of individuals and firms make cities ideal settings for innovation, job, and wealth creation (Rosenthal and Strange, 2004; Carlino et al., 2007; Knudsen et al., 2008; Puga, 2010).

A precise estimate of the contribution of all urban areas to global GDP is not available. However, a downscaling of global GDP during the Global Energy Assessment (Grubler et al., 2007; GEA, 2012) showed that urban areas contribute about 80 % of global GDP. Other studies show that urban economies generate more than 90 % of global gross value (Gutman, 2007; United Nations, 2011). In OECD countries, more than 80 % of the patents filed are in cities (OECD, 2006a). Not many cities report city-level GDP but recent attempts have been made by the Metropolitan Policy Program of the Brookings Institute, PriceWaterhouseCoopers (PWC), and the McKinsey Global Institute to provide such estimates. The PWC report shows that key 27 key global cities[1] accounted for 8 % of world GDP for 2012 but only 2.5 % of the global population (PwC and Partnership for New York City, 2012).

In a compilation by UN-Habitat, big cities are shown to have disproportionately high share of national GDP compared to their population (UN-Habitat, 2012). The importance of big cities is further underscored in a recent report that shows that 600 cities generated 60 % of global GDP in 2007 (McKinsey Global Institute, 2011). This same report shows that the largest 380 cities in developed countries account for half of the global GDP. More than 20 % of global GDP comes from 190 North American cities alone (McKinsey Global Institute, 2011). In contrast, the 220 largest cities in developing countries contribute to only 10 % global of GDP, while 23 global megacities generated 14 % of global GDP in 2007. The prevalence of economic concentration in big cities highlights their importance but does not undermine the role of small and medium size cities. Although top-down and bottom-up estimates suggest a large urban contribution to global GDP, challenges remain in estimating the size of this, given large uncertainties in the downscaled GDP, incomplete urban coverage, sample bias, methodological ambiguities, and limitations of the city-based estimations in the existing studies.

12.2.2 GHG emission estimates from human settlements

Most of the literature on human settlements and climate change is rather recent.[2] Since AR4, there has been a considerable growth in scientific evidence on energy consumption and GHG emissions from human settlements. However, there are very few studies that have examined the contribution of all urban areas to global GHG emissions.

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1 Paris, Hong Kong, Sydney, San Francisco, Singapore, Toronto, Berlin, Stockholm, London, Chicago, Los Angeles, New York, Tokyo, Abu Dhabi, Madrid, Kuala Lumpur, Milan, Moscow, São Paulo, Beijing, Buenos Aires, Johannesburg, Mexico City, Shanghai, Seoul, Istanbul, and Mumbai.

2 A search on the ISI Web of Science database for keywords "urban AND climate change" for the years 1900–2007 yielded over 700 English language publications. The same search for the period from 2007 to present yielded nearly 2800 English language publications.

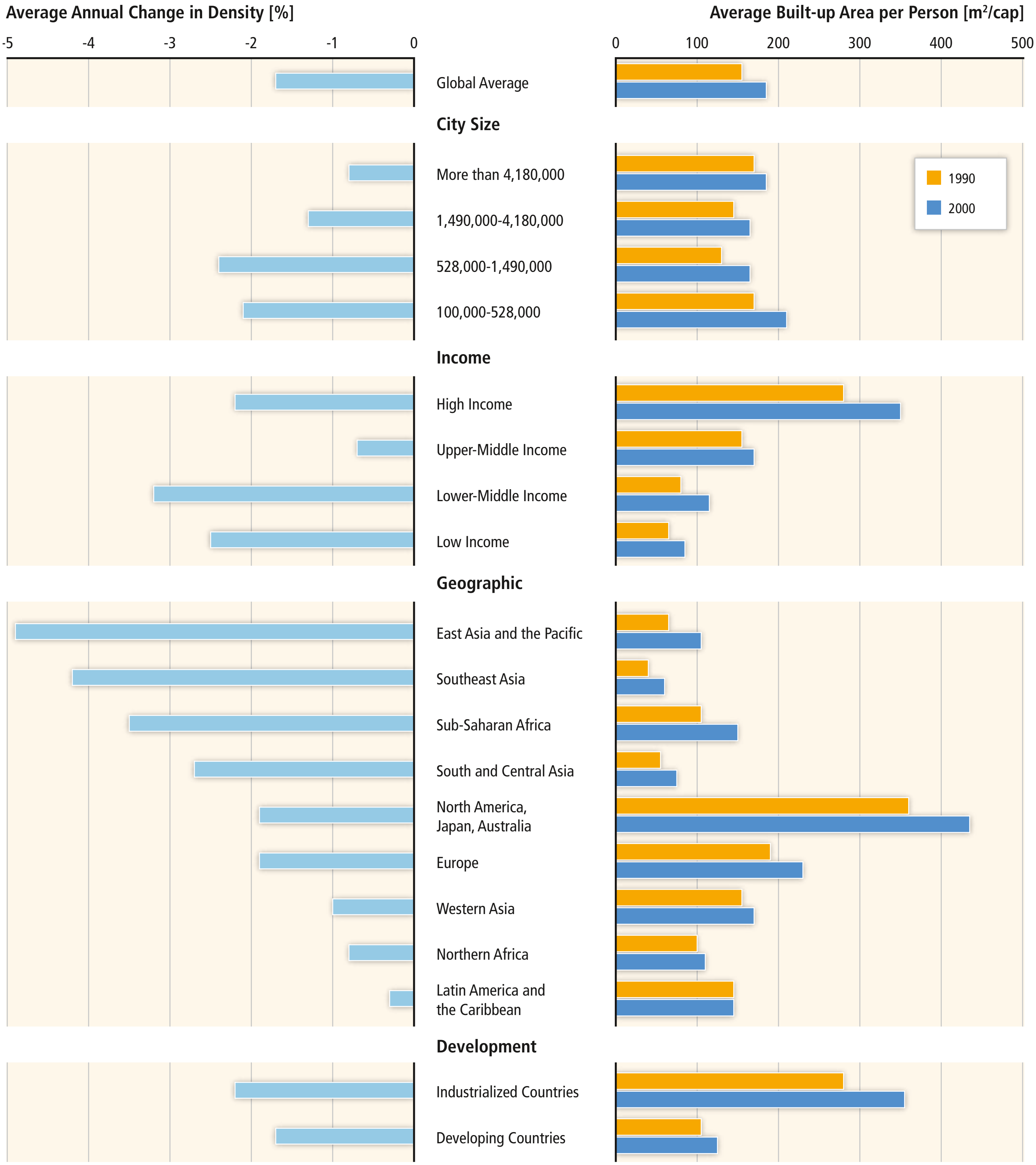

Figure 12.3 | Left: Average annual percent change in density between 1990 and 2010 (light blue). Right: Average built-up area per person (m^2) in 1990 (yellow) and 2000 (blue). Data from 120 cities. Source: Angel et al. (2005).

The few studies that do exist will be discussed in Section 12.2.2.1. In contrast, a larger number of studies have quantified GHG emissions for individual cities and other human settlements. These will be assessed in Section 12.2.2.2.

12.2.2.1 Estimates of the urban share of global emissions

There are very few studies that estimate the relative urban and rural shares of global GHG emissions. One challenge is that of boundary definitions and delineation: it is difficult to consistently define and delineate rural and urban areas globally (see Box 12.1). Another challenge is that of severe data constraints about GHG emissions. There is no comprehensive statistical database on urban or rural GHG emissions. Available global estimates of urban and rural emission shares are either derived bottom-up or top-down. Bottom-up, or up-scaling studies, use a representative sample of estimates from regions or countries and scale these up to develop world totals (see IEA, 2008). Top-down studies use global or national datasets and downscale these to local grid cells. Urban and rural emissions contributions are then estimated based on additional spatial information such as the extent of urban areas or the location of emission point sources (GEA, 2012). In the absence of a more substantive body of evidence, large uncertainties remain surrounding the estimates and their sensitivities (Grubler et al., 2012).

The *World Energy Outlook 2008* estimates urban energy related CO_2 emissions at 19.8 Gt, or 71 % of the global total for the year 2006 (IEA, 2008). This corresponds to 330 EJ of primary energy, of which urban final energy use is estimated to be at 222 EJ. The Global Energy Assessment provides a range of final urban energy use between 180 and 250 EJ with a central estimate of 240 EJ for the year 2005. This is equivalent to an urban share between 56 % and 78 % (central estimate, 76 %) of global final energy use. Converting the GEA estimates on urban final energy (Grubler et al., 2012) into CO_2 emissions (see Methodology and Metrics Annex) results in global urban energy related CO_2 emissions of 8.8—14.3 Gt (central estimate, 12.5Gt) which is between 53 % and 87 % (central estimate, 76 %) of CO_2 emissions from global final energy use and between 30 % and 56 % (central estimate, 43 %) of global primary energy related CO_2 emissions (CO_2 includes flaring and cement emissions which are small). Urban CO_2 emission estimates refer to commercial final energy fuel use only and exclude upstream emissions from energy conversion.

Aside from these global assessments, there is only one attempt in the literature to estimate the total GHG (CO_2, CH_4, N_2O and SF_6) contribution of urban areas globally (Marcotullio et al., 2013). Estimates are provided in ranges where the lower end provides an estimate of the direct emissions from urban areas only and the higher end provides an estimate that assigns all emissions from electricity consumption to the consuming (urban) areas. Using this methodology, the estimated total GHG emission contribution of all urban areas is lower than other approaches, and ranges from 12.8 $GtCO_{2eq}$ to 16.9 $GtCO_{2eq}$, or between 37 % and 49 % of global GHG emissions in the year 2000. The estimated urban share of energy related CO_2 emissions in 2000 is slightly lower than the GEA and IEA estimate, at 72 % using Scope 2 accounting and 44 % using Scope 1 accounting (see Figure 12.4). The urban GHG emissions (CO_2, N_2O, CH_4, and SF_6) from the energy share of total energy GHGs is between 42 % and 66 %. Hence, while the sparse evidence available suggests that urban areas dominate final energy consumption and associated CO_2 emissions, the contribution to total global GHG emissions may be more modest as the large majority of CO_2 emissions from land-use change, N_2O emissions, and CH_4 emissions take place outside urban areas.

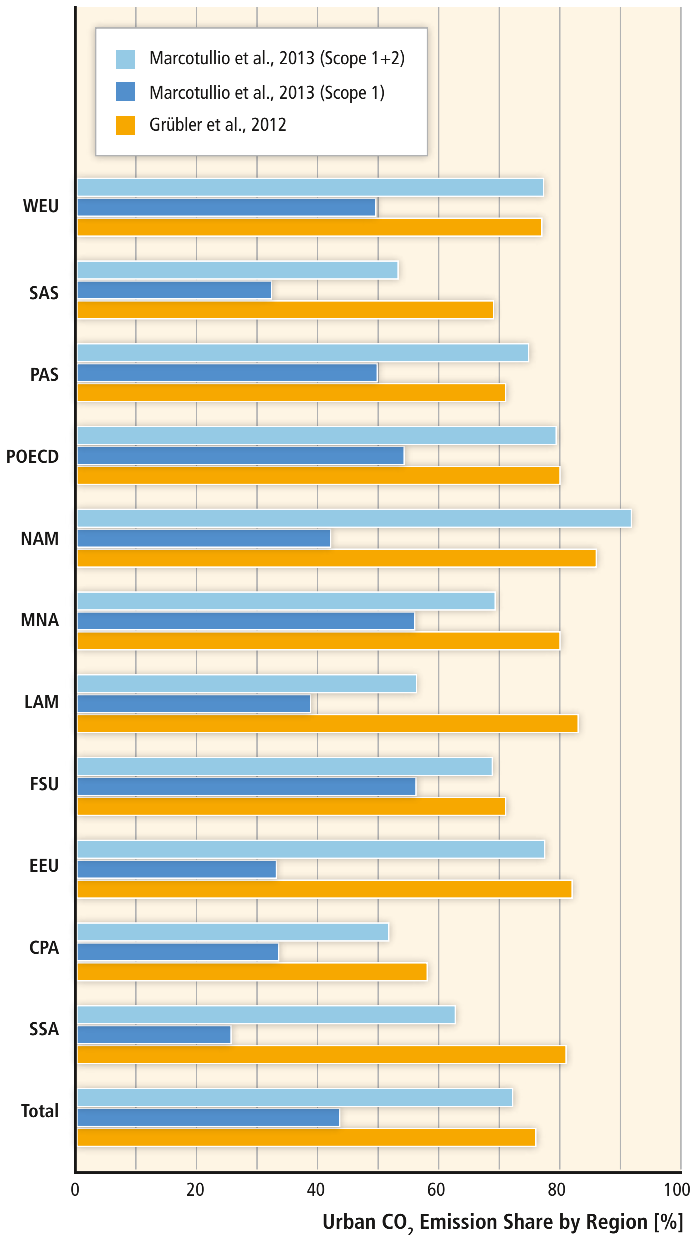

Figure 12.4 | Estimates of urban CO_2 emissions shares of total emissions across world regions. Grubler et al. (2012) estimates are based on estimates of final urban and total final energy use in 2005. Marcotullio et al. (2013) estimates are based on emissions attributed to urban areas as share of regional totals reported by EDGAR. Scope 2 emissions allocate all emissions from thermal power plants to urban areas.

Figure 12.4 shows CO_2 estimates derived from Grubler et al. (2012) and Marcotullio et al. (2013). It highlights that there are large variations in the share of urban CO_2 emissions across world regions. For example, urban emission shares of final energy related CO_2 emissions range from 58 % in China and Central Pacific Asia to 86 % in North America. Ranges are from 31 % to 57 % in South Asia, if urban final energy related CO_2 emissions are taken relative to primary energy related CO_2 emissions in the respective region.

Although differences in definitions make it challenging to compare across regional studies, there is consistent evidence that large variations exist (Parshall et al., 2010; Marcotullio et al., 2011, 2012). For example, the International Energy Agency (IEA) (2008) estimates of the urban primary energy related CO_2 emission shares are 69 % for the EU (69 % for primary energy), 80 % for the United States (85 % for primary energy, see also (Parshall et al., 2010), and 86 % for China (75 % for primary energy, see also Dhakal, 2009). Marcotullio et al. (2013) highlight that non-energy related sectors can lead to substantially different urban emissions shares under consideration of a broader selection of greenhouse gases (CO_2, CH_4, N_2O, SF_6). For example, while Africa tends to have a high urban CO_2 emissions share (64 %–74 %) in terms of energy related CO_2 emissions, the overall contribution of urban areas across all sectors and gases is estimated to range between 21 % and 30 % of all emissions (Marcotullio et al., 2013).

12.2.2.2 Emissions accounting for human settlements

Whereas the previous section discussed the urban proportion of total global emissions, this section assesses emissions accounting methods for human settlements. A variety of emission estimates have been published by different research groups in the scientific literature (e.g.,Ramaswami et al., 2008; Kennedy et al., 2009, 2011; Dhakal, 2009; World Bank, 2010; Hillman and Ramaswami, 2010; Glaeser and Kahn, 2010; Sovacool and Brown, 2010; Heinonen and Junnila, 2011a, c; Hoornweg et al., 2011; Chavez and Ramaswami, 2011; Chavez et al., 2012; Grubler et al., 2012; Yu et al., 2012; Chong et al., 2012). The estimates of GHG emissions and energy consumption for human settlements are very diverse. Comparable estimates are usually only available across small samples of human settlements, which currently limit the insights that can be gained from an assessment of these estimates. The limited number of comparable estimates is rooted in the absence of commonly accepted GHG accounting standards and a lack of transparency over data availabilities, as well as choices that have been made in the compilation of particular estimates:

- **Choice of physical urban boundaries.** Human settlements are open systems with porous boundaries. Depending on how physical boundaries are defined, estimates of energy consumption and GHG emissions can vary significantly (see Box 12.1).

- **Choice of accounting approach/reporting scopes**. There is widespread acknowledgement in the literature for the need to report beyond the direct GHG emissions released from within a settlement's territory. Complementary accounting approaches have therefore been proposed to characterize different aspects of the GHG performance of human settlements (see Box 12.2). Cities and other human settlements are increasingly adopting dual approaches (Baynes et al., 2011; Ramaswami et al., 2011; ICLEI et al., 2012; Carbon Disclosure Project, 2013; Chavez and Ramaswami, 2013).

- **Choice of calculation methods**. There are differences in the methods used for calculating emissions, including differences in emission factors used, methods for imputing missing data, and methods for calculating indirect emissions (Heijungs and Suh, 2010; Ibrahim et al., 2012).

A number of organizations have started working towards standardization protocols for emissions accounting (Carney et al., 2009; ICLEI, 2009; Covenant of Mayors, 2010; UNEP et al., 2010; Arikan, 2011). Further progress has been achieved recently when several key efforts joined forces to create a more broadly supported reporting framework (ICLEI et al., 2012). Ibrahim et al. (2012) show that the differences across reporting standards explains significant cross-sectional variability in reported emission estimates. However, while high degrees of cross-sectional comparability are crucial in order to gain further insight into the emission patterns of human settlements across the world, many applications at the settlement level do not require this. Cities and other localities often compile these data to track their own performance in reducing energy consumption and/or greenhouse gas emissions (see Section 12.7). This makes a substantial body of evidence difficult to use for scientific inquiries.

Beyond the restricted comparability of the available GHG estimates, six other limitations of the available literature remain. First, the growth in publications is restricted to the analysis of energy consumption and GHG emissions from a limited set of comparable emission estimates. New estimates do not emerge at the same pace. Second, available evidence is particularly scarce for medium and small cities as well as rural settlements (Grubler et al., 2012). Third, there is a regional bias in the evidence. Most studies focus on emissions from cities in developed countries with limited evidence from a few large cities in the developing world (Kennedy et al., 2009, 2011; Hoornweg et al., 2011; Sugar et al., 2012). Much of the most recent literature provides Chinese evidence (Dhakal, 2009; Ru et al., 2010; Chun et al., 2011; Wang et al., 2012a, b; Chong et al., 2012; Yu et al., 2012; Guo et al., 2013; Lin et al., 2013; Vause et al., 2013; Lu et al., 2013), but only limited new emission estimates are emerging from that. Evidence on human settlements in least developed countries is almost non-existent with some notable exceptions in the non peer-reviewed literature (Lwasa, 2013). Fourth, most of the available emission estimates are focusing on energy related CO_2 rather than all GHG emissions. Fifth, while there is a considerable amount of evidence for territorial emissions, studies that include Scope 2 and 3 emission components are growing but remain limited (Ramaswami et al., 2008, 2012b; Kennedy et al.,

Box 12.2 | Emission accounting at the local scale

Three broad approaches have emerged for GHG emissions accounting for human settlements, each of which uses different boundaries and units of analysis.

1) Territorial or production-based emissions accounting includes all GHG emissions from activities within a city or settlement's territory (see Box 12.1). This is also referred to as Scope 1 accounting (Kennedy et al., 2010; ICLEI et al., 2012). Territorial emissions accounting is, for example, commonly applied by national statistical offices and used by countries under the United Nations Framework Convention on Climate Change (UNFCCC) for emission reporting (Ganson, 2008; DeShazo and Matute, 2012; ICLEI et al., 2012).

However, human settlements are typically smaller than the infrastructure in which they are embedded, and important emission sources may therefore be located outside the city's territorial boundary. Moreover, human settlements trade goods and services that are often produced in one settlement but are consumed elsewhere, thus creating GHG emissions at different geographic locations associated with the production process of these consumable items. Two further approaches have thus been developed in the literature, as noted below.

2) Territorial plus supply chain accounting approaches start with territorial emissions and then add a well defined set of indirect emissions which take place outside the settlement's territory. These include indirect emissions from (1) the consumption of purchased electricity, heat and steam (Scope 2 emissions), and (2) any other activity (Scope 3 emissions). The simplest and most frequently used territorial plus supply chain accounting approach includes Scope 2 emissions (Hillman and Ramaswami, 2010; Kennedy et al., 2010; Baynes et al., 2011; ICLEI et al., 2012).

3) Consumption-based accounting approaches include all direct and indirect emissions from final consumption activities associated with the settlement, which usually include consumption by residents and government (Larsen and Hertwich, 2009, 2010a, b; Heinonen and Junnila, 2011a, b; Jones and Kammen, 2011; Minx et al., 2013). This approach excludes all emissions from the production of exports in the settlement territory and includes all indirect emissions occurring outside the settlement territory in the production of the final consumption items.

2009; Larsen and Hertwich, 2009, 2010a, b; Hillman and Ramaswami, 2010; White et al., 2010; Petsch et al., 2011; Heinonen and Junnila, 2011a, b; Heinonen et al., 2011; Chavez et al., 2012; Paloheimo and Salmi, 2013; Minx et al., 2013). Finally, the comparability of available evidence of GHG emissions at the city scale is usually restricted across studies. There prevails marked differences in terms of the accounting methods, scope of covered sectors, sector definition, greenhouse gas covered, and data sources used (Bader and Bleischwitz, 2009; Kennedy et al., 2010; Chavez and Ramaswami, 2011; Grubler et al., 2012; Ibrahim et al., 2012).

Across cities, existing studies point to a large variation in the magnitude of total and per capita emissions. For this assessment, emission estimates for several hundred individual cities were reviewed. Reported emission estimates for cities and other human settlements in the literature range from 0.5 tCO_2/cap to more than 190 tCO_2/cap (Carney et al., 2009; Kennedy et al., 2009; Dhakal, 2009; Heinonen and Junnila, 2011a, c; Wright et al., 2011; Sugar et al., 2012; Ibrahim et al., 2012; Ramaswami et al., 2012b; Carbon Disclosure Project, 2013; Chavez and Ramaswami, 2013; Department of Energy & Climate Change, 2013). Local emission inventories in the UK for 2005–2011 show that end use activities and industrial processes of both rural and urban localities vary from below 3 to 190 tCO_2/cap and more (Department of Energy & Climate Change, 2013). The total CO_2 emissions from end use activities for ten global cities range (reference year ranges 2003–2006) between 4.2 and 21.5 tCO_2eq/cap (Kennedy et al., 2009; Sugar et al., 2012), while there is variation reported in GHG estimates from 18 European city regions from 3.5 to 30 tCO_2eq/cap in 2005 (Carney et al., 2009).

In many cases, a large part of the observed variability will be related to the underlying drivers of emissions such as urban economic structures (balance of manufacturing versus service sector), local climate and geography, stage of economic development, energy mix, state of public transport, urban form and density, and many others (Carney et al., 2009; Kennedy et al., 2009, 2011; Dhakal, 2009, 2010; Glaeser and Kahn, 2010; Shrestha and Rajbhandari, 2010; Gomi et al., 2010; Parshall et al., 2010; Rosenzweig et al., 2011; Sugar et al., 2012; Grubler et al., 2012; Wiedenhofer et al., 2013). Normalizing aggregate city-level emissions by population therefore does not necessarily result in robust cross-city comparisons, since each city's economic function, trade typology, and imports-exports balance can differ widely. Hence, using different emissions accounting methods can lead to substantial differences in reported emissions (see Figure 12.4). Therefore, understanding differences in accounting approaches is essential in order to draw meaningful conclusions from cross-city comparisons of emissions.

Evidence from developed countries such as the United States, Finland, or the United Kingdom suggests that consumption-based emission estimates for cities and other human settlements tend to be higher than their territorial emissions. However, in some cases,

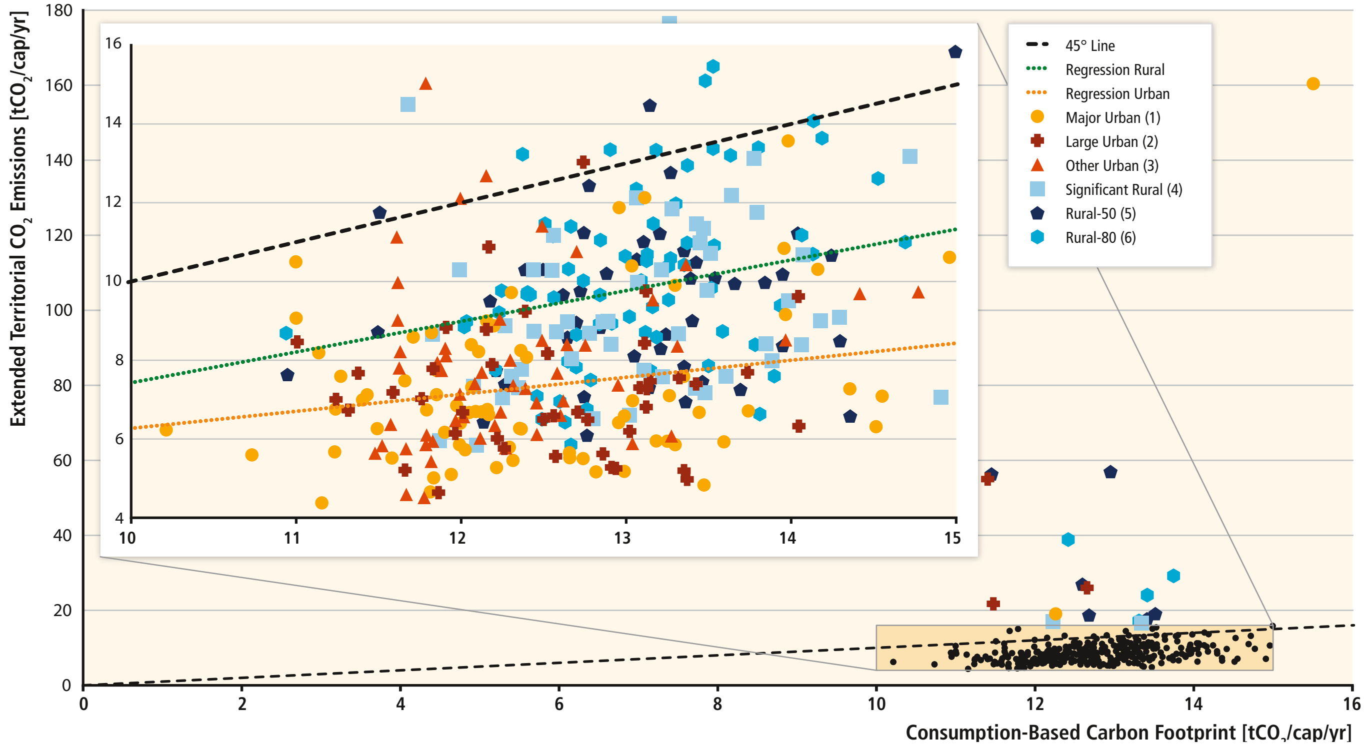

Figure 12.5 | Extended territorial and consumption-based per capita CO_2 emissions for 354 urban (yellow/orange/red) and rural (blue) municipalities in England in 2004. The extended territorial CO_2 emissions accounts assign CO_2 emissions from electricity consumption to each municipality's energy use. The consumption-based carbon footprint accounts assign all emissions from the production of goods and services in the global supply chain to the municipality where final consumption takes place. At the 45° line, per capita extended territorial and consumption-based CO_2 emissions are of equal size. Below the 45° line, consumption-based CO_2 emission estimates are larger than extended territorial emissions. Above the 45° line, estimates of extended territorial CO_2 emissions are larger than consumption-based CO_2 emissions. Robust regression lines are shown for the rural (blue) and urban (yellow/orange/red) sub-samples. In the inset, the x-axis shows 10–15 tonnes of CO_2 emissions per capita and the y-axis shows 4–16 tonnes of CO_2 emissions per capita. Source: Minx et al. (2013).

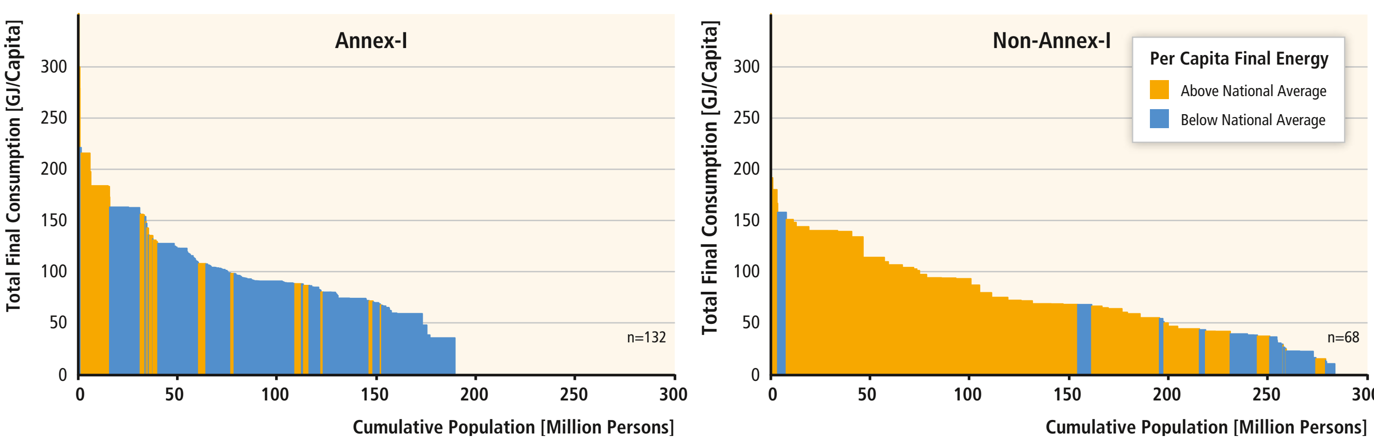

Figure 12.6 | Per capita (direct) total final consumption (TFC) of energy (GJ) versus cumulative population (millions) in urban areas. Source: Grubler et al. (2012).

territorial or extended territorial emission estimates (Scope 1 and Scope 2 emissions) can be substantially higher. This is mainly due to the large fluctuations in territorial emission estimates that are highly dependent on a city's economic structure and trade typology. Consumption-based estimates tend to be more homogenous (see Figure 12.5).

Based on a global sample of 198 cities by the Global Energy Assessment, Grubler et al. (2012) found that two out of three cities in Annex I countries have a lower per capita final energy use than national levels. In contrast, per capita final energy use for more than two out of three cities in non-Annex I countries have higher than national averages (see Figure 12.6). There is not sufficient comparable evidence available for this assessment to confirm this finding for energy related CO_2 emissions, but this pattern is suggested by the close relationship between final energy use and energy related CO_2 emissions. Individual studies for 35 cities in China, Bangkok, and 10 global cities provide additional evidence of these trends (Dhakal, 2009; Aumnad, 2010; Kennedy et al., 2010; Sovacool and Brown, 2010). Moreover, the literature suggests that differences in per capita energy consumption and CO_2 emission patterns of cities in Annex I and non-Annex I countries have converged more than their national emissions (Sovacool and Brown, 2010; Sugar et al., 2012). For consumption-based CO_2 emissions, initial evidence suggests that urban areas tend to have much higher emissions than rural areas in non-Annex I countries, but the evidence is limited to a few studies on India and China (Parikh and Shukla, 1995; Guan et al., 2008, 2009; Pachauri and Jiang, 2008; Minx et al., 2011). For Annex I countries, studies suggest that using consumption based CO_2 emission accounting, urban areas can, but do not always, have higher emissions than rural settlements (Lenzen et al., 2006; Heinonen and Junnila, 2011c; Minx et al., 2013).

There are only a few downscaled estimates of CO_2 emissions from human settlements and urban as well as rural areas, mostly at regional and national scales for the EU, United States, China, and India (Parshall et al., 2010; Raupach et al., 2010; Marcotullio et al., 2011, 2012; Gurney et al., 2012). However, these studies provide little to no representation of intra-urban features and therefore cannot be substitutes for place-based emission studies from cities. Recent studies have begun to combine downscaled estimates of CO_2 emissions with local urban energy consumption information to generate fine-scale maps of urban emissions (see Figure 12.7 and Gurney et al., 2012). Similarly, geographic-demographic approaches have been used for downscaling consumption-based estimates (Druckman and Jackson, 2008; Minx et al., 2013). Such studies may allow more detailed analyses of the drivers of urban energy consumption and emissions in the future.

12.2.3 Future trends in urbanization and GHG emissions from human settlements

This section addresses two issues concerning future scenarios of urbanization. It summarizes projected future urbanization dynamics in multiple dimensions. It assesses and contextualizes scenarios of urban population growth, urban expansion, and urban emissions.

12.2.3.1 Dimension 1: Urban population

Worldwide, populations will increasingly live in urban settlements. By the middle of the century, the global urban population is expected to reach between 5.6 to 7.1 billion, with trends growth varying substantially across regions (Table 12.2). While highly urbanized North America, Europe, Oceania, and Latin America will continue to urbanize, the increase in urbanization levels in these regions is relatively small. Urbanization will be much more significant in Asia and Africa where

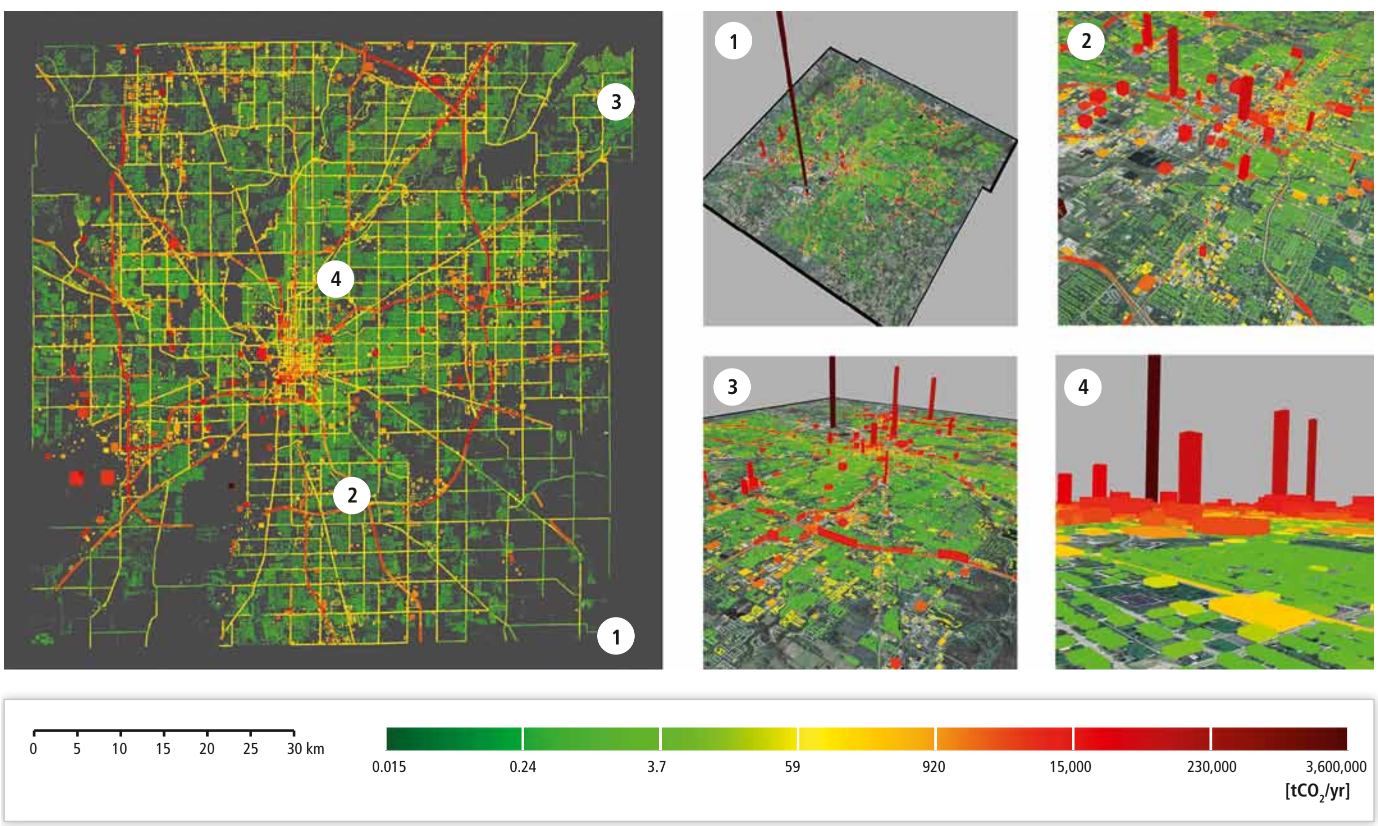

Figure 12.7 | Total fossil fuel emissions of Marion County, Indiana, USA, for the year 2002. Left map: Top-down view with numbered zones. Right four panels: Blow ups of numbered zones. Box height units: Linear. Source: Gurney et al. (2012).

Table 12.2 | Global urban population in 2050 (mid-year)

Source	Total Pop.	%	Urban Pop.
	in billions	Urban	*in billions*
IIASA Greenhouse Gas Index, A2R Scenario	10.245	69	7.069
World Bank	9.417	67	6.308
United Nations	9.306	67	6.252
IIASA Greenhouse Gas Index, B2 Scenario	9.367	66	6.182
IIASA Greenhouse Gas Index, B1 Scenario	8.721	64	5.581

Sources: IIASA (2009), UN DESA (2012), World Bank (2013).

the majority of the population is still rural. Urban population growth will also largely occur in the less developed Africa, Asia, and Latin America. The proportion of rural population in the developed regions have declined from about 60 % in 1950 to less than 30 % in 2010, and will continue to decline to less than 20 % by 2050.

Uncertainties in future global urbanization trends are large, due in part to different trajectories in economic development and population growth. While the United Nations Development Programme (UNPD) produces a single urbanization scenario for each country through 2050, studies suggests that urbanization processes in different countries and different periods of time vary remarkably. Moreover, past UN urbanization projections have contained large errors and have tended to overestimate urban growth, especially for countries at low and middle urbanization levels (Bocquier, 2005; Montgomery, 2008; Alkema et al., 2011).

Given these limitations, recent studies have begun to explore a range of urban population growth scenarios. A study undertaken at International Institute for Applied Systems Analysis (IIASA) extrapolates UN scenarios to 2100 and develops three alternative scenarios by making assumptions about long-term maximum urbanization levels (Grubler et al., 2007). However, missing from these scenarios is the full range of uncertainty over the next twenty to thirty years, the period when the majority of developing countries will undergo significant urban transitions. For instance, variation across different urbanization scenarios before 2030 is negligible (0.3 %) for India and also very small (< 4 %) for China (see Figure 12.8, dashed lines). By 2050, urbanization levels could realistically reach between 38–69 % in India, and 55–78 % in China (O'Neill et al., 2012). In other words, there are large uncertainties in urbanization trajectories for both countries. The *speed* (fast or slow) as well as the *nature* (an increase in industrialization) of urbanization could lead to significant effects on future urban energy use and emissions.

12.2.3.2 Dimension 2: Urban land cover

Recently, global forecasts of urban expansion that take into account population and economic factors have become available (Nelson et al., 2010; Angel et al., 2011; Seto et al., 2011, 2012). These studies vary in their baseline urban extent, model inputs, assumptions about future trends in densities, economic and population growth, and modelling methods. They forecast that between 2000 and 2030, urban areas will expand between 0.3 million to 2.3 million km^2, corresponding to an increase between 56 % to 310 % (see Table 12.3 and Angel et al., 2011; Seto et al., 2011, 2012). It is important to note that these studies forecast changes in urban land cover (features of Earth's surface) and not changes in the built environment and infrastructure (e.g., buildings, roads). However, these forecasts of urban land cover can be useful to project infrastructure development and associated emissions. Given worldwide trends of declining densities, the zero population density decline scenario and associated urban growth forecast (0.3 million) is unlikely, as is the *Special Report on Emissions Scenarios* (SRES) A1 scenario of very rapid economic growth and a peak in global population mid-century. According to the studies, the most likely scenarios are SRES B2 (Seto et al., 2011), > 75 % probability (Seto et al., 2012), and 2 % decline (Angel et al., 2011), which reduces the range of forecast estimates to between 1.1 to 1.5 million km^2 of new urban land. This corresponds to an increase in urban land cover between 110 % to 210 % over the 2000 global urban extent. Hurtt et al. (2011) report

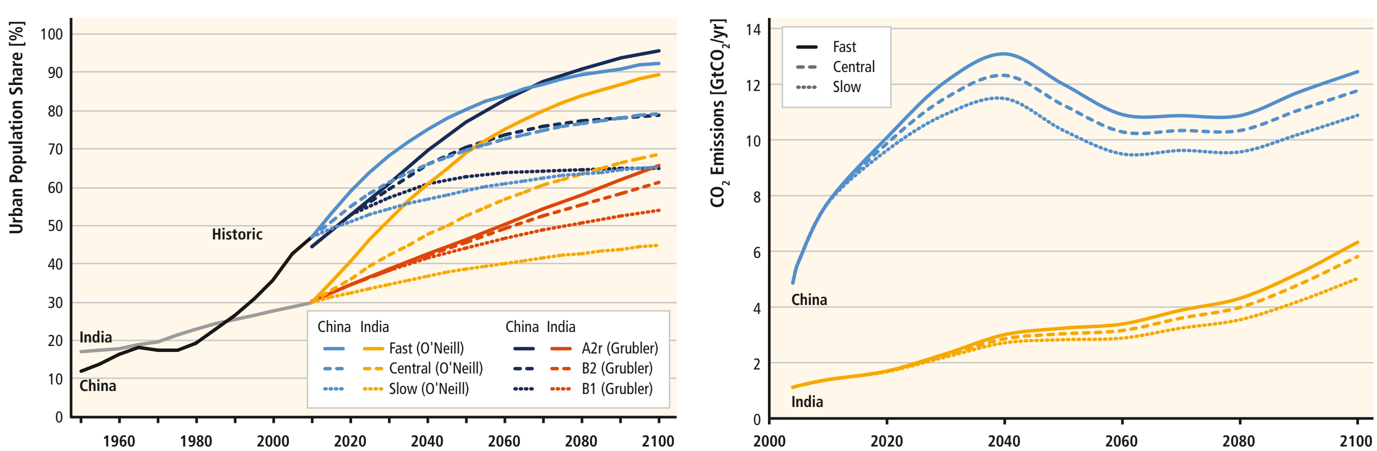

Figure 12.8 | Projected urban population growth for India and China under fast, central, and slow growth scenarios (left) and associated growth in CO$_2$ emissions (right). Sources: O'Neill et al. (2012), Grubler et al. (2007).

projected land-use transitions including urbanization, out to 2100, for the intended use in Earth System Models (ESMs). However, they do not give a detailed account of the projected urban expansion in different parts of the world.

Depending on the scenario and forecast, 55 % of the total urban land in 2030 is expected to be built in the first three decades of the 21st century. Nearly half of the global growth in urban land cover is forecasted to occur in Asia, and 55 % of the regional growth will take place in China and India (Seto et al., 2012). China's urban land area is expected to expand by almost 220,000 km^2 by 2030, and account for 18 % of the global increase in urban land cover (Seto et al., 2012). These forecasts provide first-order estimates of the likelihood that expansion of urban areas will occur in areas of increasing vulnerability to extreme climate events including floods, storm surges, sea level rise, droughts, and heat waves (see WGII AR5 Chapter 8). Urban expansion and associated land clearing and loss of aboveground biomass carbon in the pan-tropics is expected to be 1.38 PgC between 2000 and 2030, or 0.05 PgC/yr (Seto et al., 2012).

12.2.3.3 Dimension 3: GHG emissions

Recent developments in integrated models are beginning to capture the interdependence among urban population, urban land cover, and GHG emissions. Some integrated models have found that changes in urbanization in China and India have a less than proportional effect on aggregate emissions and energy use (O'Neill et al., 2012). These studies find that income effects due to economic growth and urbanization result in household consumption shifts toward cleaner cooking fuels (O'Neill et al., 2012). In India, the urbanization level in 2050 will be 16 percentage points lower under the slow urbanization scenario than under the central scenario, or 15 percentage points higher under the fast scenario than under the central scenario. However, these large differences in potential urbanization levels in India lead to relatively small differences in emissions: 7 % between the slow and central urbanization scenarios, and 6 % between the fast and central urbanization scenarios (O'Neill et al., 2012). The relatively small effect of urbanization on emissions is likely due to relatively small differences in per capita income between rural and urban areas (O'Neill et al., 2012). In contrast, large differences in per capita income between urban and rural areas in China result in significant differences in household consumption, including for energy (O'Neill et al., 2012). Differences in urbanization pathways also reflect different speeds of transition away from the use of traditional fuels toward modern fuels such as electricity and natural gas (Krey et al., 2012). Slower rates of urbanization result in slower transitions away from traditional to modern fuels (Jiang and O'Neill, 2004; Pachauri and Jiang, 2008). A large share of solid fuels or traditional biomass in the final energy mix can have adverse health impacts due to indoor air pollution (Bailis et al., 2005; Venkataraman et al., 2010).

Accounting for uncertainties in urban population growth, the scenarios show that urbanization as a demographic process does not lead to a

Table 12.3 | Forecasts of global urban land expansion to 2030. Sources: Angel et al. (2011), Seto et al. (2011, 2012).

Study	Scenario	Projected Urban Expansion to 2030 (km^2)								% of projected urban land in 2030 to be built between 2000–2030
		Urban Land 2000 (km^2)	Africa	Asia	Europe	Latin America	North America	Oceania	Total (% increase from 2000)	
Seto et al. (2011)	SRES A1	726,943	107,551	1,354,001	296,638	407,214	73,176	16,996	2,255,576 (310)	76
	SRES A2	726,943	113,423	702,772	162,179	122,438	49,487	15,486	1,165,785 (160)	62
	SRES B1	726,943	107,551	1,238,267	232,625	230,559	86,165	18,106	1,913,273 (263)	72
	SRES B2	726,943	136,419	989,198	180,265	131,016	74,572	15,334	1,526,805 (210)	68
Seto et al. (2012)	> 75 % probability	652,825	244,475	585,475	77,575	175,075	118,175	9,700	1,210,475	65
		Urban Land 2000 (km^2)	**Africa**	**Asia**	**East Asia and the Pacific**	**Europe and Japan**	**Latin America and the Caribbean**	**Land Rich Developed Countries**	**Total (% increase from 2000)**	
Angel et al. (2011)	0 % density decline	602,864	58,132	120,757	43,092	9,772	49,348	54,801	335,902 (56)	36
	1 % density decline	602,864	92,002	203,949	75,674	74,290	98,554	119,868	664,337 (110)	52
	2 % density decline	602,846	137,722	316,248	119,654	161,379	164,975	207,699	1,107,677 (184)	65

corresponding growth in emissions and energy use (Figure 12.8b). In China, for example, under the central scenario (similar to UN projections) the country will reach 70 % urban population by 2050 and the total carbon emissions will reach 11 GtC/yr. Under the slow urbanization scenario, the urbanization level is 13 % lower than the central urbanization scenario, but results in emissions that are 9 % lower than under the central urbanization scenario. Similarly, the fast urbanization scenario results in emissions that are 7 % higher than under the central scenario, but with urbanization levels that are 11 % higher.

Studies of the effects of demographic change on GHG emissions come to contradicting conclusions (Dalton et al., 2008; Kronenberg, 2009). Many of the forecasts on urbanization also do not explicitly account for the infrastructure for which there is a separate set of forecasts (Davis et al., 2010; Kennedy and Corfee-Morlot, 2013; Müller et al., 2013) including those developed by the IEA (IEA, 2013) and the Organisation for Economic Co-operation and Development (OECD) (OECD, 2006b, 2007). However these infrastructure forecasts, typically by region or country, do not specify the portion of the forecasted infrastructure in urban areas and other settlements. One study finds that both ageing and urbanization can have substantial impacts on emissions in certain world regions such as the United States, the EU, China, and India. Globally, a 16–29 % reduction in the emissions by 2050 (1.4–2.5 GtC/yr) could be achieved through slowing population growth (O'Neill et al., 2010).

12.3 Urban systems: Activities, resources, and performance

How does urbanization influence global or regional CO_2 emissions? This section discusses drivers of urban GHG emissions, how they affect different sectors, and their interaction and interdependence. The magnitude of their impact on urban GHG emissions is also discussed qualitatively and quantitatively to provide context for a more detailed assessment of urban form and infrastructure (12.4) and spatial planning (12.5).

12.3.1 Overview of drivers of urban GHG emissions

Urban areas and nations share some common drivers of GHG emissions. Other drivers of urban GHG emissions are distinct from national drivers and are locally specific. The previous section discussed important accounting issues that affect the estimation of urban-scale GHG emissions. (For a more comprehensive review, see Kennedy et al., 2009; ICLEI et al., 2012; Ramaswami et al., 2012b; Steinberger and Weisz, 2013). Another characteristic of urban areas is that their physical form and structure in terms of land-use mix and patterns, density, and spatial configuration of infrastructure can strongly influence GHG emissions (see discussion below and in 12.4). The basic constituent elements of cities such as streets, public spaces, buildings, and their design, placement, and function reflect their socio-political, economic, and technological histories (Kostof, 1992; Morris, 1994; Kostof and Tobias, 1999). Hence, cities often portray features of 'path dependency' (Arthur, 1989), a historical contingency that is compounded by the extent of pre-existing policies and market failures that have lasting impacts on emissions (see Section 12.6 below).

The following sections group and discuss urban GHG emission drivers into four clusters that reflect both the specificity of urban scale emissions as well as their commonality with national-scale drivers of GHG emissions addressed in the other chapters of this assessment:

- Economic geography and income
- Socio-demographic factors
- Technology
- Infrastructure and urban form

Economic geography refers to the function of a human settlement within the global hierarchy of places and the international division of labour, as well as the resulting trade flows of raw materials, energy, manufactured goods, and services. Income refers to the scale of economic activity, often expressed through measures of Gross Regional Product (GRP) (i.e., the GDP equivalent at the scale of human settlements), calculated either as an urban (or settlement) total, or normalized on a per capita basis.

Socio-demographic drivers of urban GHG emissions include population structure and dynamics (e.g., population size, age distribution, and household characteristics) (O'Neill et al., 2010) as well as cultural norms (e.g., consumption and lifestyle choices) and distributional and equity factors (e.g., access or lack thereof to basic urban infrastructure). Unequal access to housing and electricity is a significant social problem in many rapidly growing cities of the Global South (Grubler and Schulz, 2013) and shapes patterns of urban development. Here, 'technology' refers to macro-level drivers such as the technology of manufacturing and commercial activities. 'Infrastructure' and 'urban form' refer to the patterns and spatial arrangements of land use, transportation systems, and urban design elements (Lynch, 1981; Handy, 1996) and are discussed in greater detail in Section 12.4.

12.3.1.1 Emission drivers decomposition via IPAT

Explaining GHG emission growth trends via decomposition analysis is a widely used technique in the scientific literature and within IPCC assessments ever since Kaya (1990). The so-called IPAT identity (for a review, see Chertow, 2000) is a multiplicative identity in which Impacts (e.g., emissions) are described as being the product of Population *x* Affluence *x* Technology. First derivatives (growth rates) of the components of this identity become additive, thus allowing a first analysis on the relative weight of different drivers. The IPAT identity is

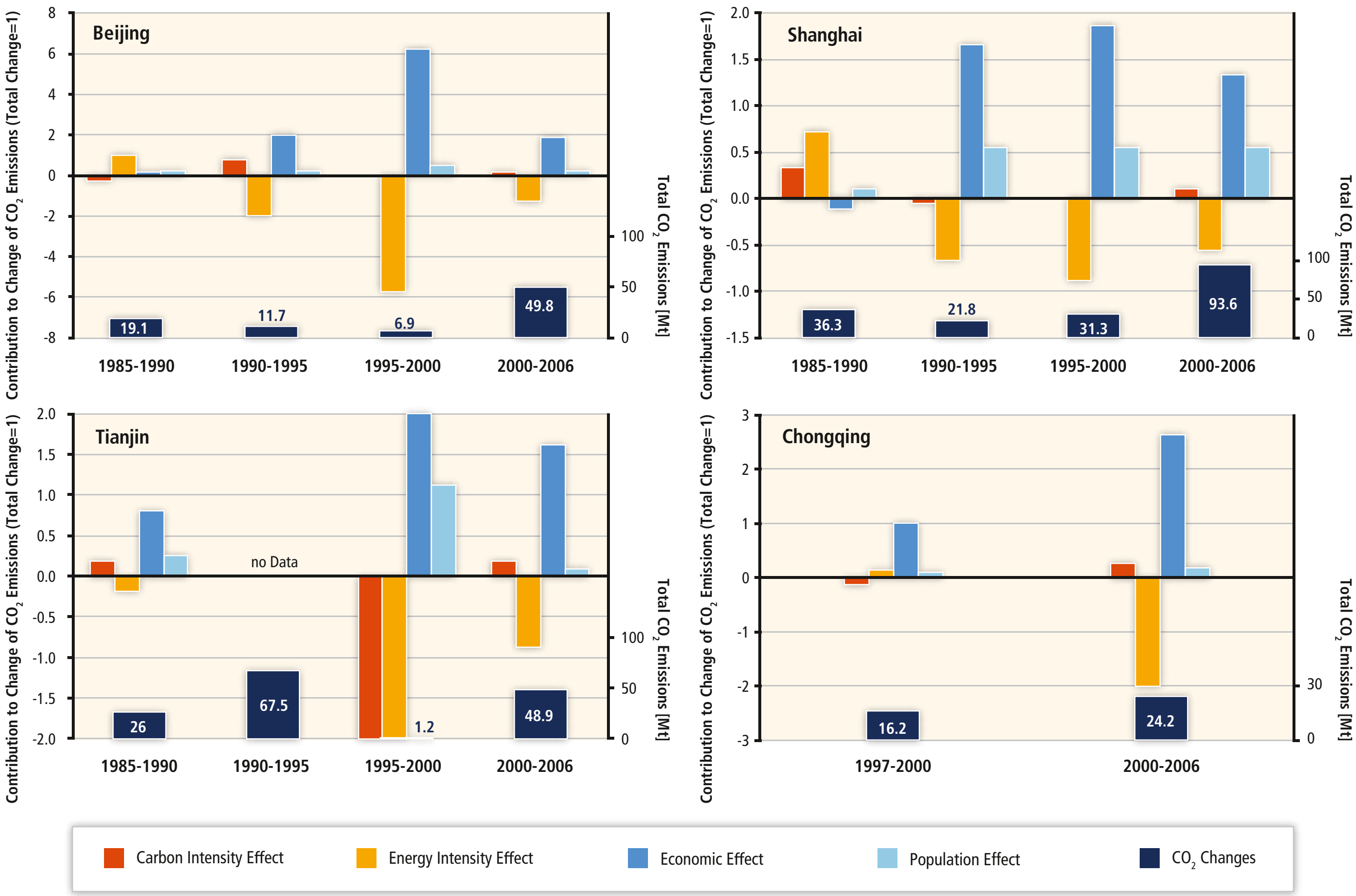

Figure 12.9 | Decomposition of urban-scale CO_2 emissions (absolute difference over time period specified (dark blue) and renormalized to index 1 (other colours)) for four Chinese cities 1985 to 2006. Source: Grubler et al. (2012) based on Dhakal (2009). Note the 'economic effect' in the graph corresponds to an income effect as discussed in the text. For comparison, per capita CO_2 emissions for these four cities range between 11.7 (Shanghai), 11.1 (Tianjin), 10.1 (Beijing), and 3.7 (Chongqing) tCO_2/cap (Hoornweg et al., 2011).

a growth accounting framework and does not lend itself to explaining differences between urban settlements in terms of absolute GHG emission levels and their driving forces (see discussion below).

There is great interest in understanding the drivers of China's urban GHG emissions, which has resulted in a large literature on the decomposition of GHG emissions for Chinese megacities. With approximately 10 tonnes of CO_2 per urban capita—three times the national average—China approaches and in some cases, surpasses levels for Annex-I countries and cities (Dhakal, 2009). Studies have used national emission inventory methods following the IPCC/OECD guidelines (Dhakal, 2009; Chong et al., 2012) or input-output techniques (Wang et al., 2013) and thus have used both production and consumption accounting perspectives. Studies have also gone beyond the simple IPAT accounting framework, such as using index decomposition (Donglan et al., 2010). Together, these studies show considerable variation in per capita GHG emissions across Chinese cities (see, for example, Figure 12.9). Although the relative contribution of different drivers of emissions varies across cities and time periods, one study of several Chinese cities found that income is the most important driver of increases in urban carbon emissions, far surpassing population growth, with improvements in energy efficiency serving as a critical counterbalancing factor to income growth (Dhakal, 2009). The importance of economic growth as a driver of urban CO_2 emissions in China has been consistently corroborated in other studies, including those that examine relatively smaller cities and with the use of alternative types of data and methods (Li et al., 2010; Liu et al., 2012; Chong et al., 2012; Jiang and Lin, 2012).

However, the evidence on whether the gains in efficiency can counterbalance the scale of infrastructure construction and income growth in China is less conclusive. Several studies implemented at different spatial scales have found that the scale of urbanization and associated consumption growth in China have outpaced gains from improvements in efficiency (Peters et al., 2007; Feng et al., 2012; Güneralp and Seto, 2012). Other studies have found that improvements in efficiency offset the increase in consumption (Liu et al., 2007; Zhang et al., 2009; Minx et al., 2011).

The literature on drivers of urban GHG emissions in other non-Annex I countries is more sparse, often focusing on emission drivers at the sectoral level such as transport (Mraihi et al., 2013) or household energy use (Ekholm et al., 2010). In these sectoral studies, income and other factors (that are highly correlated with income) such as vehicle ownership and household discount rates, are also shown as important determining variables.

Decomposition analyses are available for cities in the United States (Glaeser and Kahn, 2010), the UK (Minx et al., 2013), Japan (Makido et al., 2012), and Australia (Wiedenhofer et al., 2013). These studies show that income is an important driver of urban GHG emissions. Studies using more disaggregated emission accounts complement these findings by also identifying other significant influencing factors including automobile dependence, household size, and education (Minx et al., 2013) or additional variables such as climate represented by heating- or cooling-degree days (Wiedenhofer et al., 2013). The latter two studies are of particular interest as they provide an in-depth analysis of the determining variables of urban GHG emissions using both production and consumption-based accounting approaches. In both accounting approaches, income emerges as an important determinant of urban GHG emissions.

12.3.1.2 Interdependence between drivers

The drivers outlined above vary in their ability to be influenced by local decision making. It is difficult to isolate the individual impact of any of these factors on urban energy use and GHG emissions since they are linked and often interact across different spatial and temporal scales. The interaction among the factors and the relative importance of each will vary from place to place. Moreover, many of these factors change over time and exhibit path dependence.

A legitimate concern with the IPAT decomposition approach is that the analysis assumes variable independence, thus ignoring variable interdependence and co-variance. For instance, a study of 225 cities suggests a robust negative correlation between per capita income levels and energy intensity (Grubler et al., 2012) that holds for both high-income as well as low-income cities. Income growth has the potential to drive investment in technology, changing investment in newer and more efficient technologies, as higher income segments have lower discount rates or higher tolerance to longer payback times (Hausman, 1979).

12.3.1.3 Human settlements, linkages to sectors, and policies

The major drivers discussed above affect urban GHG emissions through their influence on energy demand in buildings, transport, industry, and services. These can be mitigated through demand-side management options. As such, human settlements cut across the assessment of mitigation options in sector-specific chapters of this Assessment (see Table 12.4). The drivers also affect the demand for urban energy, water, and waste infrastructure systems, whose GHG emissions can be mitigated via technological improvements within each individual infrastructure system (e.g., methane recovery from municipal wastewater treatment plants and landfills) as well as through improved system integration (e.g., using urban waste as an energy source). Given the interdependence between drivers and across driver groups discussed above, independent sectoral assessments have limitations and risk omitting important mitigation potentials that arise from systems integration.

On one hand, governance and institutions for addressing mitigation options at the urban scale are more dispersed (see 12.6) and face a legacy of inadequately addressing a range of market failures (see Box 12.3). On the other hand, the urban scale also provides unique opportunities for policy integration between urban form and density, infrastructure planning, and demand management options. These are key, especially in the domain of urban transport systems. Lastly, governance and institutional capacity are scale and income dependent, i.e., tend to be weaker in smaller scale cities and in low income/revenue settings. In so far as the bulk of urban growth momentum is expected to unfold in small- to medium-size cities in non-Annex I countries (see Section 12.2), mitigation of GHG emissions at the scale of human settlements faces a new type of 'governance paradox' (Grubler et al., 2012): the largest opportunities for GHG emission reduction (or avoidance of unfettered emission growth) might be precisely in urban areas where governance and institutional capacities to address them are weakest (Bräutigam and Knack, 2004; Rodrik et al., 2004).

12.3.2 Weighing of drivers

This section assesses the relative importance of the GHG drivers in different urban contexts such as size, scale, and age, and examines the differences between cities in developed and developing countries.

12.3.2.1 Qualitative weighting

In the previous discussion of the respective role of different emission drivers, the emphasis was placed on the role of drivers in terms of emission growth. That perspective is complemented in this section by a consideration of the absolute level of emissions, and the issue of urban size/scale. This section also differentiates the role of emission drivers between mature versus growing human settlements.

Importance of size and scaling

Given the significance of human settlements for global resource use, an improved understanding of their size distribution and likely growth dynamics is crucial. For many physical, biological, social, and technological systems, robust quantitative regularities like stable patterns of rank distributions have been observed. Examples of such power law-scaling patterns include phenomena like the frequency of vocabulary in languages, the hierarchy of urban population sizes across the world (Zipf, 1949; Berry and Garrison, 1958; Krugman, 1996) or the allometric scaling patterns in biology, such as Kleiber's Law, which observes the astonishing constancy in the relation between body mass and metabolic rates: for living organisms across many orders of magnitude in size that metabolic rate scales to the ¾ power of the body mass (Kleiber, 1961). There is a vigorous debate in many fields, including

Table 12.4 | Examples of policies across sectors and mitigation options at the scale of human settlements.

	ENERGY SYSTEMS (Chapter 7)	**TRANSPORT** (Chapter 8)	**BUILDINGS** (Chapter 9)	**INDUSTRY** (Chapter 10)	**AFOLU** (Chapter 11)
Carbon Sinks / Sequestration					Tradable Credits, EQ Policies
Enegy Efficiency	Taxes, Credits / Permits	Subsidies for Fuel Efficiency, Standards, Targets	Taxes, Preferential Lending, Codes, Standards	Taxes, Standards, Emissions Trading, Target-setting	
Fuel / Energy Switching / Renewables	Taxes, EQ Policies, Ren Energy Portfolio Stds, Energy Security Policies	Taxes, Biofuel Incentives, Standards			Taxes, Targets, Subsidies
High-Performance / Passive Design		Bike sharing, Urban Planning	Codes, Standards, Integrated Planning, Certification		
Improved Planning / Management	Demand Response Measures	Integrated Planning	Commissioning, Audits, Education		Land Planning, Protected Areas
Materials Efficiency			Codes, Standards, Taxes, LCA, Certification	Standards	Taxes
New / Improved Technology	B & D Policies, Low Carbon Tech Targets	Subsidies for Fuel Efficiency, Bike Sharing, Real-time Information	Real-time Information		Bioenergy Targets
Recycling / Reducing Waste				Taxes, Target-setting, Education	Education
Reduced Demand / Behavior Change		Tolls, Congestion Pricing		Taxes, Subsidies, Education	Education, Standards
Urban Form / Density		Smart Growth, Urban Planning, Growth Management	Certification, Urban Planning		

Geography (Batty, 2007, 2008), Ecology (Levin, 1992; West et al., 1999; Brown et al., 2004), Architecture (Weinstock, 2011), and Physics (Carvalho and Penn, 2004) about the extent to which underlying hierarchical networks of metabolic systems or transportation networks are the ultimate causes of the size, shape and rank-distribution of entities, be they organisms or urban systems (Decker et al., 2000, 2007).

With the scale of urbanization trends currently underway, whether the relationship between city size and GHG emissions is linear (i. e., one to one, or proportional increase), super-linear (i. e., increasing returns to scale) or sub-linear (i. e., economies of scale such as efficiency gains through shared infrastructure) will be critical for understanding future urban GHG emissions. Super-linear scaling has been observed for many urban phenomena: as a city's population increases, there is a greater than one to one increase in productivity, wages, and innovation as well as crime (Bettencourt et al., 2007, 2010). If cities exhibit sub-linear scaling with respective to energy and GHG emissions, it suggests that larger cities are more efficient than smaller ones. While there are many studies of urban scaling, few studies explicitly examine city size and GHG emissions or energy use, and the limited empirical evidence on the scaling relationship is inconclusive. A study of 930 urban areas in the United States—nearly all the urban settlements—shows a barely sub-linear relationship (coefficient=0.93) between urban population size and GHG emissions (Fragkias et al., 2013).

In a study of 225 cities across both Annex I and non-Annex I countries, Grubler and Schulz (2013) find non-uniform scaling for urban final energy use, with a distribution characterized by threshold effects across an overall convex distribution (Figure 12.10). In terms of final energy use, which is an important determinant of urban GHG emissions, increasing the urban scale in terms of energy use has different implications as a function of three different urban energy scale classes. Small cities with low levels of final energy use—below 30 PJ—present the steepest growth in energy use with respect to increasing city size: a doubling of rank position tends to increase the urban energy use by a factor of 6.1. For medium-sized cities with moderate energy use (between 30 and 500 PJ final energy use per city), a doubling of city rank corresponds to an increase in energy consumption only by a factor of 1.6. For the largest urban energy users in the dataset, cities with greater than 500 PJ of final energy use per year, a doubling of urban rank is associated with an increase in urban energy use by a factor of only 0.5. This indicates considerable positive agglomeration economies of bigger cities with respect to energy use. Only four urban agglomerations of the entire sample of 225 have an annual final energy use significantly greater than one EJ: Shanghai (2 EJ), Moscow (1.6 EJ), Los Angeles (1.5 EJ), and Beijing (1.2 EJ). With urban growth anticipated to be the most rapid in the smaller cities of fewer than 500,000 inhabitants (UN DESA, 2010), the patterns observed by (Grubler and Schulz, 2013) suggest very high elasticities of energy demand growth with respect to future increases in urban population.

Mature versus growing cities

The relative impacts of the four drivers on emissions differ depending upon whether urban areas are established and mature versus growing and developing.

Economic geography and income have high impact for both mature and growing cities. Mature cities in developed countries often have high income, high consumption, and are net consumers of goods and services, with a large share of imports. These cities have high emissions, depending upon the energy supply mix. Many imported goods are produced in growing cities in developing countries. The resulting differentiation within the international division of labour and corresponding trade flows can be categorized into three types of cities: Net Producers, Trade Balanced, and Net Consumers (Chavez and Ramaswami, 2013). As a result, differences in reported urban GHG emissions are pronounced for Net Producer and Net Consumer cities, illustrating the critical importance of taking economic geography and international trade into account when considering urban GHG emission inventory frameworks. The degree to which economic growth drives GHG emissions includes the type of economic specialization of urban activities and the energy supply mix (Brownsword et al., 2005; Kennedy et al., 2012). Cities with energy intensive industries are likely to contribute higher total and per capita GHG emissions than those whose economic base is in the service sector (Dhakal, 2009, 2010).

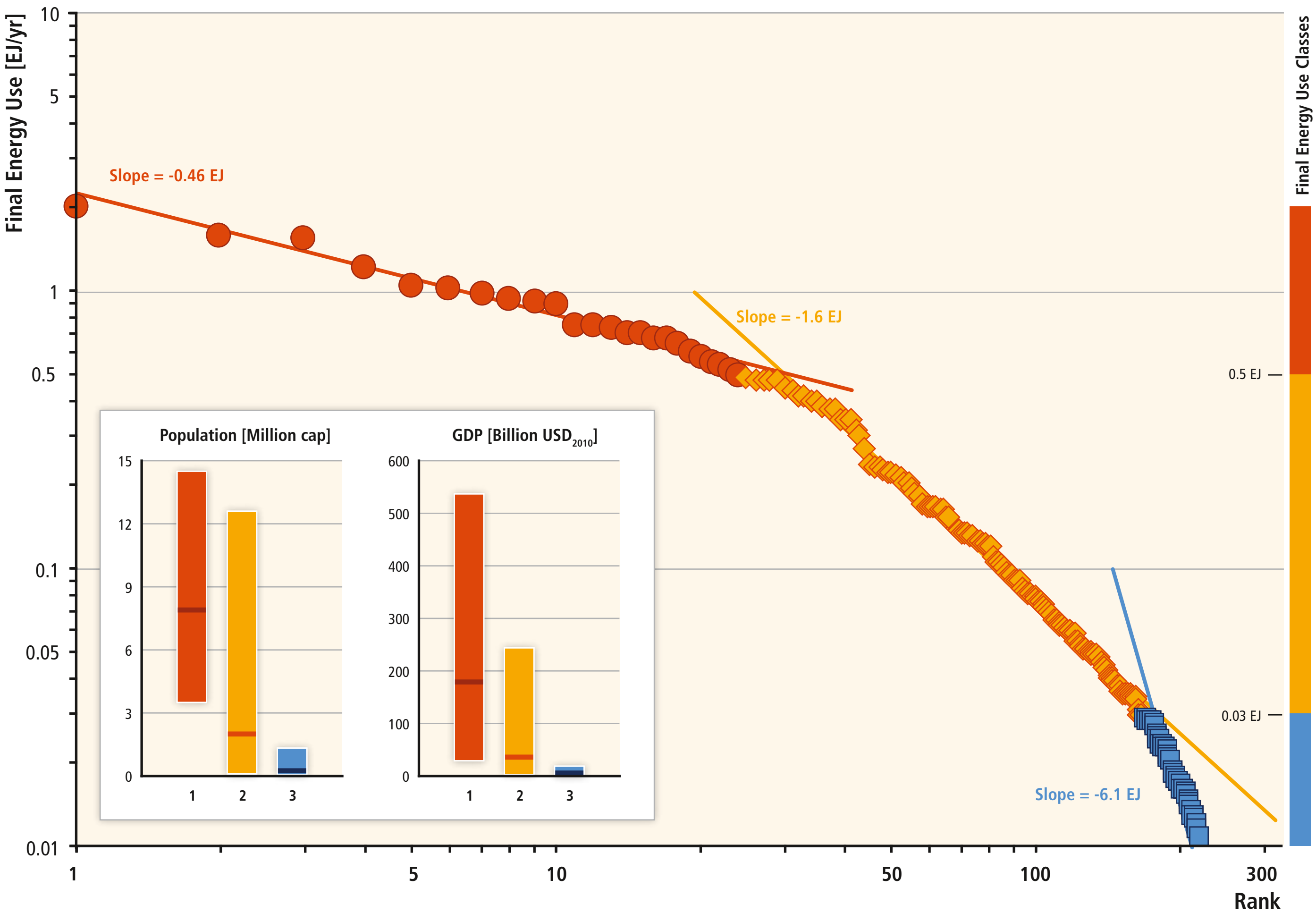

Figure 12.10 | Rank size distribution of 225 cities in terms of their final energy use (in EJ) regrouped into 3 subsamples (> 0.5EJ, 0.03–0.5EJ, < 0.03EJ) and corresponding sample statistics. The rank of a city is its position in the list of all cities sorted by size, measured in terms of final energy use. Note the different elasticities of energy use with respect to changes in urban size rank. The factors (slopes) shown in the figure detail the increase of energy use when doubling the rank for the respective groups. Source: Grubler et al. (2012) based on Grubler and Schulz (2013).

Specialization in energy-intensive sectors creates a strong correlation between economic growth and GHG emissions growth. This relationship is further strengthened if the energy supply mix is carbon intensive (Parikh and Shukla, 1995; Sugar et al., 2012).

Higher **urban incomes** are correlated with higher consumption of energy and GHG emissions (Kahn, 2009; Satterthwaite, 2009; Kennedy et al., 2009; Weisz and Steinberger, 2010; Zheng et al., 2010; Hoornweg et al., 2011; Marcotullio et al., 2012). At the household level, studies in a variety of different countries (Netherland, India, Brazil, Denmark, Japan, and Australia) have also noted positive correlations between income and energy use (Vringer and Blok, 1995; Cohen et al., 2005; Lenzen et al., 2006; Pachauri and Jiang, 2008; Sahakian and Steinberger, 2011). As such, income exerts a *high* influence on GHG emissions. The Global Energy Assessment concluded that cities in non-Annex I countries generally have much higher levels of energy use compared to the national average, in contrast to cities in Annex I countries, which generally have lower energy use per capita than national averages (see Figure 12.6 and Grubler et al., 2012). One reason for this inverse pattern is due to the significantly higher urban to rural income gradient in cities in non-Annex I countries compared to Annex I countries. That is, per capita incomes in non-Annex I cities tend to be several fold higher than rural per capita incomes, thus leading to much higher energy use and resulting emissions.

Socio-demographic drivers are of *medium* importance in rapidly growing cities, further mediated as growth rates decline, incomes increase and lifestyle choices change. Social demographic drivers are of *relatively small* importance in mature cities, where growth is slow and populations are ageing. Household size, defined as the number of persons in a household, has been steadily declining over the last fifty years. Worldwide, average household size declined from 3.6 to 2.7 between 1950 to 1990, and this trend is occurring in both developed and developing countries although at different rates (MacKellar et al., 1995; Bongaarts, 2001). Smaller household size is correlated with higher per capita emissions, whereas larger household size can take advantage of economies of scale. Evidence on the relationship between urban population size and per capita emissions is inconclusive. Scale effects have been shown for cities in Asia (Marcotullio et al., 2012) but little to no scaling effect for GHG emissions in the United States (Fragkias et al., 2013).

Infrastructure and urban form are of *medium to high* importance as drivers of emissions. In rapidly growing cities, infrastructure is of high importance where the largest share of infrastructure construction is occurring. In mature cities, urban form drivers are of high importance as they set in place patterns of transport and other energy use behaviour. In mature cities, infrastructure is of medium importance, as they are largely established, and thus refurbishing or repurposing of old infrastructures offers primary mitigation opportunities. The global expansion of infrastructure used to support urbanization is a key driver of emissions across multiple sectors. Due to the high capital costs, increasing returns, and network externalities related to infrastructures that provide fundamental services to cities, emissions associated with infrastructure systems are particularly prone to lock-in (Unruh and Carrillo-Hermosilla, 2006; Unruh, 2002, 2000). The committed emissions from energy and transportation infrastructures are especially high, with respective ranges of committed CO_2 of 127–336 and 63–132 Gt (Davis et al., 2010). For example, the GHG emissions from primary production alone for new infrastructure development for non-Annex I countries are projected to be 350 Gt CO_2 (Müller et al., 2013). For a detailed discussion see Sections 12.4 and 12.5.

Technology is a driver of *high* importance. Income and scale exert important influences on the mitigation potential for technologies. While lock-in may limit the rate of mitigation in mature cities, the opportunity exists in rapidly growing cities to leapfrog to new technologies. For mature cities, technology is important due to agglomeration externalities, Research and Development (R&D) and knowledge concentration, and access to capital that facilitate the development and early deployment of low-carbon technologies (Grubler et al., 2012). For rapidly growing cities, the importance of technology as a driver may be low for systems with high capital requirements but high for less capital-intensive (e.g., some demand-side efficiency or distributed supply) systems. The influence of all drivers depends upon governance, institutions, and finance (Section 12.6).

12.3.2.2 Relative weighting of drivers for sectoral mitigation options

Drivers affect GHG emissions via influence on energy demand (including demand management) in buildings (households and services), transport, and industry, as well as on energy supply, water, and waste systems. Over time, structural transitions change both the shares of emissions by sectors—with industrial, then services and transport shares of final energy increasing with development (Schäfer, 2005; Hofman, 2007)—as well as the relative importance of drivers. Economic geography has a large influence on emissions from the industry and service sectors (Ramaswami, 2013) plus international transport (bunkers fuels). These influences are particularly pronounced in urban agglomerations with very porous economies. For example Schulz (2010) analyzed Singapore and found that GHG emission embodied in the imports and exports of the city are five to six times larger than the emissions from the direct primary energy use of the city's population. Similarly, Grubler et al. (2012) examined New York and London, which are global transportation hubs for international air travel and maritime commerce. As a result, international aviation and maritime fuels (bunker fuels) make up about one-third of the total direct energy use of these cities, even if associated emissions are often excluded in inventories, following a practice also used in national GHG emission inventories (Macknick, 2011).

Income has a large influence on direct emissions due to energy use in buildings by influencing the floor area of residential dwellings, the amount of commercial floor space and services purchased, and buildings' energy intensities (see Table 9.2), and also on transport, including increasing vehicle ownership, activity, energy intensity and infrastructure (see Chapter 8.2). Income also has large indirect effects on emissions, for example influencing the number of products purchased (e.g., increasing sales of electronics) (see Chapter 10.2) and their energy intensity (e.g., consumables like food) (see Chapter 11.4), perhaps produced by the industrial and services sectors somewhere else, and transported to the consumers (increasing freight transport activity).

Social demographic drivers have a large effect on emissions, particularly in buildings (e.g., number of households, persons per household, see Chapter 9.2.2) and transport sectors (see Chapter 8.2.1). Infrastructure and urban form have a large impact on transport (Chapter 8.4) and medium impact on energy systems (grid layout and economics) (see Chapter 7.6). Technology has a large impact in all sectors. Income interacts with technology, increasing both innovative (e.g., R&D) and adoptive capacity (purchases and replacement rate of products, which in turn can increase energy efficiency). In demand sectors, mitigation from efficiency may be mediated by behaviours impacting consumption (e.g., more efficient yet larger televisions or refrigerators, or more efficient but larger or more powerful vehicles). See the sectoral Chapters 7–11 for further discussion of these issues.

12.3.2.3 Quantitative modelling to determine driver weights

An inherent difficulty in any assessment of emission drivers at the urban scale is that both mitigation options as well as policy levers are constrained by the legacy of past decisions as reflected in existing urban spatial structures and infrastructures, the built environment, and economic structures. Modelling studies that simulate alternative development strategies, even the entire evolution of a human settlement, or that explore the effects of policy integration across sectors can shed additional light on the relative weight of drivers as less constrained or entirely unconstrained by the existing status quo or by more limited sectoral assessment perspectives.

For instance, large-scale urban simulation models have been used to study the joint effects of policy integration such as pursuing smart-growth planning that restricts urban sprawl with market-based pricing mechanisms. One study of metropolitan regions in OECD countries concludes that policies such as those that encourage higher urban densities and road tolls such as congestion charges have lower stabilization costs than economy-wide approaches such as a carbon tax (Crassous et al., 2006; OECD, 2010a) . Models suggest that adding substantially upgraded urban services to the mix of bundled strategies yields even greater benefits. A meta-analysis of 14 urban simulations of scenarios with varying degrees of urban containment, road pricing, and transit services upgrades forecasted median transportation demand volumes (VKT, vehicle-kilometre-travelled) reductions of 3.9 % within 10 years, rising to 15.8 % declines over 40 years (Rodier, 2009). Estimates from a review of published studies of U.S. cities forecasted a 5 % to 12 % VKT reduction from doubling residential densities and as high as 25 % reductions when combined with other strategies, including road pricing (National Research Council, 2009a). GHG emissions were estimated to decline 11 % from the most aggressive combination of densification and market-based pricing. The combination of introducing VKT charges, upgrading transit, and more compact development from simulation studies in Helsinki, Dortmund, Edinburgh, and Sacramento yielded simulation-model estimates of 14.5 % reductions in VKT within 10 years and 24.1 % declines over 40 years (Rodier, 2009).

A more holistic modelling strategy with a much larger system boundary was followed with the Sincity model, a combined engineering-type systems-optimization model that integrates agent-based and spatially explicit modelling of urban form and density with transport and energy infrastructure planning to simulate the entire evolution of a 'synthetic' city (Keirstead and Shah, 2013; Steinberger and Weisz, 2013) or of large scale new urban developments (Hao et al., 2011). Using an illustrative European city of 20,000 inhabitants and with a service dominated economy (i.e., holding the economic geography and income variables constant), alternative urban designs were explored to separate out the various effects of different policy measures in determining urban energy use. The results suggest that compared to a baseline (sprawl city with current practice technologies), improvements by a factor of two each were possible by either a combination of energy efficiency measures for the urban building stock and the vehicle fleet, versus modifying urban form and density. Conversely energy systems optimization through cogeneration and distributed energy systems were found to yield improvements of between 15–30 % (Keirstead and Shah, 2013; Steinberger and Weisz, 2013). The largest improvements of a factor of three were found through an integration of policy measures across all domains.

12.3.2.4 Conclusions on drivers of GHG emissions at the urban scale

Perhaps the most significant conclusion emerging from Section 12.2 and above discussion of urban GHG emission drivers is the realization that the traditional distinction between Annex I and non-Annex I becomes increasingly blurred at the urban scale. There is an increasing number of cities, particularly in the rapidly growing economies of Asia, where per capita resource use, energy consumption, and associated GHG emissions are not different from the ones in developed economies. A second important conclusion is that economic geography and income by themselves are often such important drivers of urban GHG emissions that they dwarf the effects of technology choices or of place-based policy variables of urban form and infrastructures. However, the latter policy options are those for which urban-scale decision making can make the *largest* impact on GHG emissions.

A more detailed discussion on the different leverage effects of urban scale policy options using the example of urban energy use is provided in the Global Energy Assessment, Chapter 18 (Grubler et al., 2012), which can be combined with above assessment on the relative weight of emission drivers to derive a categorization of urban policy intervention levels as a function of potential impacts on emissions as well as the degree to which policy interventions can be implemented by urban-scale decision making processes by local governments, firms, and individuals (Figure 12.11).

The categorization in Figure 12.11 is necessarily stylized. It will vary across local contexts, but it helps to disentangle the impacts of macro- from micro-drivers. For instance, urban GHG emission levels will be strongly influenced by differences in urban function, such as the role of a city as a manufacturing centre for international markets, versus a city providing service functions to its regional or national hinterlands. Conversely, the emissions impact from smaller-scale decisions such as increasing local and urban-scale renewable energy flows—which has been assessed to be very limited, particularly for larger and more dense cities (Grubler et al., 2012)—is much smaller. The largest leverage on urban GHG emissions from urban scale decision making thus is at the 'meso' scale level of the energy/emissions and urban policy hierarchy: improving the efficiency of equipment used in a city, improving and integrating urban infrastructure, and shaping urban form towards low carbon pathways. Pursuing multiple strategies simultaneously at this scale may be most effective at reducing the urban-related emissions. This conclusion echoes concepts such as integrated community-energy-management strategies (Jaccard et al., 1997).

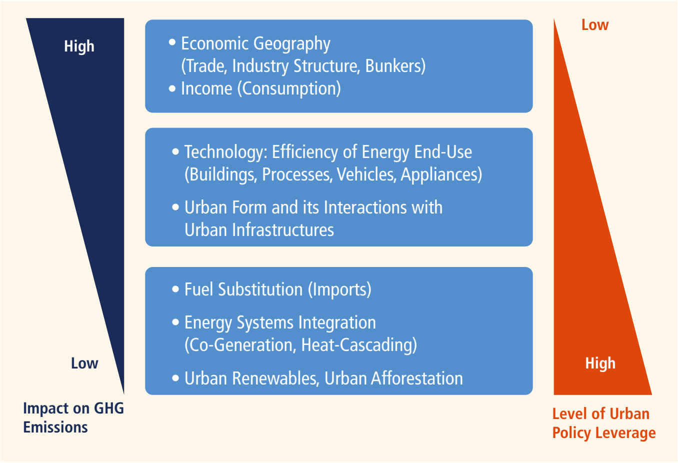

Figure 12.11 | Stylized hierarchy of drivers of urban GHG emissions and policy leverages by urban scale decision making. Cities have little control over some of the most important drivers of GHG emissions and have large control over comparatively smaller drivers of emissions. Source: Synthesized from Jaccard et al. (1997), Grubler et al. (2012) and this assessment.

12.3.3 Motivation for assessment of spatial planning, infrastructure, and urban form drivers

Urban form and infrastructure significantly affect direct (operational) and indirect (embodied) GHG emissions, and are strongly linked to the throughput of materials and energy in a city, the waste that it generates, and system efficiencies of a city. Mitigation options vary by city type and development levels. The options available for rapidly developing cities include shaping their urbanization and infrastructure development trajectories. For mature, built-up cities, mitigation options lie in urban regeneration (compact, mixed-use development that shortens journeys, promotes transit/walking/cycling, adaptive reuse of buildings) and rehabilitation/conversion to energy-efficient building designs. Urban form and infrastructure are discussed in detail in Section 12.4. A combination of integrated sustainable infrastructure (Section 12.4), spatial planning (Section 12.5), and market-based and regulatory instruments (Section 12.6) can increase efficiencies and reduce GHG emissions in already built-up cities and direct urban and infrastructure development to reduce the growth of GHG emissions in rapidly expanding cities in developing countries.

12.4 Urban form and infrastructure

Urban form and structure are the patterns and spatial arrangements of land use, transportation systems, and urban design elements, including the physical urban extent, layout of streets and buildings, as well as the internal configuration of settlements (Lynch, 1981; Handy, 1996). Infrastructure comprises services and built-up structures that support the functions and operations of cities, including transport infrastructure, water supply systems, sanitation and wastewater management, solid waste management, drainage and flood protection, telecommunications, and power generation and distribution. There is a strong connection between infrastructure and urban form (Kelly, 1993; Guy and Marvin, 1996), but the causal order is not fully resolved (Handy, 2005). Transport, energy, and water infrastructure are powerful instruments in shaping where urban development occurs and in what forms (Hall, 1993; Moss, 2003; Muller, 2004). The absence of basic infrastructure often—but not always—inhibits urban development.

This section assesses the literature on urban form and infrastructure drivers of GHG emissions, details what data exist, the ranges, effects on emissions, and their interplay with the drivers discussed in Section 12.3. Based on this assessment, conclusions are drawn on the diversity of favourable urban forms and infrastructure highlighting caveats and conflicting goals. This literature is dominated by case studies of cities in developed countries. The literature on conditions in developing country cities, especially for large parts of Africa, is

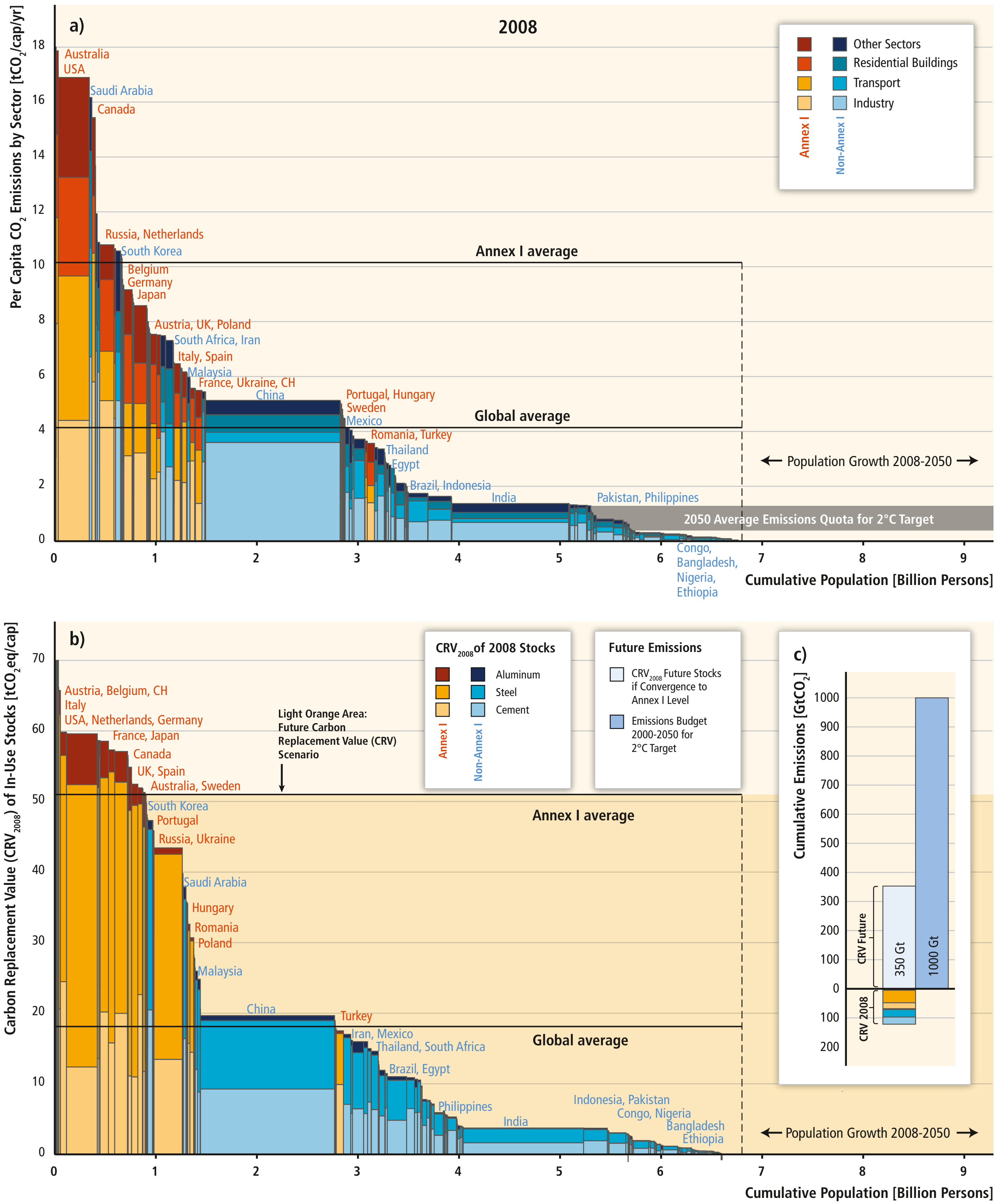

Figure 12.12 | (a) Total fuel-related per-capita CO_2 emissions in 2008 by country (red/orange/yellow and blue bars) compared to the global per-capita emission level in 2050 to reach the 2 °C target with a 50–75 % probability; (b) Carbon Replacement Value (CRV_{2008}) per capita of existing stocks by country (red/orange and blue) and as yet unbuilt stocks if developing countries converge on the current average Annex I level (light yellow background area); (c) comparison with emission budget for the period 2000–2050 to reach the 2 °C target with a 75 % probability. Of this emission budget (1000 Gt CO_2), approximately 420 GtCO2 was already emitted during the period from 2000 to 2011.Source: Müller et al. (2013).

particularly limited. This assessment reflects this limitation in the literature.

12.4.1 Infrastructure

Infrastructure affects GHG emissions primarily during three phases in its lifecycle: 1) construction, 2) use/operation, and 3) end-of-life. The production of infrastructure materials such as concrete and metals is energy and carbon intensive (Cole, 1998; Horvath, 2004). For example, the manufacturing of steel and cement, two of the most common infrastructure materials, contributed to nearly 9 % and 7 %, respectively, of global carbon emissions in 2006 (Allwood et al., 2010). Globally, the carbon emissions embodied in built-up infrastructure as of 2008 was estimated to be 122 (–20/+15) Gt CO_2 (Müller et al., 2013). Much of the research on the mitigation potential of infrastructure focuses on the use/operation phase and increasing the efficiency of the technology. Estimating emissions from urban infrastructure such as electricity grids and transportation networks is challenging because they often extend beyond a city's administrative boundaries (Ramaswami et al., 2012b) (see Section 12.2 for detailed discussion). Several studies show that the trans-boundary emissions of infrastructure can be as large as or even larger than the direct GHG emissions within city boundaries (Ramaswami et al., 2008; Kennedy et al., 2009; Hillman and Ramaswami, 2010; Chavez and Ramaswami, 2013). Thus, a full accounting of GHG emissions from urban infrastructure would need to include both primary and embodied energy of infrastructure materials, as well as energy from the use/operation phase and end-of-life, including reuse and recycling.

Rates of infrastructure construction in mature versus rapidly developing cities lead to fundamentally different impacts on GHG emissions. Infrastructure growth is hypothesized to follow an S-shaped curve starting with an early development phase, continuing with a rapid growth and expansion phase, and ending with a saturation phase (Ausubel and Herman, 1988). The build-up of infrastructure that occurs during early phases of urbanization is particularly emissions intensive. Currently, the average per capita emissions embodied in the infrastructure of industrialized countries is 53 (±6) t CO_2 (see Figure 12.12) which is more than five times larger than that in developing countries (10 (±1) t CO_2) (Müller et al., 2013). While there have been energy efficiency improvements in the industrial sector, especially steel and cement production, the scale and pace of urbanization can outstrip efficiency gains and lead to continued growth in emissions (Levine and Aden, 2008; Güneralp and Seto, 2012). China accounts for roughly 37 % of the global emissions commitments in part due to its large-scale urbanization–the United States adds 15 %; Europe 15 %, and Japan 4 %, together representing 71 % of total global emissions commitments by 2060 (Davis et al., 2010).

Emissions related to infrastructure growth are therefore tied to existing urban energy systems, investment decisions, and regulatory policies that shape the process of urban growth. The effects of these decisions are difficult to reverse: high fixed costs, increasing returns, and network externalities make emissions intensive infrastructure systems particularly prone to lock-in (Unruh and Carrillo-Hermosilla, 2006; Unruh, 2002, 2000). Furthermore, the long lifespan of infrastructure affects the turnover rate of the capital stock, which can limit the speed at which emissions in the use/operation phase can be reduced (Jaccard and Rivers, 2007).

The build-up of infrastructure in developing countries as part of the massive urbanization currently underway will result in significant future emissions. Under one scenario, if the global population increases to 9.3 billion by 2050 and developing countries expand their built environment and infrastructure to the current global average levels using available technology today, the production of infrastructure materials alone would generate approximately 470 Gt of CO_2 emissions (see Figure 12.12). This is in addition to the "committed emissions" from existing energy and transportation infrastructure, estimated to be in the range of 282 to 701 Gt of CO_2 between 2010 and 2060 (Davis et al., 2010).

The links between infrastructure and urban form are well established, especially among transportation infrastructure provision, travel demand, and VKT. In developing countries in particular, the growth of transport infrastructure and resulting urban forms are playing important roles in affecting long-run emissions trajectories (see Chapter 8). The committed emissions from existing energy and transportation infrastructure are high, with ranges of CO_2 of 127–336 and 63–132 Gt, respectively (see Figure 12.13 and Davis et al., 2010). Transport infrastructure affects travel demand and emissions in the short-run by reducing the time cost of travel, and in the long-run by shaping land-use patterns (Vickrey, 1969; Downs, 2004). Development of transport infrastructure tends to promote 'sprawl', characterized by low-density, auto-dependent, and separated land uses (Brueckner, 2000; Ewing et al., 2003). Consistent evidence of short-run effects show that the demand elasticities range between 0.1–0.2. That is, a doubling of transport infrastructure capacity increases VKT by 10–20 % in the short-run (Goodwin, 1996; Hymel et al., 2010). Other studies suggest larger short-run elasticities of 0.59 (Cervero and Hansen, 2002) and a range of 0.3–0.9 (Noland and Lem, 2002). Differences in short-run elasticities reflect fundamental differences in the methodologies underlying the studies (see Chapter 15.4 on policy evaluation). In the long-run, the elasticities of VKT with respect to road capacity are likely to be in the range 0.8–1.0 as land-use patterns adjust (Hansen and Huang, 1997; Noland, 2001; Duranton and Turner, 2011). While the links between transport infrastructure, urban form, and VKT are well studied, there are few studies that extend the analysis to estimate emissions due to transport-induced increases in VKT. One exception is a study that concludes that freezing United States highway capacity at 1996 levels would reduce emissions by 43 Mt C/yr by 2012, compared to continuing construction at historical rates (Noland, 2001).

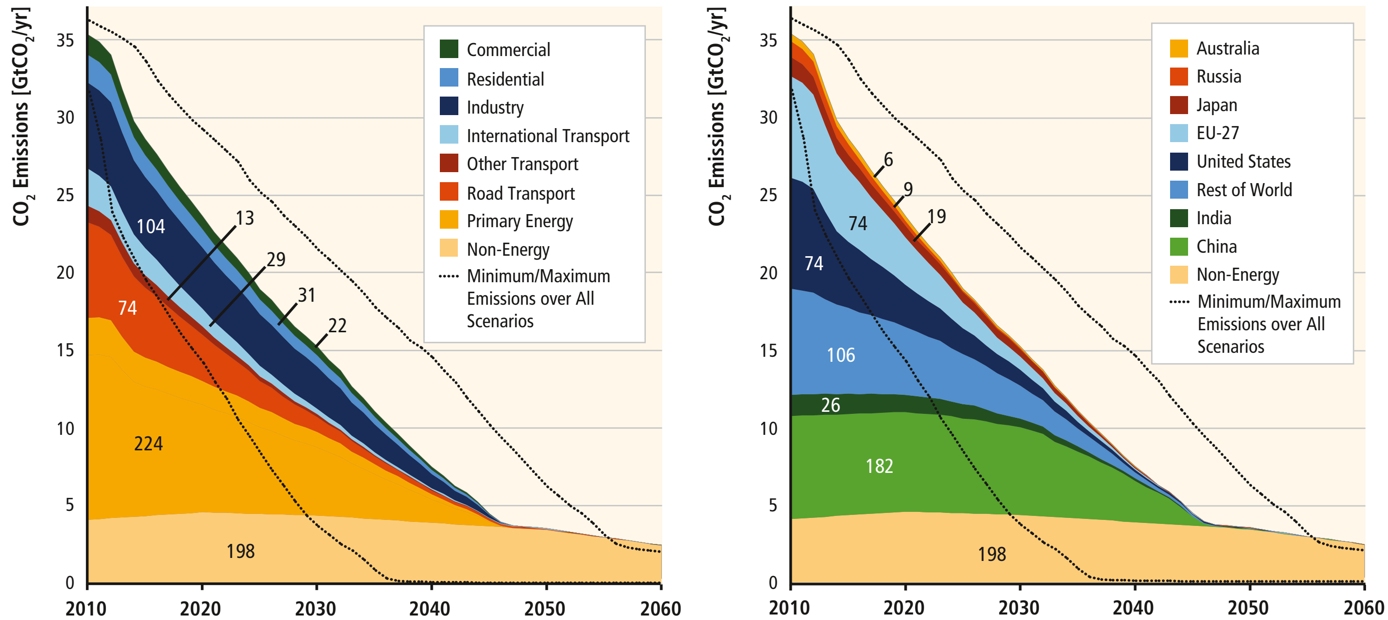

Figure 12.13 | Scenario of CO_2 emissions from existing energy and transportation infrastructure by industry sector (left) and country/region (right). Numbers in panels show the cumulated CO_2 emissions from 2010 to 2060 in Gt. Source: Davis et al. (2010).

12.4.2 Urban form

Urban form can be characterized using four key metrics: density, land use mix, connectivity, and accessibility. These dimensions are not independent from one another. Rather, they measure different aspects of urban form and structure, and each dimension impacts greenhouse gas emissions differently (Figure 12.14). The urban form drivers of GHG emissions do not work in isolation.

Impacts of changes in urban form on travel behaviour are commonly estimated using elasticities, which measure the effect of a 1 % change in an urban form metric on the percent change in vehicle kilometres travelled (see Chapter 15.4 on policy evaluation). This allows for a comparison of magnitudes across different factors and metrics. A large share of the existing evidence is limited to studies of North American cities. Moreover, much of this work is focused on larger cities (for an extensive discussion of methodological considerations see National Research Council, 2009b).

12.4.2.1 Density

Urban density is the measure of an urban unit of interest (e.g., population, employment, and housing) per area unit (e.g., block, neighbourhood, city, metro area, and nation) (Figure 12.14). There are many measures of density, and three common measures are population density (i.e., population per unit area), built-up area density (i.e., buildings or urban land cover per unit area), and employment density (i.e., jobs per unit area) (for a comprehensive review on density measures see Boyko and Cooper, 2011). Urban density affects GHG emissions in two primary ways. First, separated and low densities of employment, commerce, and housing increase the average travel distances for both work and shopping trips (Frank and Pivo, 1994; Cervero and Kockelman, 1997; Ewing and Cervero, 2001; Brownstone and Golob, 2009). These longer travel distances translate into higher VKT and emissions. Conversely, higher population densities, especially when co-located with high employment densities are strongly correlated with lower GHG emissions (Frank and Pivo, 1994; Kenworthy and Laube, 1999; Glaeser and Kahn, 2010; Clark, 2013). In the United States, households located in relatively low density areas (0–19 households/km²) produce twice as much GHG emissions as households located in relatively high density areas (1,900–3,900 households/km²) (U.S. Department of Transportation, 2009).

Second, low densities make it difficult to switch over to less energy intensive and alternative modes of transportation such as public transportation, walking, and cycling because the transit demand is both too dispersed and too low (Bunting et al., 2002; Saelens et al., 2003; Forsyth et al., 2007). In contrast, higher population densities at places of origin (e.g., home) and destination (e.g., work, shopping) concentrate demand that is necessary for mass transit alternatives. The density thresholds required for successful transit are not absolute, and vary by type of transit (e.g., bus, light rail, metro), their frequency, and characteristics specific to each city. One of the most comprehensive studies of density and emission estimates that a doubling of residential densities in the United States can reduce VKT by 5–12 % in the short run, and if coupled with mixed land use, higher employment densities, and improvements in transit, can reduce VKT as much as 25 % over the long run (National Research Council, 2009a). Urban density is thus a necessary—but not a sufficient—condition for low-carbon cities.

Comparable and consistent estimates of urban densities and changes in urban densities are difficult to obtain in part because of different methodologies to calculate density. However, multiple studies using multiple lines of evidence including satellite data (Deng et al., 2008;

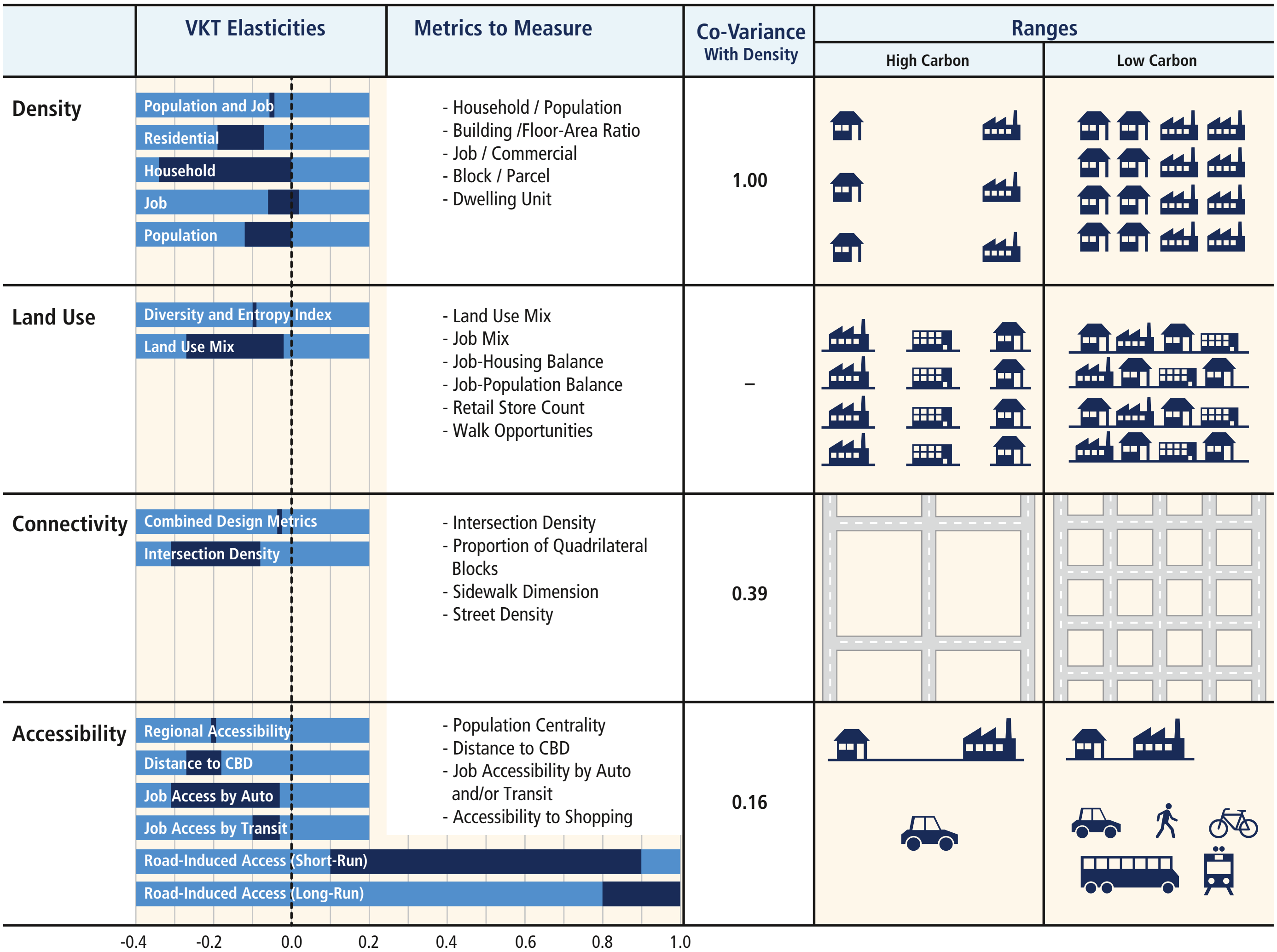

Figure 12.14 | Four key aspects of urban form and structure (density, land use mix, connectivity, and accessibility), their Vehicle Kilometre Travelled (VKT) elasticities, commonly used metrics, and stylized graphics. The dark blue row segments under the VKT elasticities column provide the range of elasticities for the studies included.

Sources: Numbers from Ewing and Cervero (2010), National Research Council (2009a), and Salon et al (2012) are based on the following original sources: **Density** (Schimek, 1996; Kockelman, 1997; Sun et al., 1998; Pickrell and Schimek, 1999; Ewing and Cervero, 2001; Holtzclaw et al., 2002; Bhatia, 2004; Boarnet et al., 2003; Bento et al., 2005; Zhou and Kockelman, 2008; Fang, 2008; Kuzmyak, 2009a; Brownstone and Golob, 2009; Ewing et al., 2009; Greenwald, 2009; Heres-Del-Valle and Niemeier, 2011); **Land Use** (Kockelman, 1997; Sun et al., 1998; Pushkar et al., 2000; Ewing and Cervero, 2001, 2010; Chapman and Frank, 2007; Frank and Engelke, 2005; Kuzmyak et al., 2006; Vance and Hedel, 2007; Brownstone and Golob, 2009; Kuzmyak, 2009b; Frank et al., 2009); **Connectivity** (Ewing and Cervero, 2001; Boarnet et al., 2003; Chapman and Frank, 2007; Frank and Engelke, 2005; Ewing et al., 2009; Greenwald, 2009; Frank et al., 2009); **Accessibility** (Goodwin, 1996; Ewing et al., 1996, 2009; Kockelman, 1997; Cervero and Kockelman, 1997; Sun et al., 1998; Pushkar et al., 2000; Ewing and Cervero, 2001, 2010; Boarnet et al., 2003; Næss, 2005; Cervero and Duncan, 2006; Zegras, 2007; Greenwald, 2009; Kuzmyak, 2009a, b; Frank et al., 2009; Zegras, 2010; Hymel et al., 2010).

Angel et al., 2010, 2011; Seto et al., 2011) and economic and census data (Burchfield et al., 2006) show that both population and built-up densities are declining across all regions around the world (see Section 12.2 for details). Although there is substantial variation in magnitudes and rates of density decline across income groups, city sizes, and regions, the overarching trend is a persistent decline in densities (Angel et al., 2010). The dominant trend is declining density, however there are some exceptions. Analyses of 100 large cities worldwide using a microwave scatterometer show significant vertical expansion of built-up areas in East Asian cities, notably those in China (see Figure 12.15 and Frolking et al., 2013).

A common misconception about density is that it can only be achieved through high-rise buildings configured in close proximity. However, the same level of density can be achieved through multiple land use configurations (Figure 12.16). Population density is strongly correlated with built density, but high population density does not necessarily imply high-rise buildings (Cheng, 2009; Salat, 2011).

Medium-rise (less than seven floors) urban areas with a high building footprint ratio can have a higher built density than high-rise urban areas with a low building footprint. These different configurations of high-density development involve important energy tradeoffs. Often, high-rise,

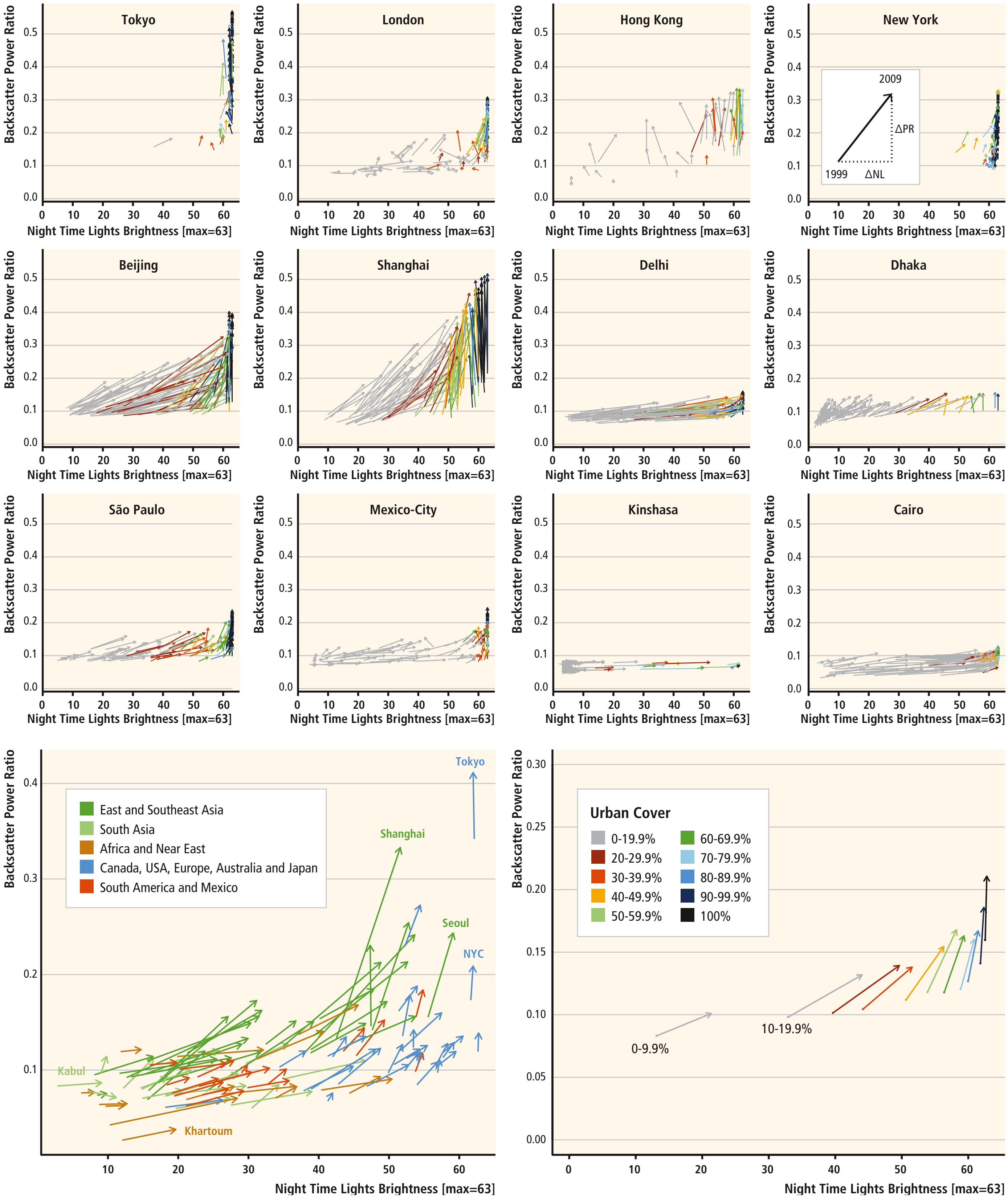

Figure 12.15 | Changes in Urban Structure, 1999–2009 using backscatter and night time lights. The top 12 panels show changes in vertical structure of major urban areas as characterized by backscatter power ratio (PR) and horizontal growth as measured by night time lights brightness (NL) for 12 large cities. Coloured arrows represent non-water, 0.05° cells in an 11x11 grid around each city's centre; tail and head are at 1999 and 2009 coordinates of cell PR and NL, respectively (see inset in top right panel). Arrow colour corresponds to percent urban cover circa 2001 (see legend in bottom right panel). Bottom right panel shows mean change of a total of 100 cities mapping into the respective urban cover categories. Bottom left panel shows change for 100 cities colour coded by world regions. Source: Frolking et al. (2013).

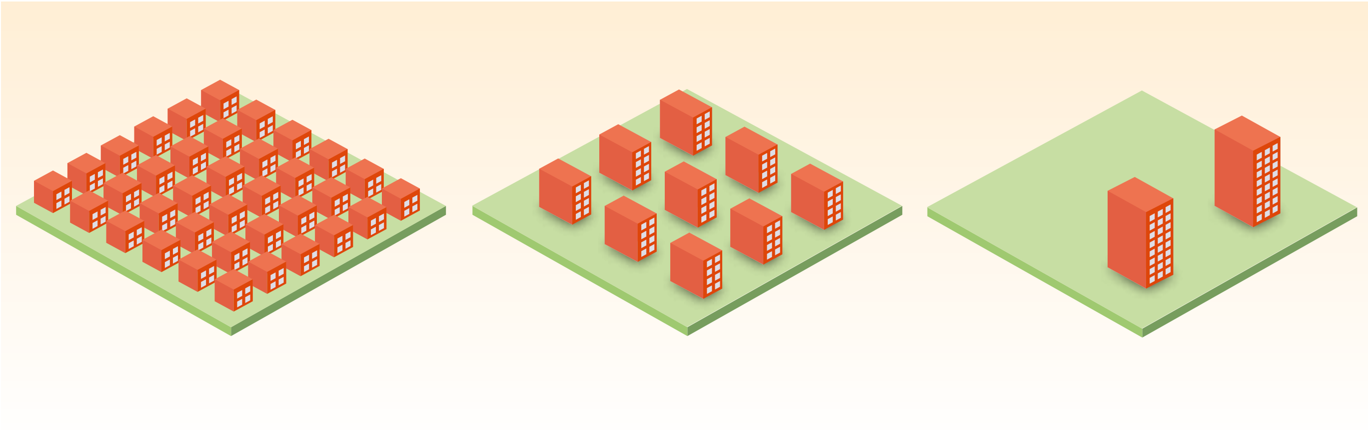

Figure 12.16 | Same densities in three different layouts: low-rise single-story homes (left); multi-story medium-rise (middle); high-rise towers (right). Adapted from Cheng (2009).

high-density urban areas involve a tradeoff between building height and spacing between buildings—higher buildings have to be more spaced out to allow light penetration. High-rise buildings imply higher energy costs in terms of vertical transport and also in heating, cooling, and lighting due to low passive volume ratios (Ratti et al., 2005; Salat, 2009). Medium-rise, high-density urban areas can achieve similar levels of density as high-rise, high density developments but require less materials and embodied energy (Picken and Ilozor, 2003; Blackman and Picken, 2010). Their building operating energy levels are lower due to high passive volume ratio (Ratti et al., 2005; Salat, 2009). Single storey, free-standing housing units are more GHG emissions intensive than multi-family, semi-detached buildings (Myors et al., 2005; Perkins et al., 2009). Thus, while the effect of building type on energy use may be relatively small, the combination of dwelling type, design, location, and orientation together can generate significant energy savings (Rickwood et al., 2008).

12.4.2.2 Land use mix

Land use mix refers to the diversity and integration of land uses (e.g., residential, park, commercial) at a given scale (Figure 12.17). As with density, there are multiple measures of land use mix, including: (1) the ratio of jobs to residents; (2) the variety and mixture of amenities and activities; and (3) the relative proportion of retail and housing. Historically, the separation of land uses, especially of residential from other uses, was motivated by the noxious uses and pollution of the industrial city. However, as cities transition from industrial to service economies, resulting in a simultaneous reduction in air pollution and other nuisances, the rationale for such separation of land uses diminishes.

In general, when land uses are separated, the distance between origin (e.g., homes) and destination (e.g., work or shopping) will be longer (Kockelman, 1997). Hence, diverse and mixed land uses can reduce travel distances and enable both walking and the use of non-motorized modes of travel (Kockelman, 1997; Permana et al., 2008), thereby reducing aggregate amounts of vehicular movement and associated greenhouse gas emissions (Lipper et al., 2010). Several meta-analyses estimate the elasticity of land use mix related VKT from –0.02 to –0.10 (Ewing and Cervero, 2010; Salon et al., 2012) while simultaneously increasing walking. The average elasticity between walking and diversity of land uses is reported to be between 0.15–0.25 (Ewing and Cervero, 2010). The effects of mixed land use on VKT and GHG emissions can applied at three spatial scales; city-regional, neighbourhood, and block.

At the city-scale, a high degree of land use mix can result in significant reductions in VKT by increasing the proximity of housing to office developments, business districts, shops, and malls (Cervero and Duncan, 2006). In service-economy cities with effective air pollution controls, mixed land use can also have a beneficial impact on citizen health and well-being by enabling walking and cycling (Saelens et al., 2003; Heath et al., 2006; Sallis et al., 2009). For cities with lower mixed land use, such as often found in North American cities and in many new urban develop-

Figure 12.17 | Three different land use mixes (Manaugh and Kreider, 2013).

ments in Asia, large residential developments are separated from jobs or retail centres by long distances. A number of studies of such single-use zoning show strong tendencies for residents to travel longer overall distances and to carry out a higher proportion of their travel in private vehicles than residents who live in mixed land use areas in cities (Mogridge, 1985; Fouchier, 1998; Næss, 2005; Zhou and Kockelman, 2008).

Mixed use at the neighbourhood scale refers to a 'smart' mix of residential buildings, offices, shops, and urban amenities (Bourdic et al., 2012). Similar to the city-scale case, such mixed uses can decrease average travel distances (McCormack et al., 2001). However, on the neighbourhood scale, the reduced travel is primarily related to non-work trips, e.g., for shopping, services, and leisure. Research on US cities indicates that the presence of shops and workplaces near residential areas is associated with relatively low vehicle ownership rates (Cervero and Duncan, 2006), and can have a positive impact on transportation patterns (Ewing and Cervero, 2010). The impacts of mixed use on non-motorized commuting such as cycling and walking and the presence or absence of neighbourhood shops can be even more important than urban density (Cervero, 1996).

At the block and building scale, mixed use allows space for small-scale businesses, offices, workshops, and studios that are intermixed with housing and live-work spaces. Areas with a high mix of land uses encourages a mix of residential and retail activity and thus increases the area's vitality, aesthetic interest, and neighbourhood (Hoppenbrouwer and Louw, 2005).

12.4.2.3 Connectivity

Connectivity refers to street density and design. Common measures of connectivity include intersection density or proportion, block size, or intersections per road kilometre (Cervero and Kockelman, 1997; Pushkar et al., 2000; Chapman and Frank, 2007; Lee and Moudon, 2006; Fan, 2007). Where street connectivity is high—characterized by finer grain systems with smaller blocks that allow frequent changes in direction—there is typically a positive correlation with walking and thereby lower GHG emissions. Two main reasons for this are that distances tend to be shorter and the system of small blocks promotes convenience and walking (Gehl, 2010).

Improving connectivity in areas where it is low (and thus associated with higher GHG emissions) requires varying amounts of street reconstruction. Many street features, such as street size, four-way intersections or intersection design, sidewalk width, the number of traffic lanes (or street width) and street medians are designed at the time of the construction of the city. As the infrastructure already exists, increasing connectivity requires investment either to redevelop the site or to retrofit it to facilitate walking and biking. In larger redevelopment projects, street patterns may be redesigned for smaller blocks with high connectivity. Alternatively, retrofitting often involves widening sidewalks, constructing medians, and adding bike lanes, as well as reducing traffic speeds, improving traffic signals, and providing parking for bikes (McCann and Rynne, 2010). Other features, such as street furniture (e.g., benches, transit stops, and shelters), street trees, and traffic signals, can be added after the initial design without much disruption or large costs.

Systematic reviews show that transport network connectivity has a larger impact on VKT than density or land use mix, between −0.06 and −0.26 (Ewing and Cervero, 2010; Salon et al., 2012). For North American cities, the elasticity of walking with respect to sidewalk coverage or length is between 0.09 to 0.27 (Salon et al., 2012). There are typically higher elasticities in other OECD countries than in the United States.

12.4.2.4 Accessibility

Accessibility can be defined as access to jobs, housing, services, shopping, and in general, to people and places in cities (Hansen, 1959; Ingram, 1971; Wachs and Kumagai, 1973). It can be viewed as a combination of proximity and travel time, and is closely related to land use mix. Common measures of accessibility include population centrality, job accessibility by auto or transit, distance to the city centre or central business district (CBD), and retail accessibility. Meta-analyses show that VKT reduction is most strongly related to high accessibility to job destinations (Ewing and Cervero, 2001, 2010). Highly accessible communities (e.g., compact cities in Europe such as Copenhagen) are typically characterized by low daily commuting distances and travel times, enabled by multiple modes of transportation (Næss, 2006). Measures to increase accessibility that are accompanied by innovative technologies and alternative energies can reduce VKT and associated GHG emissions in the cities of both developed and developing countries (Salomon and Mokhtarian, 1998; Axhausen, 2008; Hankey and Marshall, 2010; Banister, 2011). However, it should be noted that at least one study has shown that in cities where motorization is already mature, changing accessibility no longer influences automobile-dependent lifestyles and travel behaviours (Kitamura et al., 2001).

Countries and regions undergoing early stages of urbanization may therefore have a unique potential to influence accessibility, particularly in cases where income levels, infrastructure, and motorization trends are rapidly changing (Kumar, 2004; Chen et al., 2008; Perkins et al., 2009; Reilly et al., 2009; Zegras, 2010; Hou and Li, 2011; Adeyinka, 2013). In Shanghai, China, new transportation projects have influenced job accessibility and have thereby reduced commute times (Cervero and Day, 2008). In Chennai, India, differences in accessibility to the city centre between low-income communities have been shown to strongly affect transport mode choice and trip frequency (Srinivasan and Rogers, 2005). In the rapidly motorizing city of Santiago de Chile, proximity to the central business district as well as metro stations has a relatively strong association with VKT (Zegras, 2010). The typical elasticity between job accessibility and VKT across

North American cities ranges from −0.10 to −0.30 (Ewing and Cervero, 2010; Salon et al., 2012).

12.4.2.5 Effects of combined options

While individual measures of urban form have relatively small effects on vehicle miles travelled, they become more effective when combined. For example, there is consistent evidence that the combination of co-location of increased population and job densities, substantial investments in public transit, higher mix of land uses, and transportation or mobility demand management strategies can reduce VKT and travel-related carbon emissions (National Research Council, 2009a; Ewing and Cervero, 2010; Salon et al., 2012). The spatial concentration of population, coupled with jobs-housing balance, have a significant impact VKT by households. At the same time, urban form and the density of transportation networks also affect VKT (Bento et al., 2005). The elasticity of VKT with respect to each of these factors is relatively small, between 0.10 and 0.20 in absolute value. However, changing several measures of form simultaneously can reduce annual VKT significantly. Moving the sample households from a city with the characteristics of a low-density, automobile-centric city to a city with high public transit, connectivity, and mixed land use reduced annual VKT by 25 %. While in practice such change is highly unlikely in a mature city, it may be more relevant when considering cities at earlier stages of development.

A growing body of literature shows that traditional neighbourhood designs are associated with reduced travel and resource conservation (Krizek, 2003; Ewing and Cervero, 2010). A US study found those living in neo-traditional neighbourhoods made as many daily trips as those in low-density, single-family suburban neighbourhoods, however the switch from driving to walking and the shortening of trip distances resulted in a 20 % less VKT per household (Khattak and Rodriguez, 2005). Empirical research shows that the design of streets have even stronger influences than urban densities on incidences of walking and reduced motorized travel in traditional neighbourhoods of Bogota, Tehran, Taipei, and Hong Kong SAR (China) (Zhang, 2004; Cervero et al., 2009; Lin and Yang, 2009; Lotfi and Koohsari, 2011). A study in Jinan, China, found the energy use of residents living in mixed-use and grid street enclaves to be one-third that of similar households in superblock, single-use developments (Calthorpe, 2013).

Box 12.3 | Urban expansion: drivers, markets, and policies

While the literature that examines the impacts of changes in urban spatial structure and infrastructure on urban GHG emissions is sparse, there is a well-established body of literature that discusses the drivers of urban development, and policies that aim to alter its pace and shape.

Drivers of Urban Expansion—The drivers of urban development can be broadly defined into the following categories: *Economic Geography, Income, Technology* (see Section 12.3.1), as well as *Market Failures* (see Chapter 15), and *Pre-Existing Conditions,* which are structured by *Policies and Regulations* (see Section 12.5.2) that in turn shape *Urban Form and Infrastructure* (see Section 12.4 and Box 12.4).

Primary drivers of urban spatial expansion unfold under the influence of economic conditions and the functioning of markets. These are however strongly affected by **Market Failures** and **Pre-Existing Policies and Regulations** that can exacerbate or alleviate the effect of the primary drivers on urban growth.

Market Failures are the result of individuals and firms ignoring the external costs and benefits they impose on others when making economic decisions (see Chapter 15). These include:

- Failure to account for the social costs of GHG (and local) emissions that result from production and consumption activities in cities.
- Failure to account for the social costs of traffic congestion (see Chapter 8).
- Failure to assign property rights and titles for land.
- Failure to account for the social benefits of spatial amenities and mix land uses (see Section 12.5.2.3).
- Failure to account for the social benefits of agglomeration that result from the interactions of individuals and firms in cities.

Although not precisely quantified in the literature, by altering the location of individuals and firms in space (and resulting travelling patterns and consumption of space), these market failures can lead to excessive growth (see Box 12.4).

For each failure, there is a policy solution, either in the form of regulations or market-based instruments (see Section 12.5.2)

Pre-Existing Policies and Regulations can also lead to excessive growth. These include:

- **Hidden Pre-Existing Subsidies**—including the failure to charge new development for the infrastructure costs it generates (see Section 12.5.3 and Box 12.4).
- **Outdated or Poorly Designed Pre-Existing Policies and Regulations**—including zoning, building codes, ordinances, and property taxes that can distort real estate markets (see Section 12.5.2 and Box 12.4).

12.5 Spatial planning and climate change mitigation

Spatial planning is a broad term that describes systematic and coordinated efforts to manage urban and regional growth in ways that promote well-defined societal objectives such as land conservation, economic development, carbon sequestration, and social justice. Growth management is a similar idea, aimed at guiding "the location, quality, and timing of development" (Porter, 1997) to minimize 'sprawl' (Nelson and Duncan, 1995), which is characterized by low density, non-contiguous, automobile-dependent development that prematurely or excessively consumes farmland, natural preserves, and other valued resources (Ewing, 1997).

This section reviews the range of spatial planning strategies that may reduce emissions through impacts on most if not all of the elements of urban form and infrastructure reviewed in Section 12.4. It begins with an assessment of key spatial planning strategies that can be implemented at the macro, meso, and micro geographic scales. It then assesses the range of regulatory, land use, and market-based policy instruments that can be employed to achieve these strategic objectives. Given evidence of the increased emissions reduction potential associated with affecting the collective set of spatial factors driving emissions (see Section 12.4), emphasis is placed on assessing the efficacy of strategies or bundles that simultaneously impact multiple spatial outcomes (see Chapter 15.4 and 15.5 on policy evaluation and assessment).

The strategies discussed below aim to reduce sprawl and automobile dependence–and thus energy consumption, VKT, and GHG emissions–to varying degrees. Evidence on the energy and emission reduction benefits of these strategies comes mainly from case studies in the developed world even though their greatest potential for reducing future emissions lies in developing countries undergoing early stages of urbanization. The existing evidence highlights the importance of an integrated infrastructure development framework that combines analysis of mitigation reduction potentials alongside the long-term public provision of services.

12.5.1 Spatial planning strategies

Spatial planning occurs at multiple geographic scales: (1) Macro—regions and metropolitan areas; (2) Meso—sub-regions, districts, and corridors; and (3) Micro—neighbourhoods, streets, blocks. At each scale, some form of comprehensive land-use and transportation planning provides a different opportunity to envision and articulate future settlement patterns, backed by zoning ordinances, subdivision regulations, and capital improvements programmes to implement the vision (Hack et al., 2009). Plans at each scale must also be harmonized and integrated to maximize effectiveness and efficiency (Hoch et al., 2000). Different strategy bundles invite different policy tools, adapted to the unique political, institutional, and cultural landscapes of cities in which they are applied (see Table 12.5). Successful implementation requires that there be in place the institutional capacity and political wherewithal to align the right policy instruments to specific spatial planning strategies.

12.5.1.1 Macro: Regions and metropolitan areas

Macro-scale strategies are regional in nature, corresponding to the territories of many economic transactions (e.g., laboursheds and tradesheds) and from where natural resources are drawn (e.g., water tributaries) or externalities are experienced (e.g., air basins).

Regional Plan. A regional plan shows where and when different types of development are allowed, and where and when they are not. In polycentric plans, sub-centres often serve as building blocks for designing regional rail-transit networks (Calthorpe and Fulton, 2001). Regional strategies can minimize environmental spillovers and economize on large-scale infrastructure investments (Calthorpe and Fulton, 2001; Seltzer and Carbonell, 2011). Polycentric metropolises like Singapore, Tokyo, and Paris have successfully linked sub-centres with high-quality, synchronized metro-rail and feeder bus services (Cervero, 1998; Gakenheimer, 2011). Spatial plans might be defined less in terms of a specific urban-form vision and more with regard to core development principles. In its 'Accessible Ahmedabad' plan, the city of Ahmedabad, India, embraced the principle of creating a city designed for accessibility rather than mobility, without specific details on the siting of new growth (Suzuki et al., 2013).

Urban containment. Urban containment encourages cities and their peripheries to grow inwards and upwards, not outwards (Pendall et al., 2002). Urban containment can also contribute to climate change mitigation by creating more compact, less car-oriented built form as well as by preserving the carbon sequestration capacity of natural and agricultural areas in the surrounding areas (Daniels, 1998). The impact of development restrictions is uncertain and varies with the geographic and regulatory context (Pendall, 1999; Dawkins and Nelson, 2002; Han et al., 2009; Woo and Guldmann, 2011). In the United States, regional measures such as the Portland urban growth boundary have been more effective at containing development than local initiatives (DeGrove and Miness, 1992; Nelson and Moore, 1993; Boyle and Mohamed, 2007). In the UK, urban containment policies may have pushed growth to leapfrog the greenbelt to more distant locations and increased car commuting (Amati, 2008). In Seoul and in Swiss municipalities, greenbelts have densified the core city but made the metropolitan area as a whole less compact; in Seoul, commuting distances also increased by 5 % (Jun and Bae, 2000; Bae and Jun, 2003; Bengston and Youn, 2006; Gennaio et al., 2009).

Regional jobs-housing balance. Separation of workers from job sites creates long-haul commutes and thus worsens traffic and environmental conditions (Cervero, 1996). Jobs-housing imbalances are often a product of insufficient housing in jobs-rich cities and districts (Boarnet and Crane, 2001; Wilson, 2009; Pendall et al., 2012). One view holds that the market will eventually work around such problems–developers will build more housing near jobs because more profit can be made from such housing

Table 12.5 | Matching spatial planning strategies and policy instruments. Summary of the types of policy instruments that can be applied to different spatial planning strategies carried out at different geographic scales. Unless otherwise noted, references can be found in the relevant chapter sections.

	POLICY INSTRUMENTS/IMPLEMENTATION TOOLS					
	Government Regulations		Government Incentives		Market-Based Strategies	
SPATIAL STRATEGY	Land Regulation/Zoning (see 12.5.2.1)	Taxation/Finance Strategies (see 12.5.2.3)	Land Management (see 12.5.2.2)	Targeted Infrastructure/Services (see 12.5.1)	Pricing (see 12.5.2.3)	Public-Private Partnerships (see 12.5.2.3)
Metropolitan/Regional						
Urban containment	Development restrictions; UGBs	Sprawl taxes	Urban Service Boundaries	Park improvements; trail improvements		
Balanced growth	Affordable housing mandates	Tax-bases sharing	Extraterritorial zoning		Farm Tax Credits[1]	
Self-contained communities/new towns	Mixed-use zoning		Greenbelts	Utilities; urban services		Joint ventures[2]
Corridor/District						
Corridor growth management	Zoning	Impact fees; Exactions[3]		Service Districts[4]		
Transit-oriented corridors	Transfer of development rights			Urban rail; Bus rapid transit investments		Joint Powers Authorities
Neighbourhood/Community						
Urban Regeneration/Infill	Mix-use zoning/small lot designations	Split-Rate Property Taxes; Tax increment finance[5]	Redevelopment districts	Highway conversions; Context-sensitive design standards	Congestion charges (see Ch. 8)	
Traditional Neighbourhood Designs; New urbanism	Zoning overlays; form-based codes			Sidewalks; cycle tracks; bike stations[6]		
Transit oriented Development	Design codes; flexible parking	Impact Fees; Betterment Taxes[7]		Station siting; station access		Joint development[2]
Eco-Communities	Mixed-use zoning			District Heating/Cooling; co-generation (see Ch. 9.4)	Peak-load pricing	Joint venture[2]
Site/Streetscape						
Pedestrian Zones/Car-Free Districts	Street code revisions[8]	Special Improvement Districts[7]		Road entry restrictions; sidewalks[8]	Parking surcharges	
Traffic Calming/Context-Sensitive Design	Street code revisions[8]	Benefit Assessment[7]				Property owner self-assessments
Complete Streets	Design standards			Bike infrastructure; Pedestrian facilities		Design competitions

Additional sources referenced in table: **1:** Nelson (1992), Alterman (1997); **2:** Sagalyn (2007), Yescombe (2007); **3:** Hagman and Misczynski (1978), Bauman and Ethier (1987); **4:** Rolon (2008); **5:** Dye and Sundberg (1998), Dye and Merriman (2000), Brueckner (2001b); **6:** Sælensminde (2004), McAndrews et al. (2010); **7:** Rolon (2008); **8:** Brambilla and Longo (1977).

(Gordon et al., 1991; Downs, 2004). There is evidence of co-location in US cities like Boston and Atlanta (Weitz, 2003). Even in the developing world, co-location occurs as a means to economize on travel, such as the peri-urban zones of Dar es Salaam and Lagos where infill and densification, often in the form of informal settlements and shantytowns, occurs in lieu of extended growth along peripheral radial roads (Pirie, 2011).

Research on balanced growth strategies provides mixed signals on mobility and environmental impacts. Studies of Atlanta estimate that jobs-housing balance can reduce traffic congestion, emissions, and related externalities (Weitz, 2003; Horner and Murray, 2003). In the San Francisco Bay Area, jobs-housing balance has reduced travel more than intermixing housing and retail development (Cervero and Duncan, 2006). Other studies, however, suggest that jobs-housing balance has little impact on travel and traffic congestion since many factors besides commuting condition residential location choices (Levine, 1998).

Self-contained, 'complete' communities—wherein the jobs, retail commodities and services needed by workers and households exist within a community—is another form of balanced growth. Many master-planned new towns in the United States, France, South Korea, and the UK were designed as self-contained communities, however their physical isolation and economic dependence on major urban centres resulted in high levels of external motorized travel (Cervero, 1995b; Hall, 1996).

How new towns are designed and the kinds of transport infrastructure built, experiences show, have strongly influenced travel and environmental outcomes (Potter, 1984). In the UK, new towns designed for good transit access (e.g., Runcorn and Redditch) averaged far higher transit ridership and less VKT per capita than low-density, auto-oriented communities like Milton Keynes and Washington, UK (Dupree, 1987).

Telecommunities are a more contemporary version of self-contained communities, combining information and communication technologies (ICTs) with traditional neighbourhood designs in remote communities on the edges of cities like Washington, DC and Seattle (Slabbert, 2005; Aguilera, 2008). Until such initiatives scale up, their contributions to VKT and GHG reductions will likely remain miniscule (Choo et al., 2005; Andreev et al., 2010; Mans et al., 2012).

12.5.1.2 Meso: Sub-regions, corridors, and districts

The corridor or district scale captures the spatial context of many day-to-day activities, such as going to work or shopping for common household items. Significant challenges are often faced in coordinating transportation and land development across multiple jurisdictions along a corridor.

Corridor growth management. Corridor-level growth management plans aim to link land development to new or expanded infrastructure investments (Moore et al., 2007). Both land development and transport infrastructure need years to implement, so coordinated and strategic long-range planning is essential (Gakenheimer, 2011). Once a transport investment is committed and land use policies are adopted, the two can co-evolve over time. A good example of coordinated multi-jurisdictional management of growth is the 20 km Paris-Pike corridor outside of Lexington, Kentucky in the United States (Schneider, 2003). There, two county governments reached an agreement and created a new extra-territorial authority to zone land parcels for agricultural activities within a 0.5 km radius of a newly expanded road to preserve the corridor's rural character, prevent sprawl, and maintain the road's mobility function.

Transit-oriented corridors. Corridors also present a spatial context for designing a network of Transit Oriented Developments (TODs), traditional (e.g., compact, mixed-use, and pedestrian-friendly) development that is physically oriented to a transit station. TODs are expected to reduce the need to drive, and thus reduce VKT. Some global cities have directed land uses typically scattered throughout suburban developments (e.g., housing, offices, shops, restaurants, and strip malls) to transit-served corridors (Moore et al., 2007; Ferrell et al., 2011). Scandinavian cities like Stockholm, Helsinki, and Copenhagen have created 'necklace of pearls' built form not only to induce transit riding but also to produce balanced, bi-directional flows and thus more efficient use of infrastructure (Cervero, 1998; Suzuki et al., 2013).

Curitiba, Brazil, is often heralded as one of the world's most sustainable cities and is a successful example of the use of Transit Oriented Corridors (TOCs) to shape and direct growth (Cervero, 1998; Duarte and Ultramari, 2012). The city has evolved along well-defined radial axes (e.g., lineal corridors) that are served by dedicated busways. Along some transportation corridors, double-articulated buses transport about 16,000 passengers per hour, which is comparable to the capacity of more expensive metro-rail systems (Suzuki et al., 2013). To ensure a transit-oriented built form, Curitiba's government mandates that all medium- and large-scale urban development be sited along a Bus Rapid Transit (BRT) corridor (Cervero, 1998; Hidalgo and Gutiérrez, 2013). High transit use has appreciably shrunk the city's environmental footprint. In 2005, Curitiba's VKT per capita of 7,900 was half as much as in Brazil's national capital Brasilia, a city with a similar population size and income level but a sprawling, auto-centric built form (Santos, 2011).

12.5.1.3 Micro: communities, neighbourhoods, streetscapes

The neighbourhood scale is where activities like convenience shopping, socializing with neighbours, and walking to school usually take place, and where urban design approaches such as gridded street patterns and transit-oriented development are often targeted. While smaller scale spatial planning might not have the energy conservation or emission reduction benefits of larger scale planning strategies, development tends to occur parcel-by-parcel and urbanized areas are ultimately the products of thousands of individual site-level development and design decisions.

Urban Regeneration and Infill Development. The move to curb urban sprawl has spawned movements to revitalize and regenerate long-standing traditional urban centres (Oatley, 1995). Former industrial sites or economically stagnant urban districts are often fairly close to central business districts, offering spatial proximity advantages. However, brownfield redevelopment (e.g., tearing down and replacing older buildings, remediating contaminated sites, or upgrading worn out or obsolete underground utilities) can often be more expensive than building anew on vacant greenfield sites (Burchell et al., 2005).

In recent decades, British planners have turned away from building expensive, master-planned new towns in remote locations to creating 'new towns/in town', such as the light-rail-served Canary Wharf brownfield redevelopment in east London (Gordon, 2001). Recycling former industrial estates into mixed-use urban centres with mixed-income housing and high-quality transit services have been successful models (Foletta and Field, 2011). Vancouver and several other Canadian cities have managed to redirect successfully regional growth to their urban cores by investing heavily in pedestrian infrastructure and emphasizing an urban milieu that is attractive to families. In particular, Vancouver has invested in developing attractive and inviting urban spaces, high quality and dedicated cycling and walking facilities, multiple and reliable public transit options, and creating high-density residential areas that are integrated with public and cooperative housing (Marshall, 2008). Seoul, South Korea, has sought to regenerate its urban core through a mix of transportation infrastructure investments and de-investments, along with urban renewal (Jun and Bae, 2000; Jun and Hur, 2001). Reclaiming valuable inner-city land in the form of tearing down an elevated freeway and expropriating roadway lanes, replaced by expanded BRT services and pedestrian infrastructure has been the centrepiece of Seoul's urban regeneration efforts (Kang and Cervero, 2009).

Traditional neighbourhood design and new urbanism. Another movement, spearheaded by reform-minded architects and environmental and sustainability planners, has been to return communities to their designs and qualities of yesteryear, before the ascendency of the private automobile (Nasar, 2003). Referred to as 'compact cities' in much of Europe and 'New Urbanism' in the United States, the movement takes on features of traditional, pre-automobile neighbourhoods that feature grid iron streets and small rectilinear city blocks well suited to walking, narrow lots and building setbacks, prominent civic spaces that draw people together (and thus help build social capital), tree-lined narrow streets with curbside parking and back-lot alleys that slow car traffic, and a mix of housing types and prices (Kunstler, 1998; Duany et al., 2000; Talen, 2005).

In the United States, more than 600 New Urbanism neighbourhoods have been built, are planned, or are under construction (Trudeau, 2013). In Europe, a number of former brownfield sites have been redeveloped since the 1980s based on traditional versus modernist design principles (Fraker, 2013). In developing countries, recent examples of neighbourhood designs and redevelopment projects that follow New Urbanism principles to varying degrees are found in Belize, Jamaica, Bhutan, and South Africa (Cervero, 2013).

Transit Oriented Development (TOD). TODs can occur at a corridor scale, as discussed earlier for cities like Curitiba and Stockholm, or as is more common, take on a nodal, neighbourhood form. Besides being the 'jumping off' point for catching a train or bus, TODs also serve other community purposes. Scandinavian TODs often feature a large civic square that functions as a community's hub and human-scale entryway to rail stations (Bernick and Cervero, 1996; Curtis et al., 2009).

In Stockholm and Copenhagen, TOD has been credited with reducing VKT per capita to among the lowest levels anywhere among high-income cities (Newman and Kenworthy, 1999). In the United States, studies show that TODs can decrease per capita use of cars by 50 %. In turn, this could save households about 20 % of their income (Arrington and Cervero, 2008). TOD residents in the United States typically commute by transit four to five times more than the average commuter in a region (Lund et al., 2006). Similar ridership bonuses have been recorded for TOD projects in Toronto, Vancouver, Singapore, and Tokyo (Chorus, 2009; Yang and Lew, 2009). In China, a recent study found smaller differentials of around 25 % in rail commuting between those living near, versus away from suburban rail stations (Day and Cervero, 2010).

Many cities in the developing world have had long histories of being transit oriented, and feature fine-grain mixes of land uses, abundant pathways that encourage and enable walking and biking, and ample transit options along major roads (Cervero, 2006; Cervero et al., 2009; Curtis et al., 2009). In Latin America, TOD is being planned or has taken form to varying degrees around BRT stations in Curitiba, Santiago, Mexico City, and Guatemala City. TOD is also being implemented in Asian cities, such as in Kaohsiung, Qingdao and Jiaxing, China, and Kuala Lumpur, Malaysia (Cervero, 2013). Green TODs that feature low-energy/low-emission buildings and the replacement of surface parking with community gardens are being built (Teriman et al., 2010; Cervero and Sullivan, 2011). A number of Chinese cities have embraced TOD for managing growth and capitalizing upon massive rail and BRT investments. For example, Beijing and Guangzhou adopted TOD as a guiding design principle in their most recent long-range master plans (Li and Huang, 2010). However, not all have succeeded. TOD efforts in many Chinese cities have been undermined by a failure to articulate densities (e.g., tapering building heights with distances from stations), the siting of stations in isolated superblocks, poor pedestrian access, and a lack of co-benefiting mixed land uses (Zhang, 2007; Zhang and Wang, 2013).

Pedestrian zones/car-restricted districts. Many European cities have elevated liveability and pedestrian safety to the top of transportation planning agendas, and have invested in programmes that reduce dependence on and use of private automobiles (Banister, 2005, 2008; Dupuy, 2011). One strategy for this is traffic calming, which uses speed humps, realigned roads, necked down intersections along with planted trees and other vegetation in the middle of streets to slow down traffic (Ewing and Brown, 2009). With these traffic calming approaches, automobile passage becomes secondary. A related concept is 'complete streets,' which—through dedicated lanes and traffic-slowing designs—provide safe passage for all users of a street, including drivers as well as pedestrians, cyclists, and transit patrons (McCann and Rynne, 2010).

An even bolder urban-design/traffic-management strategy has been the outright banning of cars from the cores of traditional neighbourhoods and districts, complemented by an upgrading and beautification of pedestrian spaces. This practice has become commonplace in many older European cities whose narrow and winding inner-city street were never designed for motorized traffic (Hass-Klau, 1993). Multi-block car-free streets and enhanced pedestrian zones are also found in cities of the developing world, including Curitiba, Buenos Aires, Guadalajara, and Beirut (Cervero, 2013).

Empirical evidence reveals a host of benefits from street redesigns and auto-restraint measures like these. The traffic-calming measures implemented in Heidelberg, Germany during the early 1990s lead to a 31 % decline in car-related accidents, 44 % fewer casualties, and less central-city traffic (Button, 2010). A study of pedestrianization in German cities recorded increases in pedestrian flows, transit ridership, land values, and retail transactions, as well as property conversions to more intensive land uses, matched by fewer traffic accidents and fatalities (Hass-Klau, 1993). Research on over 100 case studies in Europe, North America, Japan, and Australia, found that road-capacity reductions including car-free zones, creation of pedestrian streets, and street closures, results in an overall decline in motorized traffic of 25 % (Goodwin et al., 1998).

12.5.2 Policy instruments

Spatial planning strategies rely on a host of policy instruments and levers (see Chapter 15.3 for a classification of policy instruments). Some instruments intervene in markets, aimed at correcting market failures (e.g., negative externalities). Others work with markets, aimed at shaping behaviours through price signals or public-private partnerships. Interventionist strategies can discourage or restrict growth through government fiat but they can also incentivize development, such as through zoning bonuses or property tax abatements (Bengston et al., 2004). Policy instruments can be applied to different spatial planning strategies and carried out at different geographic scales (see Table 12.5). Different strategy bundles can be achieved through a mix of different policy tools, adapted to the unique political, institutional, and cultural landscapes of cities in which they are applied. Successful implementation requires institutional capacity and political wherewithal to align the right policy instruments to specific spatial planning strategies.

The effectiveness of particular instruments introduced depends on legal and political environments. For example, cities in the Global South can lack the institutional capacity to regulate land or to enforce development regulations and tax incentives may have little impact on development in the informal sector (Farvacque and McAuslan, 1992; Sivam, 2002; Bird and Slack, 2007; UN-Habitat, 2013). Infrastructure provision and market-based instruments such as fuel taxes will more likely affect development decisions in the informal sectors, although there is little direct empirical evidence. The impact of instruments on urban form and spatial outcomes can be difficult to assess since regulations like land-use zoning are often endogenous. That is, they codify land use patterns that would have occurred under the free market rather than causing changes in urban form (Pogodzinski and Sass, 1994).

12.5.2.1 Land use regulations

Land-use regulations specify the use, size, mass and other aspects of development on a particular parcel of land. They are also known as development controls or zoning regulations. In countries like the United States and India, land-use regulations usually promote low-density, single-use developments with large amounts of parking that increase car dependence and emissions (Talen 2012; Levine 2005; Glaeser, 2011). For example, densities in the United States are often lower than developers would choose under an unregulated system (Fischel, 1999; Levine and Inam, 2004). Thus, regulatory reforms that relax or eliminate overly restrictive land-use controls could contribute to climate change mitigation. In Europe, by contrast, land-use regulations have been used to promote more compact, mixed-use, transit-friendly cities (Beatley, 2000). The following are the primary land-use regulations to reduce urban form-related GHG emissions.

Use restrictions specify which land uses, such as residential, retail or office, or a mix of uses, may be built on a particular parcel. Single-use zoning regulations which rigidly separate residential and other uses are prevalent in the United States, although some cities such as Miami have recently adopted form-based codes which regulate physical form and design rather than use (Parolek et al., 2008; Talen, 2012). Use restrictions are rare in European countries such as Germany and France, where mixed-use development is permitted or encouraged (Hirt, 2007, 2012).

Density regulations specify minimum and/or maximum permissible densities in terms of the number of residential units, floor area on a parcel, or restrictions on building height or mass. Density regulations can provide incentives for open space or other public benefits by allowing higher density development in certain parts of a city. In India, densities or heights are capped in many cities, creating a pattern of mid-rise buildings horizontally spread throughout the city and failing to allow TOD to take form around BRT and urban rail stations (Glaeser, 2011; Brueckner and Sridhar, 2012; Suzuki et al., 2013). In Europe, by contrast, land-use regulations have been used to promote more compact, mixed-use, transit-friendly cities (Beatley, 2000; Parolek et al., 2008; Talen, 2012). In Curitiba, Brazil, density bonuses provide incentives for mixed-use development (Cervero, 1998; Duarte and Ultramari, 2012). A density bonus (Rubin and Seneca, 1991) is an option where an incentive is created for the developer to set aside land for open spaces or other benefits by being allowed to develop more densely, typically in CBDs. One challenge with density bonus is that individuals may have preferences for density levels (high, low) and adjust their location accordingly.

Urban containment instruments include greenbelts or urban growth boundaries and have been employed in London, Berlin, Portland, Beijing, and Singapore. In the UK and in South Korea, greenbelts delineate the edges of many built-up and rural areas (Hall, 1996; Bengston and Youn, 2006). In many European cities, after the break-up of the city walls in the 18th and 19th centuries, greenbelts were used to delineate cities (Elson, 1986; Kühn, 2003). Some US states have passed growth management laws that hem in urban sprawl through such initiatives as creating urban growth boundaries, geographically restricting utility service districts, enacting concurrency rules to pace the rate of land development and infrastructure improvements, and tying state aid to the success of local governments in controlling sprawl (DeGrove and Miness, 1992; Nelson et al., 2004). The mixed evidence on the impacts of urban containment instruments on density and compactness (decreases in some cases and increases in others) indicates the importance of instrument choice and particularities of setting.

Building codes provide a mechanism to regulate the energy efficiency of development. Building codes affect the energy efficiency of new development, and cities provide enforcement of those regulations in some countries (Chapter 9). City policies influence emissions through energy use in buildings in several other ways, which can influence purchases and leasing of commercial and residential real estate properties. Some cities participate in energy labelling programmes for buildings (see Chapter 9.10.2.6) or have financing schemes linked to property taxes (see Property Assess Clean Energy (PACE) in Chapter 9.10.3.1). Energy efficient equipment in buildings can further reduce

Box 12.4 | What drives declining densities?

The global phenomenon of declining densities (Angel et al., 2010) is the combined result of (1) fundamental processes such as population growth, rising incomes, and technological improvements in urban transportation systems (LeRoy and Sonstelie, 1983; Mieszkowski and Mills, 1993; Bertaud and Malpezzi, 2003; Glaeser and Kahn, 2004); (2) market failures that distort urban form during the process of growth (Brueckner, 2001a; Bento et al., 2006, 2011); and (3) regulatory policies that can have unintended impacts on density (Sridhar, 2007, 2010). A range of externalities can result in lower densities, such as the failure to adequately account for the cost of traffic congestion and infrastructure development and the failure to account for the social value of open space (Brueckner, 2000).

Regulatory policies, such as zoning and Floor Area Ratio (FAR) restrictions, as well as subsidies to particular types of transportation infrastructures can have large impacts on land development, which lead to leapfrog development (Mieszkowski and Mills, 1993; Baum-Snow, 2007; Brueckner and Sridhar, 2012). The emissions impacts of these interventions are often not fully understood. Finally, the spatial distribution of amenities and services can shape urban densities through housing demand (Brueckner et al., 1999). In the United States, deteriorating conditions in city centres have been an important factor in increased suburbanization (Bento et al., 2011; Brueckner and Helsley, 2011). Conversely, the continued consolidation of amenities, services, and employment opportunities in the cores of European and Chinese cities has kept households in city centres (Brueckner et al., 1999; Zheng et al., 2006, 2009).

energy consumption and associated emissions, including electronics, appliances, and equipment (see Table 9.3). Cities that operate utilities can influence energy usage directly by using smart meters and information infrastructures (see 9.4.1.3).

Parking regulations specify minimum and/or maximum numbers of parking spaces for a particular development. Minimum parking standards are ubiquitous in much of the world, including cities in the United States, Mexico, Saudi Arabia, Malaysia, China, and India (Barter, 2011; Al-Fouzan, 2012; Wang and Yuan, 2013). Where regulations require developers to provide more parking than they would have otherwise, as in place like New York and Los Angeles (McDonnell et al., 2011; Cutter and Franco, 2012), they induce car travel by reducing the cost of driving. Minimum parking requirements also have an indirect impact on emissions through land-use, as they reduce the densities that are physically or economically feasible on a site, by 30 %–40 % or more in typical cases in the United States (Willson, 1995; Talen, 2012). Maximum parking standards, in contrast, have been used in cities such as San Francisco, London, and Zurich (Kodransky and Hermann, 2011) to reduce the costs of development, use urban land efficiently, and encourage alternate transportation modes. In London, moving from minimum to maximum residential parking standards reduced parking supply by 40 %, with most of the impact coming through the elimination of parking minimums (Guo and Ren, 2013).

Design regulations can be used to promote pedestrian and bicycle travel. For example, site-design requirements may require buildings to face the street or prohibit the placement of parking between building entrances and street rights-of-way (Talen, 2012). Design regulations can also be used to increase albedo or reduce urban heat island effects, through requiring light-coloured or green roofs or regulating impervious surfaces (Stone et al., 2012), as in Montreal and Toronto (Richardson and Otero, 2012).

Affordable housing mandates can reduce the spatial mismatch between jobs and housing (Aurand, 2010). Incentives, such as floor area ratios and credits against exactions and impact fee obligations, can be arranged for developers to provide social housing units within their development packages (Cervero, 1989; Weitz, 2003).

12.5.2.2 Land management and acquisition

The previous section discussed regulatory instruments that are primarily used to shape the decisions of private landowners. Land management and acquisition include parks, lease air rights, utility corridors, transfer development rights, and urban service districts. Urban governments can also directly shape urban form through land that is publicly owned—particularly around public transport nodes, where municipalities and public transport agencies have acquired land, assembled parcels, and taken the lead on development proposals (Cervero et al., 2004; Curtis et al., 2009; Curtis, 2012). In Hong Kong SAR, China, the 'Rail + Property' development programme, which emphasizes not only density but also mixed uses and pedestrian linkages to the station, increases patronage by about 35,000 weekday passengers at the average station. In addition to supporting ridership, an important aim of many agencies is to generate revenue to fund infrastructure, as in Istanbul, Sao Paulo, and numerous Asian cities (Peterson, 2009; Sandroni, 2010).

Transfer of Development Rights (TDR) allows the voluntary transfer or sale of development from one region or parcel where less development is desired to another region or parcel where more development is desired. They can be used to protect heritage sites from redevelopment or to redistribute urban growth to transit station areas. The parcels that 'send' development are protected through restrictive covenants or permanent conservation easements. TDR effectively redirects new growth from areas where current development is to be protected (historical sites or protected areas) to areas where more development is desired (e.g., transit station areas).

Increasing green space and urban carbon sinks can sequester carbon and reduce energy consumption for cooling. Increasing green space offers co-benefits such as increased property values, regulating stormwater, reduced air pollution, increased recreational space, provision of shade and cooling, rainwater interception and infiltration, increased biodiversity support, and enhancement of well-being (Heynen et al., 2006; Gill et al., 2007; McDonald, 2008). However, many studies show that significantly increasing urban green space would have negligible effects on offsetting total urban carbon emissions, especially when emissions generated by fuel combustion, fertilizer use, and irrigation are also considered (Pataki et al., 2009; Jim and Chen, 2009; Townsend-Small and Czimczik, 2010). Globally, urban soils could sequester 290 Mt carbon per year if designed with calcium-rich minerals (Renforth et al., 2009). Annual carbon uptake varies significantly by location and plant species. Carbon uptake per hectare for temperate urban green spaces is estimated to be 0.15–0.94 t/yr for seven cities in the United States: Atlanta, Baltimore, Boston, Jersey City, New York, Philadelphia, and Syracuse (Nowak and Crane, 2002); 0.38 t/yr in Beijing, China (Yang and Gakenheimer, 2007); and 0.53–0.8 t/yr in the South Korean cities of Chuncheon, Kangleung (Gangneung) and Seoul (Jo, 2002). United States cities in semi-tropical areas have higher levels of per hectare annual C sequestration, of 3.2 t/yr in Gainesville and 4.5 t/yr in Miami-Dade (Escobedo et al., 2010). Urban forests are estimated to sequester 1.66 t C/ha/yr in Hangzhou, China (Zhao et al., 2010). The variation in estimates across cities can be partly ascribed to differences in tree species, sizes, and densities of planting (Zhao et al., 2010), as well as land use (Whitford et al., 2001) and tree life span (Strohbach et al., 2012; Raciti et al., 2012).

12.5.2.3 Market-based instruments

Market-based instruments use taxation and pricing policies to shape urban form (see Chapter 15.5.2 for more in-depth discussion of market-based instruments). Because much low-density, single-use urban development stems from market failures or pre-existing distorted policies or regulations, a variety of market-based instruments can be introduced that correct these failures (Brueckner and Fansler, 1983; Brueckner and Kim, 2003; Brueckner, 2000; Bento et al., 2006, 2011).

Property taxes. The property tax, a local tax widely used to fund local urban services and infrastructure, typically taxes both land and structures. A variant of the property tax, a land tax or split-rate tax, levies a higher rate of tax on the value of the land, and a lower or zero rate on the value of the buildings and other improvements. This variant of the property tax can promote compact urban form through increasing the capital to land ratio, i.e., the intensity of development. There are numerous examples of the land or split-rate tax worldwide, including Jamaica, Kenya, Denmark, parts of Australia, the United States, and South Africa (Bird and Slack, 2002, 2007; Franzsen and Youngman, 2009; Banzhaf and Lavery, 2010)—although in these places, tax reform was not necessarily implemented with the aim of reducing sprawl.

In principle, moving from a standard property tax to a land or split-rate tax has ambiguous effects on urban form. The capital to land ratio could rise through an increase in dwelling size—promoting sprawl—and/or through an increase in density or units per acre—promoting compact urban form (Brueckner and Kim, 2003). In practice, however, the density effect seems to dominate. Most of the empirical evidence supporting the role of property tax reform in promoting compact urban form comes from the U.S. state of Pennsylvania, where the most thorough study found that the split-rate tax led to a 4–5 % point increase per decade in the number of housing units per hectare, with a minimal increase in unit size (for other evidence from Pennsylvania, see Oates and Schwab, 1997; Plassmann and Tideman, 2000; Banzhaf and Lavery, 2010).

Prospective or simulation studies also tend to find that land or split-rate taxes have the potential to promote compact urban form at least to some extent (many earlier studies are summarized in Roakes, 1996; Needham, 2000; for more recent work see Junge and Levinson, 2012). However, studies of land taxes in Australia have tended to find no effect on urban form (Skaburskis, 2003), although with some exceptions (e.g. Edwards, 1984; Lusht, 1992). There are several suggestions to tailor land or property taxes to explicitly support urban planning objectives. For example, the property tax could vary by use or by impervious area (Nuissl and Schroeter-Schlaack, 2009), or the tax could be on greenfield development only (Altes, 2009). However, there are few examples of these approaches in practice, and little or no empirical evidence of their impacts.

Moving from a standard property tax to a land or split-rate tax can yield efficiency and equity benefits (see Chapter 3 for definitions). The efficiency effect stems from the fact that the land tax is less distortionary than a tax on improvements, as the supply of land is fixed (Brueckner and Kim, 2003). The equity argument stems from the view that land value accrues because of the actions of the wider community, for example through infrastructure investments, rather than the actions of the landowner (Roakes, 1996). Indeed, some variants of the land tax in countries such as Colombia (Bird and Slack, 2007) take an explicit 'value capture' approach, and attempt to tax the incremental increase in land value resulting from transport projects.

Development impact fees are imposed per unit of new development to finance the marginal costs of new infrastructure required by the development, and are levied on a one-time basis. The effects of impact fees on urban form will be similar to a property tax. The main difference is that impact fees are more likely to be used by urban governments as a financing mechanism for transport infrastructure. For example, San Francisco and many British cities have impact fees dedicated to public transport (Enoch et al., 2005), and other cities such as Santiago have fees that are primarily dedicated to road infrastructure (Zegras, 2003).

Box 12.5 | Singapore: TOD and Road Pricing

The island-state of Singapore has over the years introduced a series of cross-cutting, reinforcing spatial planning and supportive strategies that promote sustainable urbanism and mobility (Suzuki et al., 2013). Guided by its visionary Constellation Plan, Singapore built a series of new master-planned towns that interact with each other because they each have different functional niches. Rather than being self-contained entities, these new towns function together (Cervero, 1998). All are interlinked by high-capacity, high-quality urban rail and bus services, and correspondingly the majority of trips between urban centres are by public transport. Congestion charges and quota controls on vehicle registrations through an auctioning system also explain why Singapore's transit services are so heavily patronized and not un-related, why new land development is occurring around rail stations (Lam and Toan, 2006).

Development taxes. To the extent that excessive urban development reflects the failure to charge developers for the full costs of infrastructure and the failure to account for the social benefits of spatially explicit amenities or open space, some economists argue that development taxes, a tax per unit of land converted to residential uses, are the most direct market-based instruments to correct for such failures (Brueckner, 2000; Bento et al., 2006). According to these studies, in contrast to urban growth boundaries, development taxes can control urban growth at lower economic costs. Urban sprawl occurs in part because the costs associated with development are not fully accounted for. Development taxes could make up for the difference between the private costs and the social costs of development, and coupled with urban growth boundaries could be effective at reducing sprawl.

Fuel prices and transportation costs. Increases in fuel taxes or transportation costs more generally have a direct effect on reducing VKT (see Chapter 8 and Chapter 15). They are also likely to have a long-run mitigation effect as households adjust their location choices to reduce travel distances, and urban form responds accordingly. An urban area that becomes more compact as households bid up the price of centrally located land is a core result from standard theoretical economic models of urban form (Romanos, 1978; Brueckner, 2001a, 2005; Bento et al., 2006).

Empirically, evidence for this relationship comes from cities in the United States, where a 10 % increase in fuel prices leads to a 10 % decrease in construction on the urban periphery (Molloy and Shan, 2013); Canada,

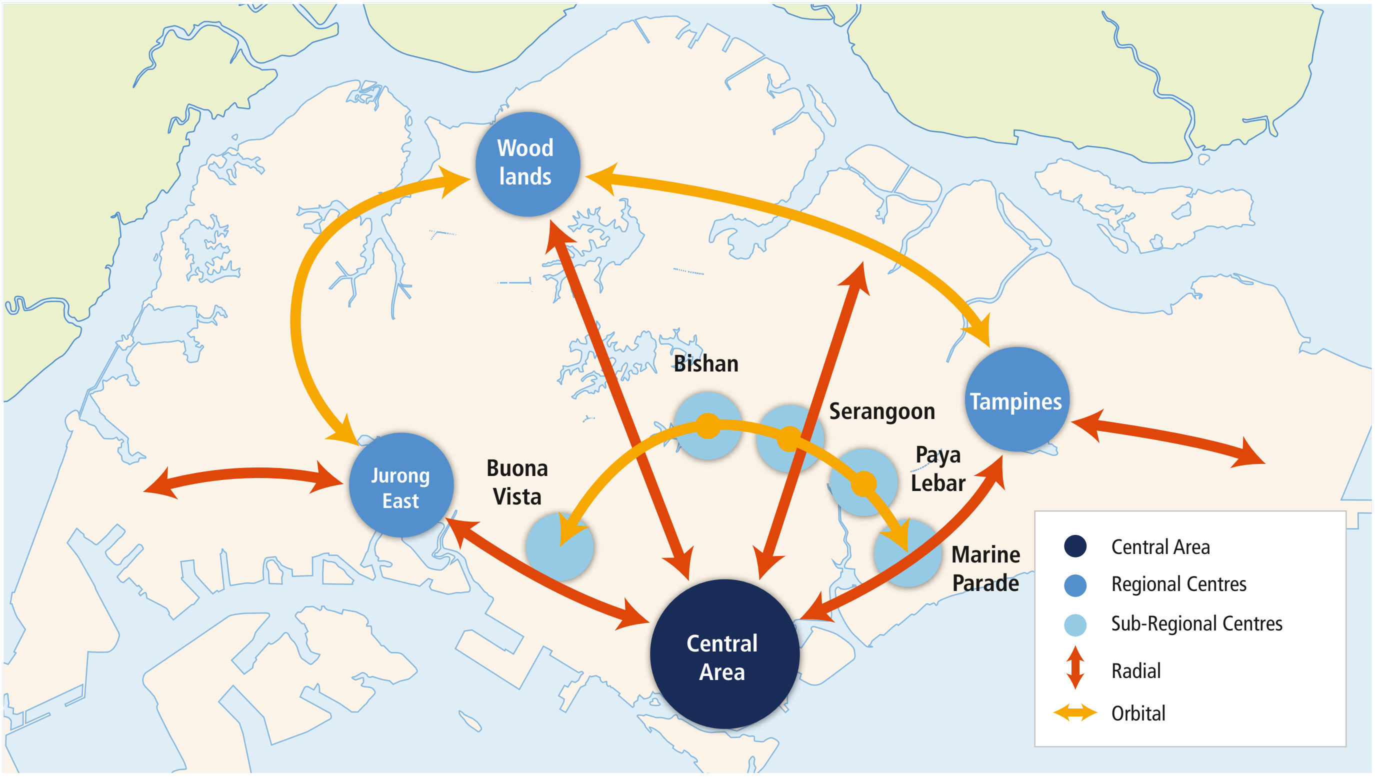

Figure 12.18 | Singapore's Constellation Plan. Source: Suzuki et al. (2013).

where a 1 % increase in gas prices is associated with a 0.32 % increase in the population living in the inner city (Tanguay and Gingras, 2012); and cross-national datasets of 35 world cities (Glaeser et al., 2001; Glaeser and Kahn, 2004). However, another cross-national study using a larger dataset found no statistically significant link, which the authors attribute to noisiness in their (national-level) fuel price data (Angel et al., 2005).

Similar impacts on urban form would be expected from other pricing instruments that increase the cost of driving. While there is clear evidence that road and parking pricing schemes reduce emissions through direct impacts on mode and travel choices (see Chapter 8.10.1), there is more limited data on the indirect impacts through land-use patterns. One of the few simulation studies found that optimum congestion pricing would reduce the radius of the Paris metropolitan area by 34 %, and the average travel distance by 15 % (De Lara et al., 2013).

12.5.3 Integrated spatial planning and implementation

A characteristic of effective spatial planning is interlinked and coordinated efforts that are synergistic, and the sum of which are greater than each individual part incrementally or individually (Porter, 1997). Relying on a single instrument or one-size-fits-all approach can be ineffective or worse, have perverse, unintended consequences. Singapore is a textbook example of successfully bundling spatial planning and supportive pricing strategies that reinforce and strengthen the influences of each other (see Box 12.5). Bundling spatial strategies in ways that produce positive synergies often requires successful institutional coordination and political leadership from higher levels of government (Gakenheimer, 2011). The U.S. state of Oregon has managed to protect farmland and restrict urban sprawl through a combination of measures, including urban growth boundaries (required for all metropolitan areas above 50,000 inhabitants), farm tax credit programmes, tax abatements for infill development, and state grants that have helped fund investments in high-quality transit, such as light rail and tramways in Portland and BRT in Eugene (Moore et al., 2007). Enabling legislation introduced by the state prompted cities like Portland to aggressively curb sprawl through a combination of urban containment, targeted infrastructure investments, aggressive expansion of pedestrian and bikeway facilities, and commercial-rate pricing of parking (Nelson et al., 2004).

Empirical evidence on the environmental benefits of policies that bundle spatial planning and market strategies continues to accumulate. A 2006 experiment in Portland, Oregon, replaced gasoline taxes with VKT charges, levied on 183 households that volunteered for the experiment. Some motorists paid a flat VKT charge while others paid considerably higher rates during the peak than non-peak. The largest VKT reductions were recorded among households in compact, mixed-use neighbourhoods that paid congestion charges matched by little change in travel among those living in lower density areas and paying flat rates (Guo et al., 2011). Another study estimated that compact development combined with technological improvements (e.g., more efficient vehicle fleets and low-carbon fuels) could reduce GHG emissions by 15 % to 20 % (Hankey and Marshall, 2010). A general equilibrium model of urban regions in the OECD concluded that "urban density policies and congestion charges reduce the overall cost of meeting GHG emissions reduction targets more than economy-wide policies, such as a carbon tax, introduced by themselves" (OECD, 2010d).

12.6 Governance, institutions, and finance

The feasibility of spatial planning instruments for climate change mitigation depends greatly upon each city's governance and financial capacities. Even if financial capacities are present, a number of other obstacles need to be surmounted. For example, many local governments are disinclined to support compact, mixed-use, and dense development. Even in cases where there is political support for low-carbon development, institutions may be ineffective in developing, implementing, or regulating land use plans. This section assesses the governance, institutional, and financial challenges and opportunities for implementing the mitigation strategies outlined in Section 12.5. It needs to be emphasized that both the demand for energy and for urban infrastructure services, as well as the efficiency of service delivery, is also influenced by behaviour and individual choices. Cultural and lifestyle norms surrounding comfort, cleanliness, and convenience structure expectations and use of energy, water, waste, and other urban infrastructure services (Miller, 1998; Shove, 2003, 2004; Bulkeley, 2013). Individual and household choices and behaviour can also strongly affect the demand for, and the delivery efficiency of, public infrastructure services, for instance by lowering or increasing load factors (utilization rates) of public transport systems (Sammer, 2013). Governance and institutions are necessary for the design and implementation of effective policy frameworks that can translate theoretical emission reduction potentials of a range of mitigation options into actual improved emission outcomes.

12.6.1 Institutional and governance constraints and opportunities

The governance and institutional requirements most relevant to changing urban form and integrated infrastructure in urban areas relate to spatial planning. The nature of spatial planning varies significantly across countries, but in most national contexts, a framework for planning is provided by state and local governments. Within these frameworks, municipal authorities have varying degrees of autonomy and authority. Furthermore, there are often divisions between land use planning, where municipalities have the authority for land regulation within their jurisdiction, and transportation planning (which is either centrally organized or done in a cross-cutting manner), in which municipal responsibilities are often more limited. Thus, spatial planning is one area where municipalities have both the authority and the institutions to address GHG emissions.

However, the best plans for advancing sustainable urbanization and low-carbon development, especially in fast-growing parts of the world, will not become a reality unless there is both the political will and institutional capacity to implement them. The ability to manage and respond to escalating demands for urban services and infrastructure is often limited in developing country cities. Multiple institutional shortcomings exist, such as an insufficiently trained and undereducated civil service talent pool or the absence of a transparent and corruption-free procurement process for providing urban infrastructure (UN-Habitat, 2013). For example, limited experience with urban management, budgeting and accounting, urban planning, finance, and project supervision have thwarted Indonesia's decentralization of infrastructure programmes from the central to local governments over the past decade (Cervero, 2013).

Although lack of coordination among local land management and infrastructure agencies is also a common problem in cities of industrialized countries (Kennedy et al., 2005), in developing cities institutional fragmentation undermines the ability to coordinate urban services within and across sectors (Dimitriou, 2011). Separating urban sector functions into different organizations—each with its own boards, staff, budgets, and by-laws—often translates into uni-sectoral actions and missed opportunities, such as the failure to site new housing projects near public transport stations. In addition, ineffective bureaucracies are notorious for introducing waste and delays in the deployment of urban transport projects.

In rapidly urbanizing cities, limited capacities and the need to respond to everyday crises often occupy most of the available time in transportation and public utility departments, with little attention left to strategically plan for prevention of such crises in the first place. As a result, strategic planning and coordination of land use and transportation across different transport modes is practically non-existent. Institutions rarely have sufficient time or funds to expand transport infrastructure fast enough to accommodate the exponential growth in travel. Public utilities for water and sanitation face similar challenges, and most local agencies operate constantly in the catch-up mode. Water utilities in southeast Asian cities, for example, are so preoccupied with fixing leaks, removing illegal connections, and meeting water purity standards that there is little time to strategically plan ahead for expanding trunk-line capacities in line with urban population growth projections. The ability to advance sustainable transport programmes, provide clean water connections, or introduce efficient pricing schemes implies the presence of conditions that rarely exist, namely a well-managed infrastructure authority that sets clear, measurable objectives and rigorously appraises the expenditure of funds in a transparent and accountable way (Cervero, 2013). Lack of local institutional capacity among developing cities is a major barrier to achieving the full potential that such cities have to reduce GHG emissions (UN-Habitat, 2013). This highlights the urban institutional climate conundrum that rapidly urbanizing cities—cities with the greatest potential to reduce future GHG emissions—are the cities where the current lack of institutional capacity will most obstruct mitigation efforts.

Curitiba, Brazil, regarded as one of the world's most sustainable cities, is a product of not only visionary spatial planning but also strong institutions and political leadership (see Box 12.6.). Other global cities are striving to follow Curitiba's lead. Bangkok recently announced a paradigm shift in planning that emphasizes redesigning the city to eliminate or shorten trips, creating complete streets, and making the city more liveable (Bangkok Metropolitan Administration, 2013). The Amman, Jordan, Master Plan of 2008 promotes high-density, mixed-use development through the identification of growth centres, intensification along select corridors across the city, and the provision of safe and efficient public transportation (Beauregard and Marpillero-Colomina, 2011). Similar transit-oriented master plans have been prepared for Islamabad, Delhi, Kuala Lumpur, and Johannesburg in recent years. Mexico City has aggressively invested in BRT and bicycle infrastructure to promote both a culture and built form conducive to sustainable mobility (Mejía-Dugand et al., 2013).

In addition to the internal institutional challenges outlined above, cities face the problem of coordinating policies across jurisdictional boundaries as their populations grow beyond the boundaries of their jurisdictions. Effective spatial planning and infrastructure provision requires an integrated metropolitan approach that transcends traditional municipal boundaries, especially to achieve regional accessibility. The fragmented local government structure of metropolitan areas facilitates the conversion of agricultural, forested, or otherwise undeveloped land to urban uses. These expanding urban areas also exhibit fiscal weaknesses, face heightened challenges of metropolitan transportation, and deficiencies in critical physical and social infrastructures (Rusk, 1995; Norris, 2001; Orfield, 2002; McCarney and Stren, 2008; Blanco et al., 2011; McCarney et al., 2011). Several efforts to address urban climate change mitigation at a metropolitan scale are emerging. The U.S. state of California, for example, is requiring metropolitan transportation agencies to develop climate change mitigation plans in concert with municipalities in their region. California's 2008 Sustainable Communities and Climate Protection Act, or SB 375, was the first legislation in the United States to link transportation and land use planning with climate change (State of California, 2008; Barbour and Deakin, 2012).

In order for integrated planning development to be successful, it must be supported at national levels (Gakenheimer, 2011). A recent example is India's National Urban Transport Policy of 2006, which embraces integrated transport and land use planning as its top priority. In this policy, the central government covers half the costs of preparing integrated transport and land use plans in Indian cities. Another example is that for the past 25 years, Brazil has had a national urban transport policy that supports planning for sustainable transport and urban growth in BRT-served cities like Curitiba and Belo Horizonte.

Box 12.6 | Sustainable Curitiba: Visionary planning and strong institutions

Developing cities such as Curitiba, Brazil, well-known for advancing sustainable transport and urbanism, owe part of their success to strong governance and institutions (Cervero, 2013). Early in Curitiba's planning process, the Instituto de Pesquisa e Planejamento Urbano de Curitiba (IPPUC) was formed and given the responsibility of ensuring the integration of all elements of urban growth. Creative design elements, such as the trinary corridors (shown in Figure 12.19) that concentrate vertically mixed development along high-capacity dedicated busways and systematically taper densities away from transit corridors, were inventions of IPPUC's professional staff. As an independent planning and research agency with dedicated funding support, IPPUC is insulated from the whims of day-to-day politics and able to cost effectively coordinate urban expansion and infrastructure development. Sustained political commitment has been another important element of Curitiba's success. The harmonization of transport and urban development took place over 40 years, marked by a succession of progressive, forward-looking, like-minded mayors who built on the work of their predecessors. A cogent long-term vision and the presence of a politically insulated regional planning organization, IPPUC, to implement the vision have been crucial in allowing the city to chart a sustainable urban pathway.

However, urban governance of land use and transport planning is not the sole province of municipal authorities or other levels of government. Increasingly, private sector developers are creating their own strategies to govern the nature of urban development that exceed codes and established standards. These strategies can relate both to the physical infrastructure being developed (e.g., the energy rating of housing on a particular development) or take the form of requirements and guides for those who will occupy new or refurbished developments (e.g., age limits, types of home appliance that can be used, energy contracts, and education about how to reduce GHG emissions). Non-governmental organizations (NGOs) aimed at industry groups, such as the U.S. Green Building Council, the Korea Green Building Certification Criteria, and UK's Building Research Establishment Environmental Assessment Method (BREEAM) have also become important in shaping urban development, particularly in terms of regeneration and the refurbishment or retrofitting of existing buildings. For example, this is the case in terms of community-based organizations in informal settlements, as well as in the redevelopment of brownfield sites in Europe and North America.

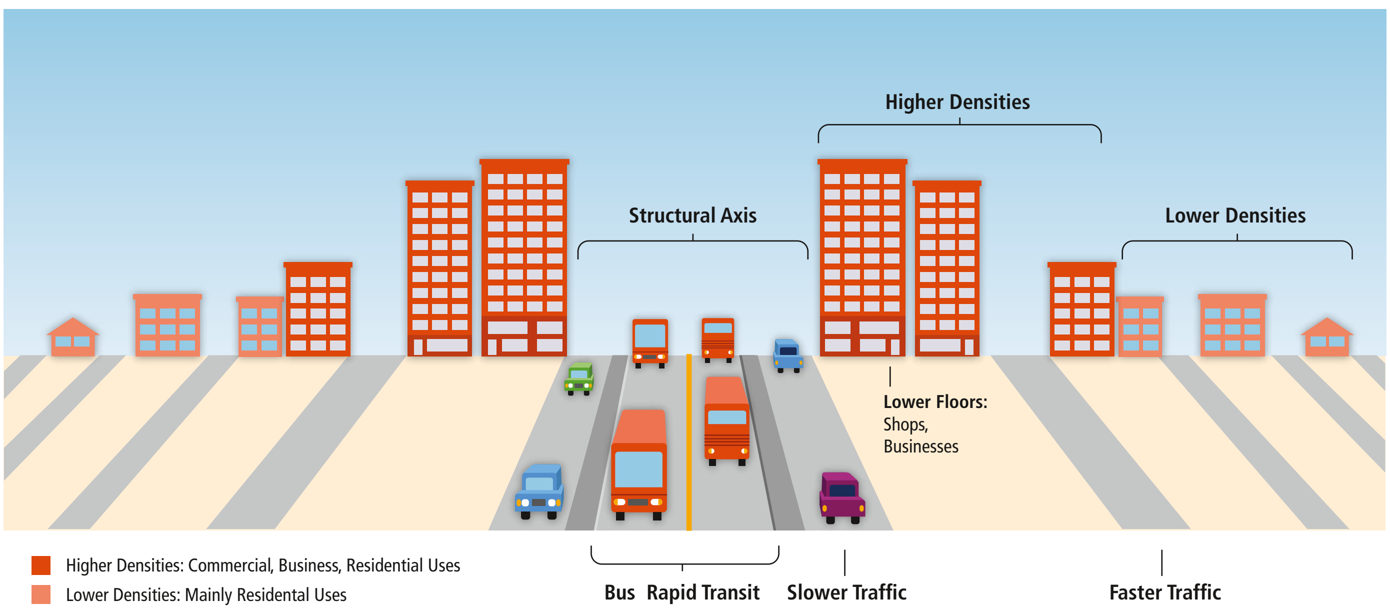

Figure 12.19 | Curitiba's stylized trinary road system. The inclusion of mixed land uses and affordable housing allows developers to increase building heights, adding density to the corridor. Source: Suzuki et al. (2013).

12.6.2 Financing urban mitigation

Urban infrastructure financing comes from a variety of sources, some of which may already be devoted to urban development. Some of these include direct central government budgetary investments, intergovernmental transfers to city and provincial governments, revenues raised by city and provincial governments, the private sector or public-private partnerships, resources drawn from the capital markets via municipal bonds or financial intermediaries, risk management instruments, and carbon financing. Such sources provide opportunities for urban mitigation initiatives (OECD, 2010b), but access to these financial resources varies from one place to another.

In many industrialized countries, national and supra-national policies and programmes have provided cities with the additional financing and facilitations for urban climate change mitigation. Where the national commitment is lacking, state and municipal governments can influence mitigation initiatives at the city scale. Cities in emerging economies are also increasingly engaging in mitigation, but they often rely on international sources of funding. GHG abatement is generally pursued as part of the urban development efforts required to improve access to infrastructure and services in the fast-growing cities of developing countries, and to increase the liveability of largely built-out cities in industrialized countries. Incorporating mitigation into urban development has important financial implications, as many of the existing or planned urban investments can be accompanied through requirements to meet certain mitigation standards (OECD, 2010b). As decentralization has progressed worldwide (the average share of sub-national expenditure in OECD countries reached 33 % in 2005), regional and local governments increasingly manage significant resources.

Local fiscal policy itself can restrict mitigation efforts. When local budgets rely on property taxes or other taxes imposed on new development, there is a fiscal incentive to expand into rural areas or sprawl instead of pursuing more compact city strategies (Ladd, 1998; Song and Zenou, 2006). Metropolitan transportation policies and taxes also affect urban carbon emissions. Congestion charges reduce GHG emissions from transport by up to 19.5 % in London where proceeds are used to finance public transport, thus combining global and local benefits very effectively (Beevers and Carslaw, 2005). Parking charges have led to a 12 % decrease of vehicle miles of commuters in U.S. cities, a 20 % reduction in single car trips in Ottawa, and a 38 % increase of carpooling in Portland (OECD, 2010c).

Another way to think about the policy instruments available to governments for incentivizing GHG abatement is to consider each instrument's potential to generate public revenues or demand for government expenditures, and the administrative scale at which it can be applied (Figure 12.20). Here, the policy instruments discussed earlier (Table 12.5) are categorized into four groups: (1) regulation; (2) taxation/charge; (3) land-based policy; and (4) capital investment. Many of these are applicable to cities in both the developed and developing countries, but they vary in degree of implementation due to limited institutional or governance capacities. Overcoming the lack of political will, restricted technical capacities, and ineffective institutions for regulating or planning land use will be central to attaining low-carbon development at a city-scale.

Fiscal crises along with public investment, urban development, and environmental policy challenges in both developed and developing counties have sparked interest in innovative financial instruments to affect spatial development, including a variety of land-based techniques (Peterson, 2009). One of these key financial/economic mechanisms is land value capture. Land value capture consists of financing the construction of new transit infrastructures using the profits generated by the land value price increase associated with the presence of new infrastructure (Dewees, 1976; Benjamin and Sirmans, 1996; Batt, 2001; Fensham and Gleeson, 2003; Smith and Gihring, 2006). Also called windfall recapture, it is a local financing option based on recouping a portion or all of public infrastructure costs from private land betterments under the 'beneficiary' principle. In contrast, value compensation, or wipeout mitigation, is commonly viewed as a policy tool to alleviate private land worsements—the deterioration in the value or usefulness of a piece of real property—resulting from public regulatory activities (Hagman and Misczynski, 1978; Callies, 1979).

The majority of the value capture for transit literature use U.S. cities as case studies in part because of the prevalence of low-density, automobile-centred development. However, there is an emerging literature on value capture financing that focus on developing country cities, which tend to be denser than those in OECD countries, and where there are more even shares of distinct travel modes (Cervero et al., 2004). Value capture typically is used for public transit projects. There are various ways to implement value capture, including: land and property taxes, special assessment or business improvement districts, tax increment financing, development impact fees, public land leasing and development right sales, land readjustment programmes, joint developments and cost/benefit sharing, connection fees (Johnson and Hoel, 1985; Landis et al., 1991; Bahl and Linn, 1998; Enoch et al., 2005; Smith and Gihring, 2006). There is much evidence that public transit investments often increase land values around new and existing stations (Du and Mulley, 2006; Debrezion et al., 2007).

In summary, the following are key factors for successful urban climate governance: (1) institutional arrangements that facilitate the integration of mitigation with other high-priority urban agendas; (2) an enabling multilevel governance context that empowers cities to promote urban transformations; (3) spatial planning competencies and political will to support integrated land-use and transportation planning; and (4) sufficient financial flows and incentives to adequately support mitigation strategies.

12.7 Urban climate mitigation: Experiences and opportunities

This section identifies the scale and range of mitigation actions being planned by municipal governments and assesses the evidence of successful implementation of the plans as well as barriers to further implementation. The majority of studies reviewed pertain to large

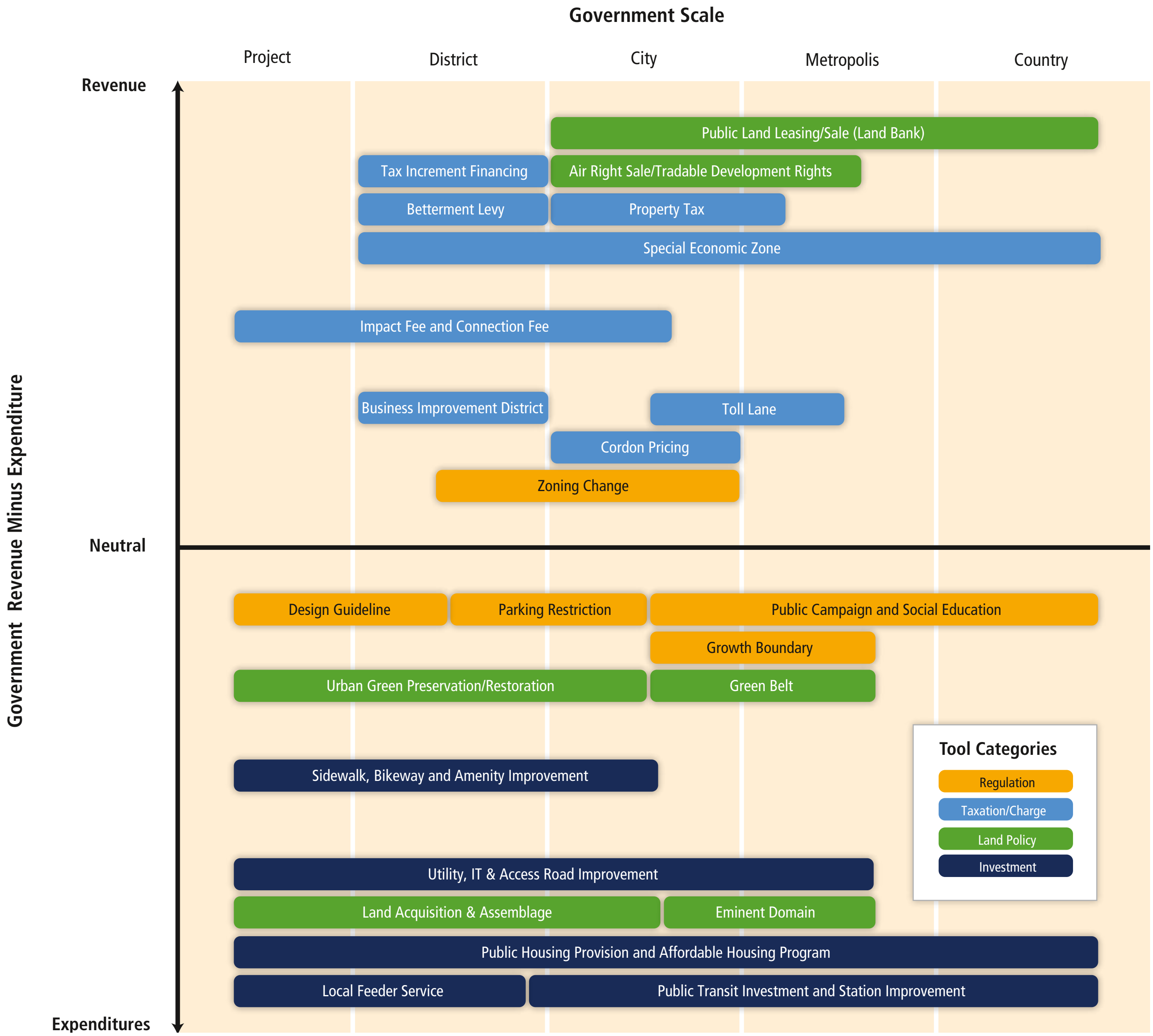

Figure 12.20 | Key spatial planning tools and effects on government revenues and expenditures across administrative scales. Figure shows four key spatial planning tools (coded in colours) and the scale of governance at which they are administered (x-axis) as well as how much public revenue or expenditure the government generates by implementing each instrument (y-axis).

Sources: Bahl and Linn (1998); Bhatt (2011); Cervero (2004); Deng (2005); Fekade (2000); Rogers (1999); Hong and Needham (2007); Peterson (2009); Peyroux (2012); Sandroni (2010); Suzuki et al. (2013); Urban LandMark (2012); U.S. EPA (2013); Weitz (2003).

cities in North America, Japan, and Europe, although there are some cross-city comparisons and case studies that include smaller cities in industrialized economies (Yalçın and Lefèvre, 2012; Dierwechter and Wessells, 2013) and cities in developing countries and emerging economies (Romero Lankao, 2007; Pitt, 2010).

Addressing climate change has become part of the policy landscape in many cities, and municipal authorities have begun to implement policies to reduce GHG emissions generated from within their administrative boundaries (Acuto, 2013; OECD, 2010a). The most visible way in which cities undertake mitigation is under the auspices of a climate action plan—a policy document created by a local government agency that sets out a programme of action to mitigate greenhouse gas emissions. Usually such plans include a GHG emissions inventory and an emissions reduction target, as well as a series of mitigation policies.

This section focuses on such climate action plans, as they provide the most comprehensive and consistent, albeit limited, evidence available regarding urban mitigation efforts. However, there is not a one-to-one correspondence between climate action plans and urban mitigation efforts. Even when included in climate action plans, mitigation measures may well have been implemented in the plan's absence, whether for climate-related or other reasons (Millard-Ball, 2012b). Conversely, climate action plans are only one framework under which cities plan for mitigation policies, and similar recommendations may also occur as part of a municipal sustainability, land-use, or transport plan (Bulkeley and Kern, 2006; GTZ, 2009; Bassett and Shandas, 2010). In these other types of plans, climate change may be one motivation, but mitigation measures are often pursued because of co-benefits such as local air quality (Betsill, 2001; Kousky and Schneider, 2003).

12.7.1 Scale of urban mitigation efforts

The number of cities that have signed up to voluntary frameworks for GHG emission reductions has increased from fewer than 50 at the start of the 1990s to several hundred by the early 2000s (Bulkeley and Betsill, 2005), and several thousand by 2012 (Kern and Bulkeley, 2009; Pitt, 2010; Krause, 2011a). These voluntary frameworks provide technical assistance and political visibility. They include the C40 Cities Climate Leadership Group (C40), which by October 2013 counted most of the world's largest cities among its 58 affiliates (C40 Cities, 2013), the Cities for Climate Protection (CCP) Campaign, and the 2013 European Covenant of Mayors, which had over 5,200 members representing over 170 million people, or roughly one-third of the European population (The Covenant of Mayors, 2013). In the United States, nearly 1,100 municipalities, representing approximately 30 % of the country's population, have joined the U.S. Conference of Mayors Climate Protection Agreement, thus committing to reduce their local GHG emissions to below 1990 levels (Krause, 2011a).

Such estimates represent a lower bound, as cities may complete a climate action plan or undertake mitigation outside one of these voluntary frameworks. In California in 2009, 72 % of cities responding

Box 12.7 Urban climate change mitigation in less developed countries

The majority of future population growth and demand for new infrastructure will take place in urban areas in developing countries. Africa and Asia will absorb the bulk of the urban population growth, and urbanization will occur at lower levels of economic development than the urban transitions that occurred in Annex I countries. There are currently multiple urban transitions taking place in developing countries, with differences in part due to their development histories, and with different impacts on energy use and greenhouse gas emissions.

Urban areas in developing and least developed countries can have dual energy systems (Martinot et al., 2002; Berndes et al., 2003). That is, one segment of the population may have access to modern energy and associated technology for heating and cooking. Another segment of the population—mainly those living in informal settlements—may rely mainly on wood-based biomass. Such non-commercial biomass is a prominent source in the urban fuel mix in Sub-Saharan Africa (50 %) and in South Asia (23 %). In other regions, Latin America and the Caribbean (12 %), Pacific Asia (8 %) and China (7 %) traditional, non-commercial energy is not negligible but a relatively smaller proportion of overall energy portfolio (Grubler et al., 2012). The traditional energy system operates informally and inefficiently, using out-dated technology. It can be associated with significant health impacts (see Section 9.7.3 in this report as well as Chapters 2 and 9 in IPCC, 2011). The unsustainable harvesting of woodfuels to supply large urban and industrial markets is significantly contributing to forest degradation and coupled with other land-use changes to deforestation (see Chapter 11). However, recent technological advances suggest that energy production from biomass can be an opportunity for low carbon development (Zeng et al., 2007; Fargione et al., 2008; Hoekman, 2009; Azar et al., 2010). Projections of significant growth in woodfuel demand (Mwampamba, 2007; Zulu, 2010; Agyeman et al., 2012) make it vital that this sector is overhauled and modernized using new technologies, approaches, and governance mechanisms.

Additionally, informal urbanization may not result in an increase in the provision of infrastructure services. Rather, unequal access to infrastructure, especially housing and electricity, is a significant problem in many rapidly growing urban centres in developing countries and shapes patterns of urban development. Mitigation options vary by development levels and urbanization trajectories. The rapid urbanization and motorization occurring in many developing and least developed countries is constrained by limited infrastructure and deteriorating transport systems. Integrated infrastructure development in these areas can have greater effects on travel demands and low-emission modal choices than in high-income countries, where infrastructure is largely set in place (see Chapter 8.9). The scale of new building construction in developing countries follows a similar path. An estimated 3 billion people worldwide rely on highly polluting and unhealthy traditional solid fuels for household cooking and heating (Pachauri et al., 2012; IEA, 2012)and shifting their energy sources to electricity and clean fuels could strongly influence building-related emissions reductions (see Box 9.1 and Section 14.3.2.1). Thus, it is in developing and least developed country cities where opportunities for integrated infrastructure and land-use planning may be most effective at shaping development and emissions trajectories, but where a 'governance paradox' exists (see Section 12.3.1).

to a survey stated they had adopted policies and/or programmes to address climate change, but only 14 % had adopted a GHG reduction target (Wang, 2013). In some countries, climate action plans are mandatory for local governments, further adding to the total. For example, in Japan, the Global Warming Law and the Kyoto Protocol Target Achievement Plan mandate that 1,800 municipal governments and 47 Prefectures prepare climate change mitigation action plans (Sugiyama and Takeuchi, 2008). In France, climate action plans are mandatory for cities with populations larger than 50,000 (Yalçın and Lefèvre, 2012). Climate action planning has been most extensive in cities in Annex I countries, particularly those in Europe and Japan. This presents a mismatch between the places with mitigation planning efforts and the places where most urban growth will occur—and where the greatest mitigation potential exists—largely in developing countries that are rapidly urbanizing.

12.7.2 Targets and timetables

One way to assess the scale of planned mitigation is through the emission reduction targets set by cities, typically as part of their climate action plans. A central feature of municipal climate change responses is that targets and timetables have frequently exceeded national and international ambitions for emissions reduction. In Germany, nearly 75 % of cities with a GHG target established their emissions goals based on national or international metrics rather than on a local analysis of mitigation options and the average city reduction target of 1.44 % per year exceeds the national target (Sippel, 2011). In the United States, signatories to the Mayors Climate Protection Agreement have pledged to reduce GHG emissions by 7 % below 1990 levels by 2012, in line with the target agreed upon in the Kyoto Protocol for the United States (Krause, 2011b). Lutsey and Sperling (2008) find that these and other targets in 684 U.S. cities would reduce total emissions in the United States by 7 % below the 2020 business-as-usual (BAU) baseline.

In Europe and Australia, several municipalities have adopted targets of reducing GHG emissions by 20 % by 2020 and long-term targets for radically reducing GHG emissions, including 'zero-carbon' targets in the City of Melbourne and Moreland (Victoria), and a target of 80 % reduction over 1990 levels by 2050 in London (Bulkeley, 2009). This approach has not been limited to cities in developed economies. For example, the city of Cape Town has set a target of increasing energy efficiency within the municipality by 12 % by 2010 (Holgate, 2007), and Mexico City has implemented and achieved a target of reducing 7 million tons of GHG from 2008 to 2012 (Delgado-Ramos, 2013). Data compiled for this assessment, although illustrative rather than systematic, indicate an average reduction of 2.74 t CO_2eq/cap if cities were to achieve their targets, with percentage targets ranging from 10 % to 100 %. In general, percentage reduction targets are larger for more distant years and in more affluent cities. However, the absolute level of the targeted reductions depends primarily on the city's population and other determinants of baseline emissions (Figure 12.21.).

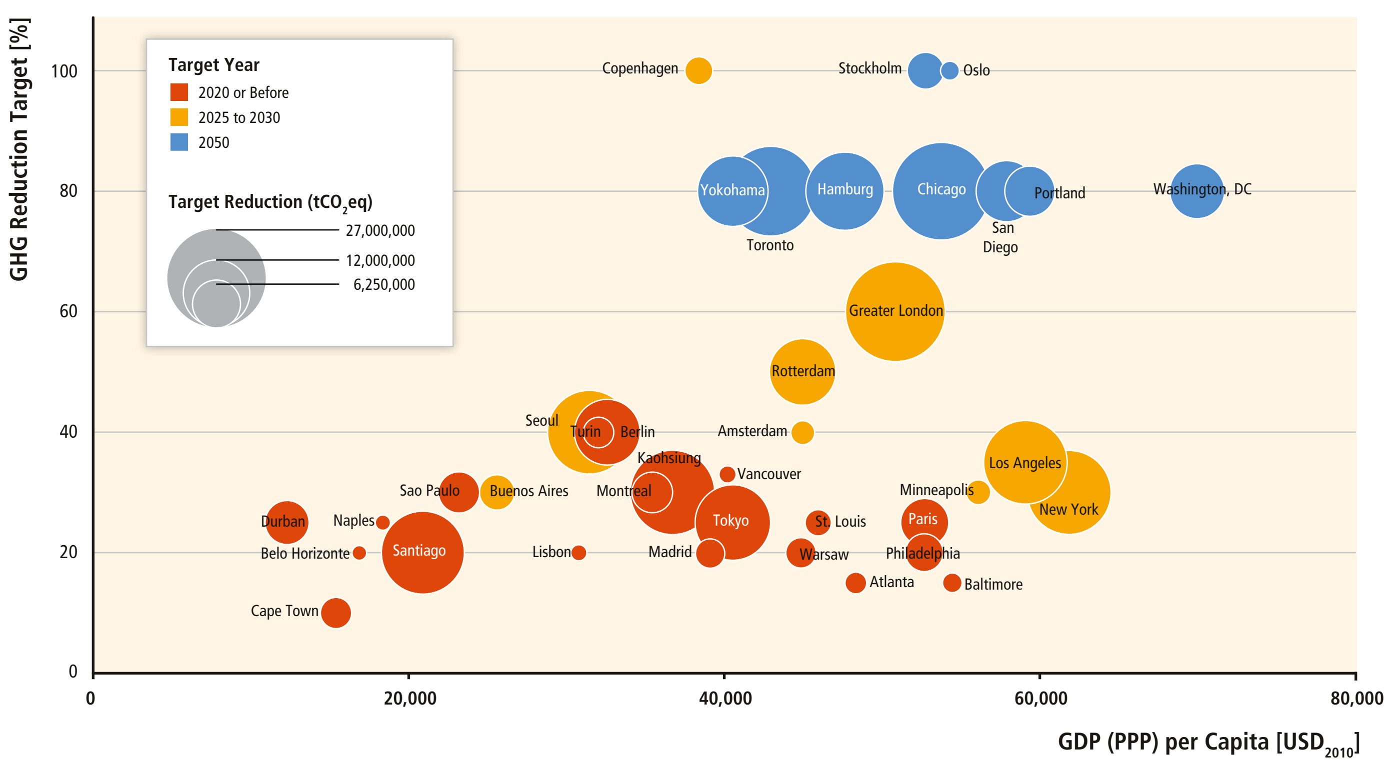

Figure 12.21 | Mitigation targets for 42 cities. Sources: Baseline emissions, reduction targets, and population from self-reported data submitted to Carbon Disclosure Project (2013). GDP data from Istrate & Nadeau (2012). Note that the figure is illustrative only; data are not representative, and physical boundaries, emissions accounting methods and baseline years vary between cities. Many cities have targets for intermediate years (not shown).

In some cases, targets may reflect patterns of potential mitigation. Targets are often arbitrary or aspirational, and reflect neither mitigation potential nor implementation. How targets translate into mitigation effort also depends on how they are quantified, e.g., whether fuel economy and similar improvements mandated at the national level are claimed by cities as part of their own reductions (Boswell et al., 2010; DeShazo and Matute, 2012). Mitigation targets are often set in absolute terms, which may be less meaningful than per-capita reductions in assessing mitigation potential at the metropolitan scale. This is a particularly important issue for central cities and inner suburbs, where population and emissions may increase within the city boundary if policies to increase density and compactness are successful (see Section 12.4; Ganson, 2008; Salon et al., 2010).

Many cities, particularly those in developing countries, do not set targets at all. For example, the Delhi Climate Change Agenda only reports Delhi's CO_2 emissions from power, transport, and domestic sectors as 22.49 $MtCO_2$ for 2007—2008 (Government of NCT of Delhi, 2010), while the contributions from commercial sectors and industries comprise a larger share of the city's total emissions. Furthermore, Delhi's climate action plan lacks clear GHG reduction targets, an analysis of the total carbon reductions projected under the plan, and a strategy for how to achieve their emissions goals. Similar limitations are apparent in mitigation plans for other global cities such as Bangkok and Jakarta (Dhakal and Poruschi, 2010). For many cities in developing countries, a reliable city GHG inventory may not exist, making the climate change actions largely symbolic. However, these city action plans provide a foundation for municipal engagement in mitigation initiatives while building momentum for collective action on a global scale.

12.7.3 Planned and implemented mitigation measures

Limited information is available on the extent to which targets are being achieved or emissions reduced. Some cities have already achieved their initial GHG reduction targets, e.g., Seattle (Boswell et al., 2011), or are on track to do so, e.g. Stockholm (City of Stock-

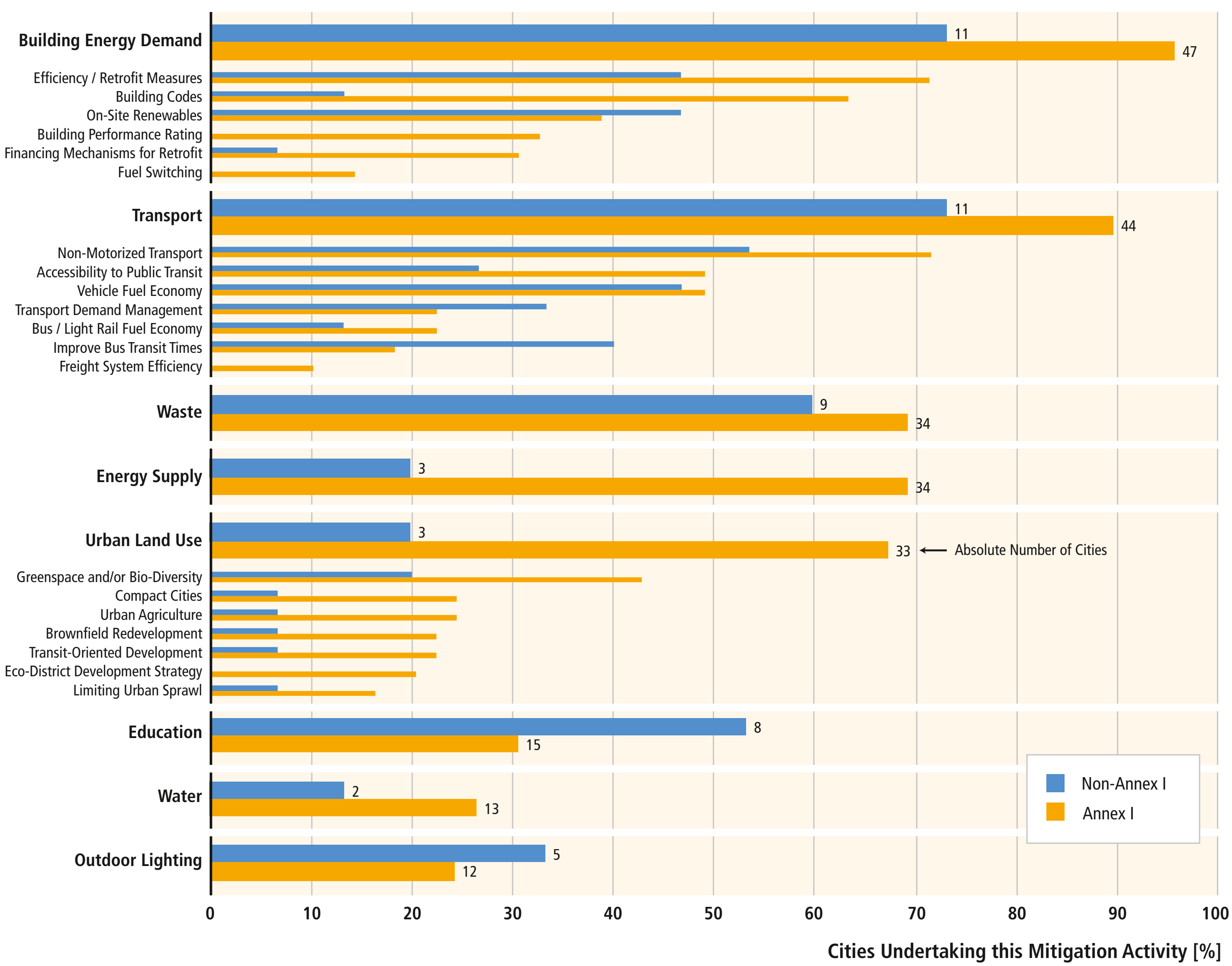

Figure 12.22 | Mitigation measures in climate action plans. Sources: Compiled for this assessment from self-reported data submitted to Carbon Disclosure Project (2013).

holm, 2013). In other places such as western Germany, few if any cities are likely to meet their targets (Sippel, 2011). Further data come from comparison of 'before' and 'after' GHG inventories. One study of six major cities found that emissions are falling by an average 0.27 t CO_2eq/cap per year (Kennedy et al., 2012). Overall, however, the available data are usually incomplete, self-reported, and subject to various biases. More fundamentally, changes in aggregate emissions do not necessarily reflect the success or failure to implement mitigation measures, because so many drivers of emissions—including the electricity generation mix and fuel taxation—are normally beyond the control of cities (DeShazo and Matute, 2012). Whether a city achieves its target has less to do with its own actions and more to do with external drivers of emissions.

An alternative way to gauge the extent of planned and implemented mitigation measures is through a bottom-up analysis of individual policies (Ramaswami et al., 2012a) or sector-specific data on green buildings, transport, or waste production (Millard-Ball, 2012a). However, there are no data from a large number of cities using these methods. Instead, available data are usually in the form of self-reported planned or implemented policies (Krause, 2011c; Castán Broto and Bulkeley, 2012; Stone et al., 2012; Bedsworth and Hanak, 2013). While these data do not reveal aggregate emission reductions, they indicate the sectoral breadth of city climate action plans and the types of measures that cities are planning. No single sector dominates mitigation plans, although transportation and building efficiency are the most common self-reported measures (Figure 12.22). Here it is worth noting that the relative contribution of sectors to total urban emissions varies greatly by city (see Section 12.3).

The types of land-use strategies discussed in Section 12.5, such as compact development, are sometimes included in municipal efforts or plans, but the popularity of such land-use measures varies considerably by context. In California, 80 % of municipal survey respondents reported that they had policies for high-density or mixed-use development in place or under consideration, and the adoption of such land-use policies rose substantially between 2008 and 2010 (Bedsworth and Hanak, 2013). In the United States, 70 % of climate action plans reviewed in one study include compact development strategies (Bassett and Shandas, 2010). In contrast, municipal climate plans in Norway and Germany focus on energy, transport and building efficiency, with little attention given to land use (Aall et al., 2007; Sippel, 2011). At a global level, self-reported data from a small sample of cities (Figure 12.22) suggests that land-use measures are relatively uncommon in climate action plans—particularly outside Annex I countries. Moreover, where land-use strategies exist, they focus on urban greenspace and/or biodiversity, rather than on the cross-sectoral measures to reduce sprawl and promote TOD that were discussed in Section 12.5.

Even if land use measures are listed in climate action plans, implementation has focused on win-win energy efficiency measures that lead to cost savings, rather than larger changes to land use, buildings or transport. This is a consistent message from qualitative studies (Kousky and Schneider, 2003; Rutland and Aylett, 2008; Kern and Bulkeley, 2009), and some larger surveys of city efforts (Wang, 2013). There has been less engagement by municipalities with sectors such as energy and water supply that often lie outside of their jurisdiction (Bulkeley and Kern, 2006; ARUP, 2011) or with the GHG emissions embodied in present patterns of urban resource use and consumption. More broadly, there is considerable variation in the nature and quality of climate change plans, particularly when it comes to specifying the detail of actions and approaches to implementation (Wheeler, 2008; Tang et al., 2011; Bulkeley and Schroeder, 2012).

Despite the implementation of comprehensive climate action plans and policies, progress for cities in developed countries is slow and the achievability of emissions targets remains uncertain. Although municipalities often highlight progress on mitigation projects, the impacts of these initiatives are not often evaluated (see Chapter 15 on policy evaluation). Cities' mitigation reduction performance is largely correlated to the national performance in mitigation reduction.

12.8 Sustainable development, co-benefits, trade-offs, and spill-over effects

Sustainable development (SD) is, and has always been, closely associated with human settlements. In fact, the very document that coined the phrase, the World Commission on Environment and Development (WCED) Report (WCED 1987), devoted a chapter to 'the urban challenge'. While averting the adverse social and environmental effects of climate change remains at the core of the urban challenge today, cities throughout the world also continue to struggle with a host of other critical challenges, including, for instance, ensuring access to clean, reliable and affordable energy services for their citizens (particularly for the urban poor); limiting congestion, noise, air and water pollution, and health and ecosystem damages; and maintaining sufficient employment opportunities and competitiveness in an increasingly globalized world.

Efforts to mitigate climate change will have important side-effects for these various policy objectives, as discussed in Sections 5.7, 6.6, 7.9, 8.7, 9.7, 10.8, 11.7 and 11.A.6. To the extent these side-effects are positive, they can be deemed 'co-benefits'; if adverse, they imply 'risks'.[3] As such side-effects are likely to materialize first in urban settings since these are the hubs of activity, commerce, and culture in

[3] Co-benefits and adverse side-effects describe co-effects without yet evaluating the net effect on overall social welfare. Please refer to the respective sections in the framing chapters as well as to the glossary in Annex I for concepts and definitions—particularly Sections 2.4, 3.6.3, and 4.8.2.

Table 12.6 | Potential co-benefits (green arrows) and adverse side-effects (orange arrows) of urban mitigation measures. Arrows pointing up/down denote a positive/negative effect on the respective objective or concern. The effects depend on local circumstances and the specific implementation strategy. For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e. g., on energy prices, consumption, growth, and trade), see Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. Numbers correspond to references listed below the table.

Mitigation measures	Effect on additional objectives/concerns		
	Economic	**Social (including health)**	**Environmental**
Compact development and infrastructure	↑ Innovation and productivity[1]	↑ Health from increased physical activity[3]	↑ Preservation of open space[4]
	↑↑ Higher rents & residential property values[2]		
	↑ Efficient resource use and delivery[5]		
Increased accessibility	↑ Commute savings[6]	↑ Health from increased physical activity[3]	↑ Air quality and reduced ecosystem and health impacts[8]
		↑ Social interaction and mental health[7]	
Mixed land use	↑ Commute savings[6]	↑ Health from increased physical activity[3]	↑ Air quality and reduced ecosystem and health impacts[8]
	↑↑ Higher rents & residential property values[2]	↑ Social interaction and mental health[7]	

References: **1:** Ciccone and Hall (1996), Carlino et al. (2007); **2:** Mayer and Somerville (2000), Quigley and Raphael (2005), Glaeser et al. (2006), Koster and Rouwendal (2012); **3:** Handy et al. (2002), Frank et al. (2004, 2009), Heath et al. (2006), Forsyth et al. (2007), Owen et al. (2007); **4:** Brueckner (2000), Bengston et al. (2004), **5:** Speir and Stephenson (2002), Guhathakurta and Gober (2007); **6:** Krizek (2003), Cervero and Duncan (2006), Ma and Banister (2006), Day and Cervero (2010); **7:** Galea et al. (2005), Berke et al. (2007), Duncan et al. (2013); **8:** Campbell-Lendrum and Corvalán (2007), Creutzig and He (2009), Milner et al. (2012), Puppim de Oliveira et al. (2013).

the modern world: this section will focus on the literature specifically linked to urban settings and refer to other sections of the report where appropriate.

Action on climate change mitigation often depends on the ability to 'reframe' or 'localize' climate change with respect to the co-benefits that could be realized (Betsill, 2001). For example, in Canada "actions to reduce GHG emissions are also deeply connected to other goals and co-benefits such as human health improvements through improved air quality, cost savings, adaptability to real or potential vulnerabilities due to climate change, and overall improvements in short, medium and long-term urban sustainability" (Gore et al., 2009). Sometimes called 'localizing' or 'issue bundling' (Koehn, 2008), these reframing strategies have proven to be successful in marshalling local support and action in developing country cities, and will continue to be an important component of developing local capacity for mitigation (Puppim de Oliveira, 2009).

12.8.1 Urban air quality co-benefits

Worldwide, only 160 million people live in cities with truly clean air—that is, in compliance with World Health Organization (WHO) guidelines (Grubler et al., 2012) (Figure 12.23). Oxides of sulfur and nitrogen (SO_x and NO_x) and ozone (O_3)—i. e., outdoor air pollutants—are particularly problematic in cities because of high concentrations and exposures (Smith et al., 2012) (see Section 9.7 for a discussion of mitigation measures in the buildings sector on indoor air pollution and Section 7.9.2). Transport remains one of the biggest emitting sectors in the industrialized world. In developing countries, a wider range of sources is to blame, with vehicle emissions playing an ever increasing role also due to continuing urbanization trends (Kinney et al., 2011; Smith et al., 2012; see also Sections 5.3.5.1 and 8.2). In a study of four Indian megacities, for instance, gasoline and diesel vehicle emissions already comprise 20–50 % of fine particulate matter ($PM_{2.5}$) emissions (Chowdhury et al., 2007). The associated health burdens are particularly high in low-income communities due to high exposures and vulnerabilities (Campbell-Lendrum and Corvalán, 2007; Morello-Frosch et al., 2011).

Major air quality co-benefits can be achieved through mitigation actions in the urban context, especially in megacities in developing countries where outdoor air pollution tends to be higher than in urban centres in industrialized countries (Molina and Molina, 2004 and section 5.7). Urban planning strategies and other policies that promote cleaner fuels, transport mode shifting, energy cogeneration and waste heat recycling, buildings, transport and industry efficiency standards can all contribute to lower rates of respiratory and cardiovascular disease (improved human health) as well as decreased impacts on urban vegetation (enhanced ecosystems) via simultaneous reductions in co-emitted air pollutant species (Campbell-Lendrum and Corvalán, 2007; Creutzig and He, 2009; Milner et al., 2012; Puppim de Oliveira et al., 2013 and Sections 7.9, 8.7, 9.7, 10.8 as well as WGII AR5 Chapter 11.9).[4] Even an action like shading parking lots, which is generally thought of in the context of limiting the urban heat-island effect, can bring air pollution co-benefits through reductions in volatile organic compounds (VOC) and, thus, low-level ozone formation from parked vehicles (Scott et al., 1999).

4 Monetized health co-benefits are found to be larger in developing countries than industrialized countries, a finding that results from the currently higher pollution levels of the former and, thus, the greater potential for improving health, particularly in the transport and household energy demand sectors (Markandya et al., 2009; Nemet et al., 2010; West et al., 2013 and Section 5.7).

In the near-term (2030), air quality co-benefits of stringent mitigation actions (i.e., in line with achieving 450 ppm CO_2eq by 2100) can be quite substantial in a highly urbanized region like Europe; decarbonization and energy efficiency (largely in transport) could reduce aggregate NO_x emissions by a further 38 % relative to a baseline scenario that includes current and planned air quality legislation by 2030 but does not consider climate policies (Colette et al., 2012). Similar co-benefits have been reported for other pollutants in other regions (Rao et al., 2013), particularly in developing Asia (Doll and Balaban, 2013; Puppim de Oliveira et al., 2013) (see Section 6.6). The potential for realizing these co-benefits depends on institutional frameworks and policy agendas at both the local and national level, as well as the interplay between the two (see Doll et al., 2013, and Jiang et al., 2013, for reviews of India and China). At the same time, the increasing role of decentralized power generation could lead to adverse air quality side-effects if this trend is not coupled with a more intensive use of low-carbon energy supply (Milner et al., 2012).

12.8.2 Energy security side-effects for urban energy systems

Mitigating climate change could have important side-effects for urban energy security (sufficient resources and resilient supply)—concerns that have re-emerged in many cities throughout the world in recent years (see Sections 6.6.2.1 and 7.9.1 for a broader discussion of energy security concerns). Perhaps the greatest energy-related vulnerability in this context is the fact that urban transport systems are at present almost entirely dependent on oil (Cherp et al., 2012). This is especially true in low-density areas where reliance on private vehicles is high (Levinson and Kumar, 1997). Therefore, any mitigation activities leading to a diversification of the transport sector away from oil could potentially also contribute to a security co-benefit (see Jewell et al., 2013 and other references in Chapter 8.7.1). Such measures might range from technology standards (e.g., for vehicles and their fuels) to integrated infrastructure, spatial planning, and mass transit policies (Sections 12.5 and 8.10). Energy efficiency regulations for buildings and industrial facilities (both existing and new) can also help to enhance the resilience of fuel and electricity distribution networks (see Chapters 9.7 and 10.8).

12.8.3 Health and socioeconomic co-benefits

Spatial planning and TOD can yield other positive side-effects that may enhance a city's liveability. For example, mass transit requires considerably less physical space than private automobiles (transit: 0.75–2.5 m^2/cap; auto: 21–28 m^2/cap) and generally emits less noise (Grubler et al., 2012), with health co-benefits in terms of cardiovascular disease and sleep disturbance (Kawada, 2011; Ndrepepa and Twardella, 2011 see also 8.7; Milner et al., 2012).

Neighbourhoods with walkable characteristics such as connectivity and proximity of destinations are correlated with higher frequency of physical activity among residents (Frank et al., 2004; Owen et al., 2007), which is correlated with lower symptoms and incidences of depression (Galea et al., 2005; Berke et al., 2007; Duncan et al., 2013).

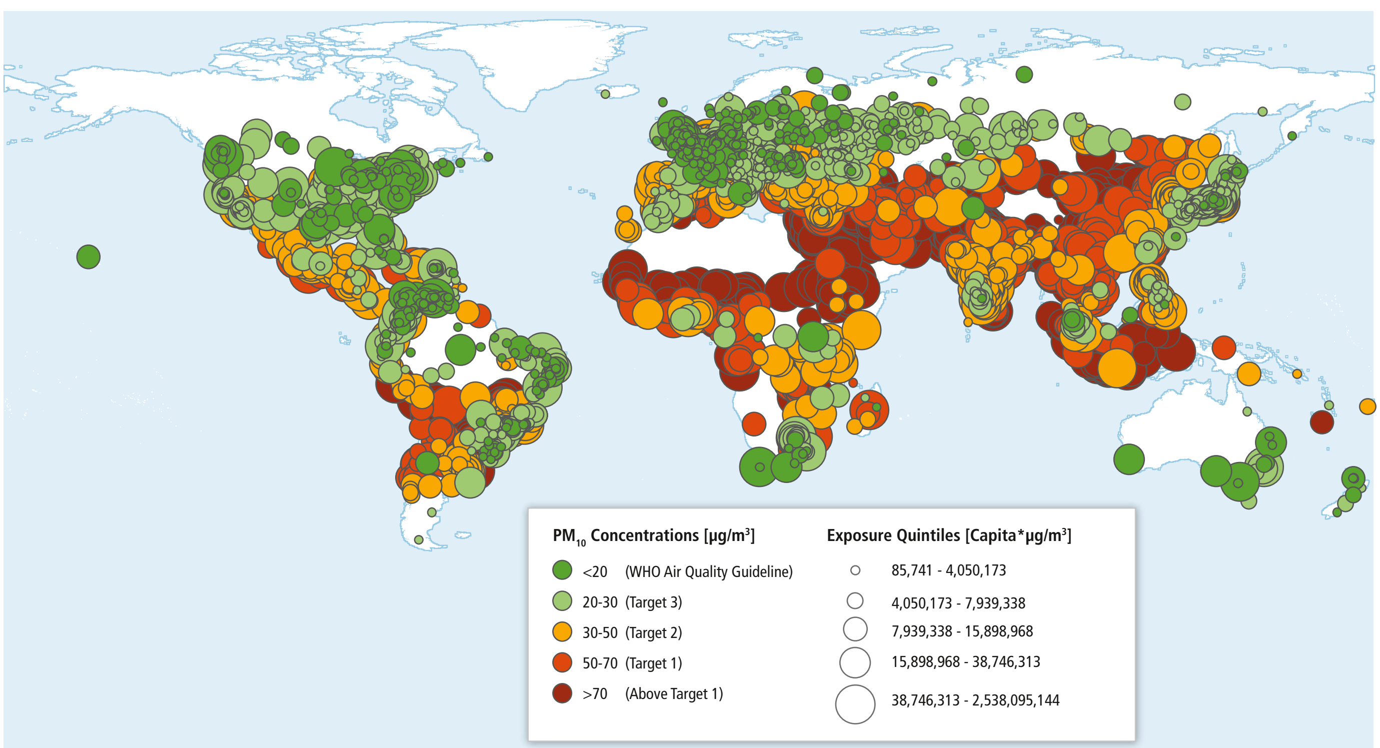

Figure 12.23 | Human risk exposure to PM_{10} pollution in 3200 cities worldwide. Source: Grubler et al.(2012) based on Doll (2009) and Doll and Pachauri (2010).

Compact neighbourhoods with more diversified land uses are correlated with higher housing prices and rents (Mayer and Somerville, 2000; Quigley and Raphael, 2005; Glaeser et al., 2006; Koster and Rouwendal, 2012). In a study of the Netherlands, neighbourhoods with more diverse land uses had a 2.5 % higher housing prices (Koster and Rouwendal, 2012).

12.8.4 Co-benefits of reducing the urban heat island effect

The urban heat island (UHI) effect presents a major challenge to urban sustainability (see WG II AR5 Chapter 8). Not only does UHI increase the use of energy for cooling buildings (and thus increasing the mitigation challenge) and thermal discomfort in urban areas, but UHI also increases smoggy days in urban areas, with smog health effects present above 32 °C (Akbari et al., 2001; O'Neill and Ebi, 2009; Mavrogianni et al., 2011; Rydin et al., 2012). Proven methods for cooling the urban environment include urban greening, increasing openness to allow cooling winds (Smith and Levermore, 2008), and using more 'cool' or reflective materials that absorb less solar radiation, i.e., increasing the albedo of the surfaces (Akbari et al, 2008; Akbari and Matthews, 2012). Reducing UHI is most effective when considered in conjunction with other environmental aspects of urban design, including solar/daylight control, ventilation and indoor environment, and streetscape (Yang et al., 2010). On a global scale, increasing albedos of urban roofs and paved surfaces is estimated to induce a negative radiative forcing equivalent to offsetting about 44 Gt of CO_2 emissions (Akbari et al., 2008).

Reducing summer heat in urban areas has several co-benefits. Electricity use in cities increases 2–4 % for each 1 °C increase in temperature, due to air conditioning use (Akbari et al., 2001). Lower temperatures reduce energy requirements for air conditioning (which may result in decreasing GHG emissions from electricity generation, depending upon the sources of electricity), reduce smog levels (Rosenfeld et al., 1998), and reduce the risk of morbidity and mortality due to heat and poor air quality (Harlan and Ruddell, 2011). Cool materials decrease the temperature of surfaces and increase the lifespan of building materials and pavements (Santero and Horvath, 2009; Synnefa et al., 2011).

The projected global mean surface temperature increases under climate change will disproportionally impact cities already affected by UHI, thereby increasing the energy requirements for cooling buildings and increasing urban carbon emissions, as well as air pollution (Mickley et al., 2004; Jacob and Winner, 2009). In addition, it is likely that cities will experience an increase in UHI as a result of projected increases in global mean surface temperature under climate change, which will result in additional global urban energy use, GHG emissions, and local air pollution. As reviewed here, studies indicate that several strategies are effective for decreasing the UHI. An effective strategy to mitigate UHI through increasing green spaces, however, can potentially conflict with a major urban climate change mitigation strategy, which is increasing densities to create more compact cities (Milner et al., 2012). This conflict illustrates the complexity of developing integrated and effective climate change policies for urban areas.

More generally, reducing UHI effects—either through mitigation measures (e.g., improved waste heat recycling, co-generation, use of reflective building materials, increased vegetation) or through mitigation—can have co-benefits for urban water supplies (e.g., cooling water for thermal or industrial plants, drinking water), given that evaporation losses rise as water bodies warm (Grubler et al., 2012).

12.9 Gaps in knowledge and data

This assessment highlights a number of key knowledge gaps:

- **Lack of consistent and comparable emissions data at local scales.** Although some emissions data collection efforts are underway, they have been undertaken primarily in large cities in developed countries. The lack of baseline data makes it particularly challenging to assess the urban share of global GHG emissions as well as develop urbanization and typologies and their emission pathways. Given the small number of city based estimates, more city data and research are needed, especially an urban emissions data system.

- **Little scientific understanding of the magnitude of the emissions reduction from altering urban form, and the emissions savings from integrated infrastructure and land use planning.** Furthermore, there is little understanding of how different aspects of urban form interact and affect emissions. The existing research on the impact of policies designed to achieve emissions reductions through urban form do not conform to the standards of policy evaluation and assessment defined in Chapter 15.

- **Lack of consistency and thus comparability on local emissions accounting methods.** Different accounting protocols yield significantly different results, making cross-city comparisons of emissions or climate action plans difficult. There is a need for standardized methodologies for local- or urban-level carbon accounting.

- **Few evaluations of urban climate action plans and their effectiveness.** There is no systematic accounting to evaluate the efficacy of city climate action plans (Zimmerman and Faris, 2011). Studies that have examined city climate action plans conclude that they are unlikely to have significant impact on reducing overall emissions (Stone et al., 2012; Millard-Ball, 2012a). Another major limitation to local or city climate action plans is their limited coordination across city sectors and administrative/hierarchical levels of governance and lack of explicitly incorporating land-based mitigation strategies. Successful local climate action plans will require coordination, integration, and partnerships among community organizations, local government, state and federal agencies, and international organizations (Yalçın and Lefèvre, 2012; Zeemering, 2012).

- **Lack of scientific understanding of how cities can prioritize climate change mitigation strategies, local actions, investments, and policy responses that are locally relevant.** Some cities will be facing critical vulnerability challenges, while other will be in the 'red zone' for their high levels of emissions. Local decision-makers need clarity on where to focus their actions, and to avoid spending resources and efforts on policies and investments that are not essential. There is little scientific basis for identifying the right mix of policy responses to address local and urban level mitigation and adaptation. Policy packages will be determined based on the characteristics of individual cities and their urbanization and development pathways, as well as on forecasts of future climate and urbanization. They will be aimed at flexing the urban- and settlement-related 'drivers' of emissions and vulnerability in order to ensure a less carbon-intensive and more resilient future for cities.

- **Large uncertainties as to how cities will develop in the future.** There is robust scientific evidence that emissions vary across cities and that urban form and infrastructure play large roles in determining the relationship between urbanization and emissions.

12.10 Frequently Asked Questions

FAQ 12.1 Why is the IPCC including a new chapter on human settlements and spatial planning? Isn't this covered in the individual sectoral chapters?

Urbanization is a global megatrend that is transforming societies. Today, more than 50 % of the world population lives in urban areas. By 2050, the global urban population is expected to increase by between 2.5 to 3 billion, corresponding to 64 % to 69 % of the world population. By mid-century, more urban areas and infrastructure will be built than currently exist. The kinds of towns, cities, and urban agglomerations that ultimately emerge over the coming decades will have a critical impact on energy use and carbon emissions. The Fourth Assessment Report (AR4) of the IPCC did not have a chapter on human settlements or urban areas. Urban areas were addressed through the lens of individual sector chapters. Since the publication of AR4, there has been a growing recognition of the significant contribution of urban areas to GHG emissions, their potential role in mitigating them, and a multifold increase in the corresponding scientific literature.

FAQ 12.2 What is the urban share of global energy and GHG emissions?

The exact share of urban energy and GHG emissions varies with emission accounting frameworks and definitions. Urban areas account for 67–76 % of global energy use and 71–76 % of global energy-related CO_2 emissions. Using Scope1 accounting, urban share of global CO_2 emissions is about 44 %.

Urban areas account for between 53 % and 87 % (central estimate, 76 %) of CO_2 emissions from global final energy use and between 30 % and 56 % (central estimate, 43 %) of global primary energy related CO_2 emissions.

FAQ 12.3 What is the potential of human settlements to mitigate climate change?

Drivers of urban GHG emissions can be categorized into four major groups: economic geography and income, socio-demographic factors, technology, and infrastructure and urban form. Of these, the first three groups have been examined in greatest detail, and income is consistently shown to exert a high influence on urban GHG emissions. Socio-demographic drivers are of medium importance in rapidly growing cities, technology is a driver of high importance, and infrastructure and urban form are of medium to high importance as drivers of emissions. Key urban form drivers of GHG emissions are density, land use mix, connectivity, and accessibility. These factors are interrelated and interdependent. As such, none of them in isolation are sufficient for lower emissions.

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13

International Cooperation: Agreements & Instruments

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Executive Summary

This chapter critically examines and evaluates the ways in which agreements and instruments for international cooperation to address global climate change have been and can be organized and implemented, drawing upon evidence and insights found in the scholarly literature. The retrospective analysis of international cooperation in the chapter discusses and quantifies what has been achieved to date and surveys the literature on explanations of successes and failures.

International cooperation is necessary to significantly mitigate climate change impacts (*robust evidence, high agreement*). This is principally due to the fact that greenhouse gases (GHGs) mix globally in the atmosphere, making anthropogenic climate change a global commons problem. International cooperation has the potential to address several challenges: multiple actors that are diverse in their perceptions of the costs and benefits of collective action, emissions sources that are unevenly distributed, heterogeneous climate impacts that are uncertain and distant in space and time, and mitigation costs that vary. [Section 13.2.1.1, 13.15]

International cooperation on climate change has become more institutionally diverse over the past decade (*robust evidence, high agreement*). The United Nations Framework Convention on Climate Change (UNFCCC) remains a primary international forum for climate negotiations, but other institutions have emerged at multiple scales: global, regional, national, and local, as well as public-private initiatives and transnational networks. [13.3.1, 13.4.14, 13.5, 13.12] This institutional diversity arises in part from the growing inclusion of climate change issues in other policy arenas (e.g., sustainable development, international trade, and human rights). These and other linkages create opportunities, potential co-benefits, or harms that have not yet been thoroughly examined. Issue linkage also creates the possibility of forum shopping and increased negotiation costs, which could distract from or dilute the performance of international cooperation toward climate goals. [13.3, 13.4, 13.5]

Existing and proposed international climate agreements vary in the degree to which their authority is centralized (*robust evidence, high agreement*). The range of centralized formalization spans: strong multilateral agreements (such as the Kyoto Protocol targets), harmonized national policies (such as the Copenhagen/Cancún pledges), and decentralized but coordinated national policies (such as planned linkages of national and sub-national emissions trading schemes). [13.4.1, 13.4.3] Additionally, potential agreements vary in their degree of legal bindingness [13.4.2.1]. Three other design elements of international agreements have particular relevance: goals and targets, flexible mechanisms, and equitable methods for effort sharing. [13.4.2]

The UNFCCC is currently the only international climate policy venue with broad legitimacy, due in part to its virtually universal membership (*robust evidence, medium agreement*). The UNFCCC continues to develop institutions and systems for governance of climate change. [13.2.2.4, 13.3.1, 13.4.1.4, 13.5]

Non-UN forums and coalitions of non-state actors, such as private businesses and city-level governments, are also contributing to international cooperation on climate change (*medium evidence, medium agreement*). These forums and coalitions address issues including deforestation, technology transfer, adaptation, and fossil fuel subsidies. However, their actual mitigation performance is unclear. [13.5.1.3, 13.13.1.4]

International cooperation may have a role in stimulating public investment, financial incentives, and regulations to promote technological innovation, thereby more actively engaging the private sector with the climate regime (*medium evidence, medium agreement*). Technology policy can help lower mitigation costs, thereby increasing incentives for participation and compliance with international cooperative efforts, particularly in the long run. Equity issues can be affected by domestic intellectual property rights regimes, which can alter the rate of both technology transfer and the development of new technologies. [13.3, 13.9, 13.12]

In the absence of—or as a complement to—a binding, international agreement on climate change, policy linkages among existing and nascent regional, national, and sub-national climate policies offer potential climate change mitigation and adaptation benefits (*medium evidence, medium agreement*) [13.3.1, 13.5.1.3]. Direct and indirect linkages between and among sub-national, national, and regional carbon markets are being pursued to improve market efficiency. Yet integrating climate policies raises a number of concerns about the performance of a system of linked legal rules and economic activities. Linkage between carbon markets can be stimulated by competition between and among public and private governance regimes, accountability measures, and the desire to learn from policy experiments. [13.3.1, 13.5.3, 13.6, 13.7, 13.13.2.3, Figure 13.4]

While a number of new institutions are focused on adaptation funding and coordination, adaptation has historically received less attention than mitigation in international climate policy, but inclusion of adaptation is increasingly important to reduce damages and may engage a greater number of countries (*robust evidence, medium agreement*). Other possible complementarities and tradeoffs between mitigation and adaptation, particularly the temporal distribution of actions, are not well-understood. [13.2, 13.3.3, 13.5.1.1, 13.14]

Participation in international cooperation on climate change can be enhanced by monetary transfers, market-based mechanisms, technology transfer, and trade-related measures (*robust evidence, medium agreement*). These mechanisms to enhance participation, along with compliance, legitimacy, and flexibility, affect the

institutional feasibility of international climate policy. [13.2.2.4, 13.3.3, 13.8.1, 13.9.2]

International trade can offer a range of positive and negative incentives to promote international cooperation on climate change (*robust evidence, medium agreement*). Three issues are key to developing constructive relationships between international trade and climate agreements: how existing trade policies and rules can be modified to be more climate friendly; whether border adjustment measures (BAMs) or other trade measures can be effective in meeting the goals of international climate agreements; whether the UNFCCC, World Trade Organization (WTO), hybrid of the two, or a new institution is the best forum for a trade-and-climate architecture. [13.8]

Climate change policies can be evaluated using four criteria: environmental effectiveness, aggregate economic performance, distributional impacts, and institutional feasibility. These criteria are grounded in several principles: maximizing global net benefits; equity and the related principles of distributive justice and common but differentiated responsibilities and respective capabilities (CBDRRC); precaution and the related principles of anticipation, and prevention of future risks; and sustainable development. These criteria may at times conflict, forcing tradeoffs among them. [13.2.1, 13.2.2]

International cooperation has produced political agreement regarding a long-term goal of limiting global temperature increase to no more than 2 °C above pre-industrial levels, but the overall level of mitigation achieved to date by cooperation appears inadequate to achieve this goal (*robust evidence, medium agreement*). Mitigation pledges by individual countries in the Copenhagen-Cancún regime, if fully implemented, will help reduce emissions in 2020 to below the projected business-as-usual level, but are unlikely to attain an emission level in 2020 consistent with cost-effective pathways, based on the immediate onset of mitigation, that achieve the long-term 2 °C goal with a greater than 50 % probability. The contribution of international cooperation outside of the UNFCCC is largely not quantified. [13.2.2.1, 13.13.1]

The Kyoto Protocol was the first binding step toward implementing the principles and goals provided by the UNFCCC, but it has had limited effects on global emissions because some countries did not ratify the Protocol, some Parties did not meet their commitments, and its commitments applied to only a portion of the global economy (*medium evidence, low agreement*). The Parties collectively surpassed their collective emission reduction target in the first commitment period, but the Protocol credited emissions reductions that would have occurred even in its absence. The Kyoto Protocol does not directly influence the emissions of non-Annex I countries, which have grown rapidly over the past decade. [13.13.1.1]

The flexible mechanisms under the Kyoto Protocol have generally helped to improve its economic performance, but their environmental effectiveness is less clear (*medium evidence, medium agreement*). The Clean Development Mechanism (CDM) created a market for emissions offsets from developing countries, generating credits equivalent to nearly 1.4 billion tCO_2eq as of October 2013, many of which have been generated by low-cost mitigation technologies. The CDM showed institutional feasibility of a project-based market mechanism under widely varying circumstances. The CDM's environmental effectiveness has been mixed due to concerns about the additionality of projects, the validity of baselines, the possibility of emissions leakage, and recent price decreases. Its distributional impacts were limited due to the concentration of projects in a limited number of countries. The Protocol's other flexible mechanisms, Joint Implementation and International Emissions Trading, have been undertaken both by governments and private market participants, but have raised concerns related to government sales of emission units. [13.7.2, 13.13.1.2]

Recent UNFCCC negotiations have sought to include more ambitious mitigation commitments from countries with commitmments under the Kyoto Protocol, mitigation contributions from a broader set of countries, and new finance and technology mechanisms (*medium evidence, low agreement*). Under the 2010 Cancún Agreement, developed countries formalized voluntary pledges of quantified, economy-wide emission reduction targets and some developing countries formalized voluntary pledges to mitigation actions. The distributional impact of the Agreement will depend in part on the magnitude and sources of financing, including the successful fulfilment by developed countries of their expressed joint commitment to mobilize 100 billion USD per year by 2020 for climate action in developing countries. Under the 2011 Durban Platform for Enhanced Action, delegates agreed to craft a future legal regime that would be 'applicable to all Parties … under the Convention' and would include substantial new financial support and technology arrangements to benefit developing countries, but the delegates did not specify means for achieving those ends. [13.5.1.1, 13.11, 13.13.1.3]

The Montreal Protocol, aimed at protecting the stratospheric ozone layer, has also achieved significant reductions in global GHG emissions (*robust evidence, high agreement*). The Montreal Protocol set limits on emissions of ozone-depleting gases that are also potent GHGs, such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). Substitutes for those ozone-depleting gases (such as hydrofluorocarbons (HFCs), which are not ozone-depleting) may also be potent GHGs. Lessons learned from the Montreal Protocol, for example, about the effect of financial and technological transfers on broadening participation in an international environmental agreement, could be of value to the design of future international climate change agreements. [13.3.3, 13.3.4, 13.13.1.4]

Assessment of proposed cooperation structures reinforces the finding that there will likely be tradeoffs between the four criteria, as they will inevitably conflict in some elements of any agreement (*medium evidence, high agreement*). Assessment of proposed climate policy architectures reveals important tradeoffs that depend on the specific design elements and regulatory mechanisms of a proposal. For example, there is a potential tradeoff between broad participation and the institutional feasibility of an ambitious environmental performance goal. The extent of this tradeoff may depend on financial transfers, national enforcement mechanisms, and the distribution and sharing of mitigation efforts. [13.2.2.5, 13.3.3, 13.13.1.4, 13.13.2]

Increasing interest in solar radiation management (SRM) and carbon dioxide removal (CDR) as strategies to mitigate the harms of climate change, pose new challenges for international cooperation (*medium evidence, high agreement*). Whereas emissions abatement poses challenges of engaging multilateral action to cooperate, SRM may pose challenges of coordinating research and restraining unilateral deployment of measures with potentially adverse side-effects. [13.4.4]

Gaps in knowledge and data: (1) comparisons among proposals in terms of aggregate and country-level costs and benefits per year, with incorporation of uncertainty; (2) assessment of the overall effect of emerging intergovernmental and transnational arrangements, including 'hybrid' approaches; (3) understanding of complementarities and tradeoffs between policies affecting mitigation and adaptation; (4) understanding how international cooperation on climate change can help achieve co-benefits and development goals, including capacity building approaches; (5) understanding the factors that affect national decisions to join and form agreements.

13.1 Introduction

Due to global mixing of greenhouse gases (GHGs) in the atmosphere, anthropogenic climate change is a global commons problem. For this reason, international cooperation is necessary to achieve significant progress in mitigating climate change. Drawing on published research, this chapter critically examines and evaluates the ways in which agreements and instruments for international cooperation have been and can be organized and implemented. The retrospective analysis of international cooperation in the chapter quantifies and discusses what has been achieved to date, and surveys the literature on explanations of successes and failures.

The scope of the chapter is defined by the range of feasible international agreements and other policy instruments for cooperation on climate-change mitigation and adaptation. The disciplinary scope spans the social sciences of economics, political science, international relations, law, public policy, psychology, and sociology; relevant humanities, including history and philosophy; and—where relevant to the discussion—the natural sciences. Where appropriate, the chapter synthesizes literature that utilizes econometric modelling, integrated modelling, game theory, comparative case studies, legal analysis, and political analysis. This chapter focuses on research and policy developments since the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007).

13.2 Framing concepts for an assessment of means for international cooperation

This section introduces the concept of a global commons problem to frame the challenge of international cooperation on climate change, principles for designing effective international climate policy, and criteria for evaluating these policies.

13.2.1 Framing concepts and principles

13.2.1.1 The global commons and international climate cooperation

Climate change is a global commons problem, meaning reduction in emissions by any jurisdiction carries an economic cost, but the benefits (in the form of reduced damages from climate change) are spread around the world—although unevenly—due to GHG emissions mixing globally in the atmosphere. Mitigation of climate change is non-excludable, meaning it is difficult to exclude any individual or institution from the shared global benefits of emissions reduction undertaken by any localized actor. Also, these benefits are non-rival, meaning they may be enjoyed by any number of individuals or institutions at the same time, without reducing the extent of the benefit any one of them receives. These public good characteristics of climate protection (non-excludability and non-rivalry) create incentives for actors to 'free ride' on other actors' investments in mitigation. Therefore, lack of ambition in mitigation and overuse of the atmosphere as a receptor of GHGs are likely.

Incentives to free ride on climate protection have been analyzed extensively and are well-understood (Gordon, 1954; Hardin, 1968; Stavins, 2011). The literature suggests that in some cases, effective common property management of local open-access resources can limit or even eliminate overuse (Ostrom, 2001; Wiener, 2009). Effective common property management of the atmosphere would require applying such management at a global level, by allocating rights to emit and providing disincentives for overuse through sanctions or pricing emissions (Byrne and Glover, 2002; Wiener, 2009).

Enhancing production of public goods may be achieved by internalizing external costs (i. e., those costs not incorporated into market prices) or through legal remedies. Economic instruments can incorporate external costs and benefits into prices, providing incentives for private actors to more optimally reduce external costs and increase external benefits (Baumol and Oates, 1988; Nordhaus, 2006; Buchholz et al., 2012). Legal remedies may include seeking injunctive relief or compensatory payments (IPCC, 2007, Chapter 13; Faure and Peeters, 2011; Haritz, 2011)

International cooperation is necessary to significantly mitigate climate change because of the global nature of the problem (WCED, 1987; Kaul et al., 1999, 2003; Byrne and Glover, 2002; Barrett, 2003; Stewart and Wiener, 2003; Sandler, 2004) Cooperation has the potential to address several challenges: multiple actors that are diverse in their perceptions of the costs and benefits of collective action; emissions sources that are unevenly distributed; heterogeneous climate impacts that are uncertain and distant in space and time; and mitigation costs that vary (IPCC, 2001, pp. 607–608).

In the absence of universal collective action, smaller groups of individual actors may be able to organize schemes to supply public goods, particularly if actors know each other well, expect repeated interactions, can exclude non-members, and can monitor and sanction non-compliance in the form of either overconsumption or underproduction (Eckersley, 2012; McGee, 2011; Nairn, 2009; Ostrom, 1990, 2010a; b, 2011; Weischer et al., 2012). Some authors are optimistic regarding such 'minilateralism' (e.g., Keohane and Victor, 2011; on the term, see Eckersley, 2012) and others are more sceptical (e.g., Depledge and Yamin, 2009; Winkler and Beaumont, 2010) . Section 13.3 discusses the literature on coalitions in more detail.

Because there is no world government, each country must voluntarily consent to be bound by any international agreement. If these are to be effective, the agreements must be attractive enough to gain broad participation (Barrett, 2003, 2007; Stewart and Wiener, 2003; Schmalensee, 2010; Brousseau et al., 2012). Considering the relationship between mitigation costs and climate benefits discussed above, there is insufficient incentive for actors at any level to reduce emissions significantly in the absence of international cooperation. Behavioural research, however, indicates that individuals are sometimes motivated to cooperate (and to punish those who do not) to a degree greater than strict rational choice models predict (Camerer, 2003; Andreoni and Samuelson, 2006). This may explain some of the observed policies being adopted to reduce GHG emissions at the national, subnational, firm, and individual level. Moreover, even under the assumption of rational action, some emission reductions can occur without cooperation due to positive externalities of otherwise self-beneficial actions, or co-benefits, such as actions to reduce energy expenditures, enhance the security of energy supply, reduce local air pollution, improve land use, and protect biodiversity (Seto et al., 2012). Co-benefits of climate protection are receiving increasing attention in the literature (Rayner, 2010; Dubash, 2009; UNEP, 2013b). However, policies designed to address climate change mitigation may also have adverse side-effects. See Section 4.8 and 6.6 for an overview of the discussion of co-benefits and adverse side-effects throughout this report.

13.2.1.2 Principles

Several principles have been advanced to shape international climate change policies. The IPCC Third Assessment Report (TAR) (IPCC, 2001) discusses principles and mentions some criteria for evaluation of policies, whereas the AR4 (IPCC, 2007), clearly differentiates principles from criteria. Principles serve as guides to design climate policies, while criteria are specific standards by which to evaluate them. The roles and applications of principles and criteria are further elaborated in Chapter 3 of this report.

Sets of principles are enumerated and explained in multiple international climate change fora, including the Rio Declaration on Environment and Development (UNEP, 1992) and the United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC, 1992). In the latter, the principles listed explicitly include: 'equity' and 'common but differentiated responsibilities and respective capabilities' (CBDRRC) (Article 3(1)), relative needs, vulnerability, burdens in countries of differing wealth (Article 3(2)), precaution and 'cost-effective[ness] so as to ensure global benefits at the lowest possible cost' (Article 3(3)), 'sustainable development' (Article 3(4)), and cooperation (Article 3(5)).

Principles of climate change policy relevant for international cooperation can be grouped into several broad categories. First, the principle of maximizing global net benefits makes the tradeoff between aggregate compliance costs and aggregate performance benefits explicit. The principle also incorporates the notion of maximizing co-benefits of climate action (Stern, 2007; Nordhaus, 2008; Bosetti et al., 2010; Rayner, 2010; Dubash, 2009) (see also Section 3.6.3). A related concept is that of cost-effectiveness, which allows for policies with the same level of performance in terms of aggregate benefits to be compared on the dimension of aggregate cost (IPCC, 2001, 2007, Chapter 13). See Section 6.6 for applied scenario studies.

Second, equity is a principle that emphasizes distributive justice across and within countries and across and within generations (Vanderheiden, 2008; Baer et al., 2009; Okereke, 2010; Posner and Sunstein, 2010; Posner and Weisbach, 2010; Somanathan, 2010; Cao, 2010c). It includes evaluating the procedures used to reach an agreement as well as the achieved outcomes. This principle may also apply in a broader assessment of well-being (Sen, 2009; Cao, 2010a). The principle of CBDRRC has been central in international climate negotiations (Rajamani, 2006, 2011a; Gupta and Sanchez, 2013). The literature refers to the varied historic responsibility—and current capability and capacity—of countries with regard to impacts of and action to address climate change (Jacoby et al., 2010; Rajamani, 2006, 2012b; Höhne et al., 2008; Dellink et al., 2009; den Elzen et al., 2013b). Some literature assesses how the principle might be applied to actors' diverse needs (Jonas, 1984; Dellink et al., 2009), including the specific needs and vulnerabilities of developing countries (Rong, 2010; Smith et al., 2011; Bukovansky et al., 2012). Recent literature suggests that this principle's application may be more nuanced as patterns of development, emissions, and impacts evolve (Bukovansky et al., 2012; Deleuil, 2012; Müller and

Mahadev, 2013; Winkler and Rajamani, 2013). The literature describes competing views regarding the meaning of this principle in terms of its legal status, operational significance, and the obligations it may entail (Höhne et al., 2006; Halvorssen, 2007; O'Brien, 2009; Winkler et al., 2009; Winkler, 2010; Hertel, 2011). The principle of CBDRRC is further analyzed in Sections 3.3 and 4.6.

Third, the principle of precaution emphasizes anticipation and prevention of future risks, even in the absence of full scientific certainty about the impacts of climate change (Bodansky, 2004; Wiener, 2007; Urueña, 2008). Some see precaution as a strategy for effective action across diverse uncertain scenarios (Barrieu and Sinclair-Desgagné, 2006; World Bank, 2010), although the application of precaution varies across risks and countries (Hammitt, 2010). A key ongoing debate concerns whether or not this principle implies the need for stringent climate change policies as an insurance against potentially catastrophic outcomes, even if they may have very low probability (Weitzman, 2007, 2009, 2011; Pindyck, 2011; Nordhaus, 2011). The application of the precautionary principle to climate risk is further discussed in Section 2.5.5.

Fourth, the principle of sustainable development, broadly defined, emphasizes consideration of the socioeconomic needs of future generations in making decisions about current resource use (IPCC, 2007, Chapter 12; World Bank, 2010). For a detailed discussion of the literature on sustainable development, see Section 4.2.1.

13.2.2 Potential criteria for assessing means of international cooperation

The principles elaborated above can be translated into criteria to evaluate forms of international cooperation, thereby assisting in the design of a distribution of efforts intended to solve the collective action problem of climate protection. The AR4 put forth one set of criteria: environmental effectiveness, cost-effectiveness, distributional considerations, and institutional feasibility (IPCC, 2007, pp. 751–752). As 'metrics of success', these evaluation criteria can be applied in the context of both ex-post evaluations of actual performance and ex-ante assessments of proposed cooperation (Hammitt, 1999; Fischer and Morgenstern, 2010). Below, this section describes four evaluation criteria that are applied in Section 13.13 to assess existing and proposed forms of international cooperation to address climate change mitigation. These criteria are subject to caveats, which are detailed in Section 13.13.

13.2.2.1 Environmental effectiveness

The environmental effectiveness of a climate change mitigation policy is the extent to which it achieves its objective to reduce the causes and impacts of climate change. Environmental effectiveness can be achieved by reducing anthropogenic sources of GHG emissions, removing GHGs from the atmosphere, or reducing the impacts of climate change directly through increased resilience. A primary objective of international cooperation has been to stabilize GHG concentrations at levels sufficient to "prevent dangerous anthropogenic interference with the climate system," in the words of the UNFCCC Article 2 (1992). This would require action within a time-frame sufficient to "allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner" (UNFCCC, 1992), Article 2). The Kyoto Protocol established specific emission-reduction targets for developed countries, while the Copenhagen Accord and Cancún Agreements expressed the environmental objective in terms of global average temperature increase. In addition to endorsing mitigation targets by developed countries and mitigation actions by developing countries, the Copenhagen and Cancún agreements recognized a goal of limiting increases in average global temperature to 2 °C above pre-industrial levels (UNFCCC, 2009a, 2010, 2011a).

13.2.2.2 Aggregate economic performance

Measuring the aggregate economic performance of a climate policy requires considering both its economic efficiency and its cost-effectiveness. Economic efficiency refers to the maximization of net benefits, the difference between total social benefits and total social costs (Stern, 2007; Nordhaus, 2008; Bosetti et al., 2010).

Cost-effectiveness refers to the ability of a policy to attain a prescribed level of environmental performance at least cost, taking into account impacts on dynamic efficiency, notably technological innovation (Jaffe and Stavins, 1995). Unlike net benefit assessment, cost-effectiveness analysis takes the environmental performance of a policy as given and seeks the least-cost strategy to attain it (Hammitt, 1999). While analysis of a policy in terms of its cost-effectiveness still requires environmental performance of the policy to be quantified, it does not require environmental performance benefits to be monetized. Thus, analysis of a policy's cost-effectiveness may be more feasible than analysis of a policy's economic efficiency in the case of climate change, as some social benefits of climate-change mitigation are difficult to monetize.

13.2.2.3 Distributional and social impacts

Distributional equity and fairness may be considered important attributes of climate policy because of their impact on measures of well-being (Posner and Weisbach, 2010) and political feasibility (Jacoby et al., 2010; Gupta, 2012). Distributional equity relates to burden- and benefit-sharing across countries and across time. Section 4.2.2 puts forward three justifications for considering distributional equity—legal, environmental effectiveness, and moral. The framing in Section 4.2 also identifies a relatively small set of core equity principles: responsibility, capacity, the right to sustainable development, and equality. These may be modelled with quantitative indicators, as discussed in Section 6.3.6.6. The moral justification draws on ethical principles, which are reflected in the principles of the Convention (see Section 13.2.1.2; and detailed treatment of the literature on ethics in Section 3.2).

Another dimension of distributional equity is the possibility for mitigation actions in one jurisdiction to have positive or negative consequences in another jurisdiction. This phenomenon, sometimes referred to as 'response measures' or as 'spillover effects' (see WGIII AR4 Glossary), can lead to an unequal distribution of the impacts of climate change mitigation actions themselves. A plausible example of a spillover effect is the impact of emissions reductions in developed countries lowering the demand for fossil fuels and thus decreasing their prices, leading to more use of such fuels and greater emissions in developing nations, partially off-setting the original cuts (Bauer et al., 2013) This dynamic can also be important for countries with large endowments of conventional oil and gas that depend on export revenues. These countries may lose energy export revenue as a result of climate policies enacted in other countries (Kalkuhl and Brecha, 2013; Bauer et al., 2013). Additionally, climate policies could also reduce international coal trading (Jewell et al., 2013). See also Sections 6.3.6, 14.4.2, and 15.5.2 for further discussion of spillover effects.

13.2.2.4 Institutional feasibility

The institutional feasibility of international climate policy may depend upon agreement among national governments and between governments and intergovernmental bodies (Wiener, 2009; Schmalensee, 2010). Institutional feasibility is closely linked to domestic political feasibility, because domestic political conditions affect participation in, and compliance with, international climate policies. This has been addressed in the literature on 'two-level' games (Kroll and Shogren, 2009; Hafner-Burton et al., 2012). Four sub-criteria of institutional feasibility can also be considered: *participation*, *compliance*, *legitimacy*, and *flexibility*.

First, *participation* in an international climate agreement might refer to the number of parties, geographical coverage, or the share of global GHG emissions covered. Participating parties might vary with regard to the nature and specificity of their commitments (e.g., actions versus quantitative emissions-reduction targets). Sovereign states are not bound by an international treaty or other arrangement unless they consent to participate. The literature has examined a broad array of incentives to promote breadth of participation in international agreements (Barrett, 2003; Barrett and Stavins, 2003; Stewart and Wiener, 2003; Hall et al., 2010; Victor, 2010; World Bank, 2010; Olmstead and Stavins, 2012). These incentives can be positive (e.g., financial support or technology transfers) or negative (e.g., trade sanctions). Some authors have suggested that participation limited to countries with the highest emissions enhances institutional feasibility (Leal-Arcas, 2011) and that incentive-based emissions-permit allocations, or rules requiring participation of key players, may enable larger coalitions (Dellink et al., 2008; Dellink, 2011).

Second, institutional feasibility is also partly determined by the *compliance* of participating countries with an agreement's provisions. Mechanisms to ensure compliance, in turn, affect decisions to participate, as well as long-term performance (Barrett, 2003). Incentives for encouraging compliance can be built into flexible mechanisms, such as tradable permit systems (Wiener, 2009; Ismer and Neuhoff, 2009; Keohane and Raustiala, 2010). Compliance is fundamentally problematic in international agreements, as it is difficult to establish an authority that can legitimately and effectively impose sanctions upon sovereign national governments. Despite that, indirect negative consequences of non-compliance can arise within the regime established by the agreement, or in other regimes, for example, adverse voting behaviour in international forums or reduction in foreign aid (Heitzig et al., 2011).

Third, *legitimacy* is a key component of institutional feasibility. Parties to a cooperative agreement must have reason to accept and implement decisions made under the agreement, meaning they must believe that the relevant regime represents them fairly. Legitimacy depends on the shared understanding both that the substantive rules (outputs) and decision-making procedures (inputs) are fair, equitable, and beneficial (Scharpf, 1999), and thus that other regime members will continue to cooperate (Ostrom, 1990, 2011). In practice, the legitimacy of substantive rules is typically based on whether parties evaluate positively the results of an authority's policies, while procedural legitimacy is typically based on the existence of proper input mechanisms of participation and consultation for the parties participating in an agreement (Stevenson and Dryzek, 2012).

Finally, the institutional feasibility of international climate policy depends in part on whether the institutions relevant for a policy can develop *flexibility* mechanisms—which typically require that the institutions themselves are flexible or adjustable. It may be important to be able to adapt to new information or to changes in economic and political circumstances. The institutionalization of learning among actors, which is referred to as 'social learning' in the literature of environmental governance (Pahl-Wostl et al., 2007), is an important aspect of success, enabling adaptation to changing circumstances. While institutional arrangements that incorporate a purposive process of experimentation, evaluation, learning, and revision may be costly, policies that do not incorporate these steps may be overly rigid in the face of change and therefore potentially even more costly (Greenstone, 2009; Libecap, 2011). Another area of current debate and research is the question of whether increased flexibility in designing obligations for states helps them align their international obligations more readily with domestic political constraints (von Stein, 2008; Hafner-Burton et al., 2012). This suggests that designing international climate policies involves a balance between the benefits of flexibility and the costs of regulatory uncertainty (Goldstein and Martin, 2000; Brunner et al., 2012). Chapter 2, for example in Section 2.6.5.1, goes into more depth on problems related to regulatory uncertainty.

Box 13.1 | International agreements and developing countries

The United Nations Framework Convention on Climate Change (UNFCCC) is a statement of aspirations, principles, goals, and the means to meet commitments. The Kyoto Protocol of the UNFCCC included, for the first time, binding mitigation commitments—for nations listed in its Annex B. Other countries may assist Annex B Parties in meeting their mitigation commitments via the Clean Development Mechanism (CDM), under the Protocol's Article 12.

Annex I countries under the UNFCCC, which include all Annex B countries under the Kyoto Protocol, are largely the wealthiest countries and largest historical emitters of GHGs. However, Annex I countries' share of historical cumulative GHG emissions in 2010 is close to the share of the non-Annex I countries (Section 13.13.1.1). Thus, the Kyoto Protocol's mitigation commitments were initially consistent with the UNFCCC principle of 'common but differentiated responsibilities and respective capabilities' (CBDRRC). However, since the UNFCCC divided countries into two categories in 1992, both income patterns and the distribution of GHG emissions have changed significantly, even as variations in income and per capita responsibility for emissions remain substantial both within and between countries. Between Conference of Parties (COP)-13 (Bali) in 2007 and COP-16 (Cancún) in 2010, many developing countries put forward quantifiable mitigation *actions* (as contrasted with quantified, economy-wide emissions reductions *targets* assumed by Annex B parties under the Kyoto Protocol) and agreed to more frequent reporting and enhanced transparency of those actions. Further pledges of actions have been made since Cancún. (Section 13.13)

For many developing countries, adaptation can have comparable priority to mitigation. This may be because countries are especially vulnerable to climate change damages or they lack confidence in progress with mitigation efforts. These countries are often the least able to finance adaptation, leaving cooperative agreements to attempt to identify sources of support. (See Chapter 16 for detail.)

International collaboration regarding public climate finance under the UNFCCC dates back to 1991, when the Climate Change Program of the Global Environment Facility (GEF) was established. The literature reflects mixed evidence on the scale and environmental effectiveness of such funding. Funding for reporting and mitigation flows through four primary vehicles: the GEF, which focuses on mitigation; the Least Developed Country Fund (LDCF) and Special Climate Change Fund (SCCF), created in 2001 for adaptation purposes and operated by the GEF; the Adaptation Fund set up in 2008; and the Green Climate Fund (GCF), established in 2010 for mitigation and adaptation. (Section 13.11, see also Section 16.2) The Copenhagen Accord set a goal to jointly mobilize 100 billion USD/yr by 2020 to address the needs of developing countries. (Section 13.11) Article 4.5 of the UNFCCC also calls for technology transfer from developed to developing countries. The Technology Mechanism, with an Executive Committee and Climate Technology Centre and Network, is seeking to fulfil this goal.

Research indicates that adaptation assistance, such as that provided by the Kyoto Protocol's Adaptation Fund, can be crucial for inclusion of developing countries in international climate agreements. Further research into the distribution of adaptation finance across countries from both UNFCCC and non-UNFCCC sources is required to assess the equity, efficiency, effectiveness, and environmental impacts of the Adaptation Fund and other funding mechanisms. Many developing countries have created institutions to coordinate adaptation finance from domestic and international funding sources. (Sections 13.3, 13.5)

The literature identifies several models for equitable burden sharing—among both developed and developing countries in international cooperation for climate change mitigation. The principles on which burden sharing arrangements may be based are described in Section 4.6.2, and the implications of these arrangements are discussed in Section 6.3.6.6. Distributional impacts from agreements will depend on the approach taken, criteria applied to operationalize equity, and the manner in which developing countries' emissions plans are financed; studies suggest potential approaches (Section 13.4, UNFCCC Secretariat 2007b, 2008). A major distributional issue is how to account for emissions from goods produced in a developing country, but consumed in an industrialized country. Such emissions have increased rapidly since 1990, as developed countries have typically been importers of embodied emissions, while many developing countries have large shares of emissions embodied in exports. (Sections 13.8, 14.3.4)

New and existing coalitions of countries have engaged in the UNFCCC negotiations, each presenting coordinated positions. Several distinct coalitions of developing countries have formed to negotiate their divergent priorities. Examples include the Group of 77 (G-77) and China, which contains sub-groups such as the African Group, the Least Developed Countries, and the Arab Group; the Alliance of Independent Latin American and Caribbean states; and a 'like-minded developing country' group that included China, India, and Saudi Arabia. Other coalitions organized to influence UNFCCC negotiations include the Alliance of Small Island States (AOSIS); various groupings of industrialized countries, including the Umbrella Group; the Environmental Integrity Group; the BASIC countries (Brazil, South Africa, India, and China); the Coalition of Rainforest Nations; and other active coalitions not limited to the climate context, for example, the Comision Centroamericana de Ambiente y Desarollo and the Bolivarian Alliance for the Americas.

13.2.2.5 Conflicts and complementarities

Criteria may be mutually reinforcing (Cao, 2010a; c), but there may also be conflicts, forcing tradeoffs between and among them. For example, maximizing global net benefits or attaining cost-effectiveness may lead to actions that decrease distributional equity (van Asselt and Gupta, 2009), which could lead to low participation. Posner and Weisbach (2010) and Baer (2009) argue that efficiency and distribution can be reconciled by either normatively adjusting the net benefit or cost calculations to account for changes in relative utility, or by adopting redistributive policy in addition to cost-effective climate policy.

Different approaches to meet the same criteria (for example, equity) may also conflict with each other when operationalized (Fischer and Morgenstern, 2010) or lead to different results (Dellink et al., 2009). Simultaneously, there are relations among sub-criteria: excessive flexibility may undermine incentives to invest in long-term solutions, and may also increase the likelihood of participation. Compromises to enable institutional feasibility of an agreement may weaken performance along other dimensions. The environmental performance of an international agreement depends largely on tradeoffs among the ambition of an agreement with regards to mitigation goals and participation, and compliance (Barrett, 2003; Bodansky, 2011a; Rajamani, 2012a). For further discussion of potential tradeoffs between participation and environmental effectiveness, see Section 13.3.3.

13.3 International agreements: Lessons for climate policy

Several lessons from research on existing international agreements, as well as game-theoretic models of such agreements, can be applied to climate change institutions. This section briefly summarizes some of the key lessons, which are addressed in more detail in subsequent sections of this chapter.

13.3.1 The landscape of climate agreements and institutions

Since the publication of IPCC AR4 in 2007, the landscape of international institutions related to climate policy has become significantly more complex. Climate change is addressed in a growing number of fora and institutions and across a wider range of scales (Keohane and Victor, 2011; Bulkeley et al., 2012; Biermann et al., 2009, 2010; Barrett, 2010; Abbott, 2011; Hoffmann, 2011; Zelli, 2011; Rayfuse and Scott, 2012).

Figure 13.1 illustrates the variety of international, transnational, regional, national, sub-national, and non-state agreements and other forms of cooperation, many of which have emerged since the mid-2000s. Some regimes that previously focused on other issues, e.g., trade (see Section 13.8), energy (see Chapter 7), biodiversity, and human rights have begun to address climate change. For a more detailed discussion of these initiatives, see also Section 13.5.

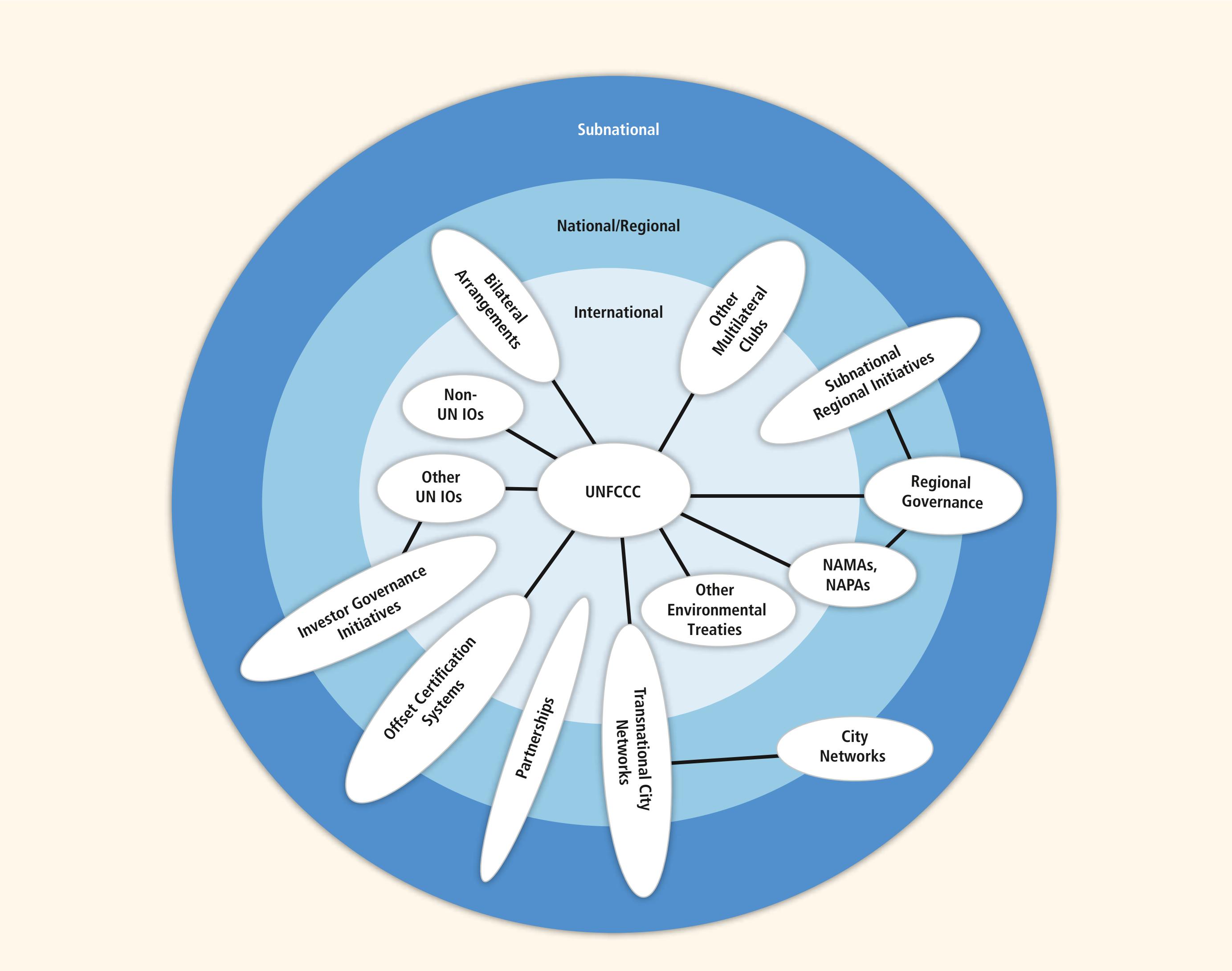
Future efforts for international cooperation on climate policy will need to account for this wide variety of agreements and institutions. Careful design of linkages and cooperative arrangements will be needed to manage the increasingly fragmented regime complex to prevent conflicts among institutions (Biermann et al., 2010; Keohane and Victor, 2011; Zelli, 2011), avoid gaps or loopholes (Downs, 2007), and maximize potential institutional synergies (Hoffmann, 2011; Rayfuse and Scott, 2012).

13.3.2 Insights from game theory for climate agreements

Game theory provides insights into international cooperation on climate policy, from research communities in environmental economics (Ward, 1993; Finus, 2001, 2003; Wagner, 2001; Barrett, 2003, 2007) and in the rationalist school of political science (Sjostedt, 1992; Downs et al., 1996; Underdal, 1998; Koremenos et al., 2001; Avenhaus and Zartman, 2007; Hafner-Burton et al., 2012). These researchers analyze the incentives and motivations of actors to join and comply with international environmental agreements (IEAs).

The game-theoretic literature on climate change agreements has grown substantially in the last two decades (Barrett, 2007; Rubio and Ulph, 2007; Chambers, 2008; Froyn and Hovi, 2008; Bosetti et al., 2009a; Asheim and Holtsmark, 2009; Dutta and Radner, 2009; Muñoz et al., 2009; Carbone et al., 2009; Weikard et al., 2010; Bréchet et al., 2011; Wood, 2011; Heitzig et al., 2011; Dietz and Zhao, 2011; Bréchet and Eyckmans, 2012; Pittel and Rübbelke, 2012). It is important, however, to treat with caution any general conclusions from recent game theory literature on climate change agreements, as many have been criticized for their simplicity. In this section, we refrain from listing assumptions in detail, and restrict attention to the most general and policy-relevant discussions. See Finus (2001, 2003) for a more detailed review of the relevant game theory literature.

By and large, the game-theoretic literature assumes actors to be states that are maximizing the welfare of their citizens (Ward, 1993; Carraro and Siniscalco, 1998; Grundig, 2006). A central premise is that there is currently no supranational institution that can impose an IEA on governments and subsequently enforce it (see Section 13.2.1.1). Thus, IEAs must be self-enforcing to engage and maintain participation and compliance (Finus, 2001; Barrett, 2007; Dutta and Radner, 2009; Rubio and Casino, 2005; Heitzig et al., 2011). Nevertheless, in theory and practice, international institutions can help to promote, negotiate, and administer an IEA. They can do so by serving to coordinate and moderate negotiations and implementation, reducing transaction costs



UNFCCC	Kyoto Protocol, Clean Development Mechanism, International Emissions Trading
Other UN Intergovernmental organizations	Intergovernmental Panel on Climate Change, UN Development Programme, UN Environment Programme, UN Global Compact, International Civil Aviation Organization, International Maritime Organization, UN Fund for International Partnerships
Non-UN IOs	World Bank, World Trade Organization
Other environmental treaties	Montreal Protocol, UN Conference on the Law of the Sea, Environmental Modification Treaty, Convention on Biological Diversity
Other multilateral 'clubs'	Major Economies Forum on Energy and Climate, G20, REDD+ Partnerships
Bilateral arrangements	e. g., US-India, Norway-Indonesia
Partnerships	Global Methane Initiative, Renewable Energy and Energy Efficiency Partnership, Climate Group
Offset certification systems	e. g., Gold Standard, Voluntary Carbon Standard
Investor governance initiatives	Carbon Disclosure Project, Investor Network on Climate Risk
Regional governance	e. g., EU climate change policy
Subnational regional initiatives	Regional Greenhouse Gas Initiative, California emissions-trading system
City networks	US Mayors' Agreement, Transition Towns
Transnational city networks	C40, Cities for Climate Protection, Climate Alliance, Asian Cities Climate Change Resilience Network
NAMAs, NAPAs	Nationally Appropriate Mitigation Actions (NAMAs) of developing countries; National Adaptation Programmes of Action (NAPAs)

Figure 13.1 | The landscape of agreements and institutions on climate change. Lines connecting different types of agreements and institutions indicate different types of links. In some cases, lines represent a formal agreement of a division of labour (e. g. between the UNFCCC and ICAO concerning aviation emissions). In other cases, lines represent a more simple mutual recognition (e. g. the accreditation of C40 cities by the UNFCCC). In others still, lines represent a functional linkage without any formal relationship (e. g. the relationship between the CDM and the NGO certification of carbon offsets). This is a rapidly-changing landscape and not all links may be captured.

of negotiations, and generating trust (Keohane, 1984, 1989; Finus and Rundshagen, 2006); changing the interests of actors by providing new information or building capacity (Haas et al., 1993); enlisting actors in domestic politics within and across states (Abbott and Snidal, 2010; Hafner-Burton et al., 2012); and inculcating norms (Bodansky, 2010a).

Alternative perspectives on game theory weaken the assumption of rationality and emphasize the roles of legitimacy, norms, and acculturation in shaping behaviour under international law and institutions (Goodman and Jinks, 2004; March and Olsen, 2008; Brunnée and Toope, 2010; Bernauer et al., 2010; Hafner-Burton et al., 2012). See Chapter 2 for a discussion of behavioural approaches in the literature.

13.3.3 Participation in climate agreements

Greater participation in climate change agreements, all else equal, improves environmental effectiveness by covering a larger share of global emissions and reducing potential leakage to non-participating areas. Greater participation may also improve aggregate economic performance by enabling lower-cost emissions abatement and reducing leakage. An international climate agreement regime might achieve depth (ambition of emissions reduction) and breadth (of participation) in different sequence. Schmalensee (1998) argues for breadth of participation first, with less emphasis on ambition. He argues that this approach allows time to develop correspondingly broad-based institutions that can potentially facilitate substantial aggregate emissions reductions over time (Schelling, 1992; Barrett, 2003). Conversely, pursuing an arrangement with depth before breadth can be motivated by the urgency of the climate-change problem. However, such an approach may make broadening participation more difficult later on (Schmalensee, 1998), and this type of agreement could induce emissions leakage, undermining effectiveness (Babiker, 2005).

In the theoretical literature, the tradeoff between the level of abatement by a sub-set of actors and participation in an IEA has been analyzed as a comparison between an 'ambitious versus a modest treaty' (Finus and Maus, 2008; Courtois and Haeringer, 2011) or between a focal (deep and narrow) versus a consensus (broad but shallow) treaty (Barrett, 2002; Hafner-Burton et al., 2012). Scholars conclude that, overall, a consensus treaty may achieve more in terms of emission reductions and global welfare than a focal treaty. Further analysis has investigated the tradeoff between breadth and depth, and how broad participation can increase environmental effectiveness (by covering more emissions and reducing leakage), and reduce costs (by encompassing more low-cost abatement options in a larger market). Through these plausible mechanisms, greater breadth enables greater ambition (subject to the costs of attracting participants) (Battaglini and Harstad, 2012).

While most existing IEAs feature open membership, some theoretical literature finds that exclusive membership can help to stabilize IEAs, prevent defection, and lead to better environmental outcomes, even in the context of a global public good such as climate protection (Carraro and Marchiori, 2003; Eyckmans and Finus, 2006; Finus, 2008a; Finus and Rundshagen, 2009). In practice, exclusive membership may reduce supply of a public good such as global emissions abatement, may increase emissions leakage (unless non-members are covered by their own coalition in a system of multiple agreements), and may conflict with norms of institutional legitimacy. Multiple agreements (i.e., multiple coalitions) may be a pragmatic, short- to mid-term strategy for achieving more effective cooperation if a universal treaty of all countries to limit emissions is not stable or attainable in the short-run (Finus and Rundshagen, 2003; Stewart and Wiener, 2003; Asheim et al., 2006; Eyckmans and Finus, 2006; Bosetti et al., 2009b; Bréchet and Eyckmans, 2012). Multiple coalition agreements involving all major emitters could potentially achieve better environmental effectiveness than a partial coalition acting while other countries do not act at all. However, for protecting a global public good, separate coalitions could forego some of the cost-effectiveness gains of a broader regime, and they could face questions of legitimacy (Karlsson-Vinkhuyzen and McGee, 2013). It remains unclear whether partial coalitions for climate policy will accelerate momentum for a more universal global agreement in the future, or undermine such momentum (Brewster, 2010).

International transfers can also attract participation in climate agreements, balancing the asymmetric gains from cooperation. These transfers can either be direct monetary transfers (e.g., contributions to a fund from which developing countries can draw), in-kind transfers (e.g., technology transfer), or indirect transfers via market-based mechanisms (e.g., through the initial allocation of tradable emission permits) (Carraro et al., 2006; Barrett, 2007; Bosetti et al., 2009a; Fuentes-Albero and Rubio, 2010; Bréchet and Eyckmans, 2012; Stewart and Wiener, 2003). Historically, transfers have been important for building participation in past international agreements (Hafner-Burton et al., 2012; Bernauer et al., 2013). The experience of the Montreal Protocol illustrates how transfers can engage participation by major developing countries through financial and technological assistance (Sandler, 2010; Kaniaru, 2007; Zhao, 2005, 2002; Andersen et al., 2007). The role of technology transfer in international cooperation is discussed in greater detail in Section 13.9, and the role of finance is discussed in Section 13.11.

Linkages across issues may also help encourage participation. Many linkages exist between climate change and other issues, such as energy, water, agriculture, sustainable development, poverty alleviation, public health, international trade, human rights, foreign direct investment, biodiversity, and national security (see Sections 3.4, 5.7, 6.6, and Section 13.2.1.1). Such linkages may create opportunities, co-benefits, or adverse side-effects, not all of which have been thoroughly examined. However, the advantages of issue linkage may diminish as the number of parties and issues increase, raising the transaction costs of negotiations (Weischer et al., 2012).

A different instrument to encourage participation is trade sanctions against non-parties to an IEA. The threat of trade sanctions can motivate participation (Barrett, 2003; Victor, 2011), as exemplified by the Montreal Protocol. However, since participation in an international treaty is voluntary, sanctions for non-participation may be difficult to justify (see Section 13.3.4). Similar to trade sanctions are 'offsetting border adjustment measures' (BAMs) (see Section 13.8 for further discussion).

Particularly vulnerable countries may be more likely to participate in agreements that address and fund adaptation activities (Huq et al., 2004; Mace, 2005; Ayers and Huq, 2009; Denton, 2010; Smith et al., 2011). Benefits of adaptation are often local, and these local benefits may be more effective incentives for countries vulnerable to climate damages to participate in an IEA relative to the benefits of mitigation and support for technological development or deployment. Both of these alternative possible incentive mechanisms are less-excludable and are of potentially less value to lower-emitting countries, compared with adaptation benefits. Recent game theoretic analyses suggest that private co-benefits from mitigation actions may not substantially increase participation in international climate agreements (Pittel and Rübbelke, 2008; Finus and Rübbelke, 2012).

A final key issue related to participation is the role played by uncertainty. Earlier research suggested that reducing uncertainty about the benefits and costs of mitigation can render IEAs less effective, showing that as parties learn of the actual costs and benefits of mitigation, their incentive to participate may shrink (Na and Shin, 1998; Kolstad, 2005; Kolstad and Ulph, 2008). However, more recent work (Finus and Pintassilgo, 2012, 2013; Dellink and Finus, 2012) has qualified this conclusion by showing that removing uncertainty only has a negative impact on cooperation in certain cases. Recent experimental evidence suggests that if there is uncertainty in the likelihood of tipping points of disastrous climate change impacts, this may reduce the success of cooperation (Dannenberg et al., 2011); conversely, reducing uncertainty about the likelihood of tipping points can increase prospects for collective action (Barrett and Dannenberg, 2012).

13.3.4 Compliance

As noted in Section 13.2.1.1, in the absence of a supranational authority, compliance with international agreements must be verified by parties to the agreement or through a related collaborative body they perceive as legitimate. Barrett (2003) sees compliance as a dimension of participation, in the sense that incentives to comply are incentives to continue participating in the agreement. The reputational costs of being a non-compliant party may differ from those of withdrawing altogether, but the magnitude of the difference is not clear. For example, there is only one case of withdrawal from the Kyoto Protocol, that of Canada in December 2011, but more than one case in which countries have not met their agreed emission targets (see Section 13.13.1.1).

Compliance does not necessarily equate with success—because countries choose whether to become party to an agreement, compliance may only reflect what countries would have done without the agreement (Downs et al., 1996). One measure of effectiveness is the extent to which the agreement changed countries' behaviour, compared to what they would have done in the absence of the agreement (the counterfactual baseline scenario) (Hafner-Burton et al., 2012). Evaluating an agreement's effectiveness is difficult because the counterfactual is not observed (Simmons and Hopkins, 2005; Mitchell, 2008; Hafner-Burton et al., 2012).

A necessary condition for successful compliance strategies is an independent and effective regime of 'measurement (or monitoring), reporting, and verification' (MRV) with a high frequency of reporting (as documented in the IPCC TAR; see also Section 2.6.4.3). Provisions for greater transparency in MRV are being developed with regard to (1) countries' GHG emissions, and (2) international financial flows from developed countries to developing countries for mitigation and adaptation measures (Winkler, 2008; Breidenich and Bodansky, 2009; Ellis and Larsen, 2008; Ellis and Moarif, 2009; Clapp et al., 2012). Lessons on MRV from other multilateral regimes—such as International Monetary Fund (IMF) consultations, Organisation for Economic Co-operation and Development (OECD) economic policy reviews, World Trade Organization (WTO) trade policy reviews, and arms control agreements—include attention to accuracy, evolution over time, combining self-reporting with third-party verification, including independent technical assessment as well as some form of political or peer review, the potential use of remote sensing or other technical means, and public domain outputs (Cecys, 2010; Pew Center, 2010; Bell et al., 2012).

Technical capabilities for monitoring emissions now include remote sensing from satellites which themselves pose new issues about the availability, diffusion, and governance of MRV capabilities for greater transparency. Greater transparency about financial flows requires detailed analysis of donor government budgeting in their legislative and administrative processes (Clapp et al., 2012; Falconer et al., 2012; Brewer and Mehling, 2014).

Measurement, reporting, and verification may be beneficially complemented by enforcement strategies, which are comprised of positive inducements—such as international transfers, financing, capacity-building, and technology transfer—and credible threats of sanctions for violating emissions commitments or reporting requirements. From a rationalist perspective, compliance will occur if the discounted net benefits from cooperation (including direct climate benefits, co-benefits, reputation, transfers, and other elements) exceed the discounted net benefits of defection (including avoided mitigation costs, avoided adverse side-effects, and expected sanctions). The institutional and behavioural reality of ensuring compliance can be more complicated. Moreover, the theoretical literature has stressed the difficulty of designing credible sanctions that are renegotiation-proof (Finus, 2001, 2003; Barrett, 2002; Asheim et al., 2006; Froyn and Hovi, 2008).

Some research suggests that the Kyoto Protocol is unusual among IEAs in that it established an 'elaborate and multifaceted' compliance system, which has been successful in assuring compliance with MRV requirements (Finus, 2008b; Oberthür and Lefeber, 2010; Brunnée et al., 2012), while many other IEAs rely on self-reporting of domestic actions. Compliance with MRV requirements can in turn improve detection of other forms of noncompliance. Even if the Kyoto Protocol compliance regime has been imperfect, it can offer lessons for future regimes, in particular with regard to MRV. The design of sanction mechanisms currently in place under the Kyoto Protocol, however, has also been criticized for not being fully credible (Halvorssen and Hovi, 2006; Barrett, 2009; Vezirgiannidou, 2009), though possibilities for improvement through modification have been identified (Finus, 2008b). For example, a sanction could take the form of a temporary suspension of monetary and technological transfers if recipient countries are found in non-compliance (Finus, 2008b). It has also been shown that a deposit system can be effective to enforce compliance: treaty members lodge a deposit into a fund from which they receive interest as long as they comply. In case of non-compliance, parts of the deposit are forfeited to compliant countries (Gerber and Wichardt, 2009, 2013).

Trade sanctions, such as those employed under the Montreal Protocol, are frequently put forward as a possible compliance mechanism (Barrett, 2003; Victor, 2011) (see Section 13.8 for institutional details and further discussion). A general reservation about trade sanctions is that they often not only affect the agreement-violator but also compliant countries, and hence this threat is not credible. Barrett (2009), Victor (2010), and others argue that trade sanctions are neither a feasible nor a desirable option for enforcing compliance with a climate agreement because trade sanctions may not be compatible with WTO rules. A WTO-compatible design may be feasible in the case of border adjustments with obligations to buy allowances (Ismer and Neuhoff, 2007; Monjon and Quirion, 2011). Meanwhile, imposition of trade sanctions would pose some risks of reducing cooperation by undermining capacity for compliance in targeted countries and could be burdensome to low-income populations in targeted countries (Murase, 2011). Especially if applied to embedded carbon (carbon from energy used to produce traded goods), the number of goods affected by the sanctions could be large, potentially fuelling a trade war that may negatively affect even those countries that intend to be the punishers (McKibbin and Wilcoxen, 2009) (see Sections 13.8 and 5.4.1 for further discussion).

Finally, there is a considerable literature on the potential use of legal remedies (such as civil liability) to address climate damages (Penalver, 1998; Grossman, 2003; Allen, 2003; Gillespie, 2004; Hancock, 2004; Burns, 2004; Verheyen, 2005; Jacobs, 2005; Smith and Shearman, 2006; Lord et al., 2011; Farber, 2011; Faure and Peeters, 2011). There has been little suggestion that such liability remedies be formally incorporated into climate agreements as compliance mechanisms, and there would be significant obstacles to doing so (including the lack of a robust international civil liability system). Nonetheless, this is a potential avenue for encouraging compliance, perhaps indirectly. The IPCC AR4 (IPCC, 2007) reported on evidence from various legal actions and potential actions that have been considered in the theoretical literature. Haritz (2011) has argued, based on an analysis of the literature and court cases, that it is theoretically possible to link the IPCC scale of likelihood with a scale based on legal standards of proof required for various kinds of legal action. Liability for climate change damage at the supranational level (de Larragán, 2011; Gouritin, 2011; Peeters, 2011), and at the national level in the United Kingdom (Kaminskaite-Slaters, 2011), the United States (Kosolapova, 2011), and the Netherlands (van Dijk, 2011), has been explored. Climate litigation and legal liability may put additional pressure on corporations and governments to be more accountable (Smith and Shearman, 2006; Faure and Peeters, 2011). However, there are key analytical hurdles to establishing important legal facts, such as causation and who is to be held liable (Gupta, 2014). While not framed in terms of liability or compensation, the UNFCCC negotiations in Doha decided to establish institutional arrangements associated with Loss and Damage (UNFCCC, 2013a).

13.4 Climate policy architectures

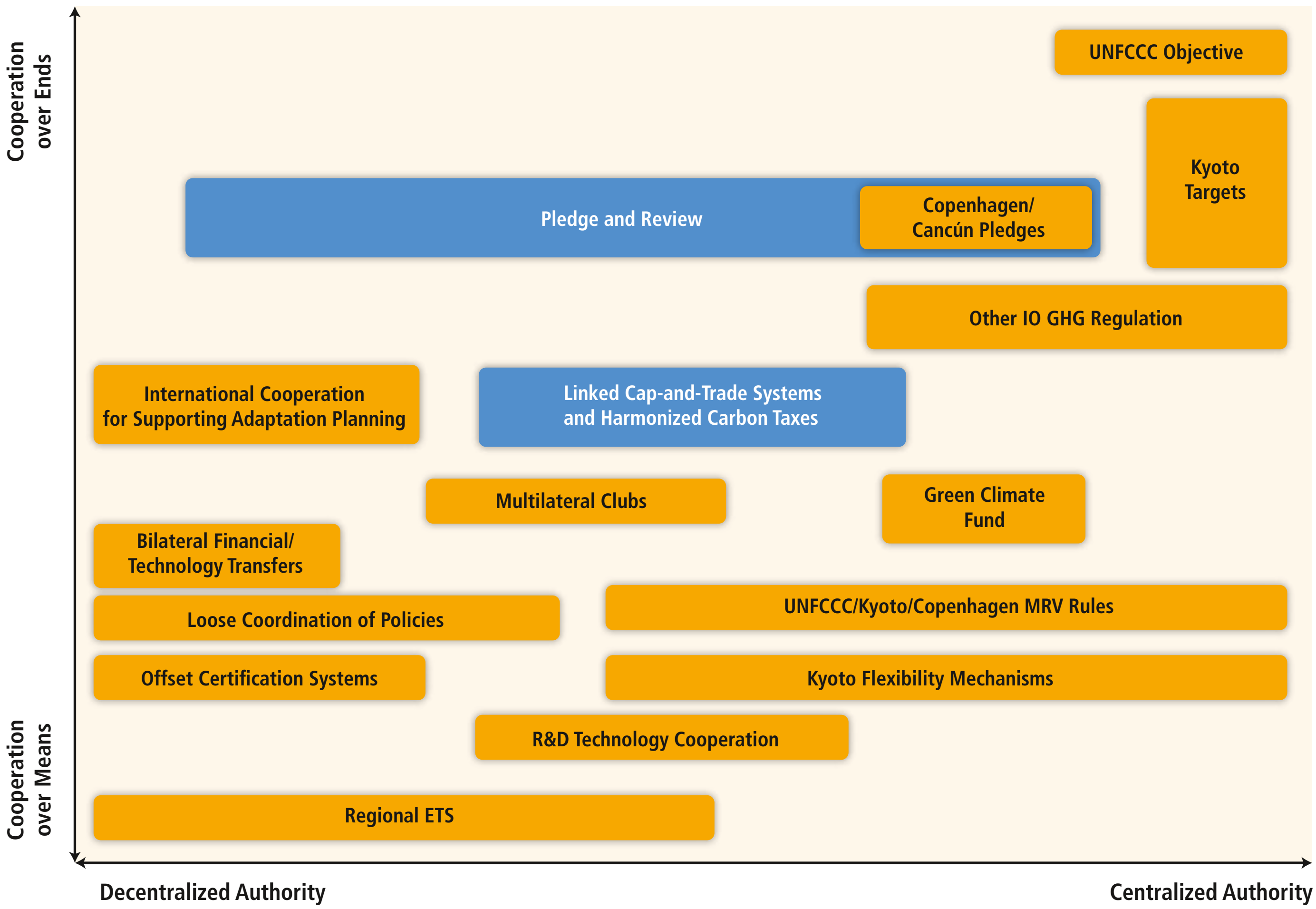
'Policy architecture' for global climate change refers to "the basic nature and structure of an international agreement or other multilateral (or bilateral) climate regime" (Aldy and Stavins, 2010a). The term includes the sense of durability, with regard to both policy structure and the institutions to implement and support that structure (Schmalensee, 1998, 2010), which is appropriate to the long-term nature of the climate-change problem.

13.4.1 Degrees of centralized authority

Absent the emergence of a global authority that has the capacity to impose an allocation of emissions rights on countries, as advocated by Tickell (2008), approaches to international cooperation all arise out of negotiated agreements among independent participants. However, they vary in the degree to which they confer authority on multilateral institutions to manage the rules and processes agreed to. On one end of the spectrum of possible approaches, referred to by some as 'top-down' (Dubash and Rajamani, 2010), actors agree to a high degree of mutual coordination of their actions with, for example, fixed targets and a common set of rules for specific mechanisms, such as emissions trading. On the other end of the spectrum, sometimes known as 'bottom-up' (Victor et al., 2005; Dubash and Rajamani, 2010), national policies are established that may or may not be linked with one another.

Figure 13.2 illustrates how existing and proposed international agreements can be placed on this spectrum (see IPCC, 2007, pp. 770–773 for a detailed list of many proposals that could be placed in this grid). The level of centralization refers to the authority an agreement confers on an international institution, not the process of negotiating the agreement. It shows that many proposals can be more or less centralized depending on the specific design. It also shows that the three idealized types discussed in the following sections have more blurred boundaries than their titles suggest. The figure also divides them into agreements focused on specific ends (emissions targets, for example)—and those that focus on means (specific policies, or technologies, for example). Finally, it should be understood that these are idealized types, and in practice there will be considerable additional complexity in how the basic design of agreements connect the actions of the various actors that make them up. There are distinct limits to what can be gleaned from the 'top-down vs bottom-up' metaphor or the degrees-of-centralization notion employed here (Dai, 2010) as, for example, emphasized in Ostrom's (2012) accounts of 'polycentric governance'.

As one prominent example, the Cancún Agreements are a 'hybrid' of top-down and bottom-up. They include voluntary mitigation pledges from many (but not all) UNFCCC parties, together with additional or elaborated common goals and centralized UNFCCC functions (e.g., with regard to adaptation, see Part II of the Cancún Agreements (UNFCCC, 2010)). It is quite possible that the agreement mandated by the Durban Platform on Enhanced Action, to be completed by 2015, will also be such a hybrid.



Loose coordination of policies: examples include transnational city networks and Nationally Appropriate Mitigation Actions (NAMAs);
R&D technology cooperation: examples include the Major Economies Forum on Energy and Climate (MEF), Global Methane Initiative (GMI), or Renewable Energy and Energy Efficiency Partnership (REEEP); Other international organization (IO) GHG regulation:
examples include the Montreal Protocol, International Civil Aviation Organization (ICAO), International Maritime Organization (IMO).

Figure 13.2 | Alternative forms of international cooperation. The figure represents a compilation of existing and possible forms of international cooperation, based upon a survey of published research, but is not intended to be exhaustive of existing or potential policy architectures, nor is it intended to be prescriptive. Examples in orange are existing agreements. Examples in blue are structures for agreements proposed in the literature. The width of individual boxes indicates the range of possible degrees of centralization for a particular agreement. The degree of centralization indicates the authority an agreement confers on an international institution, not the process of negotiating the agreement.

13.4.1.1 Centralized architectures and strong multilateralism

A centralized architecture, such as that generated by strong commitments to multilateral processes and institutions, is an agreement that establishes goals, targets, or both which are generally binding, for participating countries, within a specific time-frame, and establishes collective processes for monitoring progress towards meeting those goals. The Kyoto Protocol adopted targets and timetables for participating Annex B countries, one realisation of strong multilateralism (Bodansky, 2007). Other centralized approaches to international cooperation could expand on targets-and-timetables by also specifying the mechanism for implementation of the goals and/or targets of the agreement. Such an approach could establish, for example, a global cap-and-trade system or global carbon tax.

In the literature, targets-and-timetables have been coupled with specific notions of fairness, prospective conditions for political acceptance, or both—to establish quantitative targets and timetables for all countries and all years in a potential international agreement (Agarwala, 2010; Frankel, 2010; Höhne et al., 2008; Bosetti and Frankel, 2011; Cao, 2010c; IPCC, 2007, Chapter 13).

13.4.1.2 Harmonized national policies

A less-centralized approach would be to structure international cooperation around policies that would be harmonized, such as via collective monitoring, but where relatively little centralized authority is established or employed. In this class of approaches, aspects of national policies are made similar or even equivalent to one another. Examples include the G20 and Asia-Pacific Economic Cooperation (APEC) agreement in 2009 to phase out fossil fuel subsidies that encourage wasteful consumption (Barbier, 2010); the EU's use of private certification schemes for biofuels to link to its import policies for such fuels; efforts to harmonize private carbon-accounting systems, such as in the Carbon Disclosure Standards Board (Lovell and MacKenzie, 2011); hypothetical national carbon taxes that would be harmonized internationally (Cooper, 2010); adjusting design details of cap-and-trade schemes that are to be linked; and implementation of similar technology or performance standards. Many of these involve—or would involve—relatively limited numbers of actors, compared to UNFCCC agreements, reflecting the 'minilateralism' discussed in Section 13.2.1.1.

The so-called 'pledge and review' approach, exemplified to some degree by the Copenhagen Accord and the Cancún Agreements, is an architecture in which a participating nation or region voluntarily registers to abide by its stated domestic reduction targets or actions (pledges). The degree of centralization generated by this approach could vary considerably (see Figure 13.2), depending on the particular arrangement. If a pledge and review system, such as that represented by the Cancún Agreements, involved cooperation in forging an agreement that provided some centralized administration or monitoring (in addition to the voluntary announcement of pledges by individual countries), it could be considered an example of strong multilateralism, although perhaps with less centralized authority than the Kyoto Protocol or of coordinated national policies.

13.4.1.3 Decentralized approaches and coordinated policies

Finally, even more decentralized architectures may arise out of different regional, national, and sub-national policies, and subsequently vary in the extent to which they are connected internationally (Victor et al., 2005; Hoffmann, 2011). One form of decentralized architecture is linked regional, national, or sub-national tradable permit systems (Jaffe et al., 2009; Ranson and Stavins, 2012; Mehling and Haites, 2009). In such a system, smaller-scale tradable permit systems can be linked directly (e.g., through mutual recognition of the permits from other systems) or indirectly (e.g., through mutual recognition of an emission reduction credit system such as the Kyoto Protocol's CDM). In practice, such a system of linkage is already emerging. However, there remains the challenge of harmonizing the design details of the various trading systems, as discussed above (e.g., emissions reductions requirements, proportions of target emissions that may be covered by offset credits, use of ceiling or floor prices, and accounting units (Jaffe et al., 2009; Bernstein et al., 2010).

Similarly, heterogeneous regional, national, or sub-national policies could be linked either directly or indirectly (e.g., cap and trade in one jurisdiction linked with a tax in another) (Metcalf and Weisbach, 2012). Linkage of heterogeneous policies can occur through trade mechanisms (e.g., import allowance requirements or border adjustments) or via access to a common emission reduction credit system (e.g., the CDM, as with indirectly linked tradable permit systems).

13.4.1.4 Advantages and disadvantages of different degrees of centralization

Some authors conclude, particularly post-Copenhagen, that attempts to develop a comprehensive, integrated climate regime have failed, due to resistance to costly policies in both developed and developing countries and lack of political will (Michonski and Levi, 2010; Keohane and Victor, 2011), or alternatively because of the complexity that characterizes the problem (Hoffmann, 2011). Other analyses emphasize the legitimacy of the UN, particularly citing its universal membership (Hare et al., 2010; Winkler and Beaumont, 2010; Müller, 2010; La Viña, 2010) and noting that fragmentation of the climate regime could create opportunities for forum shopping, a loss of transparency, and reduced ambition (Biermann et al., 2009; Hare et al., 2010; Biermann, 2010). Other studies have examined (1) the evolution of multilateralism (Bodansky and Diringer, 2010) and possible transitional arrangements from fragmentation to a comprehensive agreement (Winkler and Vorster, 2007), and (2) how to manage fragmentation so that it may become synergistic rather than prone to conflict (Biermann et al., 2009; Oberthür, 2009).

13.4.2 Current features, issues, and elements of international cooperation

The policy architecture for climate change raises a number of specific questions about the structure of international cooperation. Four specific elements are of particular contemporary relevance: legal bindingness; goals, actions, and metrics; flexibility mechanisms; and participation, equity, and effort-sharing methods. These four elements deal with the key questions of how much an agreement insists on compliance with its obligations, what obligations it establishes, how flexible the implementation of the obligations may be, and how the obligations may vary across actors and situations. The discussion below focuses on mitigation of GHG emissions, but the four key elements apply as well to adaptation, financing, and other potential topics of international agreements on climate change. For example, UNFCCC Article 4(1)(b) (UNFCCC, 1992) calls on "all parties" to formulate and implement both "measures to mitigate climate change" by reducing net GHG emissions, and "measures to facilitate adequate adaptation to climate change." Understanding what is meant by such obligations requires examining these four key elements.

13.4.2.1 Legal bindingness

States choose whether to join an agreement, and can withdraw from an agreement, so international agreements exist by consent of the parties (Waltz, 1979; Thompson, 2006). Having said this, international agreements among states (national governments) may be more or less 'legally binding' on their parties. The degree of 'bindingness' depends on both the legal form of the agreement and the costs to the state of noncompliance.

Among the indicators of legal bindingness in the agreement itself are (1) legal type (e.g., treaty, protocol to a treaty, decision of the UNFCCC Conference of the Parties, and political declaration); (2) mandatory commitments, i.e., whether a commitment is 'expressed in obligatory language' (e.g., 'shall' or 'must,' vs. 'should' or 'aim') (Werksman, 2010)(Werksman, 2010)(Werksman, 2010); (3) specificity, i.e., "… whether [commitments] are expressed in sufficient detail to accurately assess compliance"; and (4) the type of enforcement procedures, mechanisms, and sanctions designed to implement an agreement by monitoring, reviewing, and encouraging compliance with commitments (Werksman, 2010).

International agreements may be labelled 'hard law' (such as treaties, their protocols, and contracts) that are legally binding on the

Table 13.1 | Taxonomy of legal bindingness: examples of commitments in international agreements for climate change.

Legal character (noting relevance of indicators 1–4 discussed in the text)	Description	Example
Mandatory provision in a legally binding agreement with enforcement mechanisms. (1)–(4)	A legally binding commitment can be subject to a compliance regime, with authority to sanction non-compliant parties. Enforcement can also come in the form of reciprocity for non-compliant actions.	The targets and timetables in the Kyoto Protocol (UNFCCC, 1998) and the Marrakech Accords (UNFCCC, 2001), with specific quantitative emissions limits, a compliance system that sanctions non-compliance, and flexibility mechanisms. (Outside the climate arena, the World Trade Organization is the most prominent example of this type.)
Mandatory provision in a legally binding agreement without enforcement mechanism. (1) and (2); possibly (3); but not (4)	'Legally binding,' but subject only to self-enforcement.	Article 4.1 of the UNFCCC (1992), mandating, *inter alia*, national emissions inventories, measures to mitigate, and measures to facilitate adaptation.
Non-mandatory provision in a legally binding agreement. (1), but not (2)–(4)	Such a provision does not demand compliance, but carries somewhat more weight than a political agreement.	Article 4.2 (a) and (b) of the UNFCCC (1992) commit developed countries to adopt policies and measures to limit their net GHG emissions (a mandatory provision); 4.2(a) then 'recognizes' that returning these emissions to earlier levels by the year 2000 would be desirable, and 4.2(b) provides the 'aim' of returning to 1990 levels (both non-mandatory provisions).
Mandatory provision in a non-legally binding ('political') agreement. (2), possibly (3); but not (1) or (4)	Such a provision may induce the party to act, through norms, reputation, and reciprocity.	The pledges on targets and actions submitted by states pursuant to the Copenhagen Accord (UNFCCC, 2009a) and Cancún Agreements (UNFCCC, 2010). (Outside the climate arena, the moratorium on high seas driftnet fishing is treated as binding by many states, even though United Nations General Assembly (UNGA) resolutions are not binding.)
Non-mandatory provision in a non-legally binding ('political') agreement. None of (1)–(4)	An aim or aspiration, expressed in hortatory, non-binding language. This type of provision typically includes one or more statements of principles or norms.	Targets set in the Noordwijk Declaration (1989), at a ministerial conference on climate change held prior to the 1992 Rio summit.

parties, or 'soft law' (such as declarations, resolutions, and guidelines) that are not legally binding. But the reality is more complex (Baxter, 1980; Abbott et al., 2000; Bodansky, 2010a; Guzman and Meyer, 2010). Across types of agreements, commitments may be more or less legally binding; for example, although treaties often contain mandatory commitments, a treaty may also contain hortatory provisions, such as aims and pledges, which are understood to be aspirational; while a political declaration may nonetheless contain provisions that raise strong expectations and consequences for failure (Raustiala, 2005). Some commitments may be specific and subject to monitoring and accountability, while others are vague and difficult to verify (Abbott and Snidal, 2000). Further, across types of agreements, the enforcement mechanism may be weak or rigorous, ranging from inaction to admonishments to trade sanctions to military force.

The bindingness of an agreement depends on the costs to a state of nonparticipation, noncompliance, or withdrawal—as well as to legal form. These costs include, as discussed above (see Section 13.3.4), not only the costs of sanctions imposed by the agreement's enforcement mechanism, but also the costs incurred from the state's loss of reputation and from the loss of mutual cooperation by other states. Reputational costs and lost-cooperation costs can influence states to adhere to (initially informal) norms; hence strong norms with high costs of violation are sometimes called 'binding' (Hoffmann, 2005, 2011; MacLeod, 2010).

Table 13.1 provides a taxonomy of the bindingness of international agreements (Bodansky, 2003, 2009). The usage of 'mandatory' in the table refers to the specific wording of the commitment—not to a state's choice of whether to participate or not.

Research has not resolved whether or under what circumstances a more binding agreement elicits more effective national policy. In general, a more legally binding commitment is more subject to monitoring and enforcement (both internationally and domestically), is more likely to require ratification by domestic institutions, and signals a greater seriousness by states (Bodansky, 2003; Rajamani, 2009). These factors increase the costs of violation (through enforcement and sanctions at international and domestic scales, the loss of mutual cooperation by others, and the loss of reputation and credibility in future negotiations).

On the other hand, there may be situations where there is a tradeoff between legal bindingness and ambition (stringency of commitments). Because greater legal bindingness implies greater costs of violation, states may prefer more legally binding agreements to embody less ambitious commitments, and may be willing to accept more ambitious commitments when they are less legally binding. (Rajamani, 2009; Raustiala, 2005; Guzman and Meyer, 2010; Albin, 2001; Grasso and Sacchi, 2011; Bodansky, 1999; Bernstein, 2005; See also Sections 13.2.2.5 and 13.3.3)

13.4.2.2 Goals and targets

Most agreements that advance international cooperation to address climate change incorporate goals. 'Goals' are 'long-term and systemic' (as contrasted with absolute emissions-reduction 'targets,' which may flow logically from the goals but which are 'near-term and specific') (IPCC, 2007, Chapter 13). The goals of an international agreement might include, for example, stabilization levels (or a reduction in a previously agreed stabilization level) of atmospheric concentrations of GHGs—or reductions in impacts of climate change.

Targets can be classified according to whether they require absolute GHG cuts relative to a historical baseline, or reductions relative to economic output, population growth, or business-as-usual projections (intensity targets). In recent literature on targets´ metrics, there has been a focus on whether or not intensity targets are superior to fixed ones when there is uncertainty about the future (Jotzo and Pezzey, 2007; Marschinski and Edenhofer, 2010; Sue Wing et al., 2009; Conte Grand, 2013). There are tradeoffs between reduced uncertainty about the cost of abatement, associated with intensity targets, and reduced uncertainty about environmental effectiveness, associated with absolute targets (Ellerman and Wing, 2003; Herzog, Timothy et al., 2006).

In the UNFCCC climate negotiations, examples of fixed targets are Kyoto Annex B country-emission reductions by 2008–2012 with respect to 1990 levels, and Copenhagen pledges (Some of the developed countries propose emissions reductions by 2020 with respect to some base year—1990, 2000, or 2005—while some of the developing economies suggest reductions by 2020 with respect to their business-as-usual trends). On the other hand, intensity targets have been proposed by China and India: their pledge is a reduction of carbon intensity (i.e., emissions/gross domestic product (GDP)) between 40 and 45 % and 20 and 25 % respectively by 2020 with respect to 2005 (Steckel et al., 2011; Zhang, 2011; Yuan et al., 2012; Cao, 2010b; Government of India, 2012). Another carbon target linked to GDP was the one planned by Argentina in 1999 (Barros and Conte Grand, 2002).

13.4.2.3 Flexible mechanisms

One focus of international negotiations has been enabling states to have flexibility in meeting obligations. In principle, there are numerous ways this could be achieved. For example, there could be provisions for renegotiating targets. The most often-cited benefit of flexibility is reduction in the costs associated with GHG-emissions reductions. However, Hafner-Burton et al. (2012) explore whether increased flexibility in designing obligations for states helps them align their international obligations more readily with domestic political constraints.

In existing interstate agreements, flexibility has been pursued principally through mechanisms that create markets. The rationale for these is to lower the cost of reducing emissions, relative to traditional regulatory regimes, as they direct investments in emissions reductions toward lower-cost abatement opportunities available in various jurisdictions. Such flexible mechanisms can involve trading emissions allowances under a fixed overall cap, generating offset credits, or combinations of the two. Generally, offset credits can be generated through project-based mechanisms or crediting of policies and sectoral actions. The former have been developed since the mid-1990s, with the CDM as by far the largest programme (Michaelowa and Buen, 2012); the literature assessing the CDM is reviewed in Section 13.13.1.1.) The latter are still being discussed with regards to post-2012 climate policies in the context of 'new market mechanisms' related to mitigation policies in developing countries (Nationally Appropriate Mitigation Actions (NAMAs)). Additionally, inter-temporal flexibility may be added to an allowance-trading regime through banking and borrowing of allowances, by which regulated entities may transfer current obligations to the future or vice versa. However, the environmental effectiveness and distributional impact of carbon markets have also raised concerns (Lohmann, 2008; Böhm and Dabhi, 2009).

The Kyoto Protocol provides three flexible mechanisms: Joint Implementation (JI), the CDM, and international emissions trading (IET) (in Articles 6, 12, and 17, respectively). Joint Implementation and CDM both generate offset credits from projects that reduce GHG emissions, and IET allows for government-to-government trading of Kyoto emissions allowances. Most attention in the research on these mechanisms has focused on the CDM, in part because of the volume of trading compared to the others (on the relatively small volume in Kyoto emissions trading, see Aldrich and Koerner, 2012).

The credits from JI and CDM may be used by Annex B countries to meet their emissions-reduction obligations. In practice, the key driver of investment in CDM projects has been the European Union (EU) Emission Trading Scheme (ETS), which allows regulated entities (companies or installations) to use credits from the CDM (referred to as 'Certified Emission Reductions' (CERs) and from JI (referred to as 'Emissions Reduction Units' or ERUs) to meet a portion of their ETS obligations (see Sections 13.6.1 and 14.4.2.1 for details). The EU ETS has accounted for about 84 % of demand for CERs and ERUs from 2008–2012. The next largest source of demand for CERs and ERUs comes from Japan, at 15 % of demand (Kossoy and Guigon, 2012).

Market-based flexibility mechanisms are evolving. Japan is pursuing bilateral crediting approaches under its Joint Crediting Mechanism/Bilateral Offset Crediting Mechanism (Ministry of the Environment, Government of Japan, 2012). COP-17 in Durban in 2011 mandated two approaches be pursued in the UNFCCC negotiations leading to a new international agreement in late 2015: (1) top-down, operating under authority of the COP ('new market-based mechanism'), which, as noted, focuses in large part on sectoral crediting; and (2) bottom-up, developed by countries 'in accordance with their national circumstances' ('framework for various approaches'), which attempts to coordinate heterogeneous policies across countries. COP-18 in Doha, Qatar, in 2012 reiterated and developed further details regarding these two approaches (UNFCCC, 2013b).

13.4.2.4 Equitable methods for effort sharing

While universal participation might be desirable in principle, actors participate in a context of heterogeneity in both economic capacity and emissions levels. Variations in both wealth and emissions have evolved over time; for example, many countries classified in the 1992 UNFCCC as developing (non-Annex I) have since experienced increasing incomes and increasing emissions (in some cases exceeding the incomes and/or emissions of some countries classified in 1992 as developed (Annex I)). These variations and continued differences are discussed further in Section 4.1.2.2. As to participation in international agreements, in general, a country is less likely to participate in an international agreement the more the country perceives the agreement to be unfair to its own economic and environmental interests. Addressing climate change equitably can thus be central to pursuing broad participation in climate agreements.

There is disagreement, however, about how to put equity principles into practice in international agreements. The UNFCCC adopted the principle of CBDRRC of parties (Article 3.1) (UNFCCC, 1992). Several different approaches have been advanced for putting this principle into practice. Deleiul (2012) argues that CBDRRC initially facilitated agreement and participation in the UNFCCC, but has become more contentious as national variations in income and emissions have evolved over time (hence Deleiul sees promise in the Durban Platform, which calls for mitigation contributions from all parties in a new treaty concluded by 2015, to take effect by 2020).

Section 4.6.2 elaborates these different approaches in detail, and suggests they can be broadly divided into those that start with the status quo of emissions, that thus focus on the question of 'effort-sharing' or 'burden sharing,' and those that start with a specific account of 'rights' to GHG emissions (such as equal per capita or equal per GDP emissions) and derive targets for countries from that formula (known as 'resource-sharing'). Rao (2011) refers to these as burden sharing vs. resource-sharing equity principles. Burden sharing methods are reviewed in (Jotzo and Pezzey, 2007; den Elzen and Höhne, 2008, 2010; Winkler et al., 2009; Chakravarty et al., 2009; Mearns and Norton, 2010; Frankel, 2010; Ekholm et al., 2010; Marschinski and Edenhofer, 2010; Cao, 2010c; Tavoni et al., 2013; den Elzen et al., 2013b; Höhne et al., 2013). 'Resource-sharing' approaches are examined in (Höhne et al., 2006; Chakravarty et al., 2009; Baer et al., 2009; Kanitkar et al., 2010; Jayaraman et al., 2011; Rao, 2011; Kartha et al., 2012).

Section 6.3.6.6 elaborates a wide range of possible approaches and quantifies them in terms of levels of emissions reductions for various world regions. One recent example is Winkler et al. (2013), which evaluates several approaches for mitigation of and adaptation to climate change, and suggests that these call for more mitigation in wealthier countries. Recent research is also comparing various measures of equity for climate policy within developing countries (Casillas and Kammen, 2012). Section 13.13 assesses existing and proposed agreements in light of these criteria.

Table 13.2 | Description of recent proposals for climate change policy architectures.

Proposed Architecture (recent references)	Description
Strong multilateralism	
Indicator-linked national participation and commitments (Baer et al., 2009; Chakravarty et al., 2009; Frankel, 2010; Bosetti and Frankel, 2011; WBGU, 2009; Cao, 2010c; BASIC Project, 2007; Winkler et al., 2011)	All countries adopt emissions targets and timetables, with time of participation and/or target levels based on one or more indicators (per capita income, economic cost as percentage of national income, historical emissions). Targets can both be reductions in emissions growth rates as well as absolute reductions.
Per capita commitments (Agarwala, 2010)	Countries implement equal per capita emissions targets, resulting in significant emissions increases for many developing countries, and significant decreases for industrialized countries.
Top-down burden sharing (Baer et al., 2009; Kartha et al., 2012; Cao, 2010c; Kanitkar et al., 2010; Jayaraman et al., 2011)	Emissions targets based on equal per capita emissions, mitigation burden proportional to cumulative emissions and ability to pay, countries with similar economic circumstances have similar burdens, and poorest countries and individuals exempt from obligations.
Sectoral approaches (Sawa, 2010; Schmidt et al., 2008; Barrett, 2010; den Elzen et al., 2008)	Countries develop national emissions targets by sector, and governments make international commitments to implement policies to achieve targets (Sawa, 2010) or based on staged sectoral approach (den Elzen et al., 2008); can be developed in a portfolio of treaties (Barrett, 2010). Alternatively, developing countries pledge to meet voluntary sectoral targets; reductions beyond targets can be sold to industrialized countries (Schmidt et al., 2008).
Portfolio system of treaties (Barrett, 2010; Stewart et al., 2012)	Separate international treaties concluded for different sectors, different GHGs. Treaty obligations apply globally, and developing countries offered financial assistance to aid compliance and induce participation. Trade restrictions used to enforce agreements in trade-sensitive sectors.
Harmonized national policies	
Global emissions permit trading system (Ellerman, 2010)	The EU ETS serves as prototype for a global emissions trading system. Design informed by EU ETS experience, which has a central coordinating institution (the European Commission), mechanisms to expand participation to new Member States, and effective financial flows resulting from trading. Distributional impacts addressed by specific design features.
International carbon tax (Cooper, 2010; Nordhaus, 2008; Metcalf and Weisbach, 2009)	A common charge levied on all global GHG emissions, most practically upstream (at oil refineries, gas pipelines, mine mouths, etc.). Each country collects and keeps its own revenues. Charges rise over time according to schedule to induce cost-effective technological change. Distributional impacts addressed by allocation of revenues.
Hybrid market-based approaches (Fell et al., 2012)	A tradable emissions permit system includes a price ceiling, a price floor, or a combination of the two (a price collar). System functions like a hybrid of a tax and a tradable permit system. The price ceiling (often called a 'safety valve') can take the form of unlimited allowances sold at a fixed price or a limited allowance reserve.
Decentralized architectures and coordinated national policies	
Linked domestic cap-and-trade systems (Jaffe and Stavins, 2010; Jaffe et al., 2009; Bernstein et al., 2010; Metcalf and Weisbach, 2012; Ranson and Stavins, 2013)	Domestic and international emissions trading and emissions reduction credit systems linked, directly or indirectly, to achieve cost savings. Direct linkages require more coordination, while indirect linkages (of cap-and-trade systems through a common credit system, for example) require less. Linkage achieved independently (as a bottom-up architecture), as a transition to a new top-down architecture, or as an element of a broader climate agreement.
Linked heterogeneous policy instruments (Metcalf and Weisbach, 2012)	Domestic and international emissions trading systems linked with carbon tax systems, allowing emissions permits from one country to be remitted as tax payments, and/or allowing payments in excess of the tax in one country to satisfy the requirement to own a permit in another. Alternatively, fixed emissions standards (or even technology standards) linked with taxes or tradable permit systems across countries or regions.
Technology-oriented agreements (Newell, 2009, 2010a; de Coninck et al., 2008)	International climate change agreements to cover issues such as knowledge sharing and coordination, joint research and development, technology transfer, and/or technology deployment mandates or incentives. Distributional impacts affected by intellectual property sharing rules.

13.4.3 Recent proposals for future climate change policy architecture

An extensive literature has examined what options could be pursued 'post-2012', after the end of the first commitment period (CP1) of the Kyoto Protocol. The literature now contains several surveys of diverse proposals (see summaries of pre-2007 literature in Höhne et al., 2008; Moncel et al., 2011; Aldy and Stavins, 2010b; Rajamani, 2011b, 2012a; IPCC, 2007, Chapter 13). Table 13.2 describes recent proposals for climate policy architectures. Qualitative and quantitative performance assessments of these proposals, where available, are surveyed in Section 13.13.

13.4.4 The special case of international cooperation regarding carbon dioxide removal and solar radiation management

Since the publication of AR4, carbon dioxide removal (CDR) and solar radiation management (SRM) have received increasing attention as a means to address climate change, distinct from mitigation and adaptation. These two approaches are often collectively referred to as 'geoengineering' or 'climate engineering' (for more detail, see Working Group (WG) I contribution to the IPCC Fifth Assessment Report (AR5) Section 6.9). Carbon dioxide removal refers to techniques to extract GHGs directly from the atmosphere and store them in sinks, or to directly enhance such sinks. Solar radiation management aims to reduce the amount of solar radiation absorbed by the Earth's surface. Proposed SRM projects can be atmospheric (e.g., cloud brightening or adding reflective sulphate particles to the lower stratosphere), terrestrial (e.g., enhancing the albedo of the ground, or painting pavements and roof materials white to reflect solar radiation) and space-based (e.g., placing mirrors in space). See WGI report, Section 7.7, for details of these.

Some SRM options (e.g., injecting sulphate particles into the lower stratosphere) may be inexpensive enough for individual states (Barrett, 2008a) and even non-state actors, such as wealthy individuals, to undertake (Barrett, 2008a; Victor, 2008; Lin, 2009; Victor et al., 2009; Bodansky, 2011b). CDR and other SRM approaches might need to be implemented by numerous countries in order to be effective (Humphreys, 2011). Some SRM options may also have specific regional impacts (e.g., regional temperature and precipitation effects, leaf albedo enhancement, or ocean circulation modification), providing direct and perhaps excludable benefits to actors undertaking them (Millard-Ball, 2012) and external costs to others (Ricke et al., 2010, 2013). See also WGII 19.5.4 for detailed discussion of the risks of SRM.

Smaller-scale actors that are particularly vulnerable to climate change impacts may perceive advantages to be first-movers with SRM, in order to ensure both global climate protection and a favourable distribution of regional impacts from their selected SRM projects (Ricke et al., 2010; Millard-Ball, 2012). Hardly any cooperation might be needed for SRM's development and deployment—indeed, countries facing severe impacts might rush to launch a preferred SRM project (Millard-Ball, 2012). If the benefits of such an SRM project outweigh the adverse side-effects, and its costs are indeed low, then such an SRM project might be desirable. But such unilateral action could also produce significant adverse side-effects and costs for other actors, if the SRM option chosen is one that secures climate benefits for one part of the world while creating climate or other damages in other parts (Lin, 2009). Solar radiation management may also be ineffective in mitigating some climate impacts, for example the acidification of oceans from absorption of excessive CO_2 (Humphreys, 2011). Further, SRM does not reduce concentrations of atmospheric GHGs, and interrupting SRM after concentrations have risen significantly could allow temperatures to rise rapidly (see also Smith and Rasch, 2012).

Solar radiation management poses the converse of the collective action and governance challenges arising from emissions-reduction efforts: rather than mobilizing hesitant action to limit emissions, SRM governance involves restraining hasty unilateral action (Victor, 2008; Victor et al., 2009; Virgoe, 2009; House of Commons Science and Technology Committee, 2010; Lloyd and Oppenheimer, 2014; Millard-Ball, 2012; Bodansky, 2011b). One of the main issues for international cooperation will be to develop institutions and norms to address potential negative consequences of SRM in other social or environmental fields, or for parts of the world either not protected or negatively affected by the SRM option chosen. Thus, some analysts have recommended that international governance be organized for SRM research and testing, to learn about the benefits and side-effects of SRM options, to develop institutions to decide if and when to deploy SRM, to learn how to maintain SRM capabilities, and to monitor and evaluate this research and its use (Victor et al., 2009; Blackstock and Long, 2010; Lin, 2009; Solar Radiation Management Governance initiative, 2011).

Some existing international agreements may be relevant to geoengineering. The UNFCCC already includes a provision, Article 4.1(f), requiring assessment of the adverse impacts of mitigation measures. The UN Convention on Law of the Sea contains important provisions on environmental protection (Redgwell, 2006), and may have increased significance with regards to the governance of marine-based carbon dioxide storage or geo-engineering options (Virgoe, 2009). Under the London Convention and Protocol, the International Maritime Organization (IMO) held that, given the uncertainty surrounding negative impacts, ocean fertilization other than 'legitimate scientific research' ought not be permitted (Reynolds, 2011; IMO resolution LC-LP.1, 2008 and LC-LP.2, 2010). Several multilateral fora have recently taken up the issue of SRM. The 1992 Convention on Biological Diversity (CBD) adopted a decision calling for a moratorium on 'geo-engineering activities that may affect biodiversity' (Convention on Biological Diversity, 2010; Tollefson, 2010). Other existing multilateral treaties and agreements that may relate to geo-engineering include: the 1977 UN Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques (the ENMOD Convention) (though it restricts only 'hostile' actions); the convention on Environmental Impact Assessment in a Transboundary Context (UNECE, 1991); the 1959 Antarctic Treaty System (US Department of State, 2002); and ongoing developments in human rights law and in environmental law (Reynolds, 2011; Convention on Biological Diversity, 2012). Further, the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (United Nations, 2002) may apply to the use of sun-deflecting mirrors in space.

13.5 Multilateral and bilateral agreements and institutions across different scales

This section builds on the description of the climate policy landscape in Section 13.3.1 and plausible climate policy architectures in Section 13.4. It considers the experience and evolution of international and transnational cooperation on climate change between states and non-state actors since 2007 when the Fourth Assessment Report of the IPCC was published.

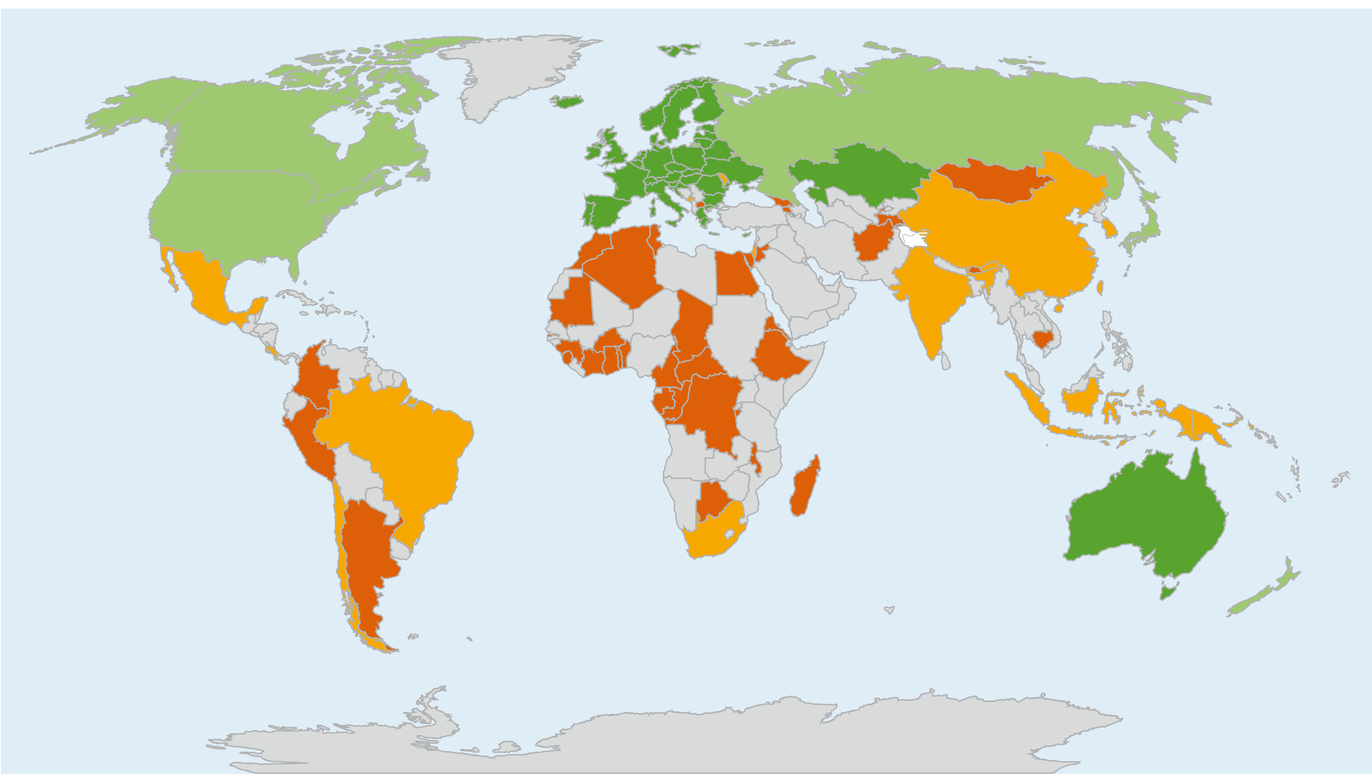
13.5.1 International cooperation among governments

13.5.1.1 Climate agreements under the UNFCCC

The UNFCCC's universal membership provides it with a high degree of legitimacy among parties around the world (Karlsson-Vinkhuyzen and McGee, 2013). Steps taken under the Convention and its Kyoto Protocol have led to more extensive action than under other forms of international cooperation on climate change.

Evolution of the multilateral climate regime since AR4

At COP-13 in Bali in 2007, discussions on long-term cooperative action under the Convention turned into negotiations under the Bali Action Plan (UNFCCC, 2007a). Also in Bali, countries agreed to MRV of mitigation commitments or actions by developed countries and mitigation actions by developing countries and support for those. Under the Copenhagen Accord (UNFCCC, 2009a) and Cancún Agreements (UNFCCC, 2010), Forty-two developed countries (including the 27 EU member states) submitted absolute reduction commitments against various base years in the form of quantified economy-wide emissions targets for 2020. Fifty-five developing countries and the African Union submitted information on NAMAs to the UNFCCC (as of May 2013), which are subject to domestic and international MRV. These 55 developing countries expressed their proposed goals in a variety of ways (e.g., relative emission reductions, deviation below business-as-usual, absolute reductions, and goals related to carbon neutrality); 16 proposed economy-wide goals for mitigation of GHGs. Since 2010, no major economy has significantly changed its emission reduction proposal under the UNFCCC, though some countries have clarified their assumptions and business-as-usual emission levels (UNEP, 2010, 2011, 2012, 2013b; den Elzen et al., 2013a; Sharma and Desgain, 2013; UNFCCC, 2013c). Figure 13.3 displays the different categories of actions and pledges taken by countries under the Cancún Agreements and the Kyoto Protocol as of September 2013.



- Developed countries with Quantified Emission Limitation or Reduction Commitments (QELROs) under the Kyoto Protocol and Cancún agreements
- Developed countries with Quantified Economy-Wide Emission Reduction Targets (QEERTs) under Cancún agreements
- Developing countries with Nationally Appropriate Mitigation Actions stating their impact on greenhouse gas emissions (Reduction relative to BAU; Reduction in carbon intensity of GDP, compared to 2005 levels)
- Developing countries with Nationally Appropriate Mitigation Actions, termed as policy-, sectoral-, and project-level actions
- Countries with no pledges

Figure 13.3 | Global map showing the different categories of reduction proposals or commitments for 2020 under the Cancún Agreements and Kyoto Protocol, based on UNEP (2012, 2013b) with underlying data supported by UNFCCC (2011b, 2012d, 2013c).

COP-17 in Durban in 2011 produced the Durban Platform for Enhanced Action (UNFCCC, 2011a), in which the delegates agreed "to launch a process to develop a protocol, another legal instrument or an agreed outcome with legal force under the Convention applicable to all Parties" (UNFCCC, 2011a) and "complete its work as early as possible but no later than 2015 in order to adopt this protocol, another legal instrument or an agreed outcome with legal force at the twenty-first session of the Conference of the Parties and for it to come into effect and be implemented from 2020" (UNFCCC, 2011a).

Evolution of coalitions among UNFCCC parties

New and existing coalitions of countries have engaged in the UNFCCC negotiations, each presenting coordinated positions. Several distinct coalitions of developing countries have formed to negotiate their divergent priorities. Examples include the G77 & China, which represents 131 developing countries operating in the UNFCCC and the UN system more broadly and which contains sub-groups such as the African Group, the Least Developed Countries, and the Arab Group; the Alliance of Independent Latin American and Caribbean states; and a 'like-minded developing country' group that included China, India, and Saudi Arabia (Grubb, 2013). Other coalitions organized to influence UNFCCC negotiations include the Alliance of Small Island States (AOSIS), which has played a significant role in UNFCCC negotiations since the early 1990s; various groupings of industrialized countries, including the Umbrella Group; the Environmental Integrity Group, which was the first coalition to include both industrialized and developing countries; the BASIC countries (Brazil, South Africa, India and China) (Olsson et al., 2010; Rong, 2010; Nhamo, 2010); the Coalition of Rainforest Nations, which has increased the salience of forests in climate negotiations; and other active coalitions not limited to the climate context, for example the Comision Centroamericana de Ambiente y Desarollo and the Bolivarian Alliance for the Americas.

Negotiations under the Kyoto Protocol

Negotiations on a second commitment period (CP2) of the Kyoto Protocol were launched in Montréal in 2005. These negotiations concluded in late 2012 at COP-18 in Doha, Qatar with a decision and amendment establishing the second commitment period of the Protocol for 2013–2020. However, a number of Annex I countries (Belarus, Canada, Japan, New Zealand, Russia, the United States, and Ukraine) decided not to participate in the second commitment period. The other Annex I countries (Australia, the EU and its member states, Iceland, Liechtenstein, Monaco, New Zealand, Norway, Switzerland, and Ukraine) adopted quantified emission reduction commitments (Figure 13.3), covering 13 % of global GHG emissions at 2010 emission levels (UNFCCC, 2012d; JRC/PBL, 2013). At COP-18 in Doha in 2012, parties also agreed upon rules for transferring surplus Kyoto emissions allowances from the first to the second period. These rules are assessed in Section 13.13.1.1, and the evolution of market-based flexibility mechanisms in the UNFCCC negotiations is discussed in Section 13.4.2.3.

New institutions under the UNFCCC and the Kyoto Protocol

The UNFCCC and its Kyoto Protocol have brought about a number of new institutions focused on adaptation (funding and coordination), finance, and technology. The Adaptation Fund was established to provide direct access to financing for developing countries and is governed by a majority of developing countries. The Adaptation Committee was established to coordinate previously fragmented aspects of adaptation policy under the Convention, with modalities and linkages to other institutions to be defined (UNFCCC, 2011c) (see Section 13.11.1.1). The GCF is accountable to the Conference of the Parties, and, when it is fully operational, may be a major channel for the provision of climate finance (Brown et al., 2011). The Standing Committee on Finance supports the parties in coordinating and providing accountability for the financial mechanism of the Convention. The Climate Technology Centre and Network (CTCN), together with the Technology Executive Committee (TEC), was established to exchange information regarding technology development and transfer for adaptation and mitigation (UNFCCC, 2011c).

13.5.1.2 Other UN climate-related forums

Acting on climate change may require functions other than negotiation under the UNFCCC or other forms of high-level cooperation, such as analytical support and implementation assistance for mitigation and adaptation efforts. A diverse set of forums both within and outside the UN system has taken up the issue of climate change since AR4, possibly contributing to broader institutional learning and effectiveness (Depledge, 2006; Stewart et al., 2012).

The United Nations Environment Programme (UNEP) has had a natural concern with climate change for many years, given its mission, and it collaborates closely with the UNFCCC. Since AR4, UNEP has provided increasingly significant analytical support to the international process, in part through its emissions-gap reports (UNEP, 2010, 2012, 2013b; Höhne et al., 2012b; Hof et al., 2013), but also through a wide range of other analytical efforts and support for institution building.

United Nations forums beyond the UNFCCC are increasingly addressing funding for adaptation and mitigation. Fragmentation in the various objectives, conditions, and eligibility requirements of the different funds may make it difficult for developing countries to identify and access appropriate funding (Czarnecki and Guilanpour, 2009). The literature examines the relationship between adaptation and development finance, including concerns about measuring official development assistance (ODA) and how much adaptation funding is 'new and additional' (Stadelmann et al., 2010; Smith et al., 2011). A number of developing countries have established "national funding entities to coordinate domestic and international funding for adaptation with development funding" (Smith et al., 2011).

Other UN agencies have also addressed the connections of climate change with human development (UNDP, 2007; UNDESA, 2009), the

CO_2 emissions gap (Convention on Biological Diversity, 2012; Höhne et al., 2012b), finance (AGF, 2010), and human rights (see Section 13.5.2.2).

The Montreal Protocol on Substances that Deplete the Stratospheric Ozone Layer (concluded in 1987 under UN auspices)—and the Protocol's subsequent amendments, adjustments, and decisions—have also contributed to reductions in GHGs. One notable proposed amendment would accelerate the phaseout of substitutes of ozone depleting substances that are also strong GHGs (Mauritius & Micronesia, 2009; Velders et al., 2012).

13.5.1.3 Non-UN forums

Climate change is increasingly addressed in forums for international cooperation outside of the UN. The AR4 (IPCC, 2007, Chapter 13) assessed several partnerships focused on particular themes, technologies, or regions.

Some international partnerships have defined themselves as complements to the UNFCCC rather than as alternatives. For example, the REDD+ Partnership helps coordinate measures for reducing emissions from deforestation and degradation (REDD) in the UNFCCC process. The Partnership focuses on conservation, sustainable forest management, and forest carbon stock enhancement. In 2010, more than 50 countries signed a non-binding agreement to pledge more than 4 billion USD to REDD+ (Bodansky and Diringer, 2010). Michaelowa (2012a) and Stewart el al. (2009) describe multiple avenues for climate change financing to assist transitions to low-carbon technologies, such as through the International Renewable Energy Agency (IRENA). Established in 2009, IRENA seeks to advance the development and transfer of renewable energy technologies, with a focus on financing renewable energy in its 163 member and signatory states (plus the European Union) (Florini, 2011; International Renewable Energy Agency, 2013).

The MEF, organized by the United States, provides a forum for informal consultation. Its members—Australia, Brazil, Canada, China, the European Union, France, Germany, India, Indonesia, Italy, Japan, the Republic of Korea, Mexico, Russia, South Africa, the United Kingdom, and the United States—together account for about 70 % of global GHG emissions (JRC/PBL, 2013). Its meetings are intended to advance discussion of international climate change agreements (MEF, 2009), and it has generated a related Clean Energy Ministerial. MEF participants recognize the group as a venue for discussion rather than a forum for negotiating binding agreements. The MEF produces a chairs' summary instead of formally agreed text (Leal-Arcas, 2011). The existence of the MEF may be evidence of an overall increase in the fragmentation of global environmental governance (Biermann and Pattberg, 2008; Biermann, 2010). Some may also be concerned about a small set of large countries reaching even informal decisions that affect a much larger set, and some may not be comfortable with a process chaired by a single nation (Stavins, 2010).

The Group of Twenty (G20) finance ministers from industrialized and developing economies could have the capacity to address climate finance, building on its core mission to discuss economic and finance policy. The make-up of the G20 is similar to that of the MEF, with the addition of Argentina, Saudi Arabia, and Turkey. Houser (2010) finds that the G20 might help to accelerate the deployment of clean energy technology, help vulnerable countries adapt to climate change impacts, and help phase out inefficient fossil-fuel subsidies. At its meeting in Pittsburgh in 2009 (G20, 2009), the G20 gave considerable attention to climate change policy issues, in particular to fossil-fuel subsidies. Likewise, since 2005, the smaller Group of Eight (G8) heads of state and government have held a series of meetings relating to climate change and recognized the broad scientific view that the increase in global average temperature above pre-industrial levels ought not exceed 2 °C (G8, 2009). Van de Graaf and Wsetphal (2011) explore both opportunities for and constraints on the G20 and G8 with regard to climate.

Two forums of growing importance, providing analytical support for international cooperation on climate change, are the International Energy Agency (IEA) and the OECD. While the IEA has limited its membership to industrialized oil-importing countries (Scott, 1994; Goldthau and Witte, 2011), the OECD has granted membership to advanced developing countries. Both institutions have received increasingly strong mandates by their members to provide analytical support for climate change mitigation decisions. The OECD has a unit for economic analysis of climate policy and impacts, and already plays a role in building knowledge (OECD, 2009). The IEA could play a key role to reduce uncertainty about countries' performance by collecting, analyzing, and comparing energy and industry-related emissions data (Harvard Project on Climate Agreements, 2010). The IEA and OECD have formed and jointly manage the Climate Change Expert Group, whose explicit mission is to provide analytical support on technical issues to the international negotiations.

The Cartagena Dialogue for Progressive Action includes around 30 industrialized and developing countries, which have met both during and between formal sessions since 2009. The Dialogue is open to countries working toward an ambitious, comprehensive, and legally binding regime in the UNFCCC, and who are committed to domestic policy to reduce emissions. The aim of the Dialogue is to openly discuss positions, to increase understanding, and to explore areas where convergence and enhanced joint action could emerge (Oberthür, 2011).

In February 2012, a group of seven partners (Bangladesh, Canada, Ghana, Mexico, Sweden, and the United States, together with the UNEP) launched a new 'Climate and Clean Air Coalition' as a forum for dialogue among state and non-state actors outside the UNFCCC process. The goal of the Coalition is to reduce levels of black carbon, methane, and hydrofluorocarbons (HFCs) among its 34 state members (including the European Commission) in collaboration with nine international organizations and 29 non-state partners (as of September 2013). The Coalition has received funding from a number of countries, including Canada, Japan, and the United States to implement projects (Blok et al., 2012; UNEP, 2013a).

New initiatives on international cooperation for adaptation and its funding have also been created, such as the World Bank's Pilot Program on Climate Resilience, and the European Commission-established Global Climate Change Alliance (GCCA), which pledges regional and country-specific finance.

13.5.2 Non-state international cooperation

13.5.2.1 Transnational cooperation among sub-national public actors

A prominent development since AR4 is the emergence of a large number of international agreements between non-state entities (den Elzen et al., 2011a; Höhne et al., 2012b; Hare et al., 2012). These are most commonly referred to as 'transnational climate governance initiatives' (Biermann and Pattberg, 2008; Pattberg and Stripple, 2008; Andonova et al., 2009; Bulkeley et al., 2012). In the most comprehensive survey, (Bulkeley et al., 2012) document 60 of these initiatives, which can be grouped into four principal types: public-private partnerships, private sector governance initiatives, non-governmental organization (NGO) transnational initiatives, and sub-national transnational initiatives. The first two, involving private actors, are discussed in Section 13.12.

NGO transnational initiatives attempt to influence the activities of corporations directly through transnational partnerships, some of which involve collaboration with the private sector. They have set up certification schemes for carbon offset credits, such as the Gold Standard, which is limited to renewable energy and demand-side energy efficiency projects, and the Community Carbon and Biodiversity Association standard, which aims to increase the quality of forestry credits (Bayon et al., 2007; Bumpus and Liverman, 2008). Certified offset credits have commanded a price premium above other ('standard') credits (Sterk and Wittneben, 2006; Ellis et al., 2007; Nussbaumer, 2009; Newell and Paterson, 2010). These certification schemes have been used for the Voluntary Carbon Market as well as for the CDM (Conte and Kotchen, 2010).

Sub-national transnational initiatives involve sub-national actors, such as city-level governments, collaborating at an international scale. One example of this form of cooperation is the International Council for Local Environmental Initiatives (ICLEI)—Local Governments for Sustainability network. This organization has taken action through its Cities for Climate Protection programme from 1993 and more recently through a partnership the C40 Cities Climate Leadership Group (Kern and Bulkeley, 2009; Román, 2010; Bulkeley et al., 2012). A World Mayors Summit in November 2010 had participation from 138 cities and agreed on a Global Cities Covenant on Climate, otherwise known as the Mexico City Pact. A related initiative, the 'carbonn' Cities Climate Registry, is an effort of local governments to regularly measure, report, and verify cities' actions on climate change mitigation and adaptation (Chavez and Ramaswami, 2011; Ibrahim et al., 2012; Otto-Zimmermann and Balbo, 2012; Richardson, 2012). Recognition of local governments as governmental stakeholders in paragraph I.7 of the Cancún Agreements is a reflection of the growing role of sub-national transnational cooperation in the UNFCCC processes.

Larger sub-national units have developed transnational collaborative schemes. Most notable are the North American sub-federal cap-and-trade schemes, including the Western Climate Initiative (WCI). The WCI was originally envisaged to link state and provincial cap-and-trade systems in seven western U.S. states and four Canadian provinces beginning in 2012. The original aim of the initiative was reducing GHG emissions by the member states and provinces to 15 % below 2005 levels by 2020 (Rabe, 2007; WCI, 2007; Selin and VanDeveer, 2009; Bernstein et al., 2010). While the U.S. state of California's ETS began operating in January 2013, the launch of the WCI system has been delayed. The WCI currently includes only California and Québec, although Ontario, British Columbia, and Manitoba are considering accession.

13.5.2.2 Cooperation around human rights and rights of nature

Human rights law could conceivably frame an approach to climate change (Bodansky, 2010b; Bell, 2013; Gupta, 2014). Some recent literature argues that a human rights framing helps 'to counteract gross imbalances of power' between states and individuals (Sinden, 2007; Bratspies, 2011; Akin, 2012). The human rights approach to climate change has been acknowledged by the UN Human Rights Council in its Resolution 7/23 and the Office of the United Nations High Commissioner for Human Rights (UNHRC, 2008; Limon, 2009; OHCHR, 2009). The literature discusses a variety of specific issues, including the implications for climate adaptation; the impacts of climate change on human rights to water, food, health, and development; obligations to undertake mitigation actions; and whether human rights law implies an obligation to receive climate refugees.

Refugees displaced from their homes due to climate change may strain the capacity of existing institutions (Biermann and Boas, 2008). However, policies to address climate refugees face legal hurdles, including the issue of causality: who is to be held responsible, who is the rights-bearer, and the issue of standing (Limon, 2009). Proposals have been made in the literature for a new protocol to the UNFCCC, a new convention, and funding mechanisms to address the issues associated with climate refugees (Biermann and Boas, 2008; Docherty and Giannini, 2009). Such efforts could build on the 1951 Geneva Convention Relating to the Status of Refugees. In the absence of coordinated efforts, the Special Procedures and the Universal Periodic Review of the Human Rights Council are advancing the human rights and climate change agenda (Cameron and Limon, 2012).

In 2010, the government of Bolivia convened government and non-government representatives in the World People's Conference on Climate Change and the Rights of Mother Earth, which culminated in a People's Agreement (WPCCC and RME, 2010). The participation of social movements in international cooperation on climate change may enhance recognition of 'radical climate justice' (Roberts, 2011) and an approach to law that seeks to establish 'rights of nature' (Cullinan, 2002; Sandberg and Sandberg, 2010; Aguirre and Cooper, 2010).

13.5.3 Advantages and disadvantages of different forums

The literature has considered the strengths and weaknesses of negotiating climate policy across multiple forums and institutions. Some studies suggest that, in addition to its own action, the UNFCCC effect of catalyzing efforts by others and providing coherence to multiple initiatives may result in greater aggregate impact (Moncel and van Asselt, 2012). Other literature suggests that 'regime complexes' may emerge from smaller 'clubs' and then expand (Keohane and Victor, 2011; Victor, 2011). Regimes need (external) incentives for participation and (internal) incentives for compliance (Aldy and Stavins, 2010c). A key advantage of smaller forums or 'clubs' may be greater efficiency in the negotiation process, as emphasized in the general political science literature on negotiations (for example, Oye, 1985). But the literature also reflects key disadvantages, including that such clubs lack universality and hence legitimacy (Moncel et al., 2011), and that the environmental effectiveness of clubs may be undercut by leakage of emissions sources to other countries outside the club (Babiker, 2005). Some have suggested clubs as a way forward outside the UNFCCC, while others suggest they could contribute to the UNFCCC, for example by assisting in catalyzing greater ambition (Weischer et al., 2012). Several smaller 'clubs' that cut across categories (e.g., public/ private) and scales (from international to local) are assessed in Section 13.5.1.2. Flexibility is another advantage cited for smaller clubs. Climate change mitigation through 'clubs' is not necessarily superior (Keohane and Victor, 2011) and action through this form of cooperation has to date not brought about high levels of participation and action. Smaller clubs must address conflicts where the climate change regime intersects with other major policy regimes (Michonski and Levi, 2010). Analysis of existing clubs suggests they enable incremental change and suggests that a set of incentives (related to trade, investment, labour mobility, or access to finance) could turn these into 'transformational clubs' (Weischer et al., 2012).

In a fragmented world, linking multiple agreements into a coherent whole is a major challenge. The aggregate effectiveness (in terms of the criteria discussed in Section 13.2) of the landscape of climate agreements and related institutions (Figure 13.1) can be enhanced by coordinated linkages among multiple elements. The actual forms and effects of policy linkages, existing or future, must be evaluated in each context. Policy linkages across the landscape of agreements on climate change might take several forms, such as mandated action and reporting by subsidiary bodies, agreed links between institutions (e.g., memoranda of understanding), loose coordination, information sharing, and delegation. The literature on transnational governance acknowledges a gap in that "interactions are understudied in all areas of transnational governance" (Weischer et al., 2012). Some characteristics of potential linkages may stimulate their formation, for example, competition among public and private governance regimes (Helfer and Austin, 2011), accountability (Bäckstrand, 2008; Ballesteros et al., 2010), learning (Kolstad and Ulph, 2008), and experimentation. Related literatures suggest that other important characteristics of linkages across regime components may be reciprocity (Saran, 2010), relationships of conflict or interpretation (ILC, 2006), collaboration (Young, 2011), the catalytic role of the UNFCCC (UNFCCC, 2007a), NGOs as norm entrepreneurs (Finnemore and Sikkink, 1998), evaluation of policy approaches (Stewart and Wiener, 2003; Greenstone, 2009), and delegation to other institutions (Green, 2008).

13.6 Linkages between international and regional cooperation

13.6.1 Linkages with the European Union Emissions Trading Scheme

Due to the scale effects that occur when carbon markets are enlarged, market-based mechanisms may be an important means of regional policy integration. The largest carbon market is the EU ETS, which began operating in 2005, and now includes all 28 European Union member states and is linked with the Norwegian system. The EU ETS is described and evaluated in detail in Section 14.4.2.1.

The EU ETS interacts with international carbon markets through the project-based Kyoto mechanisms. Import of units through international emissions trading is not allowed, but companies covered by the EU ETS can import CDMs and JI credits. A relatively liberal import regime for the pilot phase was established in a 'Linking Directive' approved in 2004 (Flåm, 2009). Forestry credits were banned and additional criteria for large hydropower projects were set. For the EU ETS's second phrase, which corresponded to the Kyoto Protocol's first commitment period, 2008–2012, countries proposed import thresholds;

several proposals were adjusted downwards by the Commission. For the third phase, 2013–2020, imports were limited to credits from CDM projects registered before 2013 in the absence of an international climate change agreement. New (2013 inception or later) CDM projects can only be used in the EU ETS if located in least developed countries (LDCs) (Skjærseth, 2010; Skjærseth and Wettestad, 2010). However, CDM credits from new projects in non-LDCs can be accepted after 2013 if the EU has concluded a bilateral agreement with the country in question regulating their level of use.

The European Union could potentially link the EU ETS to other schemes, and legislation for the period until 2020 allows negotiation of such bilateral treaties. The EU and Australia have already agreed to a one-way indirect link to commence on 1 July 2015, meaning that EU credits will be allowed for compliance under the Australia system (European Commission, 2012). This agreement will transition to a two-way direct link by no later than 1 July 2018, provided that the Australian system goes forward.

13.6.2 Linkages with other regional policies

The Asia-Pacific Partnership for Clean Development and Climate, which was time-limited and has now concluded, involved about 50 % of the world population, GHG emissions, and world economic output (Kelly, 2007). The partnership included countries that had not ratified the Kyoto Protocol, and while it was 'soft' in terms of legal bindingness, it may have had a modest impact on governance (Karlsson-Vinkhuyzen and van Asselt, 2009; McGee and Taplin, 2009) and encouraged voluntary action (Heggelund and Buan, 2009). After the end of the Partnership, the Global Superior Energy Performance Partnership (GSEP) Clean Energy Ministerial took over some of the Partnership's activities.

In addition to coordination by international organizations, such as ICLEI—Local Governments for Sustainability, voluntary mitigation action of cities is taking a regional/global character (Kern and Bulkeley, 2009). In Europe, the Climate Alliance has about 1700 member cities from a number of countries. The Climate Alliance has supported rainforest conservation projects in the Amazon region (Climate Alliance, 2013).

13.7 Linkages between international and national policies

As the landscape of multilateral and other international agreements on climate has become more complex, the interactions between international and national levels have become more varied.

13.7.1 Influence of international climate policies on domestic action

International policy may trigger more ambitious national policies. Treaties provide greater certainty that others will act, thus addressing key concerns that countries will free ride. International climate policy can shape domestic climate discourse, even if it may not be the main inspiration for proactive action (Tompkins and Amundsen, 2008).

National policies also affect the effectiveness of international policies. The implementation of international policy is affected by national political structure. Examples of studies on how varying domestic political structures affect the implementation of international policies include studies in: Italy (Massetti et al., 2007), France (Mathy, 2007), Canada (Harrison, 2008), China (Teng and Gu, 2007), the UK (Barry and Paterson, 2004; Compston and Bailey, 2008) and the Netherlands (Gupta et al., 2007). National and sub-national settings, where actions may be less risky or more politically feasible, may also provide useful 'laboratories' to test policy instruments before implementation at the international level (Michaelowa et al., 2005; Moncel et al., 2011; Zelli, 2011).

13.7.2 Linkages between the Kyoto mechanisms and national policies

Linking national policies with international policies may provide flexibility by allowing a group of parties to meet obligations in the aggregate. The Kyoto Protocol (Article 4) provides for such inter-regional flexibility, and the European Union has taken advantage of the Protocol's provision through its internal burden sharing decision. This decision allowed the EU's Kyoto commitment of an 8 % emissions reduction below 1990 for the 2008–2012 period to be redistributed among EU-15 member states; commitments of these states range from –28 % (Luxembourg) to +27 % (Portugal) (Michaelowa and Betz, 2001; Hunter et al., 2011).

Use of the CDM and JI Kyoto mechanisms has been driven by national mitigation policies to achieve developed countries' emissions commitments. While governments of some developed countries buy emissions credits directly, others introduce instruments with emissions commitments for private companies, like the EU ETS; some countries, such as Denmark, have done both. These companies can then use emissions credits generated under the Kyoto Protocol to satisfy part of their commitments (Michaelowa and Buen, 2012). Another example is Japan's Industry Voluntary Action Plan that includes diverse sectors, each of which has its own target set either in absolute terms, in emissions´ intensity, or in terms of energy consumption (Mitsutsune, 2012).

Many industrialized countries limit imports of credits generated by the Kyoto mechanisms for various reasons; two have been posited in the literature: (1) to keep the domestic carbon price high to induce technological diffusion and possibly innovation; and (2) to avoid diminishing environmental effectiveness by allowing required emissions-reduction to occur in other jurisdictions because of concerns about the quality of credits ('additionality'). For example, the European Union has prohibited the import of Assigned Amount Units (AAU) into the EU-ETS to prevent the use of surplus units from countries in transition, colloquially called 'hot air' (Michaelowa and Buen, 2012). Japanese companies have used AAUs from Green Investment Schemes for meeting their targets (Tuerk et al., 2010). In 2011, credits from certain CDM project types were banned for use in the EU-ETS from 2013 onwards (Schneider, 2011). The ban includes CERs generated from projects involving destruction of trifluoromethane (HFC-23) and nitrous oxide (N_2O) from adipic acid production.

The Kyoto mechanisms also interact with the national policies of countries in which projects are implemented. However, the CDM Executive Board decided that the effects of new policies implemented in host countries that reduce emissions should not be considered when assessing the additionality of new projects to avoid perverse incentives not to adopt mitigation policies (Winkler, 2004; Michaelowa, 2010). Instead, countries may subsidize renewable energy while generating CDM credits. There are indications that the availability of CDM credits has accelerated the introduction of feed-in tariffs in China (Schroeder, 2009). Freeing emission units for sale under international emissions trading requires national mitigation policies unless there is a surplus of units in a business-as-usual situation, as in countries in transition (Böhringer et al., 2007).

Investment law, defined through private international law and more than 3000 multilateral and bilateral investment treaties (UNCTAD, 2013), applies to the CDM and emissions trading contracts. Proposed standardized contracts link the CDM to investment law by covering the choice of language and the process and forum for dispute resolution. These contracts could expose contractors to the costs associated with international arbitration (Gupta, 2008; Klijn et al., 2009).

13.7.3 International linkage among regional, national, and sub-national policies

International linkages can be established among regional, national, or sub-national policies. These can be direct or indirect. Under direct linkage, the same units are valid throughout the linked systems. Under indirect linkage, a unit in a certified emission reduction credit system is accepted by multiple systems. Figure 13.4 shows sub-national, national, and regional GHG cap-and-trade schemes and existing and planned linkages between them. The only formal direct linkage between two trading schemes is that arranged between the Australian ETS and the EU ETS, which was officially announced in August 2012. A strong indirect linkage between carbon markets exists through the CDM, whose credits are accepted under the EU-ETS, the Australian Carbon Pricing Mechanism, and the New Zealand ETS. Nazifi (2010) finds that EU demand has driven the price for CDM credits.

Review of unilateral and bilateral direct linkages demonstrates that bilateral direct linkage reduces mitigation costs, increases credibility of the price signal, and expands market size and liquidity (Anger, 2008; Flachsland et al., 2009; Jaffe et al., 2009; Dellink et al., 2010; Cason and Gangadharan, 2011; Lanzi et al., 2012). However, direct linkage also raises a variety of concerns (Jaffe et al., 2009), including that linking can lead to a dilution of mitigation achieved through trading schemes, as linked systems are only as environmentally effective as the weakest among them (e. g., the one that allows imports of offsets with the lowest standards). Grubb (2009) also warns that countries may be unwilling to accept an increase of carbon prices that would result from linking with a more ambitious system.Tuerk et al. (2009) see the biggest challenges to linking in differential stringencies of targets in each system, varying degrees of enforcement, differences in eligible project-based credits, and the existence of cost-containment measures, such as price ceilings. Haites and Mehling (2009) highlight that only bilateral links (or reciprocal unilateral links) yield the full benefits of linkage. Bilateral links often face lengthy adoption procedures as well as legal and procedural constraints, whereas reciprocal unilateral links, possibly framed by an informal agreement, are often easier to implement and provide more flexibility for almost the same benefits.

Also attractive are indirect linkages among regional, national, or sub-national cap-and-trade systems, an approach that maintains the benefits of linkage without much of the downside. Such indirect linkages achieve cost savings and avoid risk diversification without the need for deliberative harmonization of emerging and existing cap-and-trade systems. Indirect linkage is attractive because de facto linkages limit potential distributional concerns and preserve a high degree of national control over allowance markets (Jaffe et al., 2009).

In addition, both direct and indirect linkages can occur among heterogeneous regional, national, and sub-national policy instruments (Metcalf and Weisbach, 2012). Some such linking would be relatively straightforward, such as forming a link between a cap-and-trade system and a carbon tax. Other links would be more challenging, such as between a cap-and-trade system and a quantity standard. Others would be even more difficult, such as between a cap-and-trade system and a technology mandate, and some linkages between heterogeneous policy instruments would simply not be possible (Metcalf and Weisbach, 2012).

13.8 Interactions between climate change mitigation policy and trade

Research on interactions between climate change mitigation policy and trade indicates a diversity of compatibilities, synergies, conflicts, and cooperative arrangements (Brewer, 2003, 2004, 2010; Cosbey, 2007; ICTSD, 2008; Cottier et al., 2009; Epps and Green, 2010; Rao, 2012; Leal-Arcas, 2013). Consideration of these and other issues and options needs to take into account the context of the provisions of the principal existing multilateral climate change framework (Yamin and Depledge, 2004) and multilateral trade framework (Hoekman and Kostecki, 2009). Negotiators acknowledged the opportunities for international cooperation on interactions between climate change and trade in both the UNFCCC (1992) and in a Ministerial Decision at the time of the negotiations of the Marrakech Agreement establishing the WTO (1994). But there is also a potential for conflict between climate and trade issues. According to Article 3.5 of the UNFCCC, "Measures taken to combat climate change, including unilateral ones, should not constitute a means of arbitrary or unjustifiable discrimination or a disguised restriction on international trade". The Kyoto Protocol notes in Article 2.3 that Annex I Parties "shall strive to implement policies and measures under this Article in such a way as to minimize adverse effects, including … effects on international trade."

Trade and climate policy interact at many levels (Copeland and Taylor, 2005; Tamiotti et al., 2009; UNEP, 2009; UNCTAD, 2010; World Bank, 2010). For instance, on the one hand, according to Peters and Hertwich (2008), "almost one-quarter of carbon dioxide released to the atmosphere is emitted in the production of internationally traded goods and services" (see also Peters et al., 2011). Transportation associated with trade is another related issue (Conca, 2000). On the other hand, various climate change policies currently in place affect the relative prices of goods and services, which thereby affect trade flows and the total volume of traded goods (Whalley, 2011). Moreover, trade barriers and obligations regarding intellectual property (IP) rights of 'green technology' as well as many other WTO obligations impinge on climate policy (Thomas, 2004; Khor, 2010a; Johnson and Brewster, 2013). Victor (1995) suggested that lessons from the trade regime could be used in the development of the climate regime, but comparative governance studies of the trade and climate regimes have not been thoroughly utilized to gain insights into how the two regimes might address trade-climate interactions (Bell et al., 2012 an exception).

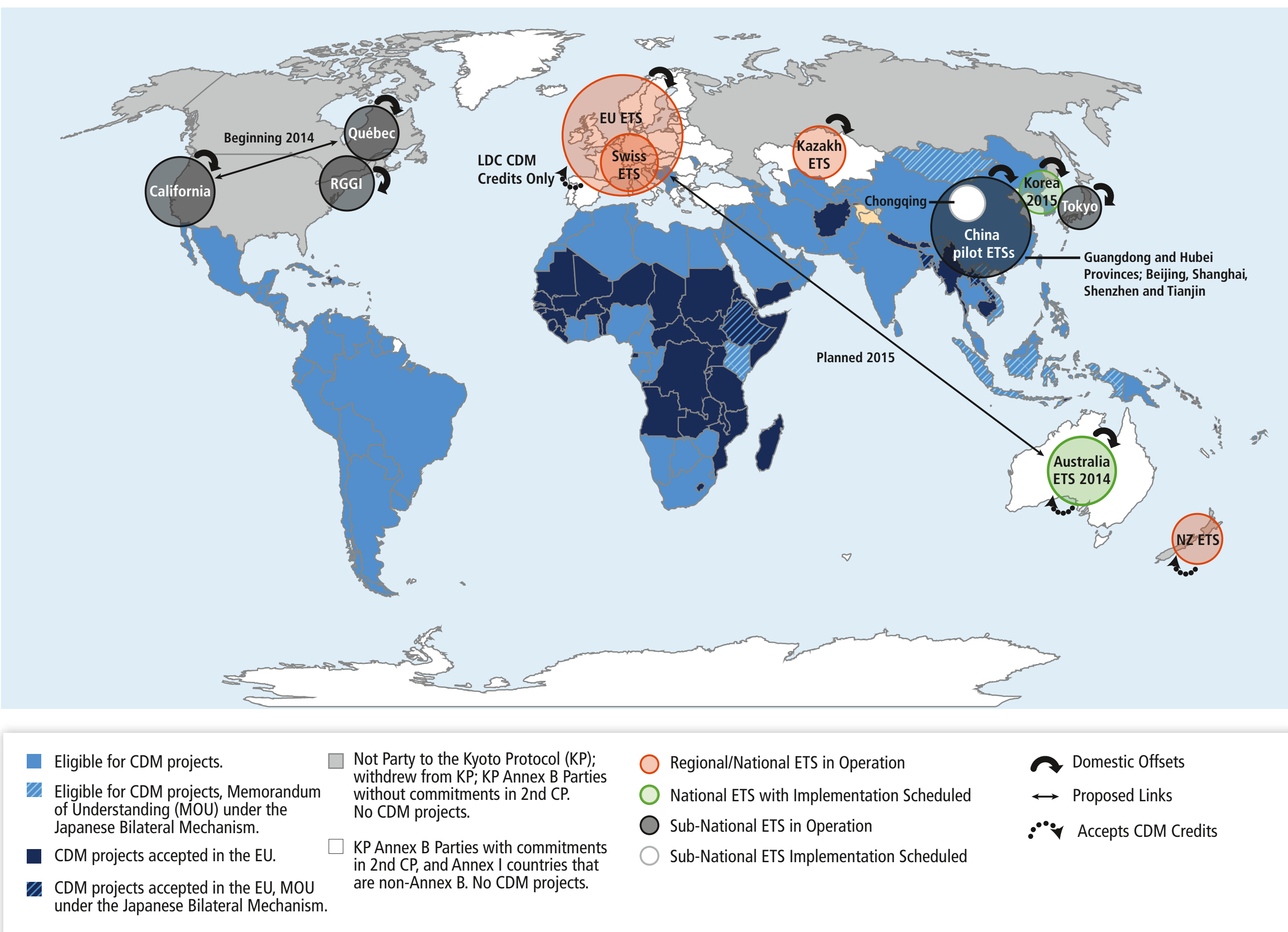


Figure 13.4 | Cap-and-trade schemes with existing and planned linkages. Linkage through proposed acceptance of offsets and Joint Implementation projects not displayed. In some cases, countries otherwise eligible to host CDM projects must first establish a Designated National Authority. Accurate as of March 2014.

The production of internationally traded goods gives rise to a 'labelling' issue, a problem for accounting purposes and also for possible policy intervention. The issue arises because a proportion of a country's GHG emissions resulting from the production of goods and services in one country may be 'embedded' in traded products that are consumed in other countries. At issue is whether to attribute the emissions to the producing (exporting) country or consuming (importing) country (Kainuma et al., 2000; Peters and Hertwich, 2008) (see also Sections 5.4.1 and 14.3.4.2). There is an ethical and equity issue about how to define climate responsibility and allocate climate mitigation costs (discussed in detail in Sections 3.3, 4.1, and 4.2). There is also a political and economic issue whether climate policy instruments ought to address production- or consumption-induced GHGs (Droege, 2011a, b; see also Section 14.3.4). Finally, there is a technical issue as territorial measurement is the current GHG accounting practice under the UNFCCC, and switching to consumption-induced measurement may be technically more difficult (Droege, 2011a; b; Peters et al., 2011; Caldeira and Davis, 2011).

There are significant differences among researchers and policymakers in their perspectives on the relationship between climate change and trade. These differences include fundamental empirical assumptions and policy preferences concerning the roles of markets and governments (Bhagwati, 2009), specifically concerning whether government measures are required to address market failures that produce climate change (Stern, 2007), or government regulations tend to create inefficiencies and distort trade (Krugman, 1979; Rodrik, 2011). Trade measures (e.g., trade sanctions, trade enticements, and trade-relevant domestic product standards; see Section 13.8.1 below) could be used to address free-rider problems of international agreements, specifically participation and/or compliance problems (Victor, 2010), and some (e.g., Victor, 2011) suggest these may be useful in achieving an effective climate agreement. However, there are also some who conclude that trade measures are an inappropriate tool to pursue climate change policy objectives, pointing to the possibility of 'green protectionism' (Khor, 2010a; Johnson and Brewster, 2013). The potential use of trade measures to enhance participation and/or compliance poses major institutional design questions (see Section 13.4).

13.8.1 WTO-related issues

A central issue for WTO members is whether policies are consistent with principles of non-discrimination. Most Favoured Nation Treatment prohibits favourable treatment of the goods, services, or corporations of any one member as compared with other members, while National Treatment prohibits less favourable treatment of foreign relative to domestic goods, services or corporations. Of the more than 60 WTO agreements that apply these principles, many are pertinent to climate change, including the General Agreement on Tariffs and Trade (GATT), the General Agreement on Trade in Services (GATS), the Agreement on Trade Related Intellectual Property Rights (TRIPs), the Agreement on Technical Barriers to Trade (TBT), the Agreement on Trade Related Investment Measures (TRIMs) and the Dispute Settlement Understanding (DSU), as well as agreements on subsidies, government procurement, and agriculture (Brewer, 2003, 2004, 2010; Cottier et al., 2009; Hufbauer et al., 2009; Epps and Green, 2010). Studies have suggested that ETSs can be designed to be compatible with WTO obligations (Werksman, 1999; Petsonk, 1999).

Trade issues concerning CDM projects have received special attention (Werksman et al., 2001; Rechsteiner et al., 2009; Werksman, 2009). Although no trade or investment disputes have arisen yet in connection with CDM projects, there is the possibility that they will in the future as the number and economic significance of CDM projects continues to increase. Significant attention has also been given to product labelling and standards issues that can arise in relation to the WTO Agreement on TBT (Appleton, 2009), which could be pertinent to the use of labels concerning 'food miles' (ICTSD, 2007; World Bank, 2010). Although long-distance air transport of agricultural products itself is GHG-intensive, the agricultural practices of many exporting countries are less GHG-intensive than those of the importing countries, and determining the relative GHG emissions levels of imported versus domestic products thus requires complete lifecycle analyses of individual products and specific pairs of exporting-importing countries.

Government procurement policies that entail buy-local practices concerning climate-friendly goods and services have emerged as an issue under the principle of non-discrimination in the context of national economic stimulus programmes. The applicability of the WTO Agreement on Government Procurement to such trade issues is limited because many countries have not agreed to it; among those that have, there are many government agencies whose programmes are not covered (van Asselt et al., 2006; Hoekman and Kostecki, 2009; Malumfashi, 2009; van Calster, 2009).

Government subsidies for renewable energy and energy-efficiency goods and services have also become issues in relation to the WTO Agreement on Subsidies and Countervailing Measures, as well as the TRIMs agreement. Such issues have prompted WTO dispute cases, including one involving subsidies for producers of wind turbines (WTO, 2010) and another involving feed-in tariffs (WTO, 2011). The application of WTO subsidy rules could slow the development and diffusion of climate-friendly technologies, but it is not yet clear whether this has or will have an effect (see Bigdeli, 2009; Howse and Eliason, 2009; Howse, 2010 on subsidy issues).

There are WTO-related issues related to tariffs and non-tariff barriers resulting from climate change policy. In general, non-tariff barriers tend to be more important barriers than tariffs at the climate-trade interface, but tariffs are still high in some industries and countries (Steenblik, 2006; World Bank, 2008a). Countries may seek to limit competitive disadvantage introduced by domestic climate policy by raising tariffs and introducing non-tariff barriers that restrict imports, or by other BAMs. One example of a BAM would be a country that has imposed a domestic carbon tax also (1) imposing the carbon tax on imported goods and services at a rate proportional to the emissions associated with their production and (2) offering reimbursement to domestic exporters who sell a good or service outside of the jurisdiction of the carbon tax (Wooders et al., 2009; Elliott et al., 2010; Monjon and Quirion, 2011). Barriers to transfers of technologies identified by IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) as potential contributors to climate change mitigation have been issues in the on-going WTO Doha Round negotiations (Tamiotti et al., 2009). Domestic subsidies such as those for biofuels have also been at issue in the Doha Round.

Border adjustment measures to offset international differences in costs—and thus possible international leakage (see Section 5.4.1) arising from international differences in mitigation policy—have become one of the most contentious and researched points of interaction (Babiker, 2005; de Cendra, 2006; Cosbey and Tarasofsky, 2007; Ismer and Neuhoff, 2007; Genasci, 2008; Frankel, 2008; Tamiotti and Kulacoglu, 2009; O'Brien, 2009; van Asselt and Brewer, 2010; Tamiotti, 2011; Zhang, 2012). This issue draws particular attention to differences between production-based and consumption-based emissions in both developed and developing countries (Figure 1.5 in Chapter 1). BAMs include policy options ranging from: (1) tariffs on imports or subsidies on exports based on the amount of GHGs released in their production to (2) 'compensatory measures,' as for instance the free-allocation emission permits in the EU ETS or export rebates to energy-intensive sectors. Theoretical arguments in favour of BAMs can be grouped into three classes, each discussed below: the reduction of economic inefficiencies in the context of an externality, the reduction of carbon leakage, and increasing participation and compliance in a climate agreement.

The economic research on BAMs stresses that the inclusion of more countries in climate policy, e. g., by linking permit trading schemes and including more sectors and countries, reduces economic inefficiencies relative to unilateral BAMs. While, BAMs can enhance the competitiveness of GHG- and trade-intensive industries within a given climate regime (Kuik and Hofkes, 2010; Böhringer et al., 2012a; Balistreri and Rutherford, 2012; Lanzi et al., 2012), welfare effects may be negative for consumers and countries facing BAMs on their exports. Overall welfare effects accounting for externalities are mainly perceived to be positive at an abstract theoretical level (Gros and Egenhofer, 2011); the evidence is more blurred at an empirical level and is sensitive to assumptions (The Carbon Trust, 2010; Fischer and Fox, 2012; Lanzi et al., 2012). Export rebates, the exclusion of energy and CO_2-intensive industries from regulation, or the free-allocation of permits to these industries are recognized as causing efficiency losses (Lanzi et al., 2012). Most empirical studies also do not confirm a need at the macro-economic level for BAMs in the first place: they tend to find that climate policy is not a significant trade issue at the macro-economic level of national economies, though there are competitiveness and leakage issues for a few industries which are both GHG-intensive and trade-intensive. They hold that the main channel of impact of climate policies is through world energy prices and not through manufactured goods (Grubb and Neuhoff, 2006; Houser et al., 2008; Aldy and Pizer, 2009; The Carbon Trust, 2010).

The economic modelling literature on the effectiveness of BAMs to reduce carbon leakage finds that carbon leakage rates tend to decline by 2–12 % following the introduction of a border adjustment tax (Böhringer et al., 2012a). The political literature on the appropriateness of using BAMs to address carbon leakage, on the other hand, tends to be divided into two perspectives. Developed countries and/or countries with some form of mitigation policy either already in place or considering this for the future argue that BAMs are necessary to avoid carbon controls driving production abroad. Arguments along this line have emerged in the European Union and the United States for instance (see Veel, 2009; The Carbon Trust, 2010; Fischer and Fox, 2012). Developing countries tend to oppose BAMs, as many are concerned about negative welfare effects for their countries and what they see as a violation of the principle of CBDRRC as agreed under the UNFCCC (Khor, 2010a; Droege, 2011a; Scott and Rajamani, 2012). Nevertheless, the technical difficulties of measuring production-induced or consumption-induced GHG emissions are significant (Droege, 2011a), and addressing them may be associated with high administrative costs, possibly outweighing the potential benefits (McKibbin and Wilcoxen, 2009).

Participation and compliance in climate agreements might be enhanced by BAMs. However, conceptual thinking on the question does not reveal a consensus, and direct evidence on the point is insufficient to reach definitive conclusions (see Barrett, 2003, 2009, 2010; Victor, 2010, 2011). Because BAMs affect the distribution of abatement costs across countires, enacting a BAM could result in welfare loss, particularly for exporting developing countries, and even retaliatory countermeasures (de Cendra, 2006; Mattoo et al., 2009; Böhringer et al., 2012b; Balistreri and Rutherford, 2012). For more discussion on the topic, see Section 13.3.3 on participation and Section 13.3.4 on compliance.

From the research on legal issues related to BAMs, four major conclusions emerge. First, BAMs may clash with WTO obligations, a point which is emphasized by many observers (Wooders et al., 2009; Condon, 2009; ICTSD, 2009; Holzer, 2010, 2011; Tamiotti, 2011; Du, 2011). Second, it is possible to design BAMs to be compatible with these obligations, according to other observers (Condon, 2009; Droege, 2011a; b), particularly when BAMs are targeted to countries based on their production technology efficiency (Ismer and Neuhoff, 2007). Third, WTO obligations and their legal interpretation have evolved over time, allowing for the possibility to bring trade and climate policy goals more in line in the future (Kelemen, 2001; Neumayer, 2004). Finally, the use of BAMs for climate change purposes may be politically controversial (Khor, 2010a).

A final WTO-related issue concerns the distinction between products and 'process and production methods' (PPMs). The legal notion of PPMs, as applied in the WTO, can be based on several aspects of production processes and can have a variety of effects on climate change-related policies. (For extensive discussions of the technical legal issues and their relevance to climate change issues see Cottier et al., 2009).

13.8.2 Other international venues

Two GHG-emitting industries that are centrally involved in international trade as modes of transportation are covered by separate international agreements outside the WTO system (see also Chapter 8). International aviation issues are covered by the Chicago Convention and the International Civil Aviation Organization (ICAO), while international maritime shipping issues have been addressed by the IMO (see Section 13.13.1.4 for performance assessments of the ICAO and IMO).

There has been increasing interest in recent years in both ICAO and IMO in industry practices concerning GHG emissions, with some efforts at international cooperation to address them. However, there has been international conflict about the European Union's inclusion of international aviation within the EU ETS. The Kyoto Protocol in Article 2.2 recognized ICAO as the venue for negotiations on matters concerning international aviation emissions, but in the absence of what was seen in the EU as adequate progress in the ICAO, the EU decided to include aviation in the EU ETS. This unilateral decision prompted strong reactions (Mueller, 2012; Scott and Rajamani, 2012), and flights in and out of the EU were temporarily exempted in April 2013 through the ICAO General Assembly scheduled for September-October 2013. Among the concerns expressed about the inclusion of aviation in the EU ETS has been the assertion that it represents a violation of the principle of CBDRRC of the UNFCCC (Scott and Rajamani, 2012; Ireland, 2012), though this concern only applies to developing countries. There are also legal issues about the relationship of the EU ETS to the Chicago Convention, which has traditionally been the international legal basis for aviation policies. Though studies indicate that the economic impacts of the EU ETS provisions are small relative to other airline expenses and ticket prices and that much of the cost can be passed on to consumers (Scheelhaase and Grimme, 2007; Anger and Köhler, 2010), political and legal issues have nevertheless made international cooperation difficult. The IMO (2009) concluded that a significant potential for CO_2 reduction exists through technical and operational measures, many of which appear to be cost-effective; the IMO adopted an energy efficiency design index (International Maritime Organization (IMO), 2011). A link of carbon controls of aviation and shipping to the EU ETS and/or a possible U.S. ETS is suggested by Haites (2009) with the view that carbon offsets under the CDM could also be used.

There are other international institutional contexts within which climate change-trade interaction issues have been addressed, namely, the World Bank, G8, G20, IEA, MEF, and OECD (Section 13.5).

13.8.3 Implications for policy options

In terms of WTO and/or UNFCCC involvement, there are logically four possible sets of options for institutional architectures at the multilateral level for addressing climate change-trade interactions: WTO-based, UNFCCC-based, joint UNFCCC-WTO, and stand-alone. In addition, there could be hybrid arrangements involving combinations of these four types. For instance, proposals for Sustainable Energy Trade Agreements (SETAs) could be addressed in a variety of venues (ICTSD, 2011).

Of the four options, WTO-based architectures have received the most attention in the literature. Alternatives include making revisions in existing WTO arrangements or undertaking new arrangements (Epps and Green, 2010). Possible changes in existing WTO arrangements include a 'peace clause' (Hufbauer et al., 2009) or waiver agreement (Howse and Eliason, 2009; Howse, 2010), whereby WTO members would agree—within some limits—not to challenge on WTO grounds, respectively, climate policies in general or climate-related subsidies in particular. An extensive list of other possible changes to existing WTO arrangements has been discussed by Epps and Green (2010), whose suggestions include: change GATT Article XX (which allows exceptions to members' obligations, including measures for the 'conservation of exhaustible natural resources') so that climate measures are explicitly identified as qualifying for exceptional treatment; add a similar provision to the Subsidies Agreement; change the burden of proof or standard of review for the scientific evidence presented in climate change cases to Dispute Settlement panels; change Dispute Appellate Body rules to take into account the scientific uncertainties in climate change cases; establish a notification process for members to inform other members of the adoption of climate policies with trade implications; and establish a Climate Change Committee, which could facilitate conflict resolution without resorting to the Dispute Resolution process.

Many possibilities for a new Climate Change Agreement at the WTO have also been discussed by (Epps and Green, 2010). The elements of such an agreement could include: establishment of a Climate Change Committee (as above); establishment of a notification procedure for climate change measures (as above); establishment of climate change mitigation as a legitimate objective; development of a 'non-aggression clause' that would prohibit unilateral actions, such as BAMs; adoption of transparency requirements for national climate change policymaking processes to determine their legitimacy in relation to climate change concerns and protect against disguised trade protectionism; adoption of environmental rationales for subsidies; reviews of members' trade-related climate measures to insure that they are substantive responses to climate issues; and clarification of the potential application of PPMs questions to climate change disputes. Although these ideas have been mentioned in the literature, they have not been formulated as specific proposals to the WTO.

UNFCCC-based options have been discussed in the literature (Werksman et al., 2009) relating to the possible creation of a 'level' playing field, such as through border charges on imports, or border rebates for exports, though views differ greatly, as indicated above in the discussion of BAMs.

A potential joint UNFCCC-WTO agreement has not yet received much attention in the published literature (Epps and Green, 2010). However, there are already in effect arrangements whereby the UNFCCC secretariat is an observer in meetings of the WTO Committee on Trade and Environment (CTE) and is invited on an ad hoc basis to meetings of the Committee overseeing the specific trade and environment negotiations (CTESS) (Cossey and Marceau, 2009). In addition, WTO Secretariat staff members attend the annual UNFCCC COP meetings. Finally, a stand-alone arrangement could be developed (Epps and Green, 2010), a possibility that has not yet been analyzed in the published literature.

There are numerous and diverse unexplored opportunities for greater international cooperation in trade-climate policy interactions. While mutually destructive conflicts between the two systems have thus far been largely avoided, pre-emptive cooperation could protect against such developments in the future. Whether such cooperative arrangements can be most effectively devised within the existing institutional architectures for trade and for climate change or through new architectures is an unsettled issue (Section 13.4).

13.9 Mechanisms for technology and knowledge development, transfer, and diffusion

Technology-related policies could conceivably play a significant role in an international climate regime (de Coninck et al., 2008). These policies have the potential to lower the cost of climate change mitigation and increase the likelihood that countries will commit to reducing their GHG emissions. By lowering the relative cost of more environmentally sound technologies, technology policy can increase incentives for countries to comply with international climate obligations and could therefore play an important role in increasing the robustness of long-run international frameworks (Barrett, 2003). Such policies might generate incentives for participation in international climate agreements by facilitating access to climate-change-mitigating technologies or funding to cover the additional costs of such technologies.

The role of international cooperation in facilitating technological change, including access to, facilitation of, and transfer of technology, is explicitly recognized in Article 4(1)(c) and (h), 4(5), 4(7), 4(8), and 4(9) of the UNFCCC. Article 4.5 states that "The developed country Parties and other developed Parties included in Annex II shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other Parties, particularly developing country Parties…." The performance of international institutional arrangements and the adequacy of financing are subject to a variety of interpretations. (See Section 14.3.6.2 for a discussion of the UNFCCC CTCN, and see Section 15.12 for a discussion of financial issues.)

Although international technology transfer issues for climate change mitigation or adaptation have become concerns in numerous countries, these concerns have been especially acute in developing countries. Concerns over technology transfer in developing countries are frequently embedded in broader capacity building, sustainable development, and other equity issues (for discussions of the broader issues of CBDRRC and equity, see respectively Sections 13.2.1.2 and 13.4.2.4, and also Chapter 3 and Sections 4.1 and 4.2) (Brewer, 2008; GEA, 2012; Ockwell and Mallett, 2012).

Technology-oriented agreements could include activities across the technology life cycle for knowledge sharing, coordinated or joint research and development of climate-change-mitigating technologies, technology transfer, and technology deployment policies (such as technology or performance standards and incentives for technology development or adoption). International technology policy may play an important role in improving the efficiency of existing research and development (R&D) activities by increasing the international exchange of scientific and technical knowledge and by reducing duplicated R&D effort that could be shared across nations. (Newell, 2010a).

13.9.1 Modes of international incentive schemes to encourage technology-investment flows

Absent additional market failures, underinvestment in innovative activity relative to socially optimal levels can occur due to several well-understood general properties of innovation (see Section 15.6). At a global level, international carbon markets and the flexibility mechanisms they may employ, such as international linkage of domestic emission programmes, offsets, and the CDM, may be used to finance emission reductions in developing countries and transferring technology between nations and regions (see Section 13.13 and Haščič and Johnstone, 2011). Clear rules for these markets and their associated flexibility mechanisms may be established under international agreements and domestic policies to aid the removal of unnecessary barriers to technology transfer and to facilitate investment flows.

Because private-sector investments constitute more than 85 % of global financial flows (UNFCCC, 2007b), international trade and foreign direct investment are the primary means by which new knowledge and technology are transferred between countries (World Bank, 2008b). While domestic actions can improve the conditions to enable technology transfer investments (e.g., through regulatory flexibility, transparency, and stability), international actions can also contribute. In particular, the literature has identified tariffs and non-tariff trade barriers as impediments to energy technology transfer (World Bank, 2008b). An existing example is OECD regulation of export credits, with specific conditions to foster technology transfer for climate change mitigation (OECD, 2013).

In summary, national and supra-national policies that provide incentives for climate change mitigation will likely play an essential role in stimulating public investment, financial incentives, and regulations to promote innovation in the necessary new technologies for mitigation goals. Reducing fossil-fuel subsidies may have a similar effect (UNEP, 2008).

13.9.2 Intellectual property rights and technology development and transfer

The strength of IP right protection, together with other conditions related to the rule of law, regulatory transparency, and market openness affect technology transfer rates (Newell, 2010a) (see also Sections 3.11 and 16.8).

The goal of IP protection is to foster both the development of new technologies (innovation), and the diffusion of new technologies across countries (technology transfer) and within countries (technology adoption). In theory, such protection achieves these ends by increasing and/or maintaining the private economic incentive to create and transfer technology. At the same time, protection of IP also works to slow the diffusion of new technologies, because it raises their cost and potentially limits their availability. To the extent that IP protection raises the cost and limits the availability around the world of mitigation technologies, the potential for new technologies to reduce the cost of mitigation will be hampered. Concern by developing countries that IP protection for low-carbon technology will make climate action excessively costly has been a contentious issue in the climate negotiations (Government of India, 2013). On the other hand, IP protection may encourage firms to innovate more than they otherwise would, thus potentially increasing the supply and reducing the cost of new technology.

In order to balance the possible incentive effects of IP protection against the adverse impact of such protection on costs and availability, it is important to assess the empirical significance of the incentive effects, both with respect to innovation and technology diffusion. The empirical evidence regarding the effect of IP policy on innovation is discussed in Section 15.6.2.1.

Even if stronger IP protection does not foster creation and development of new technologies, it may be beneficial for mitigation if it fosters transfer of technologies from developed to less developed countries. Theoretically, strong IP protection in developing countries may be necessary to limit the risk for foreign firms that transfer of their technology will lead to imitation and resulting profit erosion. Looking at technology transfer in general, empirical literature finds a role for strong IP protection in receiving countries in facilitating technology transfer from advanced countries through exports, foreign direct investment (FDI), and licensing for transfers from the OECD (Maskus and Penubarti, 1995); FDI to 16 countries originating in the United States, Germany and Japan (Lee and Mansfield, 1996; Mansfield, 2000); and transfers from the United State (Smith, 1999). Regarding recipients, Awokuse and Yin (2010) find evidence for transfers to China, and Javorcik (2004) for FDI to 24 Eastern European transition economies. Branstetter et al. (2006) assessed FDI to 16 middle-income countries after those countries strengthened their IP protection and found indicators for United States technology transfer increasing subsequently.

The empirical evidence suggests that the effects of IP strength on technology licensing parallel those for FDI. The Branstetter et al. (2006) results discussed above included royalty payments among the measures of technology transfer that increased after IP strengthening. Smith (2001) finds that the association between strong IP and licenses is stronger than the relationship between IP and exports. In general, the evidence indicates a systematic impact of IP protection on technology transfer through exports, FDI, and technology licensing for middle-income countries for which the risk of imitation in the absence of such protection is relatively high. It is unclear whether or not these effects extend to the least developed countries whose absorptive capacity and ability to appropriate foreign technology in the absence of strong IP protections is less (Hall and Helmers, 2010). It is also important to note that IP rules are but one of many factors affecting FDI decisions. Others, particularly more general aspects of the legal and institutional environment that affect the riskiness of investments, may be more significant (Fosfuri, 2004).

Literature on the role of IP rights in the development of low-carbon technologies remains limited (Reichman et al., 2008). For example, Barton (2007) analyzes existing solar, wind, and biofuel technologies, and Lewis (2007, 2011) and Pueuo et al. (2011) find that IP protection has induced innovation in wind technologies without compromising technology transfer. However, problems could arise if new, very broad patents were granted that impede the development of future, more efficient technologies (though even then, IP rights may provide flexibility). Compulsory licensing has been proposed as a mechanism to encourage technology transfer. Such an action would compensate a patent holder while overcoming market power inhibitions on voluntary licensing (Reichman and Hasenzahl, 2003). Despite short-run technology transfer benefits, compulsory licensing of mitigation technologies may not be desirable in the long-run, and current international law may limit the circumstances under which compulsory licensing can be used to achieve climate change mitigation objectives (Fair, 2009; Maitra, 2010).

In summary, there is inadequate evidence in the literature regarding the impact of IP policy on transfer of GHG-mitigating technologies to draw robust conclusions. If the experience from other technology sectors is indicative, maintenance of effective protection of IP may be a factor in determining the transfer of mitigation technology to middle-income countries, although other aspects of the legal and institutional environments are likely to be at least as important. There is little empirical evidence that protection of IP rights is a major factor affecting technology transfer to the least developed countries.

13.9.3 International collaboration to encourage knowledge development

International cooperation on climate change mitigation has been linked to technology transfer policy, as transferring knowledge and equipment internationally, and ensuring that technologies are deployed in appropriate national contexts, may require additional international action (Newell, 2010a). International cooperation on climate-relevant technology policy can include efforts to share technological knowledge, collaborate or coordinate R&D, and directly facilitate and finance technology transfer.

13.9.3.1 Knowledge sharing, R&D coordination, and joint collaboration

International cooperation on knowledge-sharing and R&D coordination can include information exchange, coordinated or harmonized research agendas, measurement and technology standards, and coordinated or cooperative R&D (IEA, 2008; de Coninck et al., 2008; GEA, 2012). Examples of such existing forms of cooperation include the Carbon Sequestration Leadership Forum, the former Asia Pacific Partnership on Clean Development and Climate, the U.S.-China Clean Energy Research Center, and the International Partnership for a Hydrogen Economy. Empirically, a higher degree of collaboration has been more frequently observed in research areas of more fundamental science without larger commercial interests (for example, the ITER fusion reactor and the CERN supercollider) (de Coninck et al., 2008). In addition to enhancing the cross-border flow of scientific and technical information, joint R&D can increase the cost-effectiveness of R&D through complementary expertise and reduced duplication of effort (Newell, 2010a).

The IEA has coordinated the development of more than 40 Implementing Agreements. Under these agreements, IEA member countries may engage either in task-sharing programmes pursued within participating countries and funded by individual country contributions, or in cost-sharing programmes funded by countries but performed by a single contractor. All existing Implementing Agreements incorporate some degree of task sharing while about half incorporate cost sharing (Newell, 2010a).

13.9.3.2 International cooperation on domestic climate technology R&D funding

Public sector investment in energy- and climate-related R&D has decreased since the early 1980s, although there has been a relative increase in recent years (Newell, 2010a, 2011). Newell (2010a), using the precedent of European Union cooperation on setting R&D spending goals, has proposed an international agreement that would increase domestic R&D funding for climate technologies (either in absolute terms, percentage increases from historic levels, or relative to GDP) in an analogous fashion to internationally agreed emission targets. Also, at a G8 meeting, in the context of a consideration of how to address climate change, there was agreement to seek to double public investment in R&D between 2009 and 2015 (G8, 2009).See Torvanger and Meadowcroft (2011) and Fischer et al. (2012) on issues in the design and support of climate friendly technologies. International coordination of R&D portfolios may reduce the duplication of R&D effort, cover a broader technological base, and enhance the exchange of information gained through national-level R&D processes. This coordination could cover the allocation of effort by government scientists and engineers, the targeting of extramural research funding to specific projects, and public-private partnerships. Engaging developing economies in developing and deploying new technologies may require further technology development to meet the needs of domestic institutions and norms.

Bringing newly developed technologies to full commercialization often presents challenges, and for some technologies, such as carbon dioxide capture and storage (CCS) (de Coninck et al., 2009), the private sector may not have sufficient incentives to commercialize new technologies in the absence of international cooperation. Since some of the economic risk the private sector faces reflects uncertainty about the incentives that future climate policies would create, governments may have a role in financing technology demonstration projects (Newell, 2007). The case for such demonstration projects may be stronger in developing and emerging economies, where incomplete capital markets may undermine investment in commercializing these technologies.

13.10 Capacity building

Several articles in the UNFCCC (4.1(i), 4.5, 6 and 9.2(d)) and the Kyoto Protocol (Article 10(e)) acknowledge the role of capacity building in promoting collective action on climate change. While the texts give special attention to building capacity in developing countries, they also recognize a general need for all countries to improve policy, planning, and education on climate issues.

A variety of public, private, and NGO initiatives have undertaken capacity building efforts both within and outside of the UNFCCC, focusing primarily on three issues: (1) adaptation policy and planning; (2) mitigation policy and planning; and (3) measurement, reporting, and verification of mitigation actions. Capacity building efforts with respect to technology transfer are addressed in Section 13.9. Section 4.6.1 considers adaptive capacity and mitigative capacity jointly as dimensions of 'response capacity' and Section 15.10 considers capacity building in a national context.

Capacity building for adaptation includes (i) risk management approaches to address adverse effects of climate change, (ii) maintenance and revision of a database on local coping strategies, and (iii) maintenance and revision of the adaptation practices interface (Yohe, 2001; UNFCCC, 2009b). The process of preparing the National Adaptation Programmes of Action (NAPAs) for and by LDCs identifies their most 'urgent' adaptation needs. However, capacity building for adaptation is likely insufficient because the costs in such regards are rarely estimated (Smith et al., 2011; see also WGII, 3.6.4). At the community level, adaptation projects require time and patience and can be successful if they raise awareness, develop and use partnerships, combine reactive and anticipatory approaches, and are in line with local culture and context (Engels, 2008; Dumaru, 2010).

Capacity building for mitigation includes technical assistance and policy planning support. In CDM, capacity building has focused on the establishment of Designated National Authorities (DNAs), the training of private and public personnel, and project support (Michaelowa, 2005; Winkler et al., 2007; Okubo and Michaelowa, 2010). Efforts aimed at capacity building for NAMAs and REDD-plus are expected (Bosetti and Rose, 2011). NAMAs are a potentially important means of action by developing countries that emerged in the negotiations under the Bali Roadmap (UNFCCC, 2007); and have been assessed in the literature (Wang-Helmreich, et al., 2011; Upadhyaya,, 2012; Tyler et al., 2013). NAMAs are discussed in detail in Section 15.2.

Monitoring and evaluation activities are important to ensure effective implementation of a capacity-building framework, helping to understand gaps and needs in capacity building, share best practices, and promote resource efficiency (UNFCCC, 2009c). There are few empirical assessments of current capacity building approaches in relation to climate change (Virji et al., 2012).

13.11 Investment and finance

Since AR4, international cooperation on climate policy has increasingly focused on mobilizing public and private investment and finance for mitigation and adaptation activities. Such cooperation has included the setup of market mechanisms to generate private investment as well as public transfers through dedicated institutions (Michaelowa, 2012b). The Copenhagen Accord of 2009 included a provision to jointly mobilize 100 billion USD per year by 2020 to address the needs of developing countries, in the context of meaningful mitigation actions and transparency of implementation (UNFCCC, 2009a). In order to reach this goal, the High-level Advisory Group on Climate Change Financing (AGF) (AGF, 2010) identified four potential sources of finance: public sources (funds mobilized under the UNFCCC), development bank instruments, carbon market finance, and private capital.

In the follow-up to the Copenhagen conference, the term 'climate finance' has been coined for financial flows to developing countries, but there exists no internationally agreed definition (Buchner et al., 2011). Stadelmann et al. (2011b) provide a discussion of what could be counted and how the baseline for international climate finance could be set to provide 'new and additional' funds. See Section 16.2.2 for a description of the potential financing need and Section 16.5 for a description of possible public funding sources.

13.11.1 Public finance flows

13.11.1.1 Public funding vehicles under the UNFCCC

The largest share of UNFCCC-organized climate finance goes to mitigation: Abadie et al. (2013) provide reasons for this, such as the differences between mitigation and adaptation regarding public good characteristics and the lack of information regarding context-specific climate impacts. The UNFCCC mobilizes financial flows to developing countries and countries in transition through four primary vehicles: (1) the GEF, which focuses on mitigation (GEF, 2011); (2) the LDCF and SCCF, which focus on adaptation; (3) the Adaptation Fund, which also focuses on adaptation; and (4) the GCF, which will focus on both mitigation and adaptation when it becomes operational. The GEF is the secretariat for all funds other than the GCF. This section reviews the literature on these four mechanisms (see also Section 16.5; UNFCCC, 2012a).

The Adaptation Fund is financed through a 2 % in-kind levy on emissions credits generated by CDM projects, though parties to the Kyoto Protocol have contributed additional funding (Liverman and Billett, 2010; Horstmann, 2011; Ratajczak-Juszko, 2012). All other UNFCCC funding vehicles are based on voluntary government contributions that can be counted as official development assistance. Ayers and Huq (2009) maintain that the Adaptation Fund's governance structure avoids many of the issues of ownership and accountability faced by other funds. Harmeling and Kaloga (2011) examine the influence of competing interests on funding decisions by the Adaptation Fund Board. Under the Fund, Multilateral Implementing Entities (MIEs) have had the most success in securing funding, followed by National Implementing Entities (NIEs), but none by Regional Implementing Entities (RIEs). This disparity has led to calls for transparency in project assessment (Harmeling and Kaloga, 2011). Grasso and Sacchi (2011) discuss issues of justice in Adaptation Fund financing decisions to date. Further research into the distribution of adaptation finance across countries, sectors, and communities is required to assess the equity, efficiency, effectiveness, and environmental impacts of the operation of the Adaptation Fund (Persson, 2011).

The Conference of the Parties to the UNFCCC has decision-making power regarding the representation of country groups on the governing boards of the UNFCCC's funding vehicles, voting rules, the choice of secretariat and the choice of trustee (e.g., who oversees the finances and ensures funds go where they are supposed to go). Due to its complex structure, the GEF faces challenges coordinating with UNFCCC decisions (COWI and IIED, 2009; Ayers and Huq, 2009). Recipient countries have a majority on the board of the Adaptation Fund, while the decision-making bodies for the other UNFCCC financing institutions have equal representation for developing and industrialized countries. The Adaptation Fund has allowed the possibility of 'direct access' by host country institutions, which has been used sparingly to date (Ratajczak-Juszko, 2012). The GEF is also starting to experiment with this approach (GEF, 2011).

Funding per country eligible under the Adaptation Fund is limited to 10 million USD, essentially leading to a situation where each country gets financing for a single project. Stadelmann et al. (2013) show that this does not lead to projects ranking high on equity and efficiency criteria. The GEF operates funding floors and caps for each country (currently 2 million USD and 11 % of the total volume available, respectively) (GEF, 2010). Between these thresholds, a complex allocation formula is used whose variables consist of GDP, project portfolio performance, country environmental policy and institutional performance, GHG-emissions level, development of carbon intensity, forestry emissions, and changes in deforestation.

A step change with regards to the international coordination of public finance flows was the collective commitment by industrialized countries in the Copenhagen Accord of 2009 to provide resources approaching 30 billion USD as 'Fast Start Finance' (FSF) during the period 2010–2012 for mitigation and adaptation in developing countries (UNFCCC, 2009a). Fast Start Finance was to provide 'new and additional' resources, flowing through existing multilateral, regional, and bilateral channels. Although few countries disclose details of their FSF, studies show that FSF ranges from small grants to large loans for infrastructure development (Fransen et al., 2012; Nakhooda and Fransen, 2012; Kuramochi et al., 2012). While the FSF commitment for 2010–2012 has been exceeded, transparency regarding allocation criteria and actual disbursement is low (Ciplet et al., 2013). Official development assistance (ODA) made up a large share of total funding (Ballesteros et al., 2010) and several studies argue that the use of ODA as a substitute for new climate finance mechanisms could divert funding away from other important imperatives (Michaelowa and Michaelowa, 2007; Ayers and Huq, 2009; Gupta and van der Grijp, 2010). See also Section 16.2.1.1.

13.11.1.2 Multilateral development banks

Multilateral development banks (MDBs) have played a significant role in mobilizing, coordinating, and overseeing the growth of climate-related financial flows. The World Bank provides services as trustee or interim trustee for all the UNFCCC-related funds noted above. A group of MDBs manages and governs the Climate Investment Funds (CIFs), which were set up in 2008, are not supervised by the UNFCCC, and are financed through voluntary government contributions. The Clean Technology Fund supports investments in low-carbon technologies, and the Strategic Climate Fund is an umbrella for improving resilience against climate change, reducing deforestation and renewable energy support for low-income countries.

Tirpak and Adams (2008) see increases in MDBs' funding and shifts to low-GHG technologies being fragile owing to variability and low levels of funding. Bowen (2011) proposes expansion of the capital base of multilateral financial institutions in order to increase concessional financing (finance made available at lower than market costs) of mitigation and adaptation activities.

Over the last two decades, recipients have gained more decision-making power in the institutions under the UNFCCC, while multilateral financial institutions have not followed this trend. Financing is typically not given directly to the project recipients but provided through implementing agencies, mostly multilateral financial institutions or UN agencies that fulfil predefined fiduciary standards. Direct access, as implemented by the Adaptation Fund, is seen by some as the most appropriate model for climate finance (UNDP, 2011). However, peer-reviewed literature comparing the effectiveness of the two approaches is lacking. At the same time, national development banks (e.g., China Development Bank, Brazilian Development Bank (BNDES)), Bilateral Finance Institutions, and a planned multilateral fund of the Brazil, Russia, India, China, and South Africa (BRICS) countries have also provided or may provide substantial funding (Höhne et al., 2012a; Robles, 2012)

13.11.2 Mobilizing private investment and financial flows

Another emerging focus of international climate cooperation is on mobilizing private investment to finance mitigation and adaptation. As discussed in Sections 13.4.1.4 and 13.13.1.1, carbon credits from market mechanisms generate revenues for private sector players, thus leveraging potentially large investments in mitigation. Such leverage is seen as important by Urpelainen (2012), who presents a game-theoretical model where capacity building leverages private mitigation investment. A number of international initiatives have supported capacity building for market mechanisms (Okubo and Michaelowa, 2010). Also, the multilateral financing institutions discussed in Section 13.11.1 will 'leverage' private finance to complement their public funding.

The potential for leveraging to lead to double- and multiple-counting has led to suggestions that internationally agreed methodologies to account for leveraging are needed (Clapp et al., 2012), which would be of help in consistent reporting of finance against the goal agreed under the UNFCCC. Stadelmann et al. (2011a) find that the leverage factors, that is the ratio between mobilized private funding and mobilized public finance, for the Climate Technology Fund under the CIFs and the GEF reach self-reported levels of 8.4 and 6.2, respectively. However, an analysis of over 200 CDM and close to 400 GEF projects, Stadelmann et al. (2011a) find a leverage ratio of just 3.0–4.5. Moreover, high-leverage factors may mean that the underlying project is not additional, i.e., not contributing to mitigation. Finally, instead of leveraging in the private sector through capacity building, the World Bank engagement in the Kyoto mechanisms has at least partially crowded out private sector activities, as shown empirically by Michaelowa and Michaelowa (2011).

Besides market mechanisms, other instruments such as grants, loans at concessional rates, provision of equity through financial institutions, or guarantees can mobilize private funds. This can happen directly on the company level or be channelled through national governments (Neuhoff et al., 2010). While they can be implemented on any level of aggregation, the level of incentive provided could be coordinated internationally, e.g., by basing it on a previously agreed 'social cost of carbon' (Hourcade et al., 2012). The success of the Multilateral Investment Guarantee Agency shows that costs of guarantees are likely to be low if multilateral and bilateral financial institutions with strong financial ratings provide them (Brown et al., 2011; Buchner et al., 2011).

13.12 The role of public and private sectors and public-private partnerships

International responses to climate change ultimately depend on private sector action. Large multinational corporations produce about half of the global world product and global GHG emissions (Morgera, 2004). Hence, private companies will need to generate investment and innovation necessary to pursue a low-carbon economy (Forsyth, 2005). Given that damages from climate change are a (negative) externality, a gap remains between the need for GHG reduction and the commitments of the largest international companies (Knox-Hayes and Levy, 2011). While some business sectors may have an interest advancing policy to mitigate climate change (Pulver, 2007; Falkner, 2008; Pinkse and Kolk, 2009; Meckling, 2011), in practice the public sector typically guides, supports, and motivates private sectors to contribute to a low-carbon economy. These types of public sector interactions with the private sector can operate through government regulations (whether market-based or conventional), but may also be facilitated through public-private partnerships, the focus of this section.

13.12.1 Public-private partnerships

One channel for such guidance is through public-private partnerships focused on climate change, which have multiplied and grown in recent years (Bäckstrand, 2008; Pattberg, 2010; Andonova, 2010; Kolk et al., 2010). Public-private partnerships involve governments, businesses, and sometimes NGOs. Examples include the Renewable Energy and Energy Efficiency Partnership (REEEP) (Parthan et al., 2010); the Methane to Markets initiative (now renamed the Global Methane Initiative) (de Coninck et al., 2008); the former Asia Pacific Partnership on Climate and Energy (which was largely organized through sector-specific partnerships) (Karlsson-Vinkhuyzen and van Asselt, 2009; McGee and Taplin, 2009; Okazaki and Yamaguchi, 2011); the Global Superior Energy Performance Partnership (taking sector-specific activities from the regional scale to the global scale) (Fujiwara, 2012; Okazaki et al., 2012; see also Section 14.3.3); the CDM (where some projects can take the character of public-private partnerships) (Streck, 2004; Green, 2008; Newell, 2009); the World Bank Prototype Carbon Fund (Lecocq, 2003; Andonova, 2010); the UN Fund for International Partnerships (39% of whose environmental partnerships are in energy- or climate change-related projects) (Andonova, 2010); the UN Global Compact's 'Caring for Climate' initiative (Abbott, 2011); the Green Power Market Development Group (Andonova, 2009); and the Munich Climate Insurance Initiative (Pinkse and Kolk, 2011). These partnerships can facilitate development and commercial deployment of low-carbon technologies as governments remove barriers to the entry and provide stakeholders with new business frameworks. Industries also demonstrate leadership through active involvement with regards to their technologies, investments, and know-how (IEA, 2010).

Some international public-private partnerships concentrate on the development of specific technologies. Others focus on rural renewable energy or low-carbon energy development in general. Others center their attention on carbon market development. Few focus on adaptation, although the insurance sector is involved in such initiatives (Pinkse and Kolk, 2011). Effective partnerships are institutionalized with representatives of major stakeholders, a permanent secretariat, resources and a dedicated mission (Pattberg et al., 2012). Company willingness to engage in adaptation depends on their capacity, their past exposure to disasters, and the link between their business planning horizons and climate impact uncertainty (Agrawala et al., 2011). Some also need to ensure that they are able to adapt to changing climatic circumstances (Linnenluecke and Griffiths, 2010; Vine, 2012).

13.12.2 Private sector-led governance initiatives

Private sector actors have also engaged in direct attempts to govern aspects of climate change transnationally. First, some institutional investors now ask companies to report on their GHG emissions, strategies to reduce them, and more broadly on climate risk exposures (Kolk et al., 2008; Newell and Paterson, 2010; Harmes, 2011; MacLeod and

Park, 2011). The most important example of this is the Carbon Disclosure Project, whose signatories controlled 70 trillion USD in assets in 2011 (Carbon Disclosure Project, 2011). The private sector is playing a role in developing systems for carbon accounting (Lovell and MacKenzie, 2011).

Second, like NGOs (see Section 13.5.2), private-sector actors have developed initiatives to govern voluntary carbon markets, either through certification standards for offset markets or by developing trading exchanges, registries, and protocols for reporting GHGs (Green, 2010, 2013; Hoffmann, 2011). Many of the certification schemes are either developed by private-sector actors (such as the Voluntary Carbon Standard, developed by the International Emissions Trading Association, the Climate Group, and the World Business Council for Sustainable Development) or by such actors in collaboration with environmental NGOs (such as the Social Carbon standard).

13.12.3 Motivations for public-private sector collaboration and private sector governance

For private sector actors, partnerships with governments or NGOs on climate may create direct economic benefits through financial support, learning opportunities, risk sharing, or market access (Pinkse, 2007; Perusse et al., 2009). Since direct regulation of firms at the international level is unavailable, states have incentives to pursue partnerships to affect transnational private sector activities. International organizations pursue partnerships for similar reasons (Andonova, 2010). Partnerships or private governance may create club goods for participants (Andonova, 2009). Sometimes, firms are motivated more by concerns for public relations (Pinkse and Kolk, 2009). Private sector finance can be stimulated by a five-step approach: strategic goal setting and policy alignment, an enabling process and incentives for low-carbon and climate-resilient (LCR) investment, financial policies and instruments, harnessing resources and building capacity for a LCR economy, and promoting green business and consumer behaviour (Corfee-Morlot et al., 2012).

13.13 Performance assessment on policies and institutions including market mechanisms

This section surveys and synthesizes quantitative and qualitative assessments of existing and proposed forms of international cooperation to address climate change mitigation that have appeared in the literature since AR4. Adaptation is not treated here, as there have been few international cooperative initiatives focused on adaptation, although these are now starting to emerge (Section 13.5.1.1).

Existing cooperation is considered in Section 13.13.1 with reference to the UNFCCC, its Kyoto Protocol, the CDM, agreements under the UNFCCC pertaining to the post-2012 period, and agreements and other forms of international cooperation outside of the UNFCCC. Section 13.13.2 considers the literature that assesses various proposed forms of future international cooperation described in Section 13.4.3. Throughout, we synthesize assessments in terms of the four criteria discussed in Section 13.2: environmental effectiveness, aggregate economic performance, distributional impacts, and institutional feasibility. Table 13.3 summarizes the key findings of this section's performance assessment.

In applying the evaluation criteria to evaluate existing and proposed forms of international cooperation, five general caveats apply. First, an ex-ante evaluation of a policy may overestimate the costs and/or the benefits of that policy for several reasons, such as overestimating the extent of its implementation (Harrington et al., 2000; Harrington, 2006), failing to account for over-reporting by regulated parties (Bailey et al., 2002), and underestimating learning related to technological development (Norman et al, 2008). Second, ex-ante evaluation may over- or under-estimate the effectiveness of proposed cooperation, because interactions between proposed policies and other existing policies may be difficult to predict. These interactions can be counterproductive, inconsequential, or beneficial (Fankhauser et al., 2010; Goulder and Stavins, 2011; Levinson, 2012). Third, while evaluation of proposed policies can be informed by lessons learned from regime complexes in other contexts (see Section 13.5), such lessons may come with extrapolation bias, since it may not be appropriate to generalize to climate change findings from other contexts. Fourth, in comparing existing policies using these criteria, it can be helpful to keep in mind that as institutions evolve, the performance of particular policies may also change. Fifth and finally, the overall performance of the international regime depends also on national and regional policies (see Chapters 14 and 15, in particular Sections 14.4.2 and 15.5).

13.13.1 Performance assessment of existing cooperation

13.13.1.1 Assessment of the UNFCCC, the Kyoto Protocol, and its flexible mechanisms

The UNFCCC established a framework and a set of principles and goals for the international response to climate change. Under Article 2, the parties agreed to the objective of "prevent[ing] dangerous anthropogenic interference with the climate system," an objective which was not quantified and was subject to several caveats. Under Article 4(2)(a), the Annex I parties committed to adopt measures (which could be

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Table 13.3 | Summary of performance assessments of existing cooperation of proposed cooperation on climate change.

	Mode of International Cooperation		Assessment Criteria			
			Environmental Effectiveness	**Aggregate Economic Performance**	**Distributional Impacts**	**Institutional Feasibility**
Existing Cooperation [13.13.1]	**UNFCCC**		Aggregate GHG emissions in Annex I countries declined by 6.0 to 9.2 % below 1990 levels by 2000, a larger reduction than the apparent 'aim' of returning to 1990 levels by 2000.	Authorized joint fulfilment of commitments, multi-gas approach, sources and sinks, and domestic policy choice. Cost and benefit estimates depend on baseline, discount rate, participation, leakage, co-benefits, adverse side-effects, and other factors.	Commitments distinguish between Annex I (developed) and non-Annex I countries. Principle of 'common but differentiated responsibility.' Commitment to 'equitable and appropriate contributions by each [party].'	Ratified (or equivalent) by 195 countries and regional organizations. Compliance depends on national communications.
	The Kyoto Protocol (KP)		Aggregate GHG emissions in Annex I countries were reduced by 8.5 to 13.6 % below 1990 levels by 2011, more than the first commitment period (CP1) collective reduction target of 5.2 %. Reductions occurred mainly in EITs; emissions increased in some others. Incomplete participation in CP1 (even lower in CP2).	Cost-effectiveness improved by flexible mechanisms (Joint Implementation (JI), CDM, International Emissions Trading (IET)) and domestic policy choice. Cost and benefit estimates depend on baseline, discount rate, participation, leakage, co-benefits, adverse side-effects, and other factors.	Commitments distinguish between developed and developing countries, but dichotomous distinction correlates only partly (and decreasingly) with historical emissions trends and with changing economic circumstances. Intertemporal equity affected by short-term actions.	Ratified (or equivalent) by 192 countries and regional organizations, but took 7 years to enter into force. Compliance depends on national communications, plus KP compliance system. Later added approaches to enhance measurement, reporting, and verification (MRV).
	The Kyoto Mechanisms		About 1.4 billion tCO_2eq credits under the CDM, 0.8 billion under JI, and 0.2 billion under IET (through October 2013). Additionality of CDM projects remains an issue but regulatory reform underway.	CDM mobilized low-cost options, particularly industrial gases, reducing costs. Under-performance of some project types. Some evidence that technology is transferred to non-Annex I countries.	Limited direct investment from Annex I countries. Domestic investment dominates, leading to concentration of CDM projects in few countries. Limited contributions to local sustainable development.	Helped enable political feasibility of Kyoto Protocol. Has multi-layered governance. Largest carbon markets to date. Has built institutional capacity in developing countries.
	Further Agreements under the UNFCCC		Pledges to limit GHG emissions made by all major emitters under Cancún Agreements. Unlikely sufficient to limit temperature change to 2°C cost-effectively. Depends on treatment of measures beyond current pledges for mitigation and finance. Durban Platform calls for new agreement by 2015, to take effect in 2020, engaging all parties.	Efficiency not assessed. Cost-effectiveness might be improved by market-based policy instruments, inclusion of forestry sector, commitments by more nations than Annex I countries (as envisioned in Durban Platform).	Depends on sources of financing, particularly for actions of developing countries.	Cancún Conference of the Parties (COP) decision; 97 countries made pledges of emission reduction targets or actions for 2020.
	Agreements outside the UNFCCC	**G8, G20, Major Economies Forum on Energy and Climate (MEF)**	G8 and MEF have recommended GHG emissions reductions by all major emitters. G20 may spur GHG emissions reductions by phasing out of fossil fuel subsidies.	Action by all major emitters may reduce leakage and improve cost-effectiveness, if implemented using flexible mechanisms. Potential efficiency gains through subsidy removal. Too early to assess economic performance empirically.	Has not mobilized climate finance. Removing fuel subsidies would be progressive but have negative effects on oil-exporting countries and on those with very low incomes unless other help for the poorest is provided.	Lower participation of countries than UNFCCC, yet covers 70 % of global emissions. Opens possibility for forum-shopping, based on issue preferences.
		Montreal Protocol on Ozone-Depleting Substances (ODS)	Spurred GHG emissions reductions through ODS phaseouts approximately 5 times the magnitude of Kyoto CP1 targets. Contribution may be negated by high-GWP substitutes, though efforts to phase out HFCs are growing.	Cost-effectiveness supported by multi-gas approach. Some countries used market-based mechanisms to implement domestically.	Later compliance period for phaseouts by developing countries. Montreal Protocol Fund provided finance to developing countries.	Universal participation. but the timing of required actions vary for developed and developing countries.
		Voluntary Carbon Market	Covers 0.13 billion tCO_2eq, but certification remains an issue.	Credit prices are heterogeneous, indicating market inefficiencies.	[No literature cited.]	Fragmented and non-transparent market.

	Mode of International Cooperation		Assessment Criteria			
			Environmental Effectiveness	**Aggregate Economic Performance**	**Distributional Impacts**	**Institutional Feasibility**
Proposed Cooperation [13.13.2]	**Proposed architectures**	**Strong multi-lateralism**	Tradeoff between ambition (deep) and participation (broad).	More cost-effective with greater reliance on market mechanisms.	Multilateralism facilitates integrating distributional impacts into negotiations and may apply equity-based criteria as outlined in Ch. 4	Depends on number of parties; degree of ambition.
		Harmonized national policies	Depends on net aggregate change in ambition across countries resulting from harmonization.	More cost-effective with greater reliance on market mechanisms.	Depends on specific national policies.	Depends on similarity of national policies; more similar may support harmonization but domestic circumstances may vary. National enforcement.
		Decentralized architectures, coordinated national policies	Effectiveness depends on quality of standards and credits across countries.	Often (though not necessarily) refers to linkage of national cap-and-trade systems, in which case cost-effective.	Depends on specific national policies.	Depends on similarity of national policies. National enforcement.
	Effort (burden) sharing arrangements		Refer to Sections 4.6.2 for discussion of the principles on which effort (burden) sharing arrangements may be based, and Section 6.3.6.6 for quantitative evaluation.			

implemented jointly) to limit net emissions (covering both sources and sinks of all GHGs not controlled by the Montreal Protocol), "recognizing that the return by the end of the present decade [the year 2000] to earlier levels" would contribute to modifying long-term trends consistent with the treaty's objective. Under Article 4(2)(b), Annex I parties committed to periodically communicate information on their emissions, "with the aim of returning individually or jointly to their 1990 levels."

According to UN data, aggregate GHG emissions in Annex I countries declined by 9.2 % from 1990–2000 (if land use and forestry are included; or by 6.0 % if they are not; the base year for some countries is in the mid- or late 1980s) (UNFCCC, 2013c, Profile for Annex I Parties). This is a larger reduction than the apparent two-step 'aim' implied in Article 4(2)(a) and (b) of the UNFCCC to return emissions to 1990 levels by the year 2000. Much of this reduction, however, was due to factors other than measures adopted under the UNFCCC, such as the economic downturn in Annex I 'economies in transition' (EITs)—Russia, former Soviet Republics, and Eastern Europe—during the 1990s.

The 1997 Kyoto Protocol adopted the first binding, quantitative mitigation commitments for developed countries. The 38 countries listed in its Annex B (industrialized countries, EITs, and the European Union separately from its member states) made aggregate commitments to collectively reduce their GHG emissions by 4.2 % relative to 1990 levels (5.2 % relative to the country-specific base years used for establishing national committments) by the Protocol's first commitment period, 2008–2012 (UNFCCC, 1998, 2012b). Other parties to the Kyoto Protocol are not constrained (but can participate in other ways; in particular, see discussion of CDM in Section 13.13.1.2). The Protocol also contained a number of new mechanisms, including IET, JI, and the CDM, that aimed to help reduce GHG emissions cost-effectively.

The aggregate emissions by Annex I countries have been reduced below the Kyoto Protocol's collective 5.2 % reduction target, but, as with the UNFCCC, much of the reduction was due to factors other than Kyoto Protocol. (The list of countries in the Protocol's Annex B is nearly identical to the list of countries in the Convention's Annex I during the historical periods referenced in this section, and the difference in aggregate emissions between the two does not affect the analysis here.) According to UNFCCC GHG inventories, aggregate GHG emissions from all Annex I countries were reduced by 13.6 % from 1990–2011 (if land use and forestry-sector changes are taken into account, and 8.5 % if they are not). Not counting the United States—because it was not a party to the Kyoto Protocol—the reduction from 1990–2011 in the remaining Annex I aggregate GHG emissions was 22.9 % if land use and forestry sectors changes are taken into account and 16.6 % if they are not. Not counting the EITs, the remaining Annex I countries' aggregate GHG emissions increased by 2.1 % and 3.2 % from 1990 to 2011 (with and without land use and forestry, respectively) (UNFCCC, 2012b).

Although emissions have decreased among Annex B parties, the environmental effectiveness of the Protocol's first commitment period has been less than it could have been, for several reasons. First, not all Annex B parties have participated. The United States, until recently the country with the largest share of global emissions (Gregg et al., 2008), did not ratify the Protocol (see also Section 13.3.1). Therefore, its target emissions reduction of 7 %, which would have amounted to over 40 % of the difference in total Annex B committed emissions commitments and base year emissions levels (UNFCCC, 2012b), was not binding. In addition, Canada withdrew from the Protocol in December 2011 (effective December 2012). Russia, Japan, and New Zealand opted not to participate in the second commitment period (2013–2020).

Second, the Annex B EITs were credited for emissions reductions that would have occurred without the Protocol due to their significant economic contraction during the 1990s. These loose targets may have been necessary to engage them as parties (Stewart and Wiener, 2003). In principle, these countries were allowed to sell resultant surplus emissions-reduction credits to other Annex B parties, which might have further reduced environmental effectiveness. However, in practice, other parties bought few AAUs relative to the stock available from EITs during the first commitment period (perhaps because the United States decision not to ratify reduced demand for such allowances), and thus environmental effectiveness was not affected as much as it could have been (Brandt and Svendsen, 2002; Böhringer, 2003; IPCC, 2007, p. 778; Crowley, 2007; Aldrich and Koerner, 2012).

Current model projections imply that emission reductions achieved by Annex B parties during the first and second commitment periods of the Kyoto Protocol are not likely to be sufficient to achieve environmental performance that limits global average temperature increases to 2 °C above pre-industrial levels (Rogelj et al., 2011; Höhne et al., 2012b) (see also Section 6.4 for a discussion of scenarios that relate short-term environmental performance to long-term GHG stabilization and tempterature change goals). A key reason is that, since 1990, the Annex B countries' share of global GHG emissions has declined significantly, from approximately 56 % of global emissions in 1990 to approximately 39 % in 2010. Simultaneously, overall global GHG emissions have risen significantly; global emissions in 2010 were approximately 31 % higher than in 1990 (JRC/PBL, 2013) (see Section 5.2).

The criterion of economic performance encompasses both efficiency and cost-effectiveness (see Sections 3.7.1 and 13.2.) Assessments of the efficiency of the Kyoto Protocol depend on respective estimates of the costs and benefits of mitigation and assumptions regarding the appropriate discount rate (see Sections 2.4.3.2 and 3.6.2 on discounting). Contrasting assumptions regarding these values are the key determinants in explaining the differences between assessments that have found the Protocol inefficient (e.g., Nordhaus, 2007), and those that find it cost-effective, but insufficient (e.g., Stern, 2007; Weitzman, 2007). These latter researchers also tend to emphasize the non-zero probability of catastrophic climate outcomes. The Kyoto Protocol also fostered monitoring and reporting of emissions, and capacity building in developing countries, which may facilitate further cost-effective action in the future (Hare et al., 2010).

With respect to cost-effectiveness, the Kyoto Protocol's three market-based instruments (the CDM, JI, and IET) intended to lower the cost of the global regime (see Section 13.4.2.3 for a description of these mechanisms). Most research on the Kyoto mechanisms has focused on the CDM, primarily because transaction volumes of CDM credits have been so much greater than JI credits or AAUs. Performance assessment of the CDM is discussed separately in Section 13.13.1.2.

International Emissions Trading could, in theory, reduce abatement costs by as much as 50 % if trades took place among Annex B countries (Blanford et al., 2010; Bosetti et al., 2010; Jacoby et al., 2010). However, in practice, trading under this mechanism has been limited, partly due to the surplus problem discussed above (Aldrich and Koerner, 2012) and the absence of the United States. As of July 2013, 0.2 billion tCO_2eq have been traded through IET (Point Carbon, 2013). The few trades that were made generally required reinvestment of the revenues into projects that reduce GHG emissions, under so-called 'Green Investment Schemes.' The economic performance of IET also depends on what type of actor is doing the trading. Early expectations were that the main traders would be states (national governments), and that states would not operate as efficient traders, because they are not cost-minimizers (e.g., Hahn and Stavins, 1999). In practice, increasing shares of trades have been made by private sector firms, which may increase cost-effectiveness (Aldrich and Koerner, 2012).

Joint Implementation also has the potential to improve the cost-effectiveness of Annex B countries' activities under the Protocol (Böhringer, 2003; Vlachou and Konstantinidis, 2010). A large majority of JI projects have been in the transition economies, especially Russia and Ukraine, given the low cost of emissions reductions there relative to other Annex B countries (Korppoo and Moe, 2008). From 2008 through July 2013, JI had led to the issuance of over 0.8 billion emission reduction unit (ERU) credits (UNFCCC, 2013d), each equivalent to one tCO_2eq of reported emission abatement. Over half of this volume was issued by Ukraine and Russia, especially in 2012 in response to the limitation on carrying over surplus AAUs to the second commitment period. The actual distribution of JI projects is not consistent with the theoretical potential, as some countries, such as Ukraine, proactively supported JI, while in others, including Russia, JI lacked political support, and efficient frameworks took several years to establish. In Western Europe, a number of companies in the chemical industry generated emission credits for their own use in the EU ETS, demonstrating the cost-reduction potential (Shishlov et al., 2012). Countries without a surplus of emission units usually applied strict rules to capture part of the emission reductions achieved by JI projects (Michaelowa and O'brien, 2006; Shishlov et al., 2012).

In addition to the three Kyoto flexibility mechanisms, the Protocol provides flexibility with regard to how Annex B parties may achieve their targets; they may employ domestic or regional policies of their own choice. One result has been the development of domestic emissions trading programmes in several countries and regions (Paterson et al., 2014). Regional and national emissions trading programmes include those in the EU (the EU ETS), Australia, and New Zealand, as well as subnational trading programmes in the United States Regional Greenhouse Gas Initiative (RGGI) and California/WCI) and in China (seven regional pilot programmes launched in 2013). See Figure 13.4 above and Sections 14.4.2 and 15.5; (Convery and Redmond, 2007; Ellerman and Buchner, 2007; Ellerman and Joskow, 2008; Ellerman, 2010; Ellerman et al., 2010; Olmstead and Stavins, 2012; Newell et al., 2013).

Distributional impacts of the Kyoto Protocol have been examined both cross-sectionally (mainly geographically) and temporally. Income patterns and trends as well as distribution of GHG emissions have changed significantly since the 1990s, when the UNFCCC and Kyoto Protocol listed Annex I/Annex B countries; some countries outside these lists have become wealthier and larger emitters than some countries on these lists (U.S. Department of Energy, 2012; WRI, 2012; Aldy and Stavins, 2012). For example, in 1990, China's total CO_2 emissions were about half of United States emissions, but by 2010, China emitted more than 50 % more CO_2 than the United States. Over this same time period, China's per capita CO_2 emissions experienced an almost three-fold increase, rising to nearly equal the level in the EU, but still about 36 % of the United States level (IEA, 2012; PBL, 2012, see Annex II.9; Olivier et al., 2012; JRC/PBL, 2013). Non-Annex I countries as a group have a share in the cumulative global greenhouse emissions for the period 1850 to 2010 close to 50 %, a share that is increasing (den Elzen et al., 2013b) (see Section 5.2.1 for more detail on historical emissions).

Meanwhile, income inequality and variations in capacity remain substantial both within and across countries. While GDP per capita in some non-Annex I countries has increased and some have joined the OECD, incomes of G8 countries remain higher than those of major emerging economies such as the BASIC countries (World Bank, 2013). Poverty is much more extensive and income at lower absolute levels in the latter, compared to the former (Milanovic, 2012). Inequality in income remains related to inequalities in emissions (Padilla and Serrano, 2006; Chakravarty et al., 2009).

More broadly, although the Kyoto Protocol's quantitative mitigation requirements are limited to Annex B countries, the economic impacts of these requirements may spill over to non-Annex B countries (Böhringer and Rutherford, 2004). In terms of intertemporal distributional equity, some have noted that climate change mitigation that requires emissions reductions in the short term for uncertain long-term benefits, also involves inter-generational distributional impacts (Schelling, 1997; Leach, 2009).

Among Annex B countries, the Kyoto Protocol's emissions-target allocation is generally progressive, one common measure of distributional equity, exhibiting positive correlation between gross domestic product per capita and the degree of targeted emissions reduction below business-as-usual levels. For a 10 % increase in per capita GDP, Annex B countries' emissions reduction targets are, on average, about 1.4 % more stringent (Frankel, 1999, 2005).

In terms of institutional feasibility, it is notable that the Kyoto Protocol has been ratified (or the equivalent) by 191 countries (plus the EU separately) (Falkner et al., 2010). As noted above, participation among Annex I countries in emissions-reduction commitments dropped significantly from the first (2008–2012) to the second (2013–2020) commitment periods, though the stringency of the emission-reduction commitments of those countries still participating increased for the second period. More broadly, the high rate of ratification is likely due in part to the lack of emissions-reduction commitments asked of non-Annex B countries (Lutter, 2000).

Allowing Annex B countries the flexibility to choose policies to meet their national emissions commitments may have contributed to institutional feasibility. However, compromises made during the negotiation of the Protocol that enabled its institutional and political viability may have reduced its environmental effectiveness (Victor, 2004; Helm, 2010; Falkner et al., 2010). This serves as an example of the tradeoff across ambition, participation, and compliance discussed in Section 13.2.2.5.

Additionally, obstacles for enforcement have hurt the Protocol's institutional feasibility. Despite the Kyoto Protocol's compliance system (Oberthür and Ott, 1999; Hare et al., 2010; Brunnée et al., 2012), it is difficult in practice to enforce the Kyoto Protocol's targets because of the lack of a legal authority with enforcement powers, and the weakness of possible sanctions relative to the costs of compliance. This is, of course, true of most international agreements (van Kooten, 2003; Böhringer, 2003; Barrett, 2008b) (see also Sections 13.3.2 and 13.4.2.1.).

13.13.1.2 Assessment of the Kyoto Protocol's Clean Development Mechanism

The CDM aims to reduce mitigation costs for Annex B countries and contribute to sustainable development in non-Annex B countries (UNFCCC, 1998) (Article 12). This mechanism led to the issuance of nearly 1.4 billion emission credits from over 7300 registered projects by October 2013 (see Section 13.7.2; UNFCCC, 2014). This performance was surprising, given that the CDM suffered from many disadvantages relative to the other flexibility mechanisms (Woerdman, 2000).

The environmental effectiveness of the CDM depends on three key factors: whether a credited project actually reduces more emissions than would have been reduced in its absence (which may depend on whether the project developers are indeed motivated primarily by expected revenue from the sale of the emission credits) ('additionality'); the validity of the baseline from which emission reductions are calculated; and indirect emissions impacts ('leakage') caused by the projects.

The issue of additionality (IPCC, 2007, pp. 779–780) continues to generate controversy, despite an increasing elaboration of additionality tests by CDM regulators (Michaelowa et al., 2009). On the one hand, (Schneider, 2009) found that key assumptions regarding additionality were often not substantiated with credible, documented evidence, in a sample of 93 projects. On the other hand, (Lewis, 2010) finds a clear contribution of the CDM to the rapid upswing of the renewable energy sector in China.

Clean Development Mechanism projects in energy efficiency, transport and buildings have faced challenges in baseline determination, monitoring, and transaction costs (Sirohi and Michaelowa, 2008; Michaelowa et al., 2009; Millard-Ball and Ortolano, 2010). Kollmuss et al. (2010) suggest that it may be possible to prevent baseline gaming through a clear regulatory framework. Heeding this advice, CDM regulators have increased the conservativeness of approved methodologies, after rejecting a significant share of baseline methodology proposals (Michaelowa et al., 2009; Millard-Ball and Ortolano, 2010). Recent attempts by CDM regulators to standardize baselines have triggered a debate regarding their impacts on environmental effectiveness and transaction costs. Making the choice between standardized and project-specific baselines voluntary (Spalding-Fecher and Michaelowa, 2013), as well as "simple, highly aggregated performance standards" (Hayashi and Michaelowa, 2013) could reduce environmental effectiveness.

With regard to leakage, (Vöhringer et al., 2006) argue that emission leakage due to market price effects is unavoidable (as it is for mitigation within Annex B countries), while Kallbekken et al. (2007) stress that regardless of the baseline used, the CDM will reduce carbon leakage through the reduction in the difference in marginal mitigation costs between countries. Schneider (2011) shows that for HFC-23 reduction projects, baseline gaming enabled production of the underlying commodity to shift from industrialized to developing countries (Wara, 2008).

With regard to cost-effectiveness, the CDM offers the potential for cost savings where abatement costs are lower in developing countries. The large volume of credits and projects in the CDM indicates its cost-saving potential. Still, Castro (2012) found that many low-cost opportunities had not been taken up by CDM projects.

The long-term contribution of the CDM to cost-effectiveness depends in part on its ability to promote technological change in developing countries either through technology transfer from industrialized to developing countries (see Section 16.8 for an overview of the technology transfer component of CDM), or by stimulating innovation within developing countries (Reichman et al. 2008). Roughly a third of CDM projects involve technology transfer (Haites et al., 2006). Dechezleprêtre et al. (2008) find that the likelihood of technology transfer is higher for CDM projects operated by subsidiaries of companies from industrialized countries. Seres et al. (2009) find that 36 % of 3296 registered and proposed projects accounting for 59 % of the annual emission reductions claim to involve technology transfer, confirming Dechezleprêtre et al.'s (2008) results. But all of these technology transfer studies limit themselves to assessment of project documents, which are not subject to rigorous and independent verification. Project developers have an incentive to overstate technology transfer. Wang (2010) is an exception, and underpins his analyses of many project documents with background interviews and assesses government policies. He finds that in all but one of the industrial gas projects in China, technology transfer occurred, but only in about a quarter of wind and coal mine methane projects. Okazaki and Yamaguchi (2011) fear that transactions costs, imposed by additionality criteria and Executive Board delays, can discourage technology transfer through the CDM.

Distributional impacts of the CDM relate to contributions to sustainable development, as well as the distribution of rents generated by the sale of emission credits. Olsen (2007) provides a summary of the early literature that did not find significant support for sustainable development induced by CDM projects. Several researchers (Sutter and Parreño, 2007; Gupta et al., 2008; Headon, 2009; Boyd et al., 2009; Alexeew et al., 2010) see the process of host country responsibility for sustainable development and competition between host countries for CDM investment as a reason for the lack of sustainability benefits of CDM projects in some countries, as Designated National Authorities (national CDM-management bodies) may not adequately scrutinize the environmental or social benefits of projects. Parnphhumeesup and Kerr (2011) find that experts and the local population weight sustainability criteria differently in the context of biopower projects in Thailand. Ellis et al. (2007) found wide variation in the contribution to local sustainable development by project type, with greater contributions in small-scale renewable energy and energy efficiency than in large-scale industrial CDM projects. Using a sample of 39 projects, Nussbaumer (2009) finds that CDM projects certified by 'The Gold Standard'—referring both to the organization and the certification scheme by that name—slightly outperform other CDM projects with respect to sustainable-development benefits. A similar result is found by Drupp (2011) for a sample of 18 Gold Standard projects compared with 30 projects certified through other means. Torvanger et al. (2013) propose dividing the CDM into two tracks, one for GHG offsets and one for sustainable development (though investors in the second track would need some new incentive).

The distribution of CDM projects has been concentrated in a relatively small number of developing countries (Yamada and Fujimori, 2012; see also Section 14.3.6.4). Given that companies in developing countries finance CDM projects out of their own resources and eventually sell the credits as a new export product, with the CDM consultant receiving a share (Michaelowa, 2007), a substantial amount of the rents remain in the host country. At the same time, the demand for CERs is evidence that it reduces costs compared to domestic reductions by developed countries. The fear, even if unfounded, of losing this export revenue may be a deterrent against taking up national emissions commitments (Castro, 2012), although in practice many such countries are developing policies aimed at emissions limitations. Therefore, it has been proposed to discount CDM credits to provide an incentive for taking up stricter national targets (Schneider, 2009).

In terms of institutional feasibility, baselines, additionality, and emissions-reductions are subject to third-party audit. However, due to the inadequate quality of many audits, regulators have been forced to introduce multi-layered procedures that have led to high transaction costs. Flues et al. (2010) show econometrically that regulatory decisions about project registration and baseline methodology approval have been influenced by political economy considerations.

There is ongoing debate in the literature about the efficacy of CDM governance (Green, 2008; Lund, 2010; Michaelowa, 2011; Okazaki and Yamaguchi, 2011; Böhm and Dhabi, 2011; Newell, 2012). The UNFCCC commissioned an evaluation of the CDM in the CDM Policy Dialogue, which issued a report in September 2012 recommending several reforms of CDM governance (CDM Policy Dialogue, 2012). Michaelowa (2009) and Schneider (2009) propose a shift from the current 1:1 offsetting system to a system that only credits part of the reductions. This would improve additionality on the aggregate level and provide an incentive for advanced developing countries to accept their own emission reduction commitments. Giving preferential treatment in procedures and methodology to certain project categories, certain sectors, notably forestry (Thomas et al., 2010; CDM Policy Dialogue, 2012), or certain regions (Nguyen et al., 2010; Bakker et al., 2011) might expand the reach of CDM.

The price of CDM credits has declined, due largely to decreased demand from the EU ETS and others, following the 2008 recession, as well as changes in EU ETS rules regarding the use of CDM credits (see Section 13.6.1). In response, the CDM Policy Dialogue (2012) proposed creation of a central bank for carbon markets to bolster credit prices, as well as further standardization of baseline and additionality determination to reduce transaction costs. The benefits of these two recommendations are disputed in the literature (Hayashi and Michaelowa, 2013; Spalding-Fecher and Michaelowa, 2013).

13.13.1.3 Assessment of further agreements under the UNFCCC

As discussed in 13.5.1.1, since AR4, negotiations under the UNFCCC have produced the system of pledges in the Copenhagen Accord and the Cancún Agreements, as well as the development of the GCF and an agreement to negotiate a new agreement by 2015. In terms of

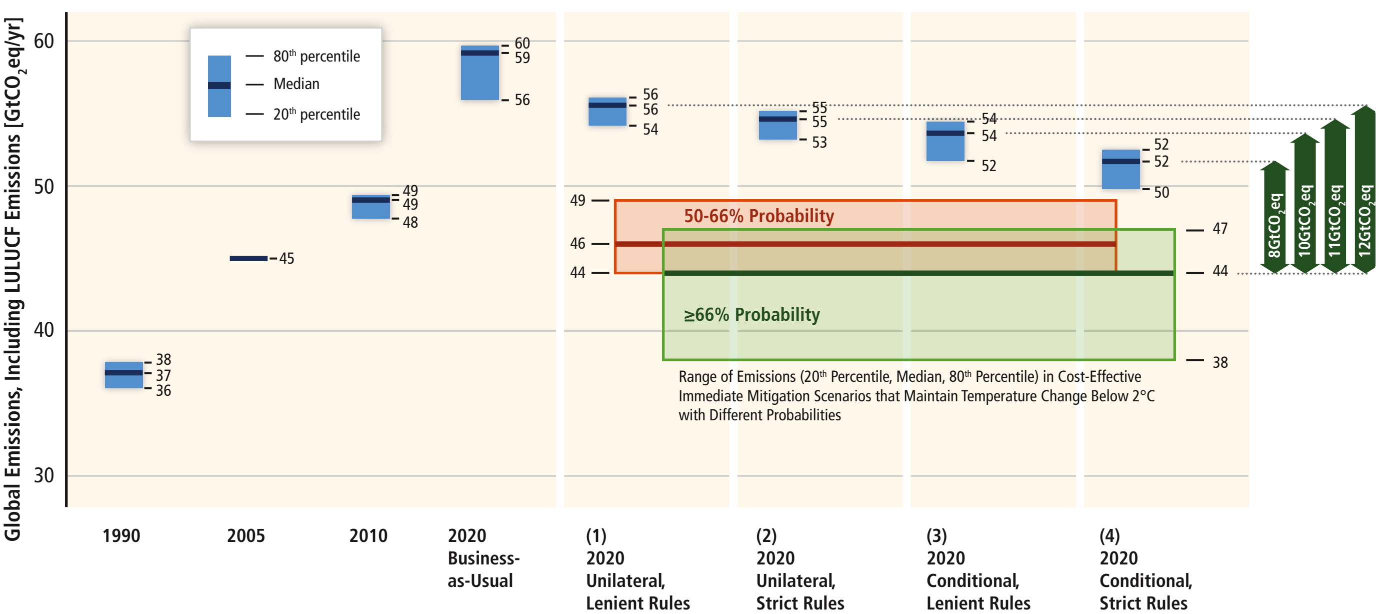

Figure 13.5 | Blue box plots show historic global GHG emissions and emissions in 2020 from business-as-usual projections and projections including Cancún pledges. Four cases are considered which combine assumptions about pledges (unconditional or conditional) and rules for complying with pledges (lenient or strict)*. The ranges of 2020 emissions (20th percentile, median, and 80th percentile) are taken directly from the UNEP Emissions Gap Report (UNEP, 2012) and represent findings from various modelling groups considering scenarios that begin mitigation immediately. The arrows indicate the difference between the median emissions projection in each case and the median emission level projected to maintain temperature change below 2 °C with a greater than 66 % probability. The ranges (20th to 80th percentiles) of 2020 emissions that maintain temperature change below 2 °C can be compared to those from cost-effective immediate mitigation scenarios from the WGIII AR5 Scenario Database: greater than 66 % probability: 36–47 $GtCO_2eq$/yr; 50–66 % probability: 43–47 $GtCO_2eq$/yr (see Chapter 6 and Annex II.10 for details, including MAGICC calculations). Differences in these ranges depend, for example, on assumptions about the availability of negative emissions technologies (see, e.g, Figure 6.31). Note that the analysis reconciles pledges for all countries against a business-as-usual counterfactual based on what has been described in the literature, even though developed country pledges for 2020 are absolute (against a historical base year) and developing country pledges relative (with rare exceptions; see Section 13.5.1).

environmental performance, these agreements acknowledged that deep reductions in GHG emissions would be required to limit global average temperature increases to 2 °C above pre-industrial levels, and recognized the possibility strengthening this target to 1.5 °C (UNFCCC, 2010). Different goals will imply different reductions in climate change impacts (see WGII AR5) and different mitigation costs (see Section 6.3).

There is broad agreement in the literature that global emissions reductions through 2020 implied by the Cancún pledges are inconsistent with cost-effective mitigation scenarios, which are based on the immediate onset of mitigation that maintain temperature change below 2 °C with a greater than 50 % probability (see Section 6.4 for detail on these scenarios). The difference between the emissions in 2020 in immediate mitigation scenarios and the Cancún pledges has been referred to as the '2°C emissions gap' (Rogelj et al., 2010; Dellink et al., 2011; den Elzen et al., 2011b; Höhne et al., 2012b). However, there are a number of delayed mitigation scenarios that delay mitigation and still meet this temperature goal and have emissions in the range of the Cancún pledges in 2020 (see Section 6.4). Analyses that have quantified the Cancún pledges exhibit substantial differences in results, owing in part to uncertainties in current and projected emissions estimates and interpretations of reduction proposals, and in part to different methodologies (UNEP, 2010, 2011, 2012, 2013b; Höhne et al., 2012b) (Figure 13.5). For example, one source of differences in analyses is due to changing rules: At COP-17 in Durban in 2011, parties agreed to new rules for using land use credits for the Kyoto Protocol's Second Commitment Period (UNFCCC, 2012c; Grassi et al., 2012), and at COP-18 in Doha in 2012, for surplus Kyoto allowances (Chen et al., 2013; UNFCCC, 2012d).

Studies suggest that the emissions gap between current Cancún pledges and a an immediate mitigation trajectory consistent with maintaining temperature change below 2°C with a 50 % or greater chance could be narrowed by implementing more stringent pledges, applying stricter accounting rules for credits from forests (Grassi et al., 2012) and surplus emission units (den Elzen et al., 2012), avoiding double-counting of offsets for both developed-country commitments and developing countries' Cancún pledges (UNEP, 2013b), increasing support for action in developing countries (Winkler et al., 2009), and implementing measures beyond current pledges (den Elzen et al., 2011b; Blok et al., 2012; Weischer et al., 2012; UNEP, 2013b).

In terms of aggregate economic performance, some analyses have estimated the direct costs of the Cancún pledges (den Elzen et al., 2011a), as well as broader economic effects (Mckibbin et al., 2011; Dellink et al., 2011; Peterson et al., 2011). For example, Dellink et al. (2011) estimate costs of action at around 0.3 % of GDP for both Annex I and non-Annex I countries and 0.5–0.6 % of global real income. However, there have been no published comparisons of the benefits and costs of the Cancún pledges, and thus no quantitative assessments of economic efficiency.

In terms of cost-effectiveness, the Cancún Agreements endorsed an on-going role for domestic and international market-based mechanisms, among various approaches, to improve cost-effectiveness. They also made a potential step forward on the cost-effectiveness criterion by emphasizing the role of mitigation actions in the forestry sector (UNFCCC, 2010; Grassi et al., 2012), which could be integrated with other actions through market mechanisms. Including forestry in market mechanisms could reduce global mitigation costs by taking advantage of low-cost mitigation opportunities in that sector (Eliasch, 2008; Busch et al., 2009; Bosetti et al., 2011; UNEP, 2013b) (see also Section 13.5.1.1).

Assessing distributional impacts accurately depends both on the mitigation costs for developing-country emission reductions and the sources of financing for such reductions. The distributional equity of recent emission-reduction pledges could be increased through financing of reductions in non-Annex I countries. By one study's estimate, between 2.1–3.3 $GtCO_2eq$ could be reduced in non-Annex I countries with 50 billion USD in financing, half of the financing agreed to under the Copenhagen Accord (Carraro and Massetti, 2012). Studies of the climate change mitigation 'financing gap' have suggested potential approaches to providing financial resources (Ballesteros et al., 2010; AGF, 2010; Haites, 2011) (see also Sections 16.2 and 13.11).

Assessments of climate agreements following the Copenhagen, Cancún, and Durban UN climate conferences reflect differing interpretations of recent negotiations with regard to institutional feasibility (Dubash, 2009; Rajamani, 2010, 2012a; Werksman and Herbertson, 2010; Müller, 2010). Copenhagen (2009) was assessed as a failure by those who expected a new climate treaty and a second commitment period of the Kyoto Protocol. Others saw the political agreement reached among a small group of world leaders (eventually espoused by more than fifty) as a major step forward, even though not legally binding, especially because it moved toward a future agreement on emissions reductions by all major emitting countries, rather than continuing to divide developed from developing countries (Ladislaw, 2010). Others noted more specific effects, such as the change in the organization of carbon markets (Bernstein et al., 2010). The literature suggests that views diverge on the Cancún Agreements: some see them as a step forward in the multilateral process (Grubb, 2011) potentially towards a subsequent legal agreement (Bodansky and Diringer, 2010), while others suggest that the move to a voluntary pledge system has weakened the multilateral climate regime (Khor, 2010b). The participation of 97 countries in the form of emission reduction pledges (42 countries) or mitigation actions (55 countries) speaks to the institutional feasibility of the Cancún Agreements (see Section 13.5.1.1). The Durban Platform in 2011 further de-emphasized the distinction between developing and developed countries, with regard to mitigation commitments, and mandated a new treaty by 2015, to take effect by 2020, mobilizing emissions reductions by all countries (UNFCCC, 2011a).

13.13.1.4 Assessment of envisioned international cooperation outside of the UNFCCC

A wide variety of international institutions outside of the UNFCCC have some role in international climate change policy. These are described in Section 13.5 and depicted graphically in Figure 13.1, above. They include activities at the international, regional, national, subnational, and local scales, and they include public, private and civil society actors. Here, we discuss those institutions for which there exist published assessments of performance for at least one of the criteria from Section 13.2.2.

The breadth of group membership poses a potential tradeoff between global participation and other aspects of institutional feasibility (see Sections 13.2.2.4, 13.3.3, and 13.5.1). To the extent that a group's membership includes only a subset of countries, this may facilitate negotiations and implementation, thereby improvinginstitutional feasibility (Houser, 2010), but this may reduce environmental and economic performance due to incomplete global coverage—omitting others' emissions, yielding leakage, and forgoing low-cost opportunities for abatement (Wiener, 1999; see also Sections 13.13.1 and 13.5.1.2). Moreover, bringing climate discussions into smaller international forums has been criticized by some as attempts to circumvent the UNFCCC and reduce its legitimacy (Hurrell and Sengupta, 2012). Because the UNFCCC's Kyoto Protocol provides for emissions commitments only by Annex B countries (which account for a declining share of global emissions, with increased risk of leakage), some of the smaller groups discussed in this subsection have tried to engage major developing countries as well, to reduce leakage and increase environmental effectiveness.

The G8

The G8 includes eight major industrialized countries (United States, United Kingdom, Canada, France, Germany, Italy, Japan, and Russia), plus the European Union. At the 2007 G8 summit, member countries agreed (though without a binding commitment) to set a goal of a 50 % reduction in GHG emissions below 1990 levels by 2050, conditional on major developing countries making significant reductions. A comparison of four models of global emission pathways (including the G8 plus China, India, and other major developing countries, a group which resembles the MEF or G20 more than the G8), to achieve concentration levels of 550, 450, or 400 ppm by 2100, found that aggregate global costs through 2100 would be below 0.8 % of global GDP to achieve 550 ppm and about 2.5 % for 400 ppm (but highly sensitive to the availability of CCS and biofuels) (Edenhofer et al., 2010); see also Section 6.3.2.1.

Analysts have examined the economic impacts of achieving reductions approximating the G8 pledge on individual countries, such as the United Kingdom (Dagoumas and Barker, 2010) and the United States (Paltsev et al., 2008).The former finds no simple tradeoff between emission reductions and economic growth in the United Kingdom. Of the more aggressive reductions modelled for the United States, Paltsev et al. (2008) finds carbon prices rising to between 120 and 210 USD by 2050, a level of cost that "would not seriously affect US GDP growth but would imply large-scale changes in its energy system." Paltsev et al. (2009) found somewhat higher costs, noting moreover that the details of policy design and incomplete sectoral coverage could raise these costs further. Meanwhile, actions by the G8 countries alone (excluding major developing countries) would address a declining share of global emissions and would be subject to leakage to non-G8 members.

The Major Economies Forum on Energy and Climate

The MEF, described in Section 13.5.1.3, is a forum for the discussion of policy options and international collaboration with regard to climate and energy, not a forum for negotiation. There are no published assessments of the MEF's effectiveness. Massetti (2011) considers a scheme that achieves the MEF's informal, aspirational objective of "reducing global emissions by 50 % in 2050" (similar to the G8 goal, described above) through hypothetical 80 % reductions by high-income MEF countries and 25–30 % reductions by low-income countries, and finds costs would exceed 1.5 % of GDP.

The G20

The G20, described in Section 13.5.1.3, came to a political agreement at its 2009 Pittsburgh meeting to "phase out and rationalize over the medium term inefficient fossil fuel subsidies while providing targeted support for the poorest" (G20, 2009). This was not followed by a legally binding agreement. In terms of environmental effectiveness, this effort could significantly affect GHG emissions, if countries in fact implemented it; by one modelled estimate, complete phaseout of such subsidies by 2020, could reduce CO_2 emissions by 4.7 % (IEA, 2011). Analysis suggests that, of the economies identified by the IEA as having fossil-fuel consumption subsidies, almost half had either implemented fossil-fuel subsidy reforms or announced related plans by 2011 (IEA et al., 2011). However, other analysts suggest that progress towards this goal can be attributed to changes in reporting and subsidy estimation, and that no fossil fuel subsidies have been eliminated under this pledge (Koplow, 2012).

Studies have confirmed that countries reforming fossil fuel consumer subsidies would realize positive economic benefits (IEA et al., 2011). However, "these economic benefits would be offset by trade impacts if other countries also removed their subsidies and thus reduced their demand for fossil-fuel imports" (IEA et al., 2011). The G20 initiative on fossil fuel subsidies could have positive distributional impacts within some countries, however. Since fossil fuel subsidies tend to benefit high-income households more than the poor in developing countries, their removal would be progressive in such nations (World Bank, 2008c).

Some note that the creation of the G20 and its elevation to a premier global international economic forum during the financial crisis in 2008 (Houser, 2010) has led to more open and dynamic negotiations between industrialized and developing countries (Hurrell and Sengupta, 2012), suggesting a potentially positive route forward.

The Montreal Protocol

The Montreal Protocol is one agreement outside of the UNFCCC that has achieved nearly universal participation and has made a significant contribution to reducing GHG emissions (Molina et al., 2009; Velders et al., 2007). (The UNFCCC does not address GHGs already controlled by the Montreal Protocol.) In its effort to reduce emissions of ozone-depleting substances (ODS), the Montreal Protocol initially phased down chlorofluorocarbons (CFCs), which harm the ozone layer and also have very high global warming potential (GWP), and in 2007 decided to accelerate the phase-down schedule for HCFCs—an interim replacement for CFCs with a somewhat lower, but still very significant, GWP. The latter decision was affected by climate considerations (Bodansky, 2011a). Even before the HCFC decision, one estimate suggested that the Montreal Protocol's overall net contribution to climate change mitigation had been approximately 5 times what the Kyoto Protocol would achieve under its first commitment period (Velders et al., 2007, 2012). However, this comparison may be unfair because the progress in reducing ozone depleting gases relative to GHGs may be due to the major ozone depleting gases being less central to economic activities than the major GHGs. In addition, the time-periods in which the two agreements have been operating makes comparison difficult.

Hydrofluorocarbons are being widely adopted as a longer-term substitute for CFCs. Many of these have extremely high GWP, and their use will partially negate climate gains otherwise achieved by the Montreal Protocol (Moncel and van Asselt, 2012). Zaelke et al. (2012) suggest that a combination of reductions of HFCs and significant cuts in CO_2, the largest contributor to climate change, can significantly increase the chances of remaining below the 2 °C limit. Proposals have been made in the Montreal Protocol process to phase down HFCs (even though these gases are not ozone-depleting substances), but as of mid-2013, parties to the Montreal Protocol had not agreed to an HFC phasedown. However, in June 2013 the presidents of the United States and China announced a joint initiative to phase down HFCs.

In terms of distributional equity, unlike the Kyoto Protocol, which placed no restrictions on developing country emissions, the Montreal Protocol applied equally-stringent emission requirements on all countries. However, the Montreal Protocol allowed for a 10-year 'grace period' for countries with low per capita CFC consumption to meet their implementation requirements, consistent with the principle of CBDRRC. The Montreal Protocol also established mechanisms for financing and provided technical support to assist developing countries in reducing their ODS emissions; the most notable mechanism is the Multilateral Fund, which has transferred more than 3 billion USD to assist developing country ODS mitigation (Molina et al., 2009).

The International Maritime Organisation and the International Civil Aviation Organisation

Under the Kyoto Protocol's Article 2.2, Annex I parties agreed to pursue GHG limitations from maritime and air transport through the IMO and ICAO.

Approximately 3.3 % of global CO_2 emissions in 2007 were attributable to shipping (IMO, 2009). In 2011, the IMO adopted the first mandatory standards for a sector relating to GHG emissions, instituting a performance-based energy-efficiency regulation for large ships "for which the building contract is placed on or after January 1, 2013" (Bodansky, 2011c). This regulation applies uniformly to all countries, extending participation in GHG emissions regulation. These standards were adopted by majority vote (over some objections), and include a provision to promote technical cooperation and assistance, especially for developing countries (Bodansky, 2011c), to address equity concerns, enhancing institutional feasibility.

The ICAO adopted a resolution on climate change in 2010. In contrast to the IMO, the ICAO's climate change goals are 'voluntary and aspirational.' Perceived inadequate progress by the ICAO toward aviation emissions reduction goals may have prompted the inclusion of aviation emissions in the EU-ETS in January 2012 (Bodansky, 2011c) (see Section 13.8.2).

Agreements among non-state actors and agreements among sub-national actors

It is unclear whether agreements among non-state (NGOs, private sector) or sub-national actors (transnational city networks) have been effective in reducing emissions. Partly this is because of their novelty and partly because the units of measurement for such effectiveness are considerably more complex than for interstate agreements (Pinkse and Kolk, 2009). For subnational efforts, the question of attribution requires better disaggregation, to understand whether reductions are additional to national effort, or only contribute to delivering national pledges. While these sub-national efforts may make a small contribution to climate action, they may be valuable in influencing nation states or helping them meet commitments (Osofsky, 2012).

Other measures of impacts do exist. In private sector initiatives, the Carbon Disclosure Project has high rates of reporting, with about 91 % of Global 500 companies surveyed in 2011 disclosing GHG emissions (Carbon Disclosure Project, 2011). There is little evidence of substantial changes in investor behaviour, with disagreement as to the potential for such changes in the future (Kolk et al., 2008; Harmes, 2011; MacLeod and Park, 2011). Some assessments have focused on how transnational city initiatives promote technology uptake within cities (Hoffmann, 2011) or on how they create a combination of competition and learning among member cities.

The voluntary carbon market (VCM) (see Section 13.5.2) had grown to 131 million tCO_2eq (about one-tenth of the size of the CDM), with a value of 424 million USD, by 2010 (Peters-Stanley et al., 2011). In 2004, virtually no VCM projects underwent third-party verified certification, but by 2010, this figure had reached 90 % and the VCM has created a varied landscape of emission-offset providers, registries, and standards (Peters-Stanley et al., 2011).

For some, the VCM is complementary to the CDM, and provides for learning about new ways of developing emissions reduction projects

(Benessaiah, 2012). However, Dhanda and Hartman (2011) find that the voluntary market is not transparent and suffers from large swings of demand for specific project types. Offset prices for the same project type differs by up to two orders of magnitude. As noted, competing registries and standard providers proliferate, and additionality of a significant share of projects is doubtful. Some regard voluntary certification systems as primarily public relations exercises (Bumpus and Liverman, 2008). An earlier assessment by Corbera et al. (2009) concluded that the voluntary market does not perform better than the CDM. However, performance in the VCM seems to improve with the increased use of third-party certification systems (Hamilton et al., 2008; Capoor and Ambrosi, 2009; Newell and Paterson, 2010).

There is evidence that the importance of partnerships between the private sector and government depends on their relationship to more traditional state-led governance. Partnerships may work once government regulations send strong signals to investors (Pfeifer and Sullivan, 2008). Rules developed in private sector agreements may then become incorporated in government regulations (Knox-Hayes and Levy, 2011), and private carbon market offset standards may be introduced into regulated carbon markets (Hoffmann, 2011).

13.13.2 Performance assessment of proposed international climate policy architectures

This section describes proposed global climate policy architectures (surveyed in Section 13.4), focusing on those that have been described for the first time since AR4, and older proposals for which new research on anticipated performance is available. Earlier proposals are listed in Table 13.2 of Gupta et al. (2007). The performance assessment of proposed architectures is difficult because it depends on both the architecture and the specific design elements of its regulatory targets and mechanisms.

For analytical purposes, this chapter classifies proposals using the taxonomy developed in Section 13.4.3 and Table 13.2: (a) strong multilateralism, (b) harmonized national policies, and (c) decentralized architectures and coordinated national policies. Combinations of these categories have also been proposed and assessed. For example, strong multilateralism can be advanced by 'clubs' of selected ambitious countries (Weischer et al., 2012)or by non-state actors (Blok et al., 2012).

13.13.2.1 Strong multilateralism

The anticipated performance of various proposals for strong multilateralism has been assessed in the literature. In addition, another body of research has examined the ends (but not the policy architecture) associated with various aggregate goals in terms of country- or region-level emission targets based on specific notions of distributional equity, so-called 'burden sharing approaches' (see Section 13.2, as well as Sections 4.6.2 and 6.3.6.6 for quantitative assessments).

Comprehensive proposals for strong multilateralism have in some cases been closely related to the targets-and-timetables approach of the Kyoto Protocol. This approach aims to be based on the UNFCCC principle of CBDRRC while introducing a more nuanced differentiation and broader base of participation, along with some details of the means of implementation. This is well reflected in the literature on reduction proposals with national emission targets and emissions trading (see Table 13.2 in Gupta et al. (2007) for literature prior to AR4). Since AR4, this literature has studied gradually-increasing emission-reduction commitments linked to indicators such as per capita income (Cao, 2010a; Frankel, 2010; Bosetti and Frankel, 2011), differentiating groups of countries (den Elzen et al., 2007; Rajamani, 2013), common but differentiated convergence (Luderer et al., 2012), and per capita targets (Agarwala, 2010).

Distributional impacts vary significantly with underlying criteria for effort sharing. For example, proposals that use 'responsibility and capability' as a criterion for allocating effort would result in relatively more stringent implied actions for 'early' emitters, assigning them lower allocations. Proposals based on the criterion of 'mitigation potential' would be less stringent for 'early' emitters, capturing the mitigation potential in developing countries, assumed to be relatively low-cost (Höhne et al., 2013). Especially for low-stabilization levels, the approaches differ in the extent to which they rely on contributions from all countries, from emissions reductions within their borders, and on international assistance between countries. Section 4.6.2 details many more possible criteria for effort sharing, and Section 6.3.6.6 quantifies the implications of these various effort sharing criteria in terms of regional emission allocations and costs.

Sectoral approaches are generally not anticipated to perform optimally in terms of environmental effectiveness or economic performance when compared with economy-wide approaches; therefore, sectoral approaches can be thought of as second-best policies (Bradley et al., 2007; Schmidt et al., 2008; den Elzen et al., 2008; Meckling and Chung, 2009). Sectors that are homogenous and already globally integrated, such as aviation, may lend themselves better to international cooperation than those that are heterogeneous. Omitting some sectors makes it more difficult to achieve emissions or stabilization goals and also reduces cost-effectiveness, relative to economy-wide approaches, as required emissions reductions must be made within-sector, failing to take advantage of the lower of heterogeneous marginal abatement costs across sectors. Transaction costs may also be higher with sectoral approaches, including, for example, greater challenges to negotiation (Bradley et al., 2007).

However, these approaches could potentially help mitigate leakage within particular industries (Bradley et al., 2007; Sawa, 2010). In terms of institutional feasibility, sectoral approaches may encourage the participation of a wider range of countries than economy-wide approaches, because sectoral agreements can be more politically manageable in domestic policy processes (Bradley et al., 2007; Sawa, 2010). Developing countries may also be more likely to participate meaningfully in sectoral processes than economy-wide agreements limiting emissions (Meckling and Chung, 2009).

Several researchers have suggested that a 'regime complex' is emerging (see Sections 13.3 and 13.5), with the strong implication that component regimes may display a range of architectures—from strong multilateralism through more decentralized systems (Carraro et al., 2007; Biermann et al., 2009; Barrett, 2010; Keohane and Victor, 2011). The portfolio of treaties approach is similar in some ways to the sectoral approaches described above. However, the approach described in (Barrett, 2010) includes much more significant enforcement possibilities, potentially increasing environmental effectiveness, while potentially reducing institutional feasibility.

13.13.2.2 Harmonized national policies

In principle, a wide variety of national climate policies can be harmonized across countries. This holds for cap-and-trade systems (e.g., a global emissions permit trading system (Ellerman, 2010)), as we discuss in the context of linkage below, as well as for national carbon or other GHG taxes. The most-studied approach in terms of performance assessments has been harmonized carbon taxes. Their environmental performance would depend upon the level of the tax, but relative to non-market-based approaches, this approach would be cost-effective. The impact of a carbon tax on economic efficiency will depend, in part, on how tax revenues are used (Bovenberg and de Mooij, 1994; Parry, 1995; Bovenberg and Goulder, 1996; Cooper, 2010).

Estimates in the recent literature of the environmental effectiveness and economic performance of proposed carbon taxes vary dramatically depending upon assumptions (Edmonds et al., 2008; Clarke et al., 2009; van Vuuren et al., 2009; Bosetti et al., 2010; Luderer et al., 2012). The distributional impacts of a carbon tax include negative impacts on the fossil fuel industry as a whole, with stronger impacts for fuels with higher carbon emissions per unit of energy. For example, impacts on coal would be much greater than on natural gas (Cooper, 2010). Impacts of national carbon taxes on consumers would likely be somewhat regressive in high-income countries but progressive in low-income countries (see Section 15.5 for detail). Tax revenues could be used by individual countries to address these domestic distributional concerns (See e.g.,Winkler and Marquard, 2011; Alton et al., 2012).

Under a harmonized national carbon tax regime, fossil-fuel-exporting countries might experience negative impacts, and net importers could experience decreasing prices due to reduced demand, while some regions could experience increased bio-energy exports (Persson et al., 2006; OECD, 2008; Cooper, 2010; Leimbach et al., 2010). International transfers drawing on revenues of such a tax could, in theory, be used to address these concerns or to encourage participation by developing countries (Nordhaus, 2006). As with emissions trading (Frankel, 2010), the extent of developing country participation in an international carbon tax scheme could be based upon income thresholds (Nordhaus, 2006).

The institutional feasibility of a global carbon tax has not been thoroughly considered in the literature. The relatively large number of studies on a global carbon tax is at least partly due to the fact that economic modellers often model a global carbon tax as a proxy for other mitigation policy instruments that would impose shadow prices on the carbon content of fossil fuels and/or CO_2 emissions.

Many hybrid market-based approaches to mitigation, combining tradable emissions permits with some characteristics of a carbon tax, have been proposed and examined in the recent literature (Pizer, 2002; Murray et al., 2009; FELL et al., 2010; Webster et al., 2010; Grüll and Taschini, 2011). In principle, these hybrid approaches can provide better aggregate economic performance, lowering compliance costs and reducing price volatility, at the potential expense of environmental effectiveness in the form of uncertain changes in aggregate emissions (Grüll and Taschini, 2011). However, recent research suggests that 'soft' price collars, which provide a modest reserve of additional emission allowances at the price ceiling, may achieve most of the expected compliance cost savings provided by 'hard' collars (unlimited supplies of additional allowances), while maintaining a more predictable cap on emissions (Fell et al., 2012). In terms of distributional equity, hybrid systems may reduce expected compliance costs for regulated firms, though they may increase regulatory costs (Grüll and Taschini, 2011). This characteristic may also increase political feasibility.

13.13.2.3 Decentralized architectures and coordinated national policies

In principle, many types of national climate policies could be linked to each other. In the literature to date, most discussion is of linked carbon markets. The recent literature on these suggests that economic performance of existing GHG allowance trading systems could be enhanced through linkage, which would reduce abatement costs and improve market liquidity (Haites and Mehling, 2009; Mehling and Haites, 2009; Sterk and Kruger, 2009; Anger et al., 2009; Jaffe et al., 2009; Jaffe and Stavins, 2010; Grüll and Taschini, 2011; Metcalf and Weisbach, 2012; Ranson and Stavins, 2013).

In terms of environmental performance, linkage can increase or reduce emissions leakage, depending on the stringency of caps, and the quality of offset credits within linked systems.

Linkages among cap-and-trade systems as well as linkages with and among emission-reduction-credit systems would create winners and losers, generating distributional impacts relative to un-linked systems, depending upon impacts on allowance prices and whether participating entities are net buyers or net sellers of emissions (Jaffe and Stavins, 2010). While it does preserve the ability of countries to meet their commitments through means of their own choice, consistent with the Kyoto Protocol, linkage also poses some challenges for institutional feasibility, since it reduces domestic control over prices, emissions, and other aspects of policy design and impact (Buchner and Carraro, 2007; Jaffe et al., 2009; Jaffe and Stavins, 2010; Ranson and Stavins, 2013). Linking may not benefit all participating countries due to potential market distortions and the rebalancing of production and consumption patterns in multiple markets (i.e., general equilibrium effects) (Marschinski et al., 2012). In one analysis that modelled the heterogeneous costs and benefits of participation in a climate coalition using a game-theoretic framework, incentives to deviate from cooperation could not be compensated by transfers (Bosetti et al., 2013).

Institutional-feasibility challenges may be more significant for linked heterogeneous policy instruments (such as taxes and emissions permit systems, or taxes and technology standards) relative to linked regimes that use similar instruments (Metcalf and Weisbach, 2012). For example, unrestricted linkage would effectively turn a permit trading system into a tax, pegging the permit price to the other country's tax rate, and allowing aggregate emissions above the permit system's established cap (Metcalf and Weisbach, 2012).

Climate policy architectures that can be characterized as technology-oriented agreements may seek to share and coordinate knowledge and enhance technology research, development, demonstration, and transfer. Some literature suggests that such agreements may increase the efficiency and environmental effectiveness of international climate cooperation, but will have limited environmental effectiveness operating alone (de Coninck et al., 2008). Though technology-oriented policies can promote the development of new technologies, environmental effectiveness hinges on the need for other policies to provide incentives for adoption (Fischer, 2008; Newell, 2010b). For example, (Bosetti et al., 2009b) show that R&D alone is insufficient to stabilize CO_2 levels without an accompanying carbon tax or functionally equivalent policy instrument. See Section 13.9.3 for details of international cooperation on technology.

13.14 Gaps in knowledge and data

Current understanding of agreements and instruments for international cooperation continues to evolve. At the time of this publication, there are a number of gaps in the scholarly literature of international cooperation for climate change mitigation, as identified below:

- There exist few comparisons of proposals in terms of any or all of the four criteria used in this report. Research that would be particularly useful would be comparisons of aggregate cost, or disaggregated regional- or country-level costs per year, with incorporation of uncertainty.
- There exist few assessments of the emerging range of new intergovernmental and transnational arrangements, including 'hybrid' approaches and approaches that interact across the landscape of climate agreements, which might enable better assessment of the sum of efforts.
- Current understanding of the complementarities and tradeoffs between policies affecting mitigation and adaptation is incomplete.
- Current understanding of how international cooperation on climate change can help achieve co-benefits and development goals of countries and what policies and practices work and do not work in capacity building projects is incomplete.
- Current understanding of the factors that affect national decisions to join and form international agreements and how international cooperation can directly influence achievement of various performance criteria is incomplete.

13.15 Frequently Asked Questions

FAQ 13.1 Given that GHG emissions abatement must ultimately be carried out by individuals and firms within countries, why is international cooperation necessary?

International cooperation is important to achieve significant emissions reductions for a number of reasons. First, climate protection is a public good that requires collective action, because firms and individuals will not otherwise bear the private costs needed to achieve the global benefits of abatement (see Section 13.2.1.1). Second, because GHGs mix globally in the atmosphere, anthropogenic climate change is a global commons problem. Third, international cooperation helps to give every country an opportunity to ascertain how responsibilities are to be divided among them, based on principles adopted in international agreements (see Section 13.3). This is important because individual countries are the entities with jurisdiction over individuals and firms, whose actions ultimately determine if emissions are abated. Fourth, international cooperation allows for linkages across policies at different scale, notably through harmonizing national and regional policies, as well as linkages across issues, and through enhanced cooperation may reduce mitigation costs, create opportunities for sharing the benefits of adaptation, increase credibility of price signals, and expand market size and liquidity. Fifth, international cooperation may help bring together international science and knowledge, which may improve the performance of cooperatively-developed policy instruments.

FAQ 13.2 What are the advantages and disadvantages of including all countries in international cooperation on climate change (an 'inclusive' approach) and limiting participation (an 'exclusive' approach)?

The literature suggests that there are tradeoffs between 'inclusive' approaches to negotiation and agreement (i.e., approaches with broad participation, as in the UNFCCC) and 'exclusive' approaches (i.e., limiting participation according to chosen criteria—for example, including only the largest emitters, or groups focused on specific issues). Regarding an 'inclusive' approach, the universal membership of the UNFCCC is an indicator of its high degree of legitimacy among states as a central institution to develop international climate policy. However, the scholarly literature offers differing views over whether or not the outcomes of recent negotiations strengthen or weaken the multilateral climate regime (Section 13.13.1.3). A number of other multilateral forums have emerged as potentially valuable in advancing the international process through an 'exclusive' approach. These smaller groups can advance the overall process through informal consultations, technical analysis and information sharing, and implementation of UNFCCC decisions or guidance (e.g., with regard to climate finance). They might also be more effective in advancing agreement among the largest emitters, but so far have not been able to do so. Examples include the MEF, the G20 and G8, and the city-level C-40 Climate Leadership Group. Section 13.5 goes into more detail, and Figure 13.1 illustrates the overall landscape of climate change-relevant agreements and institutions.

FAQ 13.3 What are the options for designing policies to make progress on international cooperation on climate change mitigation?

There are a number of potential structures for formalized international cooperation on climate change mitigation, referred to in the text as policy 'architectures' (see Section 13.4). Architectures vary by the degree to which their authority is centralized and can be roughly categorized into three groups: strong multilateralism, harmonized national policies, and decentralized architectures (see Section 13.4.1). An example of strong multilateralism is a targets-and-timetables approach, which sets aggregate quantitative emissions-reduction targets over a fixed period of time and allocates responsibility for this reduction among countries, based on principles jointly accepted. The UNFCCC's Kyoto Protocol is an example of a strong multilateral approach. The second architecture is harmonized national policies. An example in principle (though not put into practice) might be multilaterally harmonized domestic carbon taxes. An example of the third architecture, decentralized approaches and coordinated national policies, would be linkage among domestic cap-and-trade systems, driven not through a multilateral agreement but largely by bilateral arrangements. The literature suggests that each of the various proposed policy architectures for global climate change has advantages and disadvantages with regard to four evaluation criteria: environmental effectiveness, aggregate economic performance, distributional equity, and institutional feasibility. Section 13.4.1.4 goes into more detail.

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14

Regional Development and Cooperation

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Executive Summary

Regional cooperation already is a powerful force in the global economy (*medium evidence, high agreement*). This is reflected in numerous agreements related to trade and technology cooperation, as well as trans-boundary agreements related to water, energy, transport, etc. As a result, there is growing interest in regional cooperation as a means to achieving mitigation objectives. A regional perspective (where regions are defined primarily geographically, with further differentiation related to economic proximity) recognizes differences in the opportunities and barriers for mitigation, opportunities for joint action on mitigation and common vulnerabilities, and assesses what regional cooperation can and has already achieved in terms of mitigation. Regional cooperation can provide a linkage between global and national/subnational action on climate change and can also complement national and global action. [Section 14.1.2, 14.4.1]

Regions can be defined in many different ways depending upon the context. Mitigation challenges are often differentiated by region, based on their levels of development. For the analysis of greenhouse gas (GHG) projections, as well as of climate change impacts, regions are typically defined in geographical terms. Regions can also be defined at a supra-national or sub-national level. This chapter defines regions as supra-national regions (sub-national regions are examined in Chapter 15). Ten regions are defined based on a combination of proximity in terms of geography and levels of economic and human development: East Asia (China, Korea, Mongolia) (EAS); Economies in Transition (Eastern Europe and former Soviet Union) (EIT); Latin America and Caribbean (LAM); Middle East and North Africa (MNA); North America (USA, Canada) (NAM); Pacific Organisation for Economic Co-operation and Development 1990 (Japan, Australia, New Zealand) (POECD); South-East Asia and Pacific (PAS); South Asia (SAS); sub-Saharan Africa (SSA); Western Europe (WEU). Where appropriate, we also examine the category of least-developed countries (LDC), which combines 33 countries in SSA, 5 in SAS, 9 in PAS, and one each in LAM and the MNA, and which are classified as such by the United Nations based on their low incomes, low human assets, and high economic vulnerabilities. We also examine regional cooperation initiatives through actual examples that bear upon mitigation objectives, which do not typically conform to the above listed world regions. [14.1.2]

There is considerable heterogeneity across and within regions in terms of opportunities, capacity, and financing of climate action, which has implications for the potential of different regions to pursue low-carbon development (*high confidence*). Several multi-model exercises have explored regional approaches to mitigation. In general, these regional studies find that the costs of climate stabilization for an individual region will depend on the baseline development of regional emission and energy-use and energy-pricing policies, the mitigation requirement, the emissions reduction potential of the region, and terms of trade effects of climate policy, particularly in energy markets. [14.1.3, 14.2]

At the same time, there is a mismatch between opportunities and capacities to undertake mitigation (*medium confidence*). The regions with the greatest potential to leapfrog to low-carbon development trajectories are the poorest developing regions where there are few lock-in effects in terms of modern energy systems and urbanization patterns. However, these regions also have the lowest financial, technological, and human capacities to embark on such low-carbon development paths and their cost of waiting is high due to unmet energy and development needs. Emerging economies already have more lock-in effects but their rapid build-up of modern energy systems and urban settlements still offers substantial opportunities for low-carbon development. Their capacity to reorient themselves to low-carbon development strategies is higher, but also faces constraints in terms of finance, technology, and the high cost of delaying the installation of new energy capacity. Lastly, industrialized economies have the largest lock-in effects, but the highest capacities to reorient their energy, transport, and urbanizations systems towards low-carbon development. [14.1.3, 14.3.2]

Heterogeneity across and within regions is also visible at a more disaggregated level in the energy sector (*high confidence*). Access to energy varies widely across regions, with LDC and SSA being the most energy-deprived regions. These regions emit less CO_2, but offer mitigation opportunities from future sustainable energy use. Regional cooperation on energy takes different forms and depends on the degree of political cohesion in a region, the energy resources available, the strength of economic ties between participating countries, their institutional and technical capacity, political will and the available financial resources. Regional cooperation on energy offers a variety of mitigation and adaptation options, through instruments such as harmonized legalization and regulation, energy resources and infrastructure sharing (e.g., through power pools), joint development of energy resources (e.g., hydropower in a common river basin), and know-how transfer. As regional energy cooperation instruments interact with other policies, notably those specifically addressing climate change, they may affect their ability to stimulate investment in low-carbon technologies and energy efficiency. Therefore, there is a need for coordination between these energy cooperation and regional/national climate policy instruments. In this context, it is also important to consider spillovers on energy that may appear due to trade. While mitigation policy would likely lead to lower import dependence for energy importers, it can also devalue endowments of fossil fuel exporting countries (with differences between regions and fuels). While the effect on coal exporters is expected to be negative in the short- and long-term, as policies could reduce the benefits of using coal, gas exporters could benefit in the medium-term as coal is replaced by gas. The overall impact on oil is more uncertain. [14.3.2, 14.4.2]

The impact of urbanization on carbon emissions also differs remarkably across regions (*high confidence*). This is due to the regional variations in the relationship between urbanization, economic growth, and industrialization. Developing regions and their cities have significantly higher energy intensity than developed regions, partly due to different patterns and forms of urban settlements. Therefore, regional cooperation to promote environmentally friendly technology, and to follow sustainably socioeconomic development pathways, can induce great opportunities and contribute to the emergence of low-carbon societies. [14.3.3]

In terms of consumption and production of GHG emissions, there is great heterogeneity in regional GHG emissions in relation to the population, sources of emissions and gross domestic product (GDP) (*high confidence*). In 2010, NAM, POECD, EIT, and WEU, taken together, had 20.5 % of the world's population, but accounted for 58.3 % of global GHG emissions, while other regions with 79.5 % of population accounted for 41.7 % of global emissions. If we consider consumption-based emissions, the disparity is even larger with NAM, POECD, EIT, and WEU generating around 65 % of global consumption-based emissions. In view of emissions per GDP (intensity), NAM, POECD and WEU have the lowest GHG emission intensities, while SSA and PAS have high emission intensities and also the highest share of forestry-related emissions. This shows that a significant part of GHG-reduction potential might exist in the forest sector in these developing regions. [14.3.4]

Regional prospects of mitigation action and low-carbon development from agriculture and land-use change are mediated by their development level and current pattern of emissions (*medium evidence, high agreement*). Emissions from agriculture, forestry, and other land use (AFOLU) are larger in ASIA (SAS, EAS, and PAS combined) and LAM than in other regions, and in many LDC regions, emissions from AFOLU are greater than from fossil fuels. Emissions were predominantly due to deforestation for expansion of agriculture, and agricultural production (crops and livestock), with net sinks in some regions due to afforestation. Region-specific strategies are needed to allow for flexibility in the face of changing demographics, climate change and other factors. There is potential for the creation of synergies with development policies that enhance adaptive capacity. [14.3.5]

In addition, regions use different strategies to facilitate technology transfer, low-carbon development, and to make use of opportunities for leapfrogging (*robust evidence, medium agreement*). Leapfrogging suggests that developing countries might be able to follow more sustainable, low-carbon development pathways and avoid the more emissions-intensive stages of development that were previously experienced by industrialized nations. Time and absorptive capacity, i.e., the ability to adopt, manage, and develop new technologies, have been shown to be a core condition for successful leapfrogging. The appropriateness of different low-carbon pathways depends on the nature of different technologies and the region, the institutional architecture and related barriers and incentives, as well as the needs of different parts of society. [14.3.6, 14.4.3]

In terms of investment and finance, regional participation in different climate policy instruments varies strongly (*high confidence*). For example, the Clean Development Mechanism (CDM) has developed a distinct pattern of regional clustering of projects and buyers of emission credits, with projects mainly concentrated in Asia and Latin America, while Africa and the Middle East are lagging behind. The regional distribution of the climate change projects of the Global Environment Facility (GEF) is much more balanced than that of the CDM. [14.3.7]

Regional cooperation for mitigation can take place via climate-specific cooperation mechanisms or existing cooperation mechanisms that are (or can be) climate-relevant. Climate-specific regional initiatives are forms of cooperation at the regional level that are designed to address mitigation challenges. Climate-relevant initiatives were launched with other objectives, but have potential implications for mitigation at the regional level. [14.4.1]

Our assessment is that regional cooperation has, to date, only had a limited (positive) impact on mitigation (*medium evidence, high agreement*). Nonetheless, regional cooperation could play an enhanced role in promoting mitigation in the future, particularly if it explicitly incorporates mitigation objectives in trade, infrastructure, and energy policies, and promotes direct mitigation action at the regional level. [14.4.2, 14.5]

Most literature suggests that climate-specific regional cooperation agreements in areas of policy have not played an important role in addressing mitigation challenges to date (*medium confidence*). This is largely related to the low level of regional integration and associated willingness to transfer sovereignty to supranational regional bodies to enforce binding agreements on mitigation. [14.4.2, 14.4.3]

Even in areas with deep regional integration, economic mechanisms to promote mitigation (including the European Union (EU) Emission Trading Scheme (ETS)) have not been as successful as anticipated in achieving intended mitigation objectives (*high confidence*). While the EU-ETS has demonstrated that a cross-border cap-and-trade system can work, the persistently low carbon price in recent years has not provided sufficient incentives to motivate additional mitigation action. The low price is related to a number of factors, including the unexpected depth and duration of the economic recession, uncertainty about the long-term emission-reduction targets, import of credits from the CDM, and the interaction with other policy instruments, particularly related to the expansion of renewable energy as well as regulation on energy efficiency. As of the time of this assessment in late 2013, it has proven to be politically difficult to address this problem by removing emission permits temporarily, tightening the cap, or providing a long-term mitigation goal. [14.4.2]

Climate-specific regional cooperation using binding regulation-based approaches in areas of deep integration, such as EU directives on energy efficiency, renewable energy, and biofuels, have had some impact on mitigation objectives (*medium confidence*).

Nonetheless, theoretical models and past experience suggest that there is substantial potential to increase the role of climate-specific regional cooperation agreements and associated instruments, including economic instruments and regulatory instruments. In this context, it is important to consider carbon leakage of such regional initiatives and ways to address it. [14.4.2, 14.4.1]

In addition, non-climate-related modes of regional cooperation could have significant implications for mitigation, even if mitigation objectives are not a component (*medium confidence*). Regional cooperation with non-climate-related objectives but possible mitigation implications, such as trade agreements, cooperation on technology, and cooperation on infrastructure and energy, has to date also had negligible impacts on mitigation. Modest impacts have been found on the level of emissions of members of regional preferential trade areas if these agreements are accompanied with environmental agreements. Creating synergies between adaptation and mitigation can increase the cost-effectiveness of climate change actions. Linking electricity and gas grids at the regional level has also had a modest impact on mitigation as it facilitated greater use of low-carbon and renewable technologies; there is substantial further mitigation potential in such arrangements. [14.4.2]

Despite a plethora of agreements on technology, the impact on mitigation has been negligible to date (*medium confidence*). A primary focus of regional agreements surrounds the research, development, and demonstration of low-carbon technologies, as well as the development of policy frameworks to promote the deployment of such technologies within different national contexts. In some cases, geographical regions exhibit similar challenges in mitigating climate change, which can serve as a unifying force for regional technology agreements or cooperation on a particular technology. Other regional agreements may be motivated by a desire to transfer technological experience across regions. [14.4.3]

Regional development banks play a key role in mitigation financing (*medium confidence*). The regional development banks, the World Bank, the United Nations system, other multilateral institutions, and the reducing emissions from deforestation and degradation (REDD)+ partnership will be crucial in scaling up national appropriate climate actions, e.g., via regional and thematic windows in the context of the Copenhagen Green Climate Fund, such as a possible Africa Green Fund. [14.4.4]

Going forward, regional mechanisms have considerably greater potential to contribute to mitigation goals than have been realized so far (*medium confidence*). In particular, these mechanisms have provided different models of cooperation between countries on mitigation, they can help realize joint opportunities in the field of trade, infrastructure, technology, and energy, and they can serve as a platform for developing, implementing, and financing climate-specific regional initiatives for mitigation, possibly also as part of global arrangements on mitigation. [14.5]

14.1 Introduction

14.1.1 Overview of issues

This chapter provides an assessment of knowledge and practice on regional development and cooperation to achieve climate change mitigation. It will examine the regional trends and dimensions of the mitigation challenge. It will also analyze what role regional initiatives, both with a focus on climate change and in other domains such as trade, can play in addressing these mitigation challenges.

The regional dimension of mitigation was not explicitly addressed in the IPCC Fourth Assessment Report (AR4). Its discussion of policies, instruments, and cooperative agreements (Working Group III AR4, Chapter 13) was focused primarily on the global and national level. However, mitigation challenges and opportunities differ significantly by region. This is particularly the case for the interaction between development/growth opportunities and mitigation policies, which are closely linked to resource endowments, the level of economic development, patterns of urbanization and industrialization, access to finance and technology, and—more broadly—the capacity to develop and implement various mitigation options. There are also modes of regional cooperation, ranging from regional initiatives focused specifically on climate change (such as the emissions trading scheme (ETS) of the European Union (EU)) to other forms of cooperation in the areas of trade, energy, or infrastructure, that could potentially provide a platform for delivering and implementing mitigation policies. These dimensions will be examined in this chapter.

Specifically, this chapter will address the following questions:

- Why is the regional level important for analyzing and achieving mitigation objectives?
- What are the trends, challenges, and policy options for mitigation in different regions?
- To what extent are there promising opportunities, existing examples, and barriers for leapfrogging in technologies and development strategies to low-carbon development paths for different regions?
- What are the interlinkages between mitigation and adaptation at the regional level?
- To what extent can regional initiatives and regional integration and cooperation promote an agenda of low-carbon climate-resilient development? What has been the record of such initiatives, and what are the barriers? Can they serve as a platform for further mitigation activities?

The chapter is organized as follows: after discussing the definition and importance of supra-national regions, sustainable development at the regional level, and the regional differences in mitigation capacities, Section 14.2 will provide an overview of opportunities and barriers for low-carbon development. Section 14.3 will examine current development patterns and goals and their emission implications at the regional level. In this context, this section will discuss issues surrounding energy and development, urbanization and development, and consumption and production patterns. Section 14.3 will also examine opportunities and barriers for low-carbon development by examining policies and mechanisms for such development-indifferent regions and sectors. Moreover, it will analyze issues surrounding technology transfer, investment, and finance. Section 14.4 will evaluate existing regional arrangements and their impact on mitigation, including climate-specific as well as climate-relevant regional initiatives. In this context, links between mitigation, adaptation and development will be discussed. Also, the experiences of technology transfer and leapfrogging will be evaluated. Section 14.5 will formulate policy options. Lastly, Section 14.6 will outline gaps in knowledge and data related to the issues discussed in this chapter.

The chapter will draw on Chapter 5 on emission trends and drivers, Chapter 6 on transformation pathways, the sectoral Chapters 7–12, and Chapter 16 on investment and finance, by analyzing the region-specific information in these chapters. In terms of policy options, it differs from Chapters 13 and 15 by explicitly focusing on regions as the main entities and actors in the policy arena.

We should note from the outset that there are serious gaps in the peer-reviewed literature on several of the topics covered in this chapter, as the regional dimension of mitigation has not received enough attention or the issues covered are too recent to have been properly analyzed in peer-reviewed literature. We will therefore sometimes draw on grey literature or state the research gaps.

14.1.2 Why regions matter

This chapter only examines supra-national regions (i.e., regions in between the national and global level). Sub-national regions are addressed in Chapter 15. Thinking about mitigation at the regional level matters mainly for three reasons:

First, regions manifest vastly different patterns in their level, growth, and composition of GHG emissions, underscoring significant differences in socio-economic contexts, energy endowments, consumption patterns, development pathways, and other underlying drivers that influence GHG emissions and therefore mitigation options and pathways (Section 14.3). For example, low-income countries in sub-Saharan Africa, whose contribution to consumption-based GHG emissions is currently very low, face the challenge to promote economic development (including broader access to modern energy and transport) while encouraging industrialization. Their mitigation challenge relates to choosing among development paths with different mitigation potentials. Due to their tight resource situation and severe capacity constraints, their ability to choose low-carbon development paths and their opportunities to wait for more mitigation-friendly technologies is severely constrained (Collier and Venables, 2012a). Moreover, these development paths may be costly. Nonetheless, with sufficient access to finance, technologies, and the appropriate institutional environment, these countries might be able to leapfrog to low-carbon development paths that would promote their economic development and contribute to mitigating climate change in the medium to long run. Emerging economies, on the other hand, which are further along the way of carbon-intensive development, are better able to adopt various mitigation options, but their gains from leapfrogging may be relatively smaller. For more rapidly growing economies, the opportunities to follow different mitigation paths are greater, as they are able to quickly install new energy production capacities and build up transport and urban infrastructure. However, once decisions have been made, lock-in effects will make it costly for them to readjust paths. In industrialized countries, the opportunities to leapfrog are small and the main challenge will be to drastically re-orient existing development paths and technologies towards lower-carbon intensity of production and consumption. We call this the 'regional heterogeneity' issue.

Second, regional cooperation is a powerful force in global economics and politics—as manifest in numerous agreements related to trade, technology cooperation, trans-boundary agreements relating to water, energy, transport, and so on. From loose free-trade areas in many developing countries to deep integration involving monetary union in the EU, regional integration has built up platforms of cooperation among countries that could become the central institutional forces to undertake regionally coordinated mitigation activities. Some regions, most notably the EU, already cooperate on mitigation, using a carbon-trading scheme and binding regulations on emissions. Others have focused on trade integration, which might have repercussions on the mitigation challenge. It is critical to examine to what extent these forms of cooperation have already had an impact on mitigation and to what extent they could play a role in achieving mitigation objectives (Section 14.3). We call this the 'regional cooperation and integration issue'.

Third, efforts at the regional level complement local, domestic efforts on the one hand and global efforts on the other hand. They offer the potential of achieving critical mass in the size of markets required to make policies, for example, on border tax adjustment, in exploiting opportunities in the energy sector or infrastructure, or in creating regional smart grids required to distribute and balance renewable energy.

Given the policy focus of this chapter and the need to distinguish regions by their levels of economic development, this chapter adopts regional definitions that are based on a combination of economic and geographic considerations. In particular, the chapter considers the following 10 regions: East Asia (China, Korea, Mongolia) (EAS); Economies in Transition (Eastern Europe and former Soviet Union) (EIT); Latin America and Caribbean (LAM); Middle East and North Africa (MNA); North America (USA, Canada) (NAM); Pacific Organisation for Economic Co-operation and Development (OECD)-1990 members (Japan, Australia, New Zealand) (POECD); South East Asia and Pacific (PAS); South Asia (SAS); sub-Saharan Africa (SSA); Western Europe (WEU). These regions can, with very minor deviations, readily be aggregated to regions used in scenarios and integrated models. They are also consistent with commonly used World Bank regional classifications, and can be aggregated into the geographic regions used by WGII. However, if dictated by the reviewed literature, in some cases other regional classifications are used. Regional cooperation initiatives define regions by membership of these ventures. The least-developed countries (LDC) region is orthogonal to the above regional definitions and includes countries from SSA, SAS, PAS, and LAM.

14.1.3 Sustainable development and mitigation capacity at the regional level

Sustainable development refers to the aspirations of regions to attain a high level of well-being without compromising the opportunities of future generations. Climate change relates to sustainable development because there might be tradeoffs between development aspirations and mitigation. Moreover, limited economic resources, low levels of technology, poor information and skills, poor infrastructure, unstable or weak institutions, and inequitable empowerment and access to resources compromise the capacity to mitigate climate change. They will also pose greater challenges to adapt to climate change and lead to higher vulnerability (IPCC, 2001).

Figure 14.1 shows that regions differ greatly in development outcomes such as education, human development, unemployment, and poverty. In particular, those regions with the lowest level of per capita emissions also tend to have the worst human development outcomes. Generally, levels of adult education (Figure 14.1b), life expectancy (Figure 14.1c), poverty, and the Human Development Index (Figure 14.1d) are particularly low in SSA, and also in LDCs in general. Unemployment (Figure 14.1a) is high in SSA, MNA, and EIT, also in LDCs, making employment-intensive economic growth a high priority there (Fankhauser et al., 2008).

The regions with the poorest average development indicators also tend to have the largest disparities in human development dimensions (Grimm et al., 2008; Harttgen and Klasen, 2011). In terms of income, LAM faces particularly high levels of inequality (Figure 14.1f). Gender gaps in education, health, and employment are particularly large in SAS and MNA, with large educational gender gaps also persisting in SSA. Such inequalities will raise distributional questions regarding costs and benefits of mitigation policies.

When thinking about inter-generational inequality (Figure 14.2b), adjusted net savings (i.e., gross domestic savings minus depreciation of physical and natural assets plus investments in education and minus damage associated with CO_2 emissions) is one way to measure whether societies transfer enough resources to next generations. As shown in Figure 14.2b, there is great variation in these savings rates. In several regions, including SSA, MNA, LAM, as well as LDCs, there are a number of countries where adjusted net savings are negative. Matters would look even worse if one considered that—due to substantial population growth—future generations are larger in some regions, considered a broader range of assets in the calculation of depreciation, or considered that only imperfect substitution is possible between financial savings and the loss of some natural assets. For these countries, maintenance of their (often low) living standards is already under threat. Damage from climate change might pose further challenges and thereby limit the ability to engage in costly mitigation activities.

14.1.3.1 The ability to adopt new technologies

Developing and adopting low-carbon technologies might be one way to address the mitigation challenge. However, the capacity to adopt new technologies, often referred to as absorptive capacity, as well as to develop new technologies, is mainly located in four regions: NAM, EAS, WEU, and POECD. This is also shown in Figure 14.2a, which plots high-technology exports as share of total manufactured exports. High-technology exports refer to products with high research and development intensity, such as in aerospace, computers, pharmaceuticals, scientific instruments, and electrical machinery. As visible in the figure, these exports are very low in most other regions, suggesting low capacity to develop and competitively market new technologies. Since most technological innovation happens in developed regions, technological spillovers could significantly increase the mitigation potential in developing regions.

While Section 13.9 discusses inter-regional technology transfer mechanisms, which could help foster this process, there is an emerging literature that looks at the determinants and precursors of successful technology absorption. Some studies have found that for energy technologies, the more technologically developed a country is, the more likely it is to be able to receive innovations (Verdolini and Galeotti, 2011; Dechezleprêtre et al., 2013). However, more recent work looking at a wider range of mitigation technologies finds that domestic technological development tends to crowd out foreign innovations (Dechezleprêtre et al., 2013). But the determinants of the receptivity of a host country or region go beyond the technological development of the receiving countries. Some of these aspects are relatively harder (or impossible) to influence with policy interventions such as the geographical distance from innovating countries (Verdolini and Galeotti, 2011) and linkages with countries with CO_2-efficient economies (Perkins and Neumayer, 2009). However, other aspects can be influenced such as institutional capacity (Perkins and Neumayer, 2012), and in particular the strength of intellectual property laws to protect incoming technologies (Dechezleprêtre et al., 2013).

Two further challenges for promoting mitigation in different regions are the costs of capital, which circumscribe the ability to invest in new low-

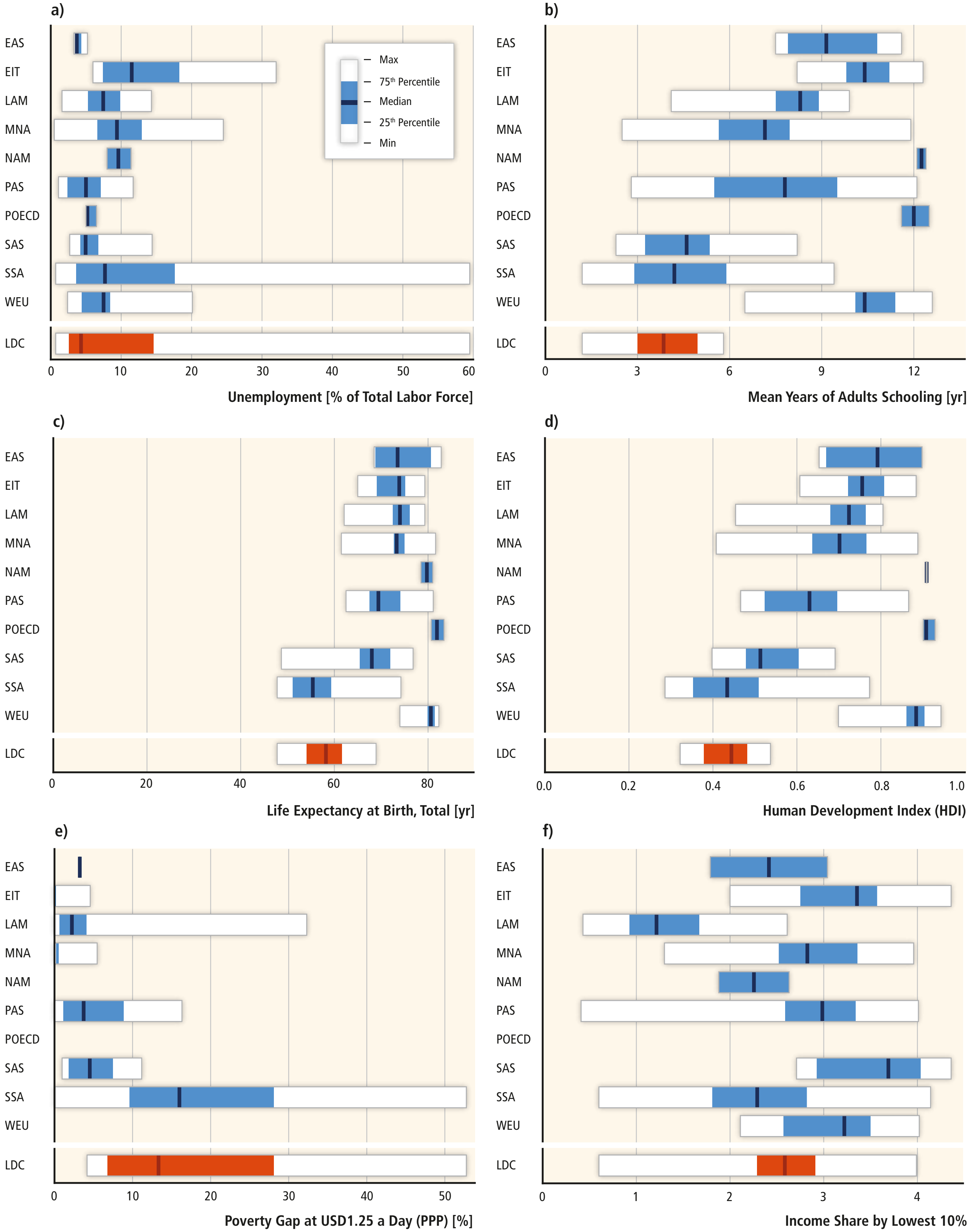


Figure 14.1 | Social provisions enabling regional capacities to embrace mitigation policies. Statistics refer to the year 2010 or the most recent year available. The red bar refers to Least Developed Countries (LDC). Source: UNDP (2010), World Bank (2011).

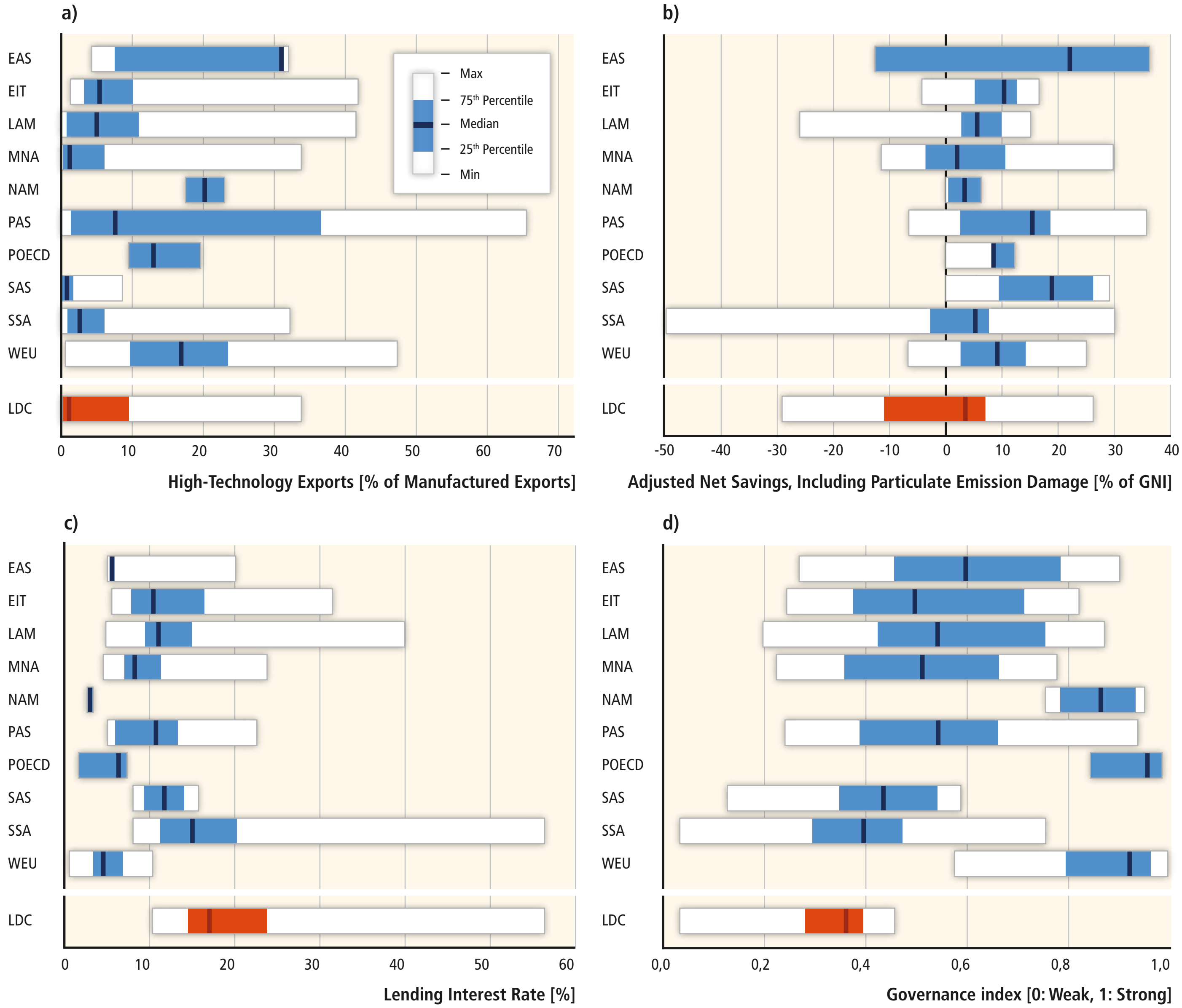


Figure 14.2 | Economic and governance indicators affecting regional capacities to embrace mitigation policies. Statistics refer to the year 2010 or the most recent year available. The red bar refers to Least Developed Countries (LDC). Source: UNDP (2010), World Bank (2011). Note: The lending interest rate refers to the average interest rate charged by banks to private sector clients for short- to medium-term financing needs. The governance index is a composite measure of governance indicators compiled from various sources, rescaled to a scale of 0 to 1, with 0 representing weakest governance and 1 representing strongest governance.

carbon technologies, and differences in governance. Figure 14.2 presents the lending interest rate (Figure 14.2c) to firms by region as well as the World Bank Governance index (Figure 14.2d). It shows that poorer regions face higher interest rates and struggle more with governance issues, both reducing the ability to effectively invest in a low-carbon development strategy.

Conversely, there are different regional opportunities to promote mitigation activities. As discussed by Collier and Venables (2012a), Africa has substantial advantages in the development of solar energy and hydropower. However, as these investments are costly in human and financial capital and depend on effective states and policies, these advantages may not be realized unless the financing and governance challenges discussed above are addressed.

In sum, differences in the level of economic development among countries and regions affect their level of vulnerability to climate change as well as their ability to adapt or mitigate (Beg et al., 2002). Given these regional differences, the structure of multi-national or multi-regional environmental agreements affects their chance of success (Karp and Zhao, 2010). By taking these differences into account, regional cooperation on climate change can help to foster mitigation that considers distributional aspects, and can help addressing climate-change impacts (Asheim et al., 2006). At the same time, disparities between and within regions diminish the opportunities that countries have to undertake effective mitigation policies (Victor, 2006).

14.2 Low-carbon development at the regional level: opportunities and barriers

There are great differences in the mitigation potential of regions. One way to assess these heterogeneities is through integrated models on the regional distribution of costs of mitigation pathways as well as regional modelling exercises that compare integrated model results for particular regions. The region-specific results are discussed in detail in Chapter 6 using a higher level of regional aggregation than adopted here (Section 6.3.6.4). They show that in an idealized scenario with a universal carbon price, where mitigation costs are distributed in the most cost-effective manner across regions, the macroeconomic costs of mitigation differ considerably by region. In particular, in OECD countries (including the regions WEU, NAM, and POECD), these costs would be substantially lower, in LAM they would be average, and in other regions they would be higher (Clarke et al., 2009; Tavoni et al., 2014). These differences are largely due to the following: First, energy and carbon intensities are higher in non-OECD regions, leading to more opportunities for mitigation, but also to higher macroeconomic costs. Second, some developing regions face particularly attractive mitigation options (e.g., hydropower or afforestation) that would shift mitigation there. Third, some developing regions, and in particular countries exporting fossil energy (which are concentrated in MNA, but include countries in other regions as well), would suffer negative terms of trade effects as a result of aggressive global mitigation policies, thus increasing the macroeconomic impact of mitigation (see also Section 14.4.2). The distribution of these costs could be adjusted through transfer payments and other burden sharing regimes. The distribution of costs would shift towards OECD countries, if there was limited participation among developing and emerging economies (de Cian et al., 2013).

One should point out, however, that these integrated model results gloss over many of the issues highlighted in this chapter, including the regional differences in financial, technological, institutional, and human resource capacities that will make the implementation of such scenarios very difficult.

As many of the region-specific opportunities and barriers for low-carbon development are sector-specific, we will discuss them in the relevant sectoral sub-sections in Section 14.2.

14.3 Development trends and their emission implications at the regional level

14.3.1 Overview of trends in GHG emissions and their drivers by region

Global GHG emissions have increased rapidly over the last two decades (Le Quéré et al., 2009, 2012). Despite the international financial and economic crisis, global GHG emissions grew faster between 2000 and 2010 than in the previous three decades (Peters et al., 2012b). Emissions tracked at the upper end of baseline projections (see Sections 1.3 and 6.3) and reached around 49–50 $GtCO_2eq$ in 2010 (JRC/PBL, 2013; IEA, 2012a; Peters et al., 2013). In 1990, EIT was the world's highest emitter of GHG emissions at 19 % of global total of 37 $GtCO_2eq$, followed by NAM at 18 %, WEU at 12 %, and EAS at 12 %, with the rest of the world emitting less than 40 %. By 2010, the distribution had changed remarkably. The EAS became the major emitter with 24 % of the global total of 48 $GtCO_2eq$ (excluding international transport) (JRC/PBL, 2013; IEA, 2012a). The rapid increase in emissions in developing Asia was due to the region's dramatic economic growth and its high population level.

Figure 14.3 shows the change in GHG emissions in the 10 regions (and additionally reporting for LDC including countries from several regions) over the period from 1990 to 2010, broken down along three drivers: Emissions intensity (emissions per unit of gross domestic product (GDP)), GDP per capita, and population. As shown in the figure, the most influential driving force for the emission growth has been the increase of per capita income. Population growth also affected the emission growth but decreases of GHG emission intensities per GDP contributed to lowering the growth rate of GHG emissions. These tendencies are similar across regions, but with notable differences. First, the magnitude of economic growth differed greatly by region with EAS showing by far the highest growth in GDP per capita, leading to the highest growth in emissions in the past 20 years; stagnating incomes in POECD contributed to low growth in emissions. Second, falling population levels in EIT contributed to lower emissions there. Third, improvements in the emission intensity were quantitatively larger than the increases in emissions due to income growth in all richer regions (WEU, POECD, NAM, and EIT), while the picture is more mixed in developing and emerging regions. Note also that in LDCs emissions were basically flat with improvements in emission intensity making up for increases in GDP and population.

Other ways to look at heterogeneity of regional GHG emissions are relative to the size of the total population, the size of the overall economy and in terms of sources of these emissions. These perspectives are shown in the two panels of Figure 14.4. In 2010, NAM, EIT, POECD, and WEU, taken together, had 20 % of the world's population, but accounted for 39 % of global GHG emissions, while other regions

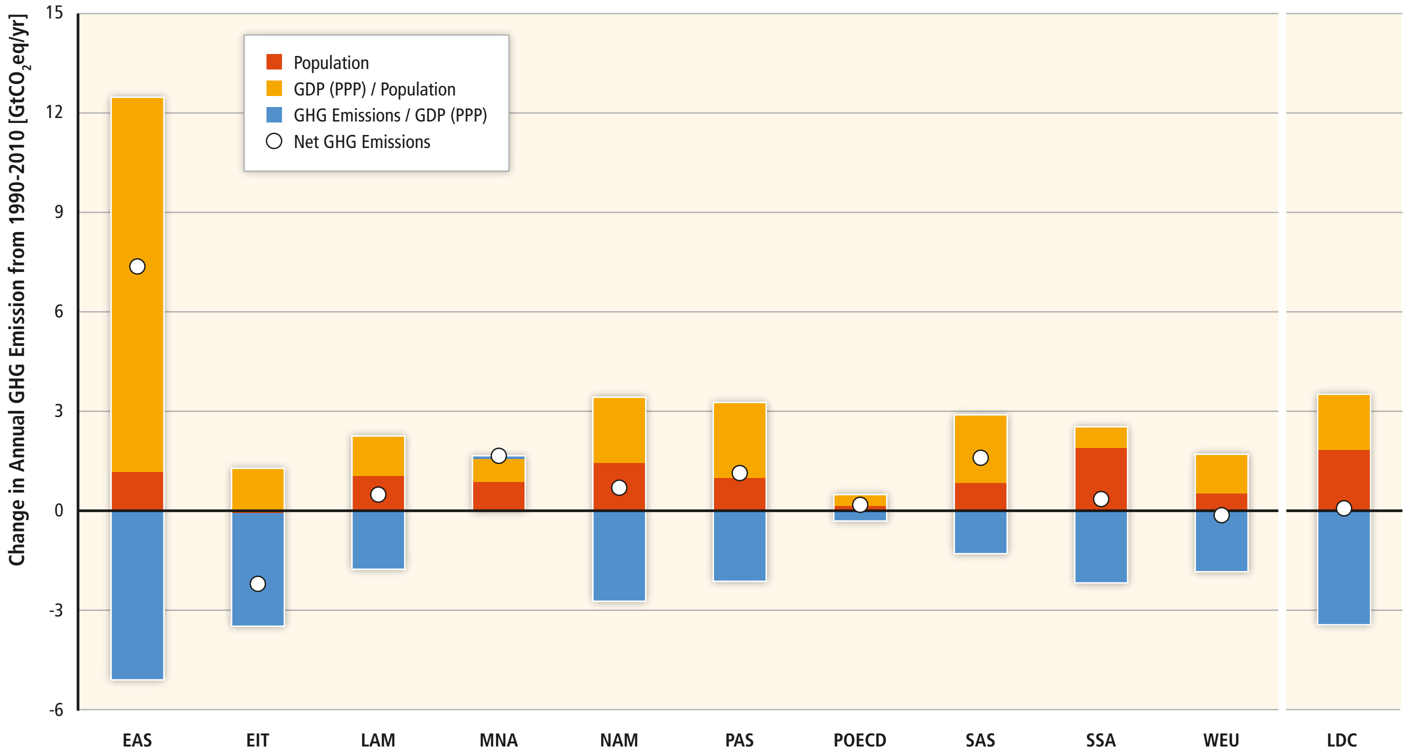


Figure 14.3 | Decomposition of drivers for changes in total annual GHG emissions (excluding international transport) in different world regions from 1990–2010 (Logarithmic Mean Divisia Index (LMDI) method according to Ang, 2004). The white dots indicate net changes of GHG emissions from 1990 to 2010, and the bars, which are divided by three colours, show the impacts on GHG emission changes resulting from changes in population, GDP per capita, and GHG emission per GDP. For example, the white dot for EAS shows its emission increased by 7.4 Gt CO_2eq, and the influence of the three driving factors are 1.2, 11, and −5.1 $GtCO_2$eq, which are indicated by red, yellow, and blue bars, respectively. Data sources: GHG emission data (in CO_2eq using 100-year GWP values) from JRC/PBL (2013) and IEA (2012a), see Annex II.9; GDP (PPP) [Int$2005] from World Bank (2013a); and population data from United Nations (2013).

with 80 % of population accounted for 61 % of global emissions (Figure 14.4). The contrast between the region with the highest per capita GHG emissions (NAM) and the lowest (SAS) is more pronounced: 5.0 % of the world's population (NAM) emits 15 %, while 23 % (SAS) emits 6.8 %. One of the important observations from Figure 14.4 (top panel) is that some regions such as SSA and PAS have the lowest levels of per capita emissions of CO_2 from non-forestry sources, but they have GHG emissions per capita that are comparable to other regions due to large emissions from land-use change and other non-CO_2 GHG emissions.

The cumulative distribution of emissions per GDP (emission intensity) shows a strikingly different picture (Figure 14.4 bottom panel). The four regions with highest per capita emissions, NAM, EIT, POECD, and WEU, have the lowest GHG emission intensities (emission per GDP), except EIT. Some regions with low per capita emissions, such as SSA and PAS, have high emission intensities and also highest share of forestry-related emissions. This shows that a significant part of GHG-reduction potential might exist in the forest sector in these developing regions (see Chapter 11).

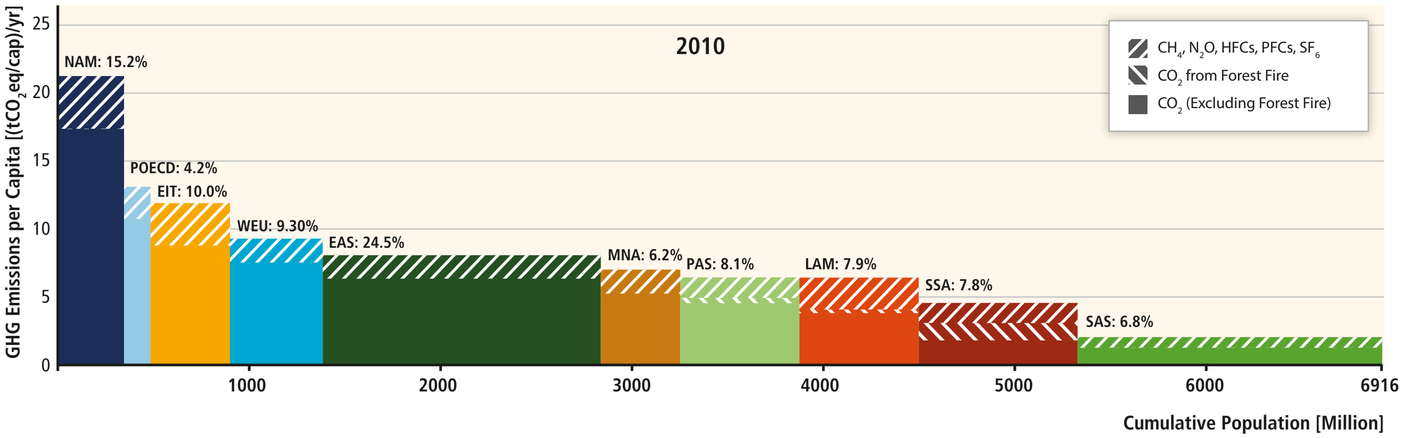
14.3.2 Energy and development

14.3.2.1 Energy as a driver of regional emissions

Final energy consumption is growing rapidly in many developing countries. Consequently, energy-related CO_2 emissions in developing country regions such as EAS, MNA, and PAS in 2010 were more than double the level of 1990, while the CO_2 emission in EIT decreased by around 30 % (Figure 14.5). The composition of energy consumption also varies by region. Oil dominates the final energy consumption in many regions such as NAM, POECD, WEU, LAM, and MNA, while coal has the highest share in EAS. The share of electricity in final energy consumption has tended to grow in all regions.

When looking at trends in CO_2 emissions by source (see Figure 14.5), the largest growth in total CO_2 emissions between 1990 and 2010 has come from coal, followed by gas and oil. In this period, CO_2 emissions from coal grew by 4.4 $GtCO_2$ in EAS, which is equivalent to roughly half of the global net increase of CO_2 emissions from fossil fuel combustion.

These observations are in line with findings in the literature emphasizing the transformation of energy use patterns over the course of eco-



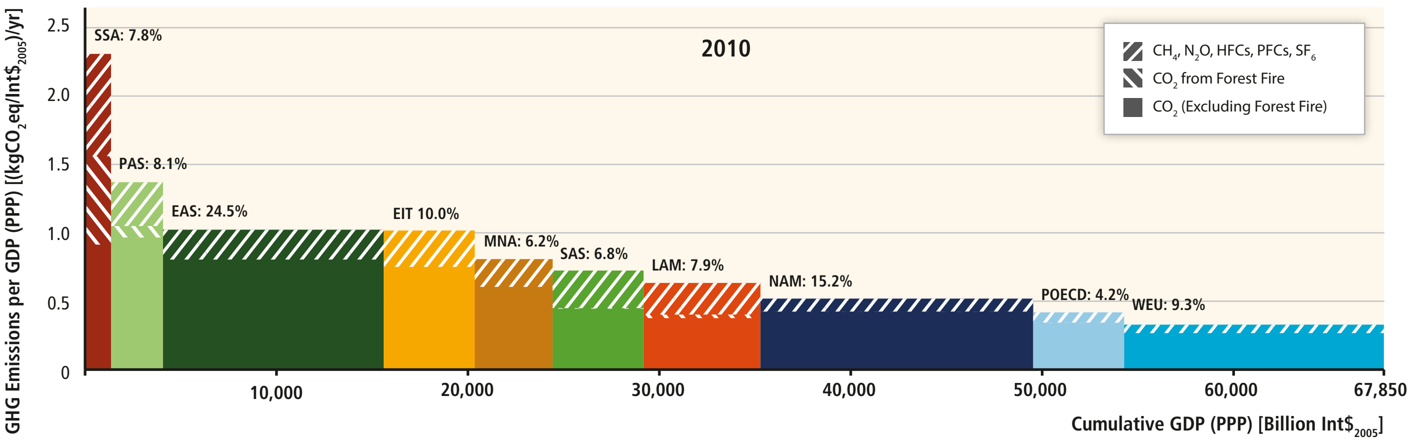


Figure 14.4 | Distribution of regional GHG emissions (excluding international transport) in relation to population and GDP: cumulative distribution of GHG emissions per capita (top panel) and GDP (bottom panel). The percentages in the bars indicate a region's share in global GHG emissions. Data sources: GHG emission data (in CO_2eq using 100-year GWP values) from JRC/PBL (2013) and IEA (2012a), see Annex II.9; GDP (PPP) [Int$2005] from World Bank (2013a); and population data from United Nations (2013).

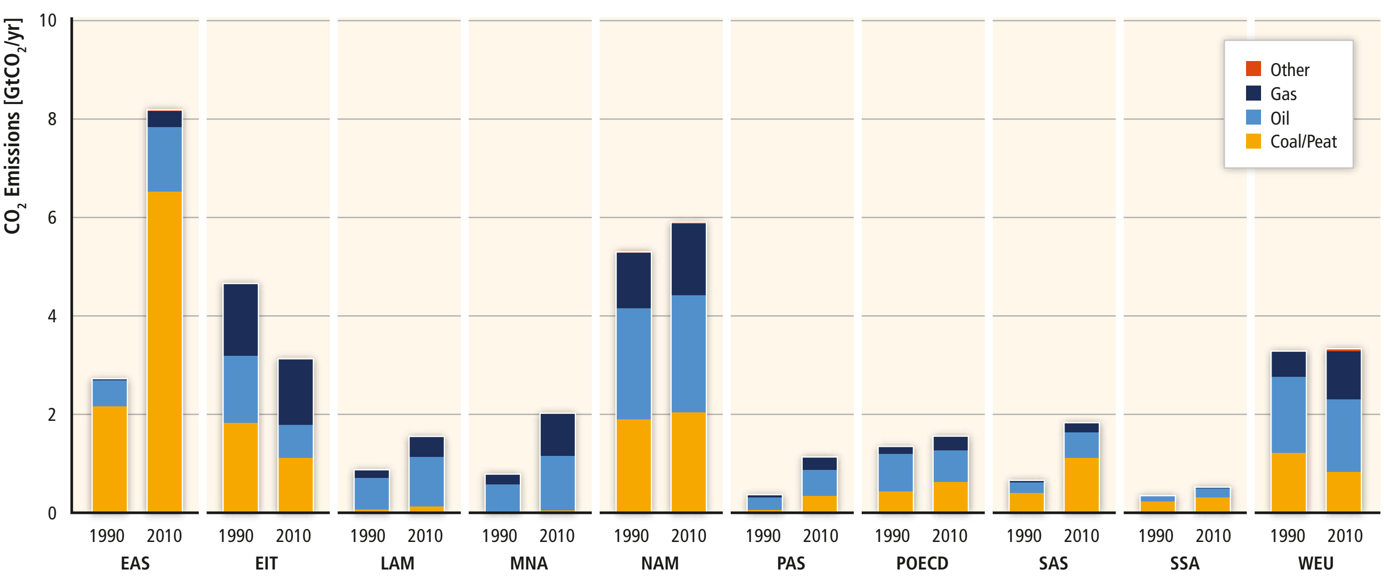


Figure 14.5 | CO_2 emissions by sources and regions. Data source: IEA (2012a).

nomic development from traditional biomass to coal and liquid fuel and finally natural gas and nuclear energy (Smil, 2000; Marcotullio and Schulz, 2007; Krausmann et al., 2008). Similar transitions in energy use are also observed for the primary energy carriers employed for electricity production (Burke, 2010) and in household energy use (Leach, 1992; Barnes and Floor, 1996).

Due to its role in global emissions growth since 1990, it is worthwhile to look a little deeper into the underlying drivers for emissions in EAS, which have been increased by nearly 8 $GtCO_2eq$ between 1990 and 2010. The major part of the increase has been witnessed in the years after 2002 (Minx et al., 2011). Efficiency gains and technological progress particularly in energy-intensive sectors that had a decreasing effect on emissions (Ma and Stern, 2008; Guan et al., 2009; Zhao et al., 2010) were overcompensated by increasing effects of structural changes of the Chinese economy after 2002 (Liao et al., 2007; Ma and Stern, 2008; Guan et al., 2009; Zhao et al., 2010; Minx et al., 2011; Liu et al., 2012a). Looking at changes from 2002 to 2005, Guan et al. (2009) find manufacturing, particularly for exports (50 %) as well as capital formation (35 %) to be the most important drivers from the demand side. Along with an increasing energy intensity of GDP, Steckel et al. (2011) identify a rising carbon intensity of energy, particularly driven by an increased use of coal to have contributed to rapid increase in emissions in the 2000s.

Table 14.1 | Access to electricity in 2009

	Population with Access (%)	Population Lacking Access (millions)
Latin America and Caribbean	93.4	30
North America	*100.0*	*0*
East Asia	97.8	29
Western Europe	*100.0*	*0*
POECD	*100.0*	*0*
Sub-Saharan Africa	32.4	487
Middle East and North Africa	93.7	23
South Asia	62.2	607
Economies in Transition	*100.0*	*0*
South East Asia and Pacific	74.3	149
Total	**79.5**	**1330**

Note: Information missing for several small islands, Mexico, Puerto Rico, Suriname, Hong Kong SAR (China), North Korea, Macao SAR (China), Burundi, Cape Verde, Central African Republic, Chad, Equatorial Guinea, Gambia, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Rwanda, Sierra Leone, Somalia, South Sudan, Swaziland, Djibouti, Malta, Turkey, West Bank and Gaza, Bhutan. For OECD and EIT, no data are listed but presumed to be 100 % access; these are recorded in italics. Source: World Bank (2012).

Figure 14.6 shows the relationship between GHG emissions and per capita income levels. Individual regions have different starting levels, directions, and magnitudes of changes. Developed regions (NAM, WEU, POECD) appear to have grown with stable per capita emissions in the last two decades, with NAM having much higher levels of per capita emissions throughout (Figure 14.6 top panel). Carbon intensities of GDP tended to decrease constantly for most regions as well as for the globe (Figure 14.6 bottom panel).

Despite rising incomes and rising energy use, lack of access to modern energy services remains a major constraint to economic development in many regions (Uddin et al., 2006; Johnson and Lambe, 2009; IEA, 2013). The energy access situation is acute in LDCs (Chaurey et al., 2012) but likely to improve there and in other parts of the world in coming decades (Bazilian et al., 2012a). Of the world's 'energy poor'[1], 95 % live in Asia and SSA (Rehman et al., 2012).

About 1.2–1.5 billion people—about 20 % of the global population—lacked access to electricity in 2010 (IEA, 2010a, 2012b; World Bank, 2012; Pachauri et al., 2012, 2013; Sovacool et al., 2012; Sustainable Energy for All, 2013) and nearly 2.5–3.0 billion—about 40 % of the global population—lack access to modern cooking energy options (Zerriffi, 2011; IEA, 2012b; Pachauri et al., 2012; Sovacool et al., 2012; Rehman et al., 2012; Sustainable Energy for All, 2013). There is considerable regional variation as shown in Table 14.1, with electricity access being particularly low in SSA, followed by SAS.

The lack of access to electricity is much more severe in rural areas of LDCs (85 %) and SSA (79 %) (IEA, 2010b; Kaygusuz, 2012). In developing countries, 41 % of the rural population does not have electricity access, compared to 10 % of the urban population (UNDP, 2009). This low access to electricity is compounded by the fact that people rely on highly polluting and unhealthy traditional solid fuels for household cooking and heating, which results in indoor air pollution and up to 3.5 million premature deaths in 2010—mostly women and children; another half-million premature deaths are attributed to household cooking fuel's contribution to outdoor air pollution (Sathaye et al., 2011; Agbemabiese et al., 2012) (Lim et al., 2012); see Section 9.7.3.1 and WGII Section 11.9.1.3). Issues that hinder access to energy include effective institutions (Sovacool, 2012b), good business models (e. g., ownership of energy service delivery organizations and finance; Zerriffi, 2011), transparent governance (e. g., institutional diversity; Sovacool, 2012a) and appropriate legal and regulatory frameworks (Bazilian et al., 2012b; Sovacool, 2013). Despite these factors, universal access to energy services by 2030 is taking shape (Hailu, 2012).

1 'Energy poor' population is defined as population without electricity access and/or without access to modern cooking technologies (Rehman et al., 2012).

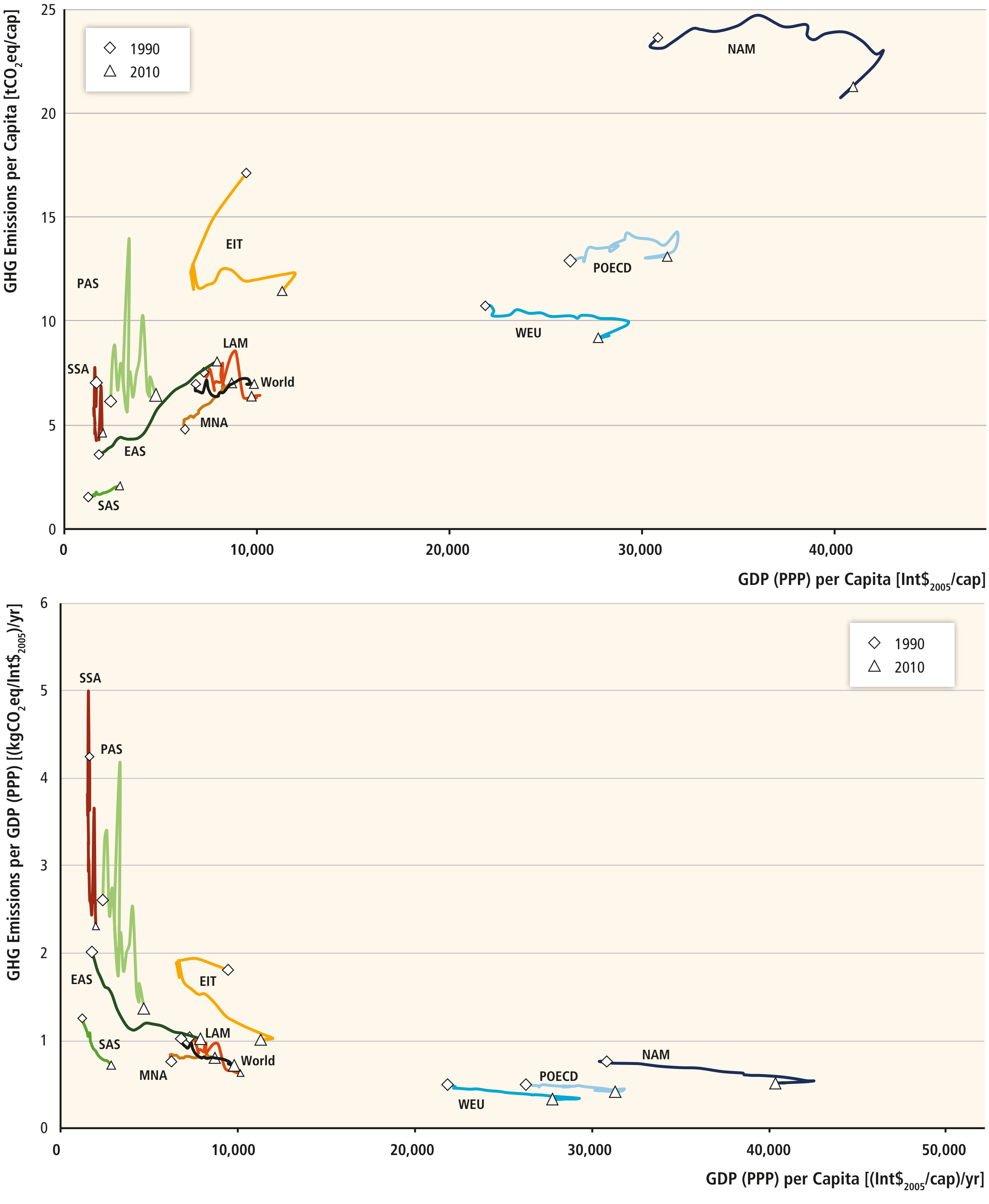


Figure 14.6 | Relationship between GHG emissions per capita and GDP per capita (top panel), and GHG emissions per GDP and GDP and per capita (bottom panel) (1990–2010). Data sources: GHG emission data (in CO_2eq using 100-year GWP values) from JRC/PBL (2013) and IEA (2012a), see Annex II.9; GDP (PPP) from World Bank (2013a); and population data from United Nations (2013).

14.3.2.2 Opportunities and barriers at the regional level for low-carbon development in the energy sector

The regional differences in opportunities and challenges for low-carbon development in the energy sector described above arise due to patters of energy production and use, the local costs and capital investment needs of particular energy technologies, as well as their implications for regulatory capacity (Collier and Venables, 2012b).The choice of present and future energy technologies depends on the local costs of technologies. Local prices indicate the opportunity cost of different inputs. While in some regions diverting resources from other productive uses to climate change mitigation has a high opportunity cost, in others the cost is lower.

Local costs mainly depend on two factors. First, they depend on the natural advantage of the region. An abundant endowment will tend to reduce the local price of resources to the extent that they are not freely traded internationally. Trade restrictions may be due to high transport costs or variability of the resource price, which reduces the return to exports and thereby the opportunity cost of using the resource domestically.

Second, local costs depend on the capital endowment of the region. Capital includes the accumulated stocks of physical capital and the financial capital needed to fund investment, the levels of human capital and skills, and the institutional and governance capacity required to implement and regulate economic activity. As shown in Section 14.1.3, developing regions are, to varying degrees, scarce in all of these types of capital. Borrowing costs for developing countries are high, education and skill levels are a serious constraint, and lack of government regulatory capacity creates barriers (a high shadow price) on running large-scale or network investments.

A number of features of energy production interact with local costs and thereby determine the extent of uptake of particular technologies in different regions. In general, the high capital intensity of many renewable technologies (IEA, 2010c) makes them relatively more expensive in many capital and skill-scarce developing economies (Strietska-Ilina, 2011). Different energy generation technologies also use different feedstock, the price of which depends upon their local availability and tradability; for example, coal-based electricity generation is relatively cheap in countries with large coal resources (Heptonstall, 2007).

Many power generation technologies, in particular nuclear and coal, but also large hydropower, create heavy demands on regulatory capacity because they have significant-scale economies and are long-lived projects. This has several implications. The first is that projects of this scale may be natural monopolies, and so need to be undertaken directly by the state or by private utilities that are regulated. Large-scale electricity systems have been ineffective in regions that are scarce in regulatory capacity, resulting in under-investment, lack of maintenance, and severe and persistent power shortages (Eberhard et al., 2011). The second implication of scale is that a grid has to be installed and maintained. As well as creating a heavy demand for capital, this also creates complex regulatory and management issues. This problem can be less severe in the cases where off-grid electrification or small-scale energy local energy systems (such as mini-hydro) are feasible and economically advantageous; but even in such cases, local institutional, financial, and regulatory capacity to build and maintain such facilities are a challenge in places where such capacity is low (see Chapter 7).

Third, if scale economies are very large, there are cross-border issues. For example, smaller economies may have difficulty agreeing on and/or funding cross-border power arrangements with their neighbors (see Section 14.4). Several studies have examined the use of roadmaps to identify options for low-carbon development (Amer and Daim, 2010), with some taking a regional focus. For example, a study by Doig and Adow (2011) examines options for low-carbon energy development across six SSA countries. More common are studies examining low-development roadmaps with a national focus, such as a recent study that explores four possible low-carbon development pathways for China (Wang and Watson, 2008).

Regional modelling exercises have also examined different mitigation pathways in the energy sector in different regions. For example, the Stanford Energy Modeling Forum (EMF)28, which focuses on mitigation pathways for Europe suggests that transformation pathways will involve a greater focus on a switch to bioenergy for the whole energy system and a considerable increase of wind energy in the power system until 2050 that catches up with nuclear, while solar PV is only of limited importance (Knopf et al., 2013). By contrast, in the Asian Modeling Exercise (AME) for Asia it will involve a greater switch to natural gas with carbon dioxide capture and storage (CCS) and solar (van Ruijven et al., 2012).

Studies that examine potentials for low-carbon development within different locations frequently focus on specific technologies and their opportunities in a specific context. For example, there are several studies on low-carbon technology potential in SSA that focus on biomass (Marrison and Larson, 1996; Hiemstra-van der Horst and Hovorka, 2009; Dasappa, 2011) and solar energy technologies (Wamukonya, 2007; Munzhedzi and Sebitosi, 2009; Zawilska and Brooks, 2011). However, other technologies have perhaps less clear regional advantages, including biofuels, which have been widely studied not just for use in Brazil or in Latin America (Goldemberg, 1998; Dantas, 2011; Lopes de Souza and Hasenclever, 2011) but also in South East Asia (focusing on Malaysia) (Lim and Teong, 2010) and in OECD countries (Mathews, 2007). Wind energy also has a wider geographic focus, with studies ranging from East and South Asia (Lema and Ruby, 2007; Lewis, 2007, 2011) to South America (Pueyo et al., 2011), and the Middle East (Gökçek and Genç, 2009; Keyhani et al., 2010; Ilkılıç et al., 2011). Examinations of geothermal energy and hydropower potential are likewise geographically diverse (Hepbasli and Ozgener, 2004; Alam

Zaigham et al., 2009; Kusre et al., 2010; Guzović et al., 2010; Kosnik, 2010; Fang and Deng, 2011).

Many developing regions are latecomers to large-scale energy production. While developed regions have sunk capital in irreversible investments in power supply, transport networks, and urban structures, many developing countries still need to do so. This creates a latecomer advantage, as developing countries will be able to use the new and more-efficient technologies that will be available when they make these investments. However, being a latecomer also implies that there are current energy shortages, a high shadow price on power, and an urgent need to expand capacity. Further delay in anticipation of future technical progress is particularly expensive (Collier and Venables, 2012b).

While the opportunities for switching to low-carbon development in different regions are circumscribed by capacity in poorer countries or lock-in effects in richer countries, there are low-cost options for reducing the carbon-intensity of the economies through the removal of energy subsidies and the introduction of energy taxes. Energy subsidy levels vary substantially by region (IEA, 2012; OECD, 2012; IMF, 2013). Pre-tax consumption subsidies compare the consumer price to a world price for the energy carrier, which may be due to direct price subsidies, subsidies to producers leading to lower prices, or low production costs for energy producers, relative to world market prices. Note that pre-tax figures therefore do not correspond to the actual fiscal outlays of countries to subsidize energy. In particular, for energy exporters, the domestic costs of production might be lower than the world market price and therefore a lower domestic price represents a lower fiscal outlay compared to an energy importer who pays world market prices (IEA, OECD, OPEC, and World Bank, 2010). Nevertheless, pre-tax figures represent the opportunity costs to these energy exporters (IEA, OPEC, OECD; and World Bank, 2011). An IMF policy paper (2013), reports that in MNA as well as EIT, pre-tax energy subsidies are very high as a share of GDP. Also in SAS, energy subsidies are substantial, and there are also some subsidies in LAM and SSA where they are concentrated among fuel exporters (IMF, 2013). Similar data on pre-tax subsidies is available from the International Energy Agency (IEA) for a reduced set of countries. These data confirm the regional distribution of pre-tax energy subsidies, particularly their high level in MNA and EIT (IEA, 2012c).

The OECD (2012) provides an inventory of various direct budgetary transfers and reported tax expenditures that support fossil fuel production or use in OECD countries. The OECD report finds that between 2005 and 2011, these incentives tended to benefit crude oil and other petroleum products (70 % in 2011) more than coal (12 %) and natural gas (18 %) in absolute terms (OECD, 2012).

Reducing energy subsidies would reduce the carbon-intensity of growth and save fiscal resources. A report prepared for the Group of Twenty Finance Ministers (G20) (IEA, OECD, OPEC, and World Bank, 2011) not only reports data on fossil fuel and other energy-support measures, but also draws some lessons on subsidy reform. It concludes that three of the specific challenges facing developing countries are strengthening social safety nets and improving targeting mechanisms for subsidies; informing the public and implementing social policy or compensatory measures; and implementing the reform in the context of broader energy sector reform (IEA, OECD, OPEC, and World Bank, 2011).This issue, as well as the political economy of fuel subsidies and fuel taxation, is discussed in more detail in Section 15.5.

14.3.3 Urbanization and development

14.3.3.1 Urbanization as a driver of regional emissions

Urbanization has been one of the most profound socioeconomic and demographic trends during the past decades, particularly in less-urbanized developed regions (UNDESA, 2010), see Section 12.2. Accompanying the changes in industrial structure and economic development, urbanization tends to increase fossil fuel consumption and CO_2 emissions at the global level (Jones, 1991; York et al., 2003; Cole and Neumayer, 2004; York, 2007; Liddle and Lung, 2010). Studies of the net impact of urbanization on energy consumption based on historical data suggest that—after controlling for industrialization, income growth and population density—a 1 % of increase in urbanization increases energy consumption per unit of GDP by 0.25 % (Parikh and Shukla, 1995) to 0.47 % (Jones, 1991), and increases carbon emissions per unit of energy use by 0.6 % to 0.75 % (Cole and Neumayer, 2004).

However, the impact of urbanization on energy use and carbon emissions differs remarkably across regions and development level (Poumanyvong and Kaneko, 2010; Martínez-Zarzoso and Maruotti, 2011; Poumanyvong et al., 2012). For instance, LAM has a similar urbanization level as NAM and WEU, but substantially lower per capita CO_2 emissions because of its lower-income level (World Bank, 2013b). In SSA, the per capita carbon emissions remained unchanged in the past four decades (JRC/PBL, 2013; IEA, 2012a), while the urbanization level of the region almost doubled (UNDESA, 2011). This is because in SSA the rapid urbanization was not accompanied by significant industrialization and economic growth, the so-called 'urbanization without growth' (Easterly, 1999; Haddad et al., 1999; Fay and Opal, 2000; Ravallion, 2002).

On the one hand, per capita energy use of developing countries is significantly lower than in developed countries (Figure 14.7 left panel). On the other hand, per capita energy use of cities in developing regions is usually higher than the national average, while the relationship is reversed in developed regions (Kennedy et al., 2009; Grübler et al., 2012). This is because in developing countries industrialization often happens through manufacturing in cities, while developed regions have mostly completed the industrialization process. Moreover, urban residents of developing regions usually have higher-income and energy-consumption levels than their rural counterparts (see Section 12.3.2 for a more-detailed discussion). This is particularly true in developing

Asia. In contrast, many cities in SSA and LAM have lower than national average per capita energy use because of the so-called 'urbanization of poverty' (Easterly, 1999; Haddad et al., 1999; Fay and Opal, 2000; Ravallion, 2002). Other studies reveal an inverted-U shape between urbanization and CO_2 emissions among countries of different economic development levels. One study suggests that the carbon emissions elasticity of urbanization is larger than 1 for the low-income group, 0.72 for the middle-income group, and negative (or zero) for the upper-income group of countries (Martínez-Zarzoso and Maruotti, 2011).

Per capita energy consumption in cities of developing countries is shown to be generally lower (Figure 14.7 left panel). At the same time, studies reveal that cities in developing regions have significantly higher energy intensity than cities in developed regions (Figure 14.7 right panel). Still, the majority of cities in both developed and developing countries (two-thirds in developed region and more than 60 % in developing regions) have lower than national average energy intensity. Important factors that contribute to the varying energy intensities across cities are the different patterns and forms of urban settlements (Glaeser and Kahn, 2010; Grübler and Fisk, 2012; see Section 12.3.2 for a detailed discussion). Comparative analyses indicate that United States cities consume 3.5 times more per capita energy in transportation than their European counterparts (Steemers, 2003) because the latter are five times as dense as the former and have significantly higher car ownership and average distance driven (Kahn, 2000). Suburbanization in the United States may also contribute to increasing residential fuel consumption and land-use change (Bento et al., 2005). See Section 12.4 for a more-detailed discussion on urban form as a driver for emissions.

14.3.3.2 Opportunities and barriers at the regional level for low-carbon development in urbanization

Urbanization has important implications for global and regional mitigation challenges and opportunities. Many developing regions are projected to become more urbanized, and future global population growth will almost entirely occur in cities of developing regions (IIASA, 2009; UNDESA, 2011) (see Section 12.1). Due to their early stage of urbanization and industrialization, many SSA and Asian countries will inevitably increase energy consumption and carbon emissions, which may become a barrier for these regions to achieve mitigation goals. Assuming that the historical effect of urbanization on energy use and carbon emissions remains unchanged, the doubling of current urbanization levels by 2050 in many low-urbanized developing countries (such as India) implies 10–20 % more energy consumption and 20–25 % more

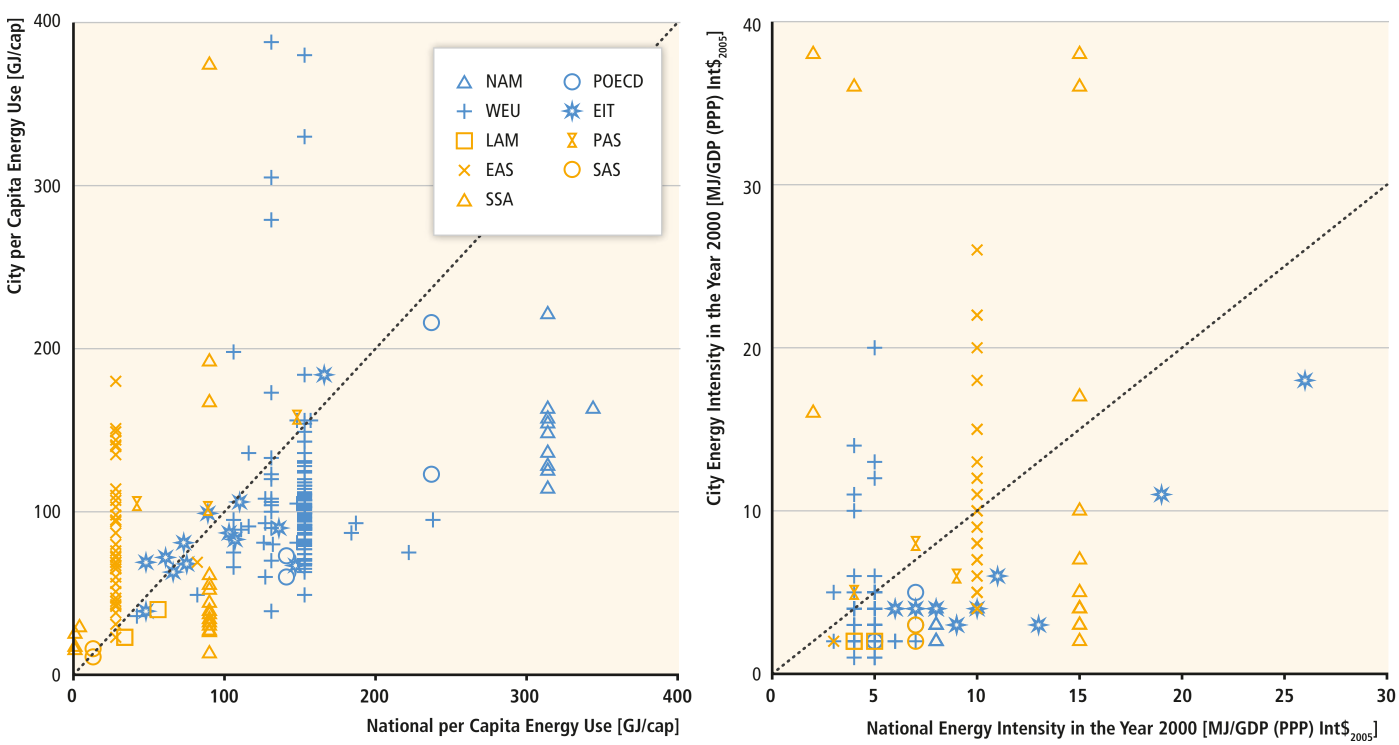


Figure 14.7 | Per capita energy use (left panel), and energy intensity in cities compared with the national average by regions (right panel), in the year 2000. The per capita energy use of cities, represented by a dot above the green line, is higher than the national average; otherwise, is lower than the national average. Data sources: (1) city energy data is from Grübler et al. (2012); (2) national energy data is from IEA energy balances (IEA, 2010d).

CO_2 emissions (Jones, 1991). On the other hand, because they are still at an early stage of urbanization and face large uncertainty in future urban development trends (O'Neill et al., 2012), these regions have great opportunities to develop energy-saving and resource-efficient urban settlements. For instance, if the African and Asian population increasingly grow into compact cities, rather than sprawl suburban areas, these regions have great potential to reduce energy intensity while proceeding urbanization.

An integrated and dynamic analysis reveals that if the world follows different socioeconomic, demographic, and technological pathways, urbanization may result in very different emission levels (O'Neill et al., 2010). The study compares the net contributions of urbanization to total emissions under the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios SRES A2 and B2 scenarios (Nakicenovic and Swart, 2000). Under the A2 scenario, the world is assumed to be heterogeneous, with fast population growth, slow technological changes and economic growth. If all regions follow the urbanization trends projected by the United Nations (UN) Urbanization Prospects (UNDESA, 2006), extrapolated up to 2100 by Grübler et al. (2007), the global total carbon emissions in 2100 increase by 3.7 GtC per year due to the impacts of urbanization growth (Figure 14.8). In a B2 world, which assumes local solutions to economic, social, and environmental sustainability issues, with continuous population growth and intermediate economic development, and faster improvement in environmentally friendly technology, the same urbanization trend generates a much smaller impact (1.1 GtC per year in 2100) on global total carbon emissions. Considering the differences in total emissions under different scenarios, the relative change in emissions due to urbanization under B2 scenarios (12 %) is also significantly lower than under A2 scenarios (15 %). Comparing the impacts in different regions, the 1.1 GtC per year more global total emissions due to urbanization under the B2 scenario is mostly due to East Asia, SAS and other less urbanized developing regions. Moreover, the relative changes in regional emissions due to urbanization are also very significant in EAS (27 %), SAS (24 %), and SSA, MNA, and PAS (15 %), considerably higher than in other regions (< 10 %). Therefore, a growing urban population in developing regions will inevitably pose significant challenges to global mitigation. Moreover, it also has important implications for adaption. However, urban climate change mitigation policies and strategies can have important co-benefits by reducing the urban heat island effect (see Section 12.8.4).

14.3.4 Consumption and production patterns in the context of development

As discussed in Section 5.4, the difference between production and consumption accounting methods are that the former identifies the place where emissions occur and the latter investigates emissions discharged for the goods and services consumed within a certain geographic area.

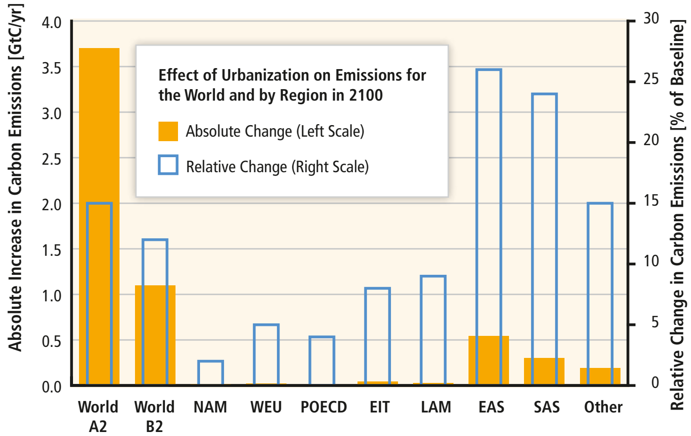


Figure 14.8 | Impact of urbanization on carbon emissions in 2100 for the world under SRES A2 and B2 scenarios and by regions only under SRES B2 scenario. This figure is based on O'Neill et al. (2010), data for NAM from the United States, POECD from Japan, EIT from Russia, LAM from Mexico and Brazil, EAS from China, SAS from India, and other from Indonesia. The urbanization scenario follows UN Urbanization Prospects (UNDESA, 2006), extrapolated up to 2100 by Grübler et al. (2007). The effect of urbanization on emissions for the world and by region is shown in absolute and relative terms.

14.3.4.1 Consumption as a driver of regional emissions growth

Researchers have argued that the consumption-based accounting method (Peters, 2008) provides a better understanding of the common but differentiated responsibility between regions in different economic development stages (Peters and Hertwich, 2008; Davis and Caldeira, 2010; Peters et al., 2011; Steinberger et al., 2012; Lenzen et al., 2012). Consequently, much research effort has been focused on estimating (1) country-level CO_2 emissions from both production and consumption perspectives (Kondo et al., 1998; Lenzen, 1998; Peters and Hertwich, 2006; Weber and Matthews, 2007; Peters et al., 2007; Nansai et al., 2008; Weber et al., 2008; Guan et al., 2009; Baiocchi and Minx, 2010); and (2) the magnitude and importance of international trade in transferring emissions between regions (Davis and Caldeira, 2010; Peters et al., 2012b; Wiebe et al., 2012). Reviews of modelling international emission transfers are provided by Wiedmann et al. (2007), Wiedmann (2009), Peters et al. (2012a), and Tukker and Dietzenbacher (2013).

During the period 1990–2008, the consumption emissions of EAS and SAS grew by almost 5–6 % annually from 2.5 to 6.5 $GtCO_2$ and from 0.8 to 2.0 $GtCO_2$, respectively. The other developing regions observed a steadier growth rate in consumption emissions of 1–2.5 % per year. This growth is largely driven by flourishing global trade, especially trade between developing countries. The transfer of emissions via traded products between developing countries grew at 21.5 % annually during 1990–2008 (Peters et al., 2011).

While per capita consumption emissions in developed regions are far larger than the average level of developing countries, many high-income households in large developing countries (e. g., China and India) are similar to those in developed regions (Feng et al., 2009;

Hubacek et al., 2009). Along with the rapid economic developments and lifestyle changes in Asia, average consumption emissions have increased 72 %, 74 %, and 120 % in PAS, SAS, and EAS, respectively, and the growth is projected to be further accelerating (Hubacek et al., 2007; Guan et al., 2008). Per capita consumption emissions in LDCs have changed relatively little, due to minimal improvements in lifestyle. In fact, per capita consumption emission in SSA has slightly decreased from 0.63 tCO_2 to 0.57 tCO_2 (Peters et al., 2011).

Methodologies, datasets, and modelling techniques vary between studies, producing uncertainties of estimates of consumption-based emissions and measures of emissions embodied in trade. These issues and associated uncertainties in the estimates are addressed in detail in Section 5.2.3.6.

14.3.4.2 Embodied emission transfers between world regions

Figure 14.9 illustrates the net CO_2 emission transfer between 10 world regions in 2007 using the Multi-Regional Input-Output Analysis (MRIO) method and economic and emissions (from fossil fuel combustion) data derived from the Global Trade Analysis Project (GTAP) Version 8. Focusing on production-related emissions, the left-hand side of Figure 14.9 explains the magnitudes and regional final consumption destinations of production emissions embodied in exports. Percentage values represent total exported production emissions as a share of total production emissions for each regional economy. Now, focusing on consumption-related emissions, the right-hand side of Figure 14.9 illustrates the magnitudes and origins of production emissions embodied

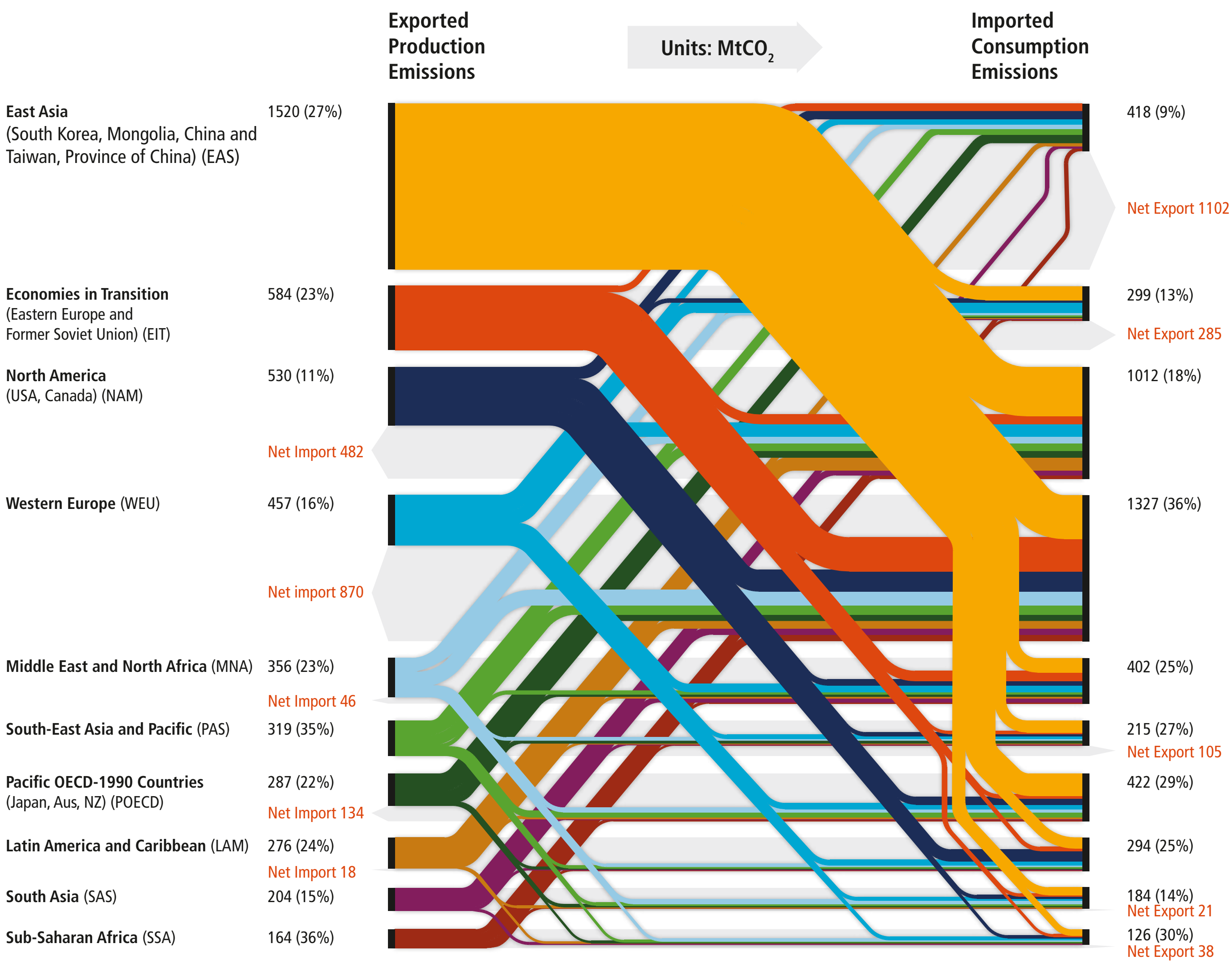


Figure 14.9 | Net transfer of CO_2 emissions (from fossil fuel combustion only) between world regions in 2007 using the multi-regional input-output (MRIO) method. Flow widths represent the magnitude of emissions (in $MtCO_2$) released by left-hand side regions that have become embodied (along global supply chains) in the goods and services consumed by the regions listed on the right-hand side. Figures for total exported production emissions and total imported consumption emissions are given, and the difference between these two measures is shown as either a net export or net import emissions transfer. Percentages on the left-hand side indicate the total exported emissions as percentage of total industry production emissions, while the percentage figures on the right-hand side indicate total imported emissions as percentage of the total industry consumption emissions. Data reports global CO_2 emissions of 26.5 $GtCO_2$ in 2007 (22.8 Gt from industry and a further 3.7 Gt from residential sources). The analysis is performed using the MRIO model and emissions data derived from GTAP Version 8 database, as explained and presented by Andrew and Peters (2013) .

in regional final consumption imports. The associated percentages represent total imported consumption emissions as a share of total consumption emissions. The difference between exported production emissions and imported consumption emissions are highlighted to represent the net emission transfer between regions.

For example, EAS was the largest net emission exporter (1102 $MtCO_2$) in 2007, with total exported production emissions (1520 $MtCO_2$) accounting for 27 % of total production emissions (5692 $MtCO_2$), while imported consumption emissions (418 $MtCO_2$) accounted for less than 10 % of total consumption emissions (4590 $MtCO_2$). OECD countries are the major destinations of export products in EAS. For example, NAM and WEU account for 34 % and 29 % of EAS's total exported production emissions, respectively. In China, the largest economy in EAS, the share of embodied emissions in exports to total annual emissions have increased from 12 % in 1987 to 21 % in 2002, further to 33 % in 2005 (Weber et al., 2008), and settled around 30 % in 2007 (Minx et al., 2011). Producing exports have driven half of emissions growth in China during 2002–2005 (Guan et al., 2009). Over 60 % of embodied emissions in Chinese exports in 2005, mainly formed by electronics, metal products, textiles, and chemical products, are transferred to developed countries (Weber et al., 2008). Based on the 2002 dataset, Dietzenbacher et al. (2012) argue that the embodied emissions in China may be over-estimated by more than 60 % if the distinction between processing exports and normal exports is not made. In contrast, WEU was the largest net emissions importer (870 $MtCO_2$) in 2007, with total exported production emissions (457 $MtCO_2$) accounting for 16 % of total production emissions, while imported consumption emissions (1327 $MtCO_2$) accounted for 36 % of total consumption emissions.

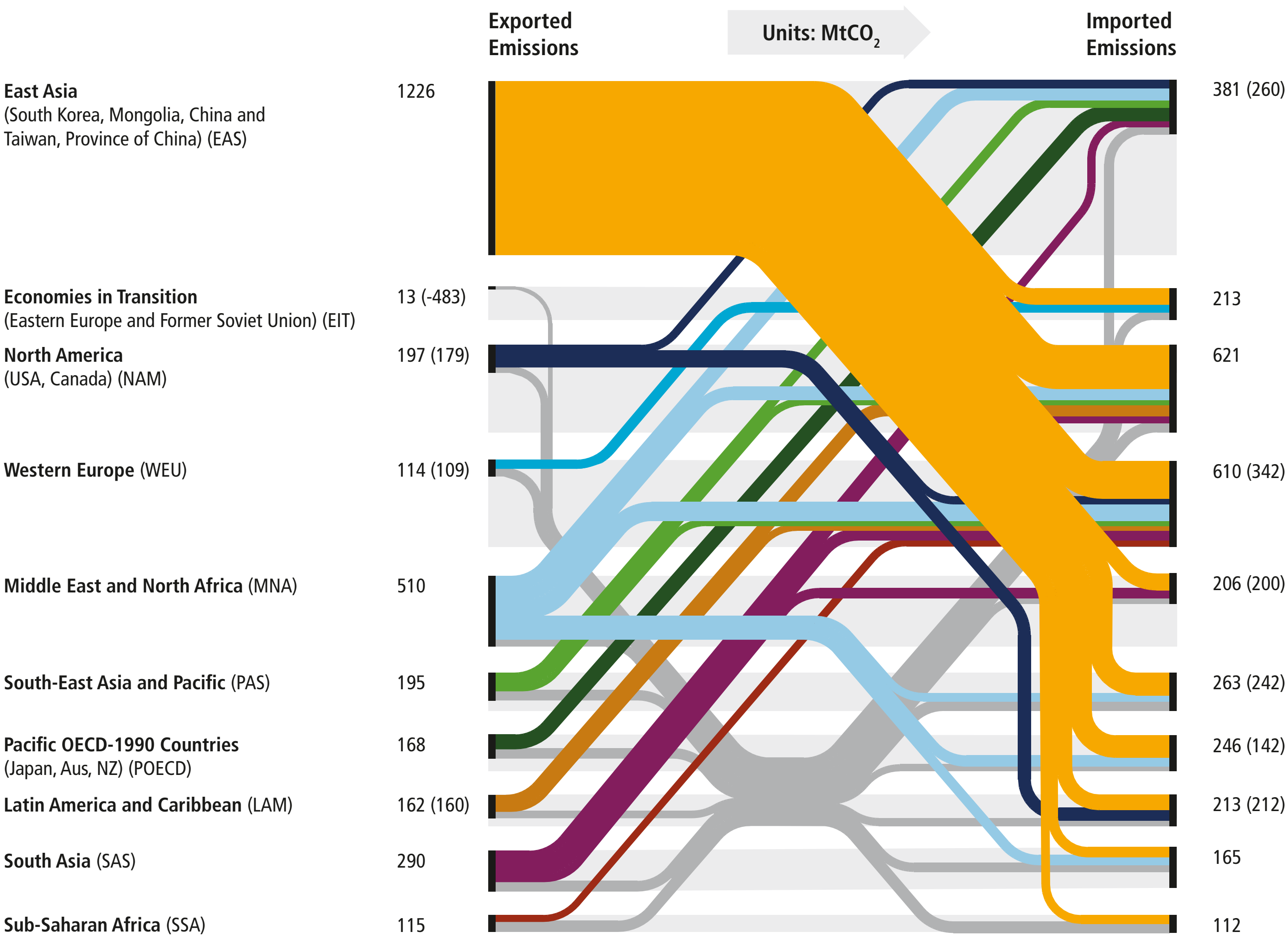


Figure 14.10 | Growth in bilateral traded CO_2 emissions between world regions from 1990 to 2008: Flow widths represent the growth in bilateral traded emissions (in $MtCO_2$) between 1990 and 2008, exported from left-hand side region and imported by right-hand side region. Flows representing a growth greater than 30 $MtCO_2$ are shown individually. Less significant flows have been combined and dropped to the background. Figures for the sum of all export/import connections of each region exhibiting positive growth are provided. Bracketed figures show the net growth in exported/imported emissions for each region after trade connections exhibiting negative growth (not shown in diagram) have been accounted for. Trade connections exhibiting significant negative growth include EIT to WEU (–267 $MtCO_2$), to EAS (–121 $MtCO_2$), to POECD (–80 $MtCO_2$), and to other regions (–15 $MtCO_2$). Total growth in inter-region traded emissions between 1990 and 2008 is found to be 2.5 $GtCO_2$ (this does not include intra-region traded emissions, e.g., between the United States and Canada). The analysis uses the emissions embodied in the bilateral trade (EEBT) approach. The input-output dataset, trade statistics, and emissions data derived from Peters et al. (2011).

Figure 14.10 demonstrates (using the emissions embodied in the bilateral trade (EEBT) method) that the embodied CO_2 emissions in international bilateral trade between the 10 world regions have grown by 2.5 Gt during 1990–2008. Considering exports, half of global growth is accounted for by exports from EAS (1226 $MtCO_2$), followed by exports from MNA and SAS with 20 % (510 $MtCO_2$) and 12 % (290 $MtCO_2$) of global growth, respectively. The NAM region has increased imports by 621 $MtCO_2$, with the three Asian regions providing 75 % of the increase. Although WEU observed positive import flows increase by 610 $MtCO_2$, it also saw a decrease of 268 $MtCO_2$ in some bilateral trade connections, primarily from EIT (257 $MtCO_2$).

Many developing country regions have also observed considerable increases in imported emissions during 1990–2008. The total growth in developing countries accounts for 48 % of the global total. For example, EAS, PAS, and LAM have increased their imported emissions by 260 $MtCO_2$, 242 $MtCO_2$, and 212 $MtCO_2$, respectively. Over half of the growth in EAS and LAM has been facilitated via trade with other developing country regions. While trade with other developing country regions has contributed over 90 % of increase in imported emissions to PAS and SAS. These results are indicative of further growth of emissions transfers within the Global South.

Recent research efforts have investigated the embodied emissions at the sectoral level (Liu et al., 2012a; b; Lindner et al., 2013; Vetőné Mózner, 2013) and emission transfers between industrial sectors within or across country borders (Sinden et al., 2011; Homma et al., 2012). Skelton et al. (2011) calculate total industrial sector production and consumption attributions to map the embodied emissions delivered from production to consumption end through the global production systems. They find that Western Europe tends to be a net importer of emissions in all sectors but particularly so in the primary and secondary sectors.

14.3.4.3 Opportunities and barriers at the regional level for low-carbon development in consumption patterns

The growing discrepancy between production- and consumption-based emissions discussed above, is most likely related to changing structures of international trade, although carbon leakage associated with efforts to curb emissions in industrialized countries can play a role here as well. It is also related to the fact that demand for emission-intensive goods has not been reduced by as much as the production of emission-intensive goods in industrialized countries. However, as identical goods can be produced with different carbon content in different countries, substitution processes need to be taken into account to assess how global emissions would change in reaction to a change of imported emissions (Jakob and Marschinski, 2013).

Climate change analysis and policies pay increasing attention to consumption (Nakicenovic and Swart, 2000; Michaelis, 2003). Analysis of household survey data from different regions shows that with improving income levels, households spend an increasing proportion of their income on energy-intensive goods (Figure 14.11) (O'Neill et al., 2010). Households in SSA and PAS have much lower income levels than more-developed regions, and spend a much larger share of their smaller income on food and other basic needs. Households in the more-developed PAS and NAM, on the other hand, spend a larger share of their income on transportation, recreation, etc. With economic growth, households in less-developed regions are expected to 'westernize' their lifestyles, which will substantially increase per capita and global total carbon emissions (Stern, 2006). Thus changing lifestyles and consumption patterns (using taxes, subsidies, regulation, information, and other tools) can be an important policy option for reducing the emission-intensity of consumption patterns (Barrett et al., 2013). To the extent that carbon leakage (see Section 5.4.1) contributes to this increasing discrepancy between production and consumption-based emissions, border-tax adjustments or other trade measures (Ismer and Neuhoff, 2007) can be an option in the absence of a global agreement on mitigation. This is discussed in more detail below.

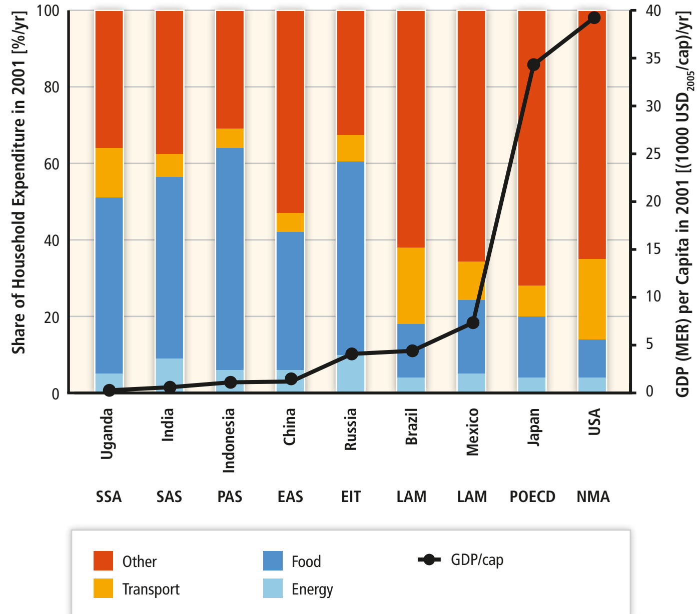


Figure 14.11 | Expenditure share of households and per capita income, 2001. Household expenditure is based on Zigova et al. (2009) and O'Neill et al. (2010). Per capita GDP is from World Bank Development Indicators (World Bank, 2011).

14.3.5 Agriculture, forestry, and other land-use options for mitigation

Emission of GHGs in the Agriculture, Forestry, and Other Land-Use (AFOLU) options sector increased by 20 % from 9.3 $GtCO_2eq/yr$ in 1970 to 11.2 $GtCO_2eq/yr$ (Figure 5.18) in 2010, and contributed about 22 % to the global total in 2010 (JRC/PBL, 2013; IEA, 2012a). Over this period, the increase in the Agriculture sub-sector was 35 %, from

4.2 $GtCO_2eq/yr$ to 5.7 $GtCO_2eq/yr$, and in the Forestry and Other Land Use (FOLU) sub-sector it rose from 5.1 $GtCO_2eq/yr$ to 5.5 $GtCO_2eq/yr$ (Section 5.3.5.4; see also Sections 11.2 and 11.3 for more-detailed sector-specific values). The AFOLU emissions have been relatively more significant in non-OECD-1990 regions, dominating, for example, total GHG emissions from Middle East and Africa (MAF) and LAM regions[2] (see Section 5.3.5.4 and Figure 5.6, Sections 11.2 and 11.4, Figures 11.5 and 11.7). In the LDCs, more than 90 % of the GHG emissions from 1970–2010 were generated by AFOLU (Figure 5.20), and emissions grew by 0.6 % per year over the past four decades (Box 5.3).

As outlined in Section 11.2.3, global FOLU CO_2 flux estimates are based on a wide range of data sources, and include different processes, definitions, and different approaches to calculating emissions; this leads to a large range across global FOLU flux estimates (Figures 11.6 and 11.7). For the period 1750–2011, cumulative CO_2 fluxes have been estimated at 660 (± 293) $GtCO_2$ based on the model approach of Houghton (2003, updated in Houghton, 2012), while annual emissions averaged 3.8 ± 2.9 $GtCO_2/yr$ in 2000 to 2009 (see Table 11.1). In Chapter 11 of this assessment, Figure 11.7 shows the regional distribution of FOLU CO_2 over the last four decades from a range of estimates. For 2000 to 2009, FOLU emissions were greatest in ASIA (1.1 $GtCO_2/yr$) and LAM (1.2 $GtCO_2/yr$) compared to MAF (0.56 $GtCO_2/yr$), OECD (0.21 $GtCO_2/yr$), and EIT (0.12 $GtCO_2/yr$) (Houghton, 2003; Pongratz et al., 2009; Hurtt et al., 2011; Pan et al., 2011; Lawrence et al., 2012); these are means across seven estimates, noting that in OECD and EIT some estimates indicate net emissions, while others indicate a net sink of CO_2 due to FOLU. Emissions were predominantly due to deforestation for expansion of agriculture, and agricultural production (crops and livestock), with net sinks in some regions due to afforestation. There have been decreases in FOLU-related emissions in most regions since the 1980s, particular ASIA and LAM where rates of deforestation have decreased (FAOSTAT, 2013; Klein Goldewijk et al., 2011; Hurtt et al., 2011).

In the agriculture sub-sector 60 % of GHG emissions in 2010 were methane, dominated by enteric fermentation and rice cultivation (see Sections 5.3.5.4, 11.2.2, Figure 11.2). Nitrous oxide contributed 38 % to agricultural GHG emissions, mainly from application of fertilizer and manure. Between 1970 and 2010 emissions of methane increased by 18 % whereas emission of nitrous oxide increased by 73 %. The ASIA region contributed most to global GHG emissions from agriculture, particularly for rice cultivation, while the EIT region contributed least (see Figure 11.5). Due to the projected increases in food production by 2030, which drive short-term land conversion, the contribution of developing countries to future GHG emissions is expected to be very significant (Box 11.6).

[2] These belong to the so called five RC5 regions, which include ASIA, OECD-1990, LAM, MAF, and Economies in Transition (EIT) (see Annex II.2). The ten RC10 regions (see also Annex II.2) used in this chapter further disaggregate OECD-1990 (WEU, NAM, POECD), MAF (MNA and SSA), and ASIA (EAS, SAS, PAS).

Trajectories from 2006 to 2100 of the four Representative Concentration Pathways (RCPs) (see Table 6.2 in Section 6.3.2.1; Meinshausen et al., 2011) show different combinations of land cover change (cropland and grazing land) and wood harvest as developed by four integrated assessment models and harmonized in the Hurtt et al. (2011) dataset. These results in regional emissions as illustrated by Figure 14.12 show the results from one Earth System Model (Lawrence et al., 2012). However, even using a common land cover change dataset, resulting forest cover, net CO_2 flux, and climate change vary substantially across different Earth System Models (Brovkin et al., 2013). Furthermore, as shown by Popp et al. (2013) projections regarding regional land cover changes and related emissions can vary substantially across different integrated models for the same concentration scenario (see Figure 11.19).

Mitigation options in the AFOLU sector mainly focus on reducing GHG emissions, increasing carbon sequestration, or using biomass to

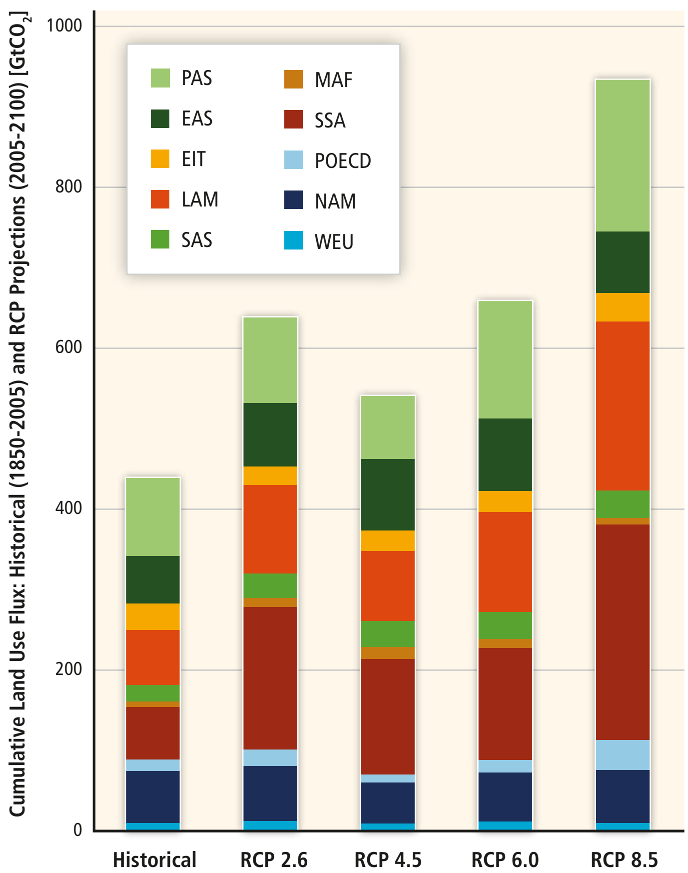


Figure 14.12 | Cumulative regional emissions of CO_2 from AFOLU. The four RCPs developed for this Assessment Report explore the implications of a broad range of future GHG concentration trajectories, resulting in a range of radiative forcing values in the year 2100: 2.6, 4.5, 6.0, and 8.5 Watts per square meter (see Table 6.2 in Section 6.3.2.1; Meinshausen et al., 2011). Past and future land cover change and wood harvest data was from Hurtt et al. (2011). The historical period is from 1850 to 2005, the RCPs cover the period from 2005 to 2100. This figure shows results running the scenarios in the Community Climate System Model (CCSM4) (Lawrence et al., 2012) as illustrative of one of several Earth System Model results presented in the IPCC Working Group I Report.

generate energy to displace fossil fuels (Table 11.2). As such, potential activities involve reducing deforestation, increasing forest cover, agroforestry, agriculture, and livestock management, and the production of sustainable renewable biomass energy (Sathaye et al., 2005; Smith et al., 2013) (see Box 11.6). Since development conditions affect the possibilities for mitigation and leapfrogging, in business-as-usual conditions, the current level of emission patterns is to persist and intensify (Reilly et al., 2001; Parry et al., 2004; Lobell et al., 2008; Iglesias et al., 2011a). This poses challenges in terms of these regions' vulnerability to climate change, their prospects of mitigation actions and low-carbon development from agriculture and land-use changes. The WGII report shows that without adaptation, increases in local temperature of more than 1 °C above pre-industrial are projected to have negative effects on yields for the major crops (wheat, rice, and maize) in both tropical and temperate regions, although individual locations may benefit (see WGII 7.4). However, the quantification of adaptation co-benefits and risks associated with specific mitigation options is still in an emerging state (see Section 6.3.3 and 6.6) and, as referred to in Section 11.5.5, subject to technological but also societal constraints.

Moreover, linking land productivity to an increase in water irrigation demand in the 2080s to maintain similar current food production, offers a scenario of a high-risk from climate change, especially for regions such as South East Asia and Africa. These regions could benefit from more technology and investment, especially at the farm level, in the means of access to irrigation for food production to decrease the impacts of climate change (Iglesias et al., 2011b). 'Bottom-up' regional strategies to merge market forces, domestic policies, and finance have been recommended for LAM (Nepstad et al., 2013). Region-specific strategies are needed to allow for flexibility in the face of impacts and to create synergies with development policies that enhance adaptive lower levels of risk. This is the case for NAM, Western and Eastern Europe, and POECD, but also South East Asia, Central America, and Central Africa (Iglesias et al., 2011a).

Studies reveal large differences in the regional mitigation potential as well as clear differences in the ranking of the most-effective options (see Section 11.6.3). For a range of different mitigation scenarios across the RC5 regions and all AFOLU measures, ASIA shows the largest economic mitigation potential, both in forestry and agriculture, followed by LAM, OECD-1990, MAF, and EIT. Reduced deforestation dominates the forestry mitigation potential in LAM and MAF, but shows very little potential in OECD-1990 and EIT. Forest management, followed by afforestation, dominate in OECD-1990, EIT, and ASIA (see Figure 11.19). Among agricultural measures, almost all of the global potential in rice management practices is in ASIA, and the large potential for restoration of organic soils also in ASIA (due to cultivated South East Asian peats), and OECD-1990 (due to cultivated Northern peatlands).

Although climate and non-climate policies have been key to foster opportunities for adaptation and mitigation regarding forestry and agriculture, the above-mentioned scenarios imply very different abilities to reduce emissions from land-use change and forestry in different regions, with the RCP 4.5 implying the most ambitious reductions. Reducing the gap between technical potential and realized mitigation requires, in addition to market-based trading schemes, the elimination of barriers to implementation, including climate and non-climate policy, and institutional, social, educational, and economic constraints (Smith et al., 2008). Opportunities for cooperation schemes arise at the regional level as, for instance, combining reducing emissions from deforestation and degradation (REDD)+ and market transformation, which could potentially mitigate climate change impacts by linking biodiversity, regional development and cooperation favouring conservation (Nepstad et al., 2013), or river basin management planning (Cooper et al., 2008; González-Zeas et al., 2012).

14.3.6 Technology transfer, low-carbon development, and opportunities for leapfrogging

The notion of 'leapfrogging' has particular resonance in climate change mitigation. It suggests that developing countries might be able to follow more sustainable, low-carbon development pathways and avoid the more emissions-intensive stages of development that were previously experienced by industrialized nations (Goldemberg, 1998; Davison et al., 2000; Lee and Kim, 2001; Perkins, 2003; Gallagher, 2006; Ockwell et al., 2008; Walz, 2010; Watson and Sauter, 2011; Doig and Adow, 2011). Other forms of technological change that are more gradual than leapfrogging include the adoption of incrementally cleaner or more energy-efficient technologies that are commercially available (Gallagher, 2006).The evidence for whether such low-carbon technology transitions can or have already occurred, as well as specific models for low-carbon development, have been increasingly addressed in the literature reviewed in this section.

Most of the energy-leapfrogging literature deals with how latecomer countries can catch up with the energy-producing or consuming technologies of industrialized countries (Goldemberg, 1998; Perkins, 2003; Unruh and Carrillo-Hermosilla, 2006; Watson and Sauter, 2011; Lewis, 2012). Case studies of successful leapfrogging have shown that both the build-up of internal knowledge within a country or industry and the access to external knowledge are crucial (Lee and Kim, 2001; Lewis, 2007, 2011; Watson and Sauter, 2011). The increasing specialization in global markets can make it increasingly difficult for developing countries to gain access to external knowledge (Watson and Sauter, 2011). Other studies have identified clear limits to leapfrogging, for example, due to barriers in introducing advanced energy technologies in developing countries where technological capabilities to produce or integrate the technologies may be deficient (Gallagher, 2006).

14.3.6.1 Examining low-carbon leapfrogging across and within regions

The strategies used by countries to leapfrog exhibit clear regional differences. Many cases of technological leapfrogging have been documented in emerging Asia, including the Korean steel (D'Costa, 1994) and automobile industries (Lee, 2005; Yoon, 2009), and the wind power industries in China and India (Lema and Ruby, 2007; Lewis, 2007, 2011, 2012; Ru et al., 2012). Within Latin America, much attention has been focused on leapfrogging in transportation fuels, and specifically the Brazilian ethanol program (Goldemberg, 1998; Dantas, 2011; Souza and Hasenclever, 2011).

Absorptive capacity, i.e., the ability to adopt, manage, and develop new technologies, has been identified in the literature as a core condition for successful leapfrogging (Katz, 1987; Lall, 1987, 1998; Kim, 1998; Lee and Kim, 2001; Watson and Sauter, 2011). While difficult to measure, absorptive capacity includes technological capabilities, knowledge, and skills. It is therefore useful to examine regional differences across such technological capabilities, using metrics such as the number of researchers within a country, and total research and development (R&D) invested. These metrics are investigated on a national and regional basis in Figure 14.13 along with total CO_2 emissions from energy use.

14.3.6.2 Regional approaches to promote technologies for low-carbon development

The appropriateness of different low-carbon development pathways relies on factors that may vary substantially by region, including the nature of technologies and their appropriateness within different regions, the institutional architectures and related barriers and incentives, and the needs of different parts of society within and across

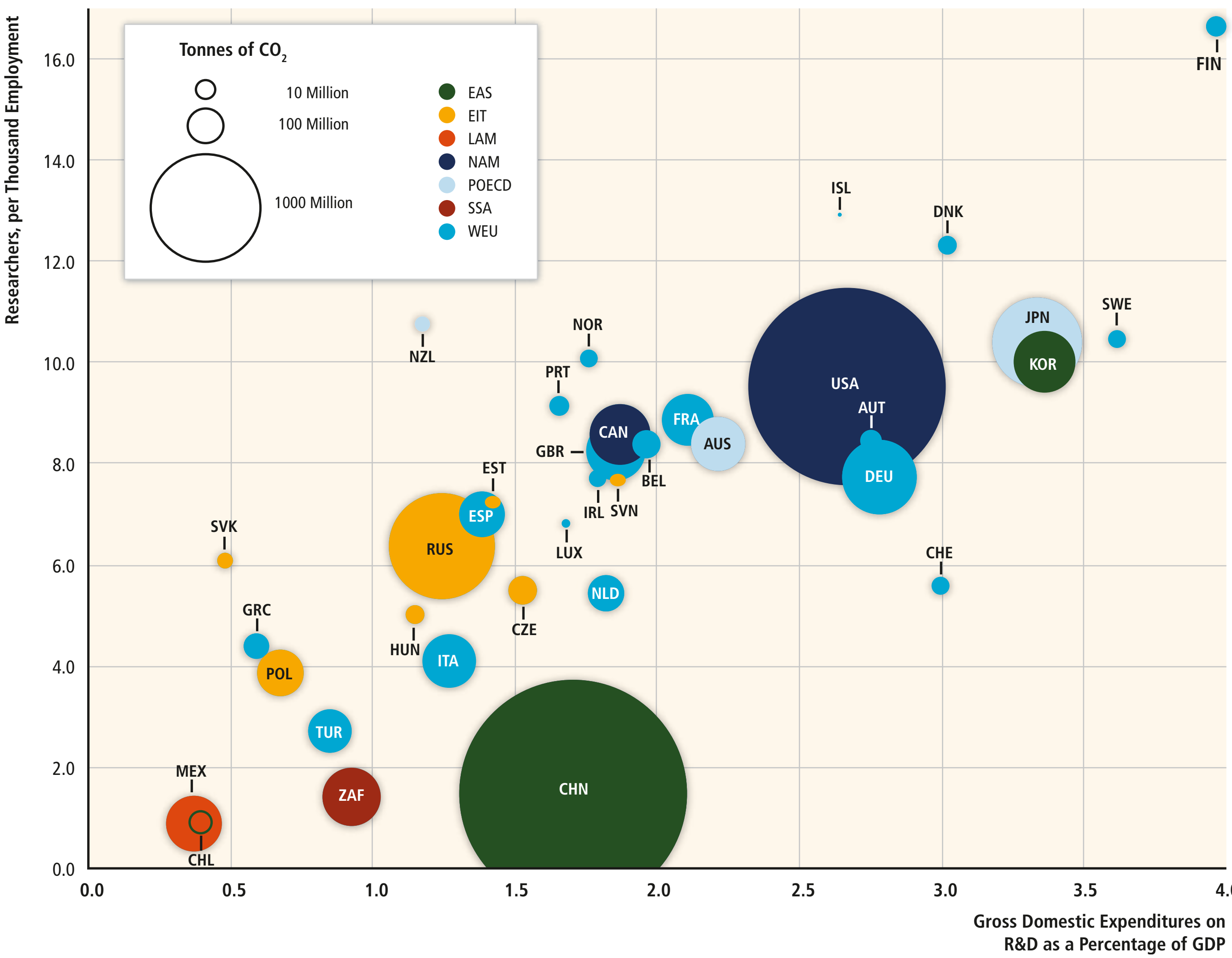
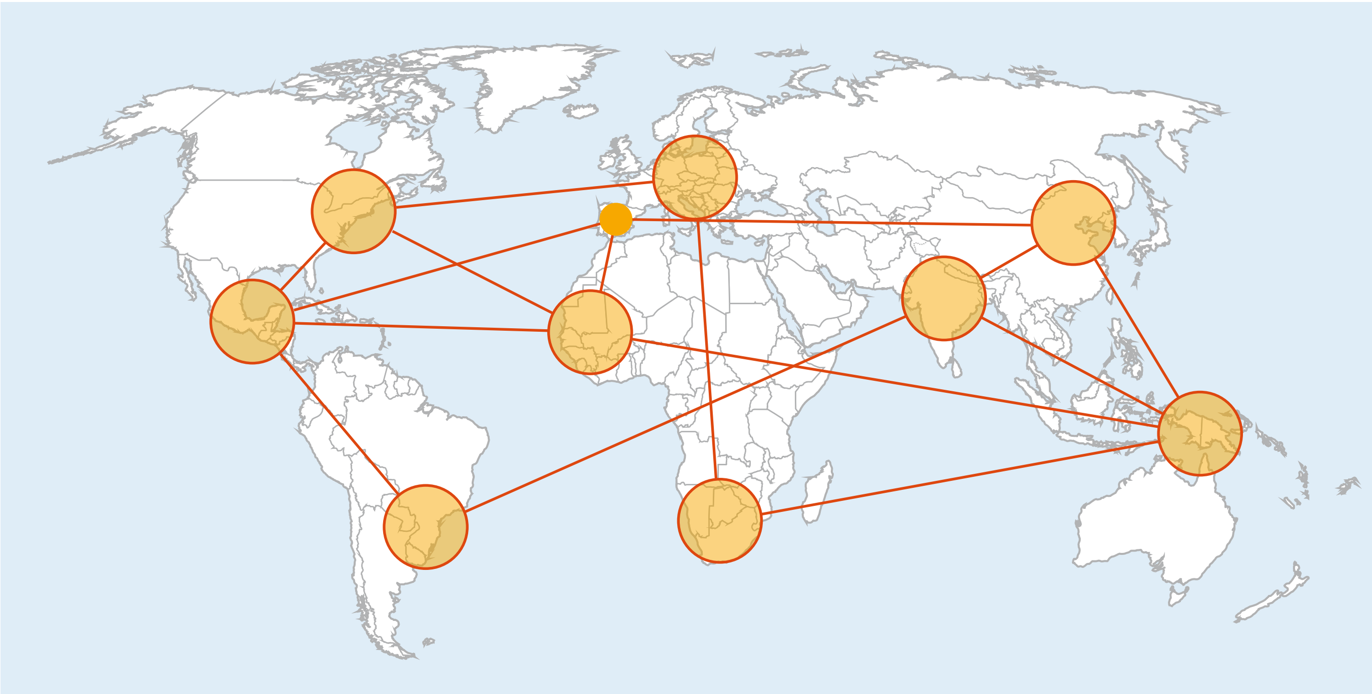


Figure 14.13 | Emissions contribution and innovative capacity: regional comparison. Source: Data on researchers and R&D expenditures as percentage of GDP from the OECD Main Science and Technology Indicators Database (OECD, 2011b); CO_2 from fossil fuels are for 2009 (IEA, 2011).



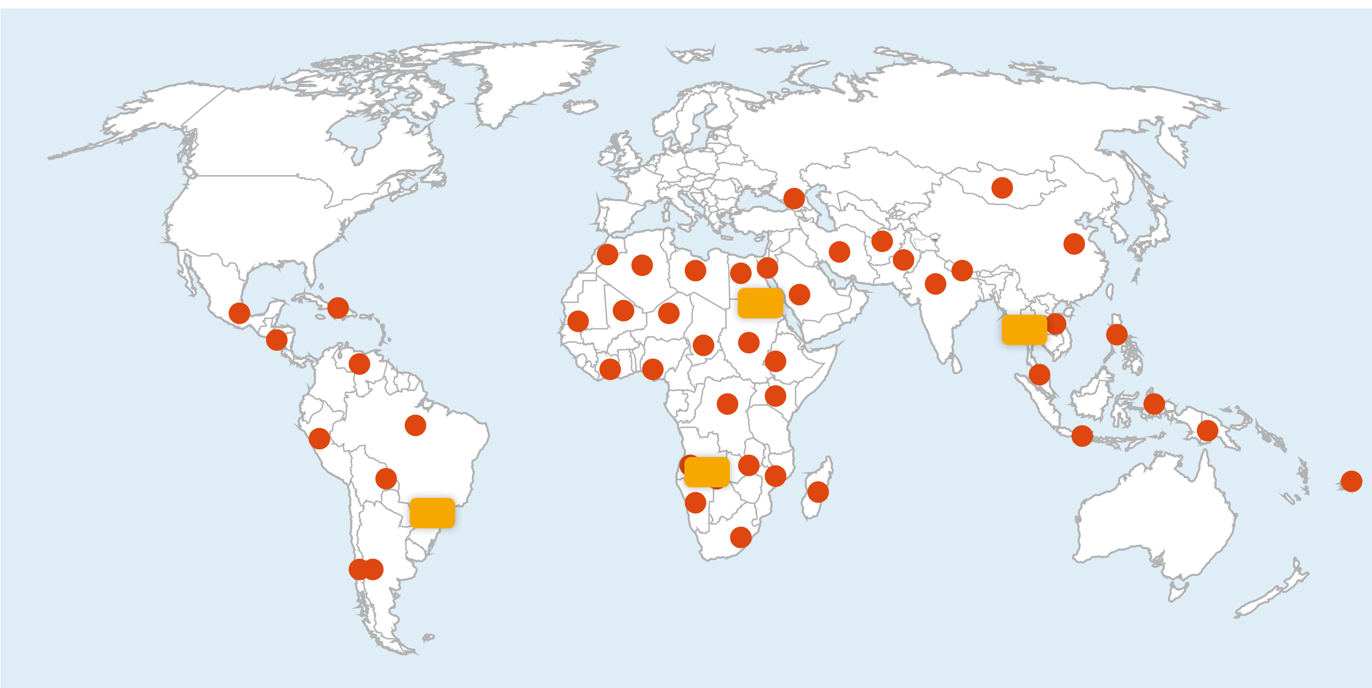


Figure 14.14 | Options for regionally coordinated climate technology networks. Upper map illustrates a network of climate technology research, development, and demonstration (RD&D) centers (large circles) with a small secretariat (small circle); lower map illustrates a network of climate technology RD&D centers with national hubs (red dots) and regional centers (yellow shapes). Source: Cochran et al. (2010).

regions. As a result, an appropriate low-carbon development pathway for a rapidly emerging economy in EAS may not be appropriate for countries in PAS or SSA (Ockwell et al., 2008). Low-carbon development pathways could also be influenced by climatic or ecological considerations, as well as renewable resource endowments (Gan and Smith, 2011).

Regional institutions for low-carbon development

Many studies propose that regions could be a basis for establishing low-carbon technology innovation and diffusion centres (Carbon Trust, 2008). Such centres could "enhance local and regional engagement with global technological developments" and "catalyze domestic capacity to develop, adapt and diffuse beneficial innovations" (Carbon

Trust, 2008). In a report prepared for the United Nations Environment Program (UNEP) by the National Renewable Energy Laboratory (NREL) and the Energy Research Center of the Netherlands (ECN), several options for structuring climate technology centres and networks were presented that focus on establishing regionally based, linked networks, as illustrated in Figure 14.14 (Cochran et al., 2010). A Climate Technology Center and Network (CTCN) was formally established by the United Nations Framework Convention on Climate Change (UNFCCC) at the Conference of Parties (COP) 17 as part of the Cancun Agreements. The CTCN, confirmed during COP 18 in Doha, is jointly managed by UNEP and the United Nations Industrial Development Organization (UNIDO), an advisory board, and 11 regionally based technology institutes serving as the CTCN consortium (UNEP Risoe Centre, 2013). The structure of the CTCN is therefore similar to the one illustrated in the left map in Figure 14.14.

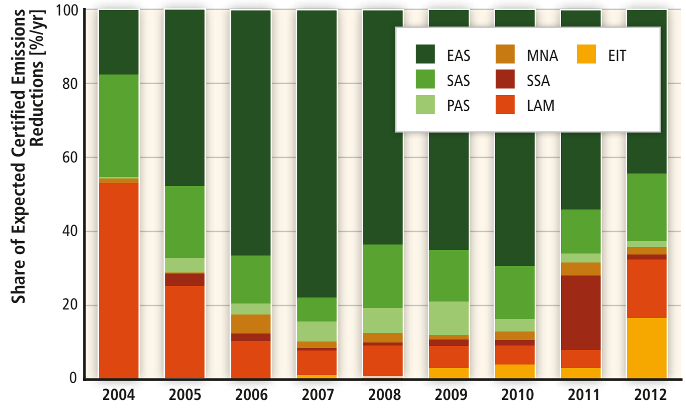


Figure 14.15 | Regional distribution of pre-2013 credit volumes for annual CDM project cohorts. Raw data source: UNEP Risoe Centre (2013).

14.3.7 Investment and finance, including the role of public and private sectors and public private partnerships

Since the signature of the UNFCCC in 1992, public finance streams have been allocated for climate change mitigation and adaptation in developing countries, e.g., through the Global Environment Facility (GEF) and the Climate Investment Funds of the World Bank, but also through bilateral flows (for a discussion of existing and proposed public climate finance instruments, see Chapter 16). Moreover, since the setup of the pilot phase for Activities Implemented Jointly in 1995 and the operationalization of the Clean Development Mechanism (CDM) and Joint Implementation (JI) from 2001 onwards, private finance has flown into mitigation projects abroad (for an assessment of these mechanisms, see Section 13.13.1). In this section, regional differences are assessed in use of public finance instruments and private finance triggered by market mechanisms.

14.3.7.1 Participation in climate-specific policy instruments related to financing

The CDM has developed a distinct pattern of regional clustering of projects and buyers of emission credits. Projects are concentrated in EAS, SAS, and LAM. PAS has a lower level of participation, while EIT, MNA, and SSA are lagging behind. Credit buyers are concentrated in WEU (see Figure 14.15 for project volumes). This pattern has been relatively stable since 2006, although in 2011 and 2012 the distribution has become more balanced in terms of volumes.

The reasons for the skewed regional concentration of CDM projects have been thoroughly researched. Jung (2006) assesses host country attractiveness through a cluster analysis, by looking at mitigation potential, institutional CDM capacity, and general investment climate. Jung's prediction that China, India, Brazil, Mexico, Indonesia, and Thailand would dominate was fully vindicated, and only Argentina and South Africa did not perform as well as expected. Oleschak and Springer (2007) evaluate host country risk according to the Kyoto-related institutional environment, the general regulatory environment, and the economic environment, and derive similar conclusions. Castro and Michaelowa (2010) assess grey literature on host country attractiveness and find that even discounting of CDM credits from advanced developing countries would not be sufficient to bring more projects to low-income countries. Okubo and Michaelowa (2010) find that capacity building is a necessary but not sufficient condition for successful implementation of CDM projects. Van der Gaast el al. (2009) discusses how technology transfer could contribute to a more equitable distribution of projects.

For CDM programmes of activities that allow bundling an unlimited number of projects, the distribution differs markedly. According to the UNEP Riso Centre (2013), the SSA's share is 10 times higher than for ordinary CDM projects, while EAS and SAS's share are one-third lower. LAM region's share remains the same. The reason for this more-balanced distribution is the higher attractiveness of small-scale projects in a low-income context (Hayashi et al., 2010). However, high fixed-transaction costs of the CDM project cycle are a significant barrier for small-scale projects (Michaelowa and Jotzo, 2005).

The distribution of JI projects, of which 90 % are implemented in the EIT region, was not predicted by Oleschak and Springer (2007)'s list of most-attractive JI countries. The shares have not shifted substantially over time.

Figure 14.15 shows the regional distribution of pre-2013 credit volumes for annual CDM project cohorts. It confirms the regionally skewed distribution of CDM projects. In contrast, the 880 climate change projects of the GEF (a total of 3.1 billion current USD spent since the early 1990s) do not show a significant regional imbalance when assessed in terms of numbers. Once volumes are assessed, they are somewhat skewed towards EAS and SAS. Academic literature has evaluated the regional distribution of GEF projects only to a very limited extent. Mee et al. (2008) note that there is a correlation between national emissions level and the number of GEF mitigation projects, which would lead to a concentration of projects in the same countries that have a high share in CDM projects. Dixon et al. (2010) describe the regional distribution of the energy efficiency, renewable energy, and transport project portfolio, but do not discuss what drives this distribution.

While the general direction of bilateral climate finance flows from the North to the South is clear, regional specificities have only partially been addressed by the literature. Atteridge et al. (2009) assess the 2008 climate finance flows from France, Germany, and Japan as well as the European Investment Bank and find that 64 % of mitigation finance went to Asia and Oceania, 9 % to SSA, 8 % to MNA, and 5 % to LAM. With 11 %, EIT had a surprisingly high share. Climate Funds Update (2013) provides data on pledges, deposits, and recipients of the fast-start finance committed in the Copenhagen Accord. Of the 31.4 billion USD funds pledged by September 2011, 53 % came from Asia, 37 % from Europe, 9 % from North America, and 1 % from Australasia. Of 3.1 billion USD allocated to approved projects, 44 % was to be spent in Asia, 37 % in Africa, 13 % in Latin America, 13 % in North America and 6 % in Europe. There is no recent peer-reviewed literature discussing flows from Multilateral Development Banks.

As of 2009, a total of 79 REDD readiness activities and 100 REDD demonstration activities were reported (Cerbu et al., 2011). REDD readiness activities were evenly distributed among regions (21 in Amazon Region of South America, 19 in East Asia and the Pacific, 13 in Central America and the Caribbean, and 22 in Africa). In contrast, East Asia and the Pacific hold major REDD demonstration projects (40), followed by 31 in Amazon, 18 in Africa, and 2 in South Asia (Cerbu et al., 2011). Thirty-six countries, mainly in Latin America (15), Africa (15), and Asia-Pacific (8) participate in the global initiative Forest Carbon Partnership Facilities (Nguon and Kulakowski, 2013).

Other global and regional REDD+ initiatives include the UN-REDD Program, which aims to support REDD+ readiness in 46 partner countries in Africa, Asia-Pacific, and Latin America; the REDD+ Partnership, which serves as an interim platform for its partner countries to scale up actions and finance for REDD+ initiatives in developing countries; and the Forest Investment Program, which supports developing countries' efforts to REDD and promotes sustainable forest management (den Besten et al., 2013) (see also Section 11.10).

14.4 Regional cooperation and mitigation: opportunities and barriers

14.4.1 Regional mechanisms: conceptual

As a global environmental challenge, mitigation of climate change would ideally require a global solution (see Chapter 13). However, when global agreement is difficult to achieve, regional cooperation may be useful to accomplish global mitigation objectives, at least partially. The literature on international environmental governance emphasizes the advantages of common objectives, common historical and cultural backgrounds, geographical proximity, and a smaller number of negotiating parties, which make it easier to come to agreement and to coordinate mitigation efforts. As a caveat, regional fragmentation might hamper the achievement of global objectives (Biermann et al., 2009; Zelli, 2011; Balsiger and VanDeveer, 2012). However, game-theoretic models using the endogenous coalition formation framework suggest that several regional agreements are better than one global agreement with limited participation (Asheim et al., 2006; Osmani and Tol, 2010). The underlying reason is that endogenous participation in a global environmental agreement is very small since free-riders profit more from the agreement than its signatories unless the number of signatories is very small.

The discussion in this section distinguishes between climate-specific and climate-relevant initiatives. Climate-specific regional initiatives address mitigation challenges directly. Climate-relevant initiatives were launched with other objectives, but have potential implications for mitigation at the regional level, e. g. regional trade agreements and regional cooperation on energy. This section will also address tradeoffs and synergies between adaptation, mitigation, and development at the regional level. Questions addressed in this chapter are in regard to what extent the existing schemes have had an impact on mitigation and to what extent they can be adjusted to have a greater mitigation potential in future. Since this section focuses on the mitigation potential of regional cooperation, well-being, equity, intra- and inter-generational justice will not be considered (see Sections 3.3 and 3.4 for a discussion on these issues).

An important aspect of regional mechanisms is related to efficiency and consistency. As GHGs are global pollutants and their effect on global warming is largely independent of the geographical location of the emission source, all emitters of GHGs should be charged the same implicit or explicit price. If this 'law of one price' is violated, mitigation efforts will be inefficient. This would imply that regions should strive for internal and external consistency of prices for GHGs. The law of one price should apply within and across regions. As regards internal consistency, regional markets for GHG emission permits, such as the EU ETS, have the potential to achieve this goal at least in theory (Montgomery, 1972). However, since existing trading schemes cover only a part of GHG emissions, the law of one price is violated and mitigation efforts tend to be inefficiently allocated.

External consistency is linked to the problem of GHG leakage. Specifically, regional climate regimes can lead to both carbon leakage (discussed in Section 5.4.1) and a decrease in competitiveness for participating countries (discussed in Section 13.8.1). Thus, the specific policies addressing these concerns, particularly the latter, have a large impact on an agreement's regional and national acceptability. One of the most widely discussed policies to correct for climate-related cost differences between countries is border tax adjustments (BTAs), which are similar to the (non-climate) value-added tax in the EU (Lockwood and Whalley, 2010). There is agreement that BTAs can enhance competitiveness of GHG- and trade-intensive industries within a given climate regime (Alexeeva-Talebi et al., 2008; Kuik and Hofkes, 2010; Böhringer et al., 2012; Balistreri and Rutherford, 2012; Lanzi et al., 2012). However, while BTAs ensure the competitiveness of acting countries, they lead to severe welfare losses for non-acting ones (Winchester et al., 2011; Böhringer et al., 2012; Ghosh et al., 2012; Lanzi et al., 2012), particularly developing countries and the global South (Curran, 2009; Brandi, 2013). Other solutions to the problem of carbon leakage include incorporating more countries into regional agreements (Peters and Hertwich, 2008, p. 1406), and linking regional emission trading systems. Tuerk et al. (2009) and Flachsland et al. (2009) show that linking regional emission trading systems does not necessarily benefit all parties, even though it is welfare-enhancing at a global level (see also Section 13.7).

14.4.2 Existing regional cooperation processes and their mitigation impacts

While there is ongoing discussion in the literature on the continued feasibility of negotiating and implementing global environmental agreements (see Chapter 13), a distinct set of studies has emerged that examines international coordination through governance arrangements that aim at regional rather than universal participation(Balsiger and VanDeveer, 2010, 2012; Balsiger and Debarbieux, 2011; Elliott and Breslin, 2011). Much of the literature adopts a regional focus (Kato, 2004; Selin and Vandeveer, 2005; Komori, 2010; van Deveer, 2011) or focuses on a particular environmental issue (Schreurs, 2011; Pahl-Wostl et al., 2012). Since 60 % of the international environmental agreements are regional (UNEP, 2001; Balsiger et al., 2012), this broader set of regional environmental agreements can provide insights on designing regional climate initiatives, although further research is needed. In addition, several regional environmental agreements have climate change components, such as the Alpine Convention’s Action Plan on Climate Change in the Alps in March 2009 (Alpine Convention, 2009).

This section examines a variety of regional initiatives with climate implications. Figure 14.16 illustrates three major areas in which regional climate change coordination can be classified: climate-specific agreements, technology-focused agreements, and trade-related agreements. Most, but not all, regionally coordinated initiatives fit into one of these three categories, though some span multiple categories. In addition, some of the programs within each category have been implemented within a single geographic region, while others are intra-regional. The following sections examine regional initiatives with climate-specific objectives, trade agreements with climate implications, regional cooperation on energy, and regional cooperation schemes where mitigation and adaptation are important.

14.4.2.1 Climate specific regional initiatives

To date, specific regional climate policy initiatives have been rare, and they need to be distinguished from transnational initiatives that abound (Andonova et al., 2009). Grunewald et al. (2013) survey existing regional cooperation agreements on mitigation (except the agreements in the European Union for which a large literature exists). Of the 15 agreements surveyed, they find that most are built on existing trade or regional integration agreements or are related to efforts by donors and international agencies. Most relate to technology (see discussion below), some to finance, and some to trade. Few of them have been rigorously evaluated and the likely impact of most of these activities appears to be limited, given their informal and mostly voluntary nature. The technology-focused agreements are discussed in more detail below. The EU has been an exception to this pattern of rather loose and voluntary agreements, where deep integration has generated binding and compulsory market-based as well as regulation-based initiatives. Therefore, the discussion of impacts of the EU experience offers lessons of the promise and challenges to use regional cooperation mechanisms to further a mitigation agenda also for other regions.

Of the wide array of mitigation policy instruments (see Chapter 15 for a discussion of such instruments), only emission trading systems have been applied on a regional scale: the EU ETS covering the EU’s 27 member states, Iceland, Norway, and Liechtenstein; and the Western Climate Initiative (WCI), which initially included several states in the United States and provinces in Canada, and now includes just California and Quebec (see Section 13.7.1.2 for a detailed review).

While the EU has tried over many years to introduce a common CO_2 tax, these efforts have failed and only a minimum level of energy taxes to apply across the EU could be defined. Most other supranational climate policy initiatives specialize on certain technologies. These include the Methane to Markets Initiative, the Climate Technology Initiative, the Carbon Sequestration Leadership Forum, and the International Partnership for the Hydrogen Economy, which are open for global membership (see Bäckstrand, (2008) for a summary of these initiatives). In selected cases regional initiatives have emerged, such as the Asia-Pacific Partnership for Climate Change, and the addition of regional collaboration in the framework of the UNFCCC (e.g., the Central Group 11 (CG 11) of Eastern European countries in transition or the African Group). An evaluation of these initiatives follows.

The EU ETS

The EU ETS is a mandatory policy, which has evolved over a decade in strong interaction between the EU Commission, the European Parliament, member state governments, and industry lobbies (for an overview of the role of the different interests, see Skjærseth (2010). It has gone through three phases, and shifted from a highly decentralized to a centralized system.

The EU ETS is by far the largest emission trading system in the world, covering over 12,000 installations belonging to over 4,000 companies

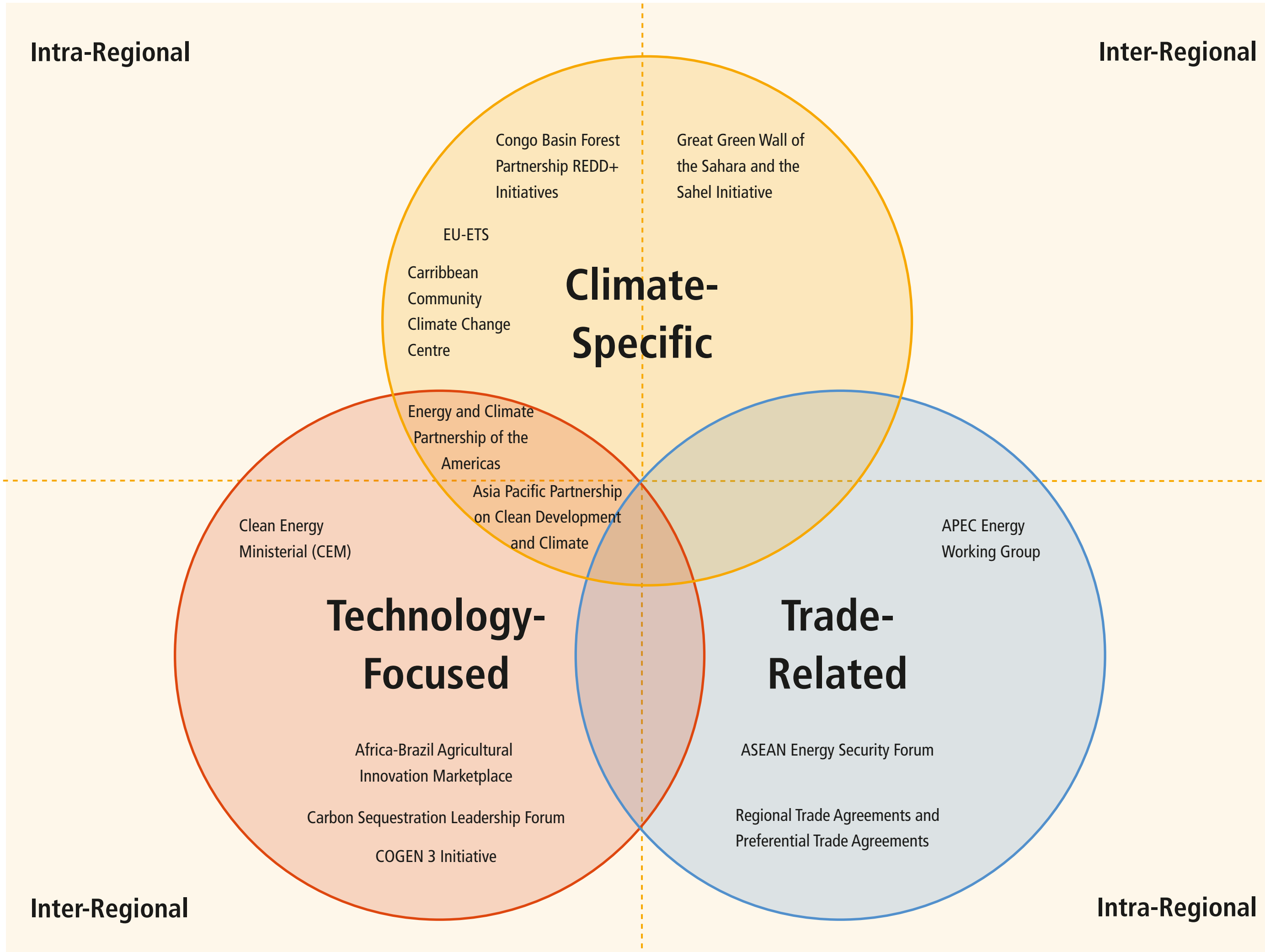


Figure 14.16 | Typology of regional agreements with mitigation implications. Figure includes selected regional agreements only, and is not comprehensive. While not all agreements fit into the typology presented in this diagram, many do.

and initially over 2 Gt of annual CO_2 emissions. It has thus been thoroughly researched (see Convery, (2009a), for a review of the literature, and Lohmann, (2011), for a general critique).

How was institutional, political, and administrative feasibility achieved in the case of the EU ETS? According to Skjærseth and Wettestad (2009), from being an opponent of market mechanisms in climate policy as late as 1997, the EU became a supporter of a large-scale emissions trading system since 2000 due to a rare window of opportunity. The Kyoto Protocol had increased the salience of climate policy, and according to EU rules, trading could be agreed through a qualified majority, whereas a carbon tax required unanimity. Industry was brought on board through grandfathering (Convery, 2009b) and the lure of windfall profits generated by passing through the opportunity cost of allowances into prices of electricity and other products not exposed to international competition.

Environmental effectiveness of the EU ETS has essentially been determined by the stringency of allowance allocation. Initially, a decentralized allocation system was put in place, which has been criticized by researchers as leading to a 'race to the bottom' by member states (Betz and Sato, 2006). Nevertheless, allowance prices reached levels of almost 40.5 USD_{2010} (30 EUR_{2008}), which was unexpected by analysts, and in the 2005–2007 pilot phase triggered emission reductions estimated from 85 $MtCO_2$ (Ellerman and Buchner, 2008) up to over 170 $MtCO_2$ (Anderson and Di Maria, 2011). The wide range is due to the difficulty to assess baseline emissions. Hintermann (2010) sees the initial price spike not as sign of a shortfall of allowances but as market inefficiency due to a bubble, exercise of market power or companies hedging against uncertain future emissions levels. This is corroborated by the fact that the release of the 2005 emissions data in April–May 2006 showed an allowance surplus and led to a price crash, as allowances could not be banked into the second period starting

2008 (see Alberola and Chevallier, (2009) for an econometric analysis of the crash). A clampdown of the EU Commission on member states' allocation plan proposals for 2008–2012 reduced allocation by 10 % (230 million tCO_2 per year for the period 2008–2012) and bolstered price levels, the crash of industrial production due to the financial and economic crisis of 2008 led to an emissions decrease by 450 $MtCO_2$ and an allowance surplus for the entire 2008–2012 period. As a result, prices fell by two-thirds but did not reach zero because allowances could be banked beyond 2012, and the Commission acted swiftly to set a stringent centralized emissions cap for the period 2013–2020 (see Skjærseth, 2010, and Skjærseth and Wettestad, 2010, for the details of the new rules and how interest groups and member states negotiated them). This stabilized prices until late 2011. But again, the unexpected persistence of industrial production decreases led to a situation of general over-allocation and pressure on allowance prices. The European Parliament and member states decided in late 2013 to stop auctioning allowances between 2013 and 2015 to temporarily take up to 900 million allowances out of the market ('backloading').

While there is a literature investigating short-term spot carbon price fluctuations, which attributes price volatility to shifts in relative coal, gas, and oil prices, weather, or business cycles (Alberola et al., 2008; Hintermann, 2010), the unexpected low prices in the EU ETS are more likely to be driven by structural factors. Four structural factors discussed in the literature are (1) the financial and economic crises (Neuhoff et al., 2012; Aldy and Stavins, 2012); (2) the change of offset regulations (Neuhoff et al., 2012); (3) the interaction with other policies (Fankhauser et al., 2010; Van den Bergh et al., 2013); and (4) regulatory uncertainty and lack of long-term credibility (Blyth and Bunn, 2011; Brunner et al., 2012; Clò et al., 2013; Lecuyer and Quirion, 2013). There is no analysis available that quantitatively attributes a relative share of these explanatory factors in the overall European Union Allowances (EUA) price development, but all four factors seemed to have played a role in the sense that the absence of any of them would have led to a higher carbon price. The following paragraphs briefly review each of the four price drivers.

Financial and economic crises—the crash of industrial production due to the financial and economic crisis of 2008 led to an emissions decrease by 450 $MtCO_2$ and an allowance surplus for the entire 2008–2012 period. This has led to a decrease in EUA prices (Aldy et al., 2003; Neuhoff et al., 2012) prices fell by two thirds but did not reach zero because allowances could be banked beyond 2012, and the Commission acted swiftly to set a stringent centralized emissions cap for the period 2013–2020 (see Skjærseth (2010) and Skjærseth and Wettestad (2010) for the details of the new rules and how interest groups and member states negotiated them). This action stabilized prices until late 2011. Nonetheless, since then the price has again dropped and the surplus has reached approximately 2 billion tCO_2 (European Commission, 2013a). Schopp and Neuhoff (2013) argue that when the surplus of permits in the market exceeds the hedging needs of market participants—which they find to be the case in the period from 2008 to at least 2020—the remaining purchase of allowance is driven by speculators applying high discount rates. As a consequence, the EUA price remains below its long-term trend in the short-term until sufficient scarcity is back in the market.

Import of offsets—The use of offsets should not have influenced the price, as market participants should consider the future scarcity of offset credits and there is a limit to the maximum cumulated use of offsets between 2008 and 2020. Most large companies covered by the EU ETS engaged in futures contracts for CER acquisition as early as 2006. However, changes in offset regulations in 2009 and 2011 led to a pressure to rapidly import Certified Emission Reductions and Emission Reduction Units (CERs, ERUs). As due to rapidly rising issuance of CERs, imports approached the maximum level allowed for the period 2008–2020, price pressure on CERs/ERUs increased, which in turn generated pressure on the price of EUAs (Neuhoff et al., 2012).

Interaction with other policies—Interaction of the EU ETS with other mitigation policies and the resulting effects on economic efficiency has been discussed by del Río (2010) for renewable energy and energy-efficiency policies, by Sorrell et al. (2009) for renewable energy certificates, by Frondel et al. (2010) for renewable feed-in tariffs, and by Kautto et al. (2012) for biomass energy. These studies find that other mitigation policies can drive the allowance price down due to a decrease in the demand of allowances (Fankhauser et al. 2010; Van den Bergh et al., 2013). However, there is no robust scientific assessment that identifies which share of the price decline is due to expansion of renewable energy and improvement of energy efficiency. Section 15.7.3 deals with this issue of policy interactions such as those of the EU ETS and EU policies on energy efficiency, renewable, and biofuels in more detail, including also a welfare analysis of such interactions.

Regulatory uncertainty and lack of long-term credibility—Regulatory uncertainty (Clò et al., 2013; Lecuyer and Quirion, 2013) and the lack of long-term credibility (Brunner et al., 2012) might also have influenced the decline of the carbon price. The uncertainties surrounding 2030 and 2040 targets, potential short-term interventions to address the low allowance price, the outcome of international climate negotiations, as well as the inherent lack of credibility of long-term commitment due to potential time inconsistency problems (Brunner et al., 2012) probably increases the discount rate applied by market participants on future carbon prices. Indeed, it has been pointed out that the current linear reduction factor of 1.74 % per year is not in line with ambitious 2050 emission targets (achieving only around 50 % emissions reduction compared to the EU's 80–95 % target) (Neuhoff, 2011). However, while lack of credibility as a factor driving EU ETS prices has been discussed in some theoretical articles, no empirical evidence on the magnitude of this factor on EUA prices is available.

Economic effectiveness of the EU ETS has been discussed with respect to the mobilization of the cheapest mitigation options. While cheap options such as biomass co-firing for coal power plants have been exploited, it is contested whether price levels of allowances have been sufficiently high after the 2005 and 2009 crashes to drive emissions reduction. Literature suggests that they have not been high enough to drive renewable energy investment in the absence of feed-in tariffs (Blanco and Rodrigues, 2008). Engels et al. (2008) surveyed companies covered by the EU ETS and found widespread evidence of irrational behavior, i.e., companies not mitigating even if costs were substantially below allowance prices. Engels (2009) even finds that many companies did not know their abatement costs. A barrier to participation in trading could have been the highly scale-specific transaction costs, which were estimated to reach over 2 EUR/EUA for small companies in Ireland (Jaraitė et al., 2010). Given that 75% of installations were responsible for just 5% of emissions in 2005–2006 (Kettner et al., 2008), this is a relevant barrier to market participation. Another way of mobilizing cheap options is increasing the reach of the EU ETS, either through linking to other trading schemes or by allowing import of offset credits. Anger et al. (2009) find that linking can substantially reduce compliance cost, especially if the allocation is done in an efficient way that does not advantage energy-intensive industries. Linking to the states of the European Economic Area and Switzerland has not been researched to a large extent, with the exception of Schäfer (2009), who shows how opposition of domestic interest groups in Switzerland and lacking flexibility of the EU prevented linking. Access to credits from the project-based mechanisms was principally allowed by the 'Linking Directive' agreed in 2004. In 2005–2007, companies covered by the EU ETS could import credits from the mechanisms without limit, but access to the mechanisms has been reduced over time, e.g., by national level limitations in the 2008–2012 period and a central limitation for 2013–2020. The import option was crucial for the development of the CDM market (Wettestad, 2009) and drove CER prices. Skjærseth and Wettestad (2008), Chevallier (2010) and Nazifi (2010) discuss the exchange between the member states and the EU Commission about import thresholds for the 2008–2012 period.

Distributional and broader social impacts of the EU ETS have not been assessed by the literature to date except for impacts on specific industrial sectors. While the majority of allowances for the electricity sector are now sold through auctions, other industries receive free allocations according to a system of 52 benchmarks. Competitiveness impacts of the EU ETS have been analyzed intensively. Demailly and Quirion (2008) find that auctioning of 50% of allocations would only lead to a 3% loss in profitability of the steel sector, while in their analysis for the cement sector Demailly and Quirion (2006) see a stronger exposure with significant production losses at 50% auctioning. Grubb and Neuhoff (2006) and Hepburn et al. (2006) extended this analysis to other sectors and concluded that higher shares of auctioning are not jeopardizing competitiveness.

Summing up the experiences from the EU ETS, institutional feasibility was achieved by a structurally lenient allocation, which puts into doubt its environmental effectiveness. There was a centralization of allocation over time, taking competences away from national governments. Several factors have pushed the carbon prices down in the second phase of the EU ETS. This has created a situation in which the target set by European policy makers is achieved, but carbon prices are low; while there are efforts to stabilize the carbon price through backloading or an ambitious emission target for 2030, at the time of this writing it has proven politically difficult to reach agreement on these matters. Future reform of the EU ETS will need to clarify the objectives of the scheme, i.e., a quantitative emissions target or a strong carbon price (e.g., to stimulate development of mitigation technologies). The link to the project-based mechanisms was important to achieve cost-effectiveness, but this has been eroded over time due to increasingly stringent import limits.

14.4.2.2 Regional cooperation on energy

Given the centrality of the energy sector for mitigation, regional cooperation in the energy sector could be of particular relevance. Regional cooperation on renewable energy sources (RES) and energy efficiency (EE) typically emerges from more general regional and/or interregional agreements for cooperation at economic, policy, and legislative levels. It also arises through initiatives to share available energy resources and to develop cross-border infrastructure. Regional cooperation mechanisms on energy take different forms depending, among others, on the degree of political cohesion in the region, the energy resources available, the strength of economic ties between participating countries, their institutional and technical capacity, and the financial resources that can be devoted to cooperation efforts.

In this context, it is also important to consider spillovers on energy that may appear due to trade. As discussed in Chapter 6 (Section 6.6.2.2), mitigating climate change would likely lead to lower import dependence for energy importers (Shukla and Dhar, 2011; Criqui and Mima, 2012). The flip side of this trend is that energy-exporting countries could lose out on significant energy-export revenues as the demand for and prices of fossil fuels drops.[3] The effect on coal exporters is very likely to be negative in the short- and long-term as mitigation action would reduce the attractiveness of coal and reduce the coal wealth of exporters (Bauer et al., 2013a; b; Cherp et al., 2013; Jewell et al., 2013). Gas exporters could win out in the medium term as coal is replaced by gas. The impact on oil is more uncertain. The effect of climate policies on oil wealth and export revenues is found to be negative in most studies (IEA, 2009; Haurie and Vielle, 2011; Bauer et al., 2013a; b; McCollum et al., 2014; Tavoni et al., 2014). However, some studies find that climate policies would increase oil export revenues of mainstream exporters by pricing carbon-intensive unconventionals out of the market (Persson et al., 2007; Johansson et al., 2009; Nemet and Brandt, 2012). See also Section 6.3.6.6.

In the following section, some examples of regional cooperation will be briefly examined, namely the implementation of directives on renewable energy resources in the EU (European Commission, 2001, 2003, 2009b) and in South East Europe under the Energy Community Treaty

[3] See also Section 13.4 on burden sharing regimes that could be used to offset the possible decrease in export revenue for fossil exporters.

(Energy Community, 2005, 2008 and 2010), and energy resource sharing through regional power pools and regional cooperation on hydropower.

Regional cooperation on renewable energy in the European Union

The legislative and regulatory framework for renewable energy in the EU has been set up through several directives of the European Commission adopted by EU member states and the European parliament (European Commission, 2001, 2003, 2009b). These directives are an example of a regulatory instrument, in contrast to the cap-and-trade mechanism of the EU ETS described above. In the past, the European Community adopted two directives on the promotion of electricity from renewable sources and on the promotion of biofuels (European Commission, 2001, 2003). These two EU directives established indicative targets for electricity from renewable sources and biofuels and other renewables in transport, respectively, for the year 2010. Furthermore, they started a process of legal and regulatory harmonization and required actions by EU member states to improve the development of renewable energy (Haas et al., 2006, 2011; Harmelink et al., 2006). There was progress toward the targets, but it did not occur at the required pace (Rowlands, 2005; Patlitzianas et al., 2005; European Commission, 2009a; Ragwitz et al., 2012). Therefore, the European Commission proposed a comprehensive legislative and regulatory framework for renewable energy with binding targets.

This led to the introduction of the Directive 2009/28/EC on the promotion of RES (European Commission, 2009b). In this directive, EU Member States agreed to meet binding targets for the share of RES in their gross final energy consumption by the year 2020. The overall target for the European Union is 20 % of EU gross final energy consumption to come from RES by the year 2020. The share of renewables in gross final energy consumption has indeed increased substantially after passage of the directive and stands at around 13 % in 2011.

The RES Directive is part of the EU climate and energy package (European Commission, 2008). As such, it has interactions with the other two pillars, namely the EU ETS and the EE-related directives. On the basis of model analysis, the European Commission (European Commission, 2011b) estimates that the implementation of the EU RES directive could represent an emissions reduction of between 600 and 900 $MtCO_2eq$ by the year 2020 in the EU-27 compared to a baseline scenario (Capros et al., 2010). The introduction of regulatory instruments targeted at RES and/or EE on top of the EU ETS appears justified on the grounds of the failure of the market to provide incentives for the uptake of these technologies (European Commission, 2013a). Still, the combined emission reductions resulting from RES deployment and EE measures leave the EU ETS with a reduced portion of the effort necessary to achieve the 20 % EU emission reduction target by 2020 (e.g., European Commission, 2013a). This, as discussed above, has contributed to a reduced carbon price in the EU ETS (Abrell and Weigt, 2008; OECD, 2011a), affecting its strength as a signal for innovation and investments in efficiency and low-carbon technologies (e.g., European Commission, 2013b). Therefore, coordination between RES and EE policies and the EU ETS is needed and could include introducing adjustment mechanisms into the EU ETS.

The implementation of the EU directives for renewable energy and the achievement of the national targets have required considerable efforts to surmount a number of barriers (Held et al., 2006; Haas et al., 2011; Patlitzianas and Karagounis, 2011; Arasto et al., 2012). One obstacle is the heterogeneity between EU member states regarding their institutional capacity, know-how, types of national policy instruments and degrees of policy implementation (e.g., European Commission, 2013c). Still, the EU directives for renewable energy have contributed to advancing the introduction of RES in the member states (Cardoso Marques and Fuinhas, 2012). This regional cooperation has taken place in the framework of a well-developed EU integration at the political, legal, policy, economic, and industrial level. Only with these close integration ties has it been possible to implement EU directives on RES.

Power pools for energy resources sharing

Power pools have evolved as a form of regional cooperation in the electricity sector and are an example of an opportunity for mitigation that only arises for geographically close countries. Electricity interconnections and common markets in a region primarily serve the purpose of sharing least-cost generation resources and enhancing the reliability of supply. Getting regional electricity markets to operate effectively supports mitigation programs in the electricity sector. Cross-border transmission systems (interconnectors), regional markets and trade, and system-operating capability play a major role in both the economics and feasibility of intermittent renewables. In some cases, power pools provide opportunities for sharing renewable energy sources, notably hydropower and wind energy, facilitating fuel switching away from fossil fuels (ICA, 2011; Khennas, 2012). In this context, there is a correlation between the development of the power pool and the ability of a region to develop renewable electricity sources (Cochran et al., 2012). A combination of electricity sector reform, allowing power utilities to be properly run and sustainable, and regional wholesale market development, with the corresponding regional grid development, is necessary to tap their potential.

An example of a well-established power pool is the Nord Pool, the common market for electricity in Scandinavia, covering Denmark, Sweden, Norway, and Finland. The Nordic power system is a mixture of hydro, nuclear, wind, and thermal fossil power. With this mix, the pool possesses sizeable amounts of flexible regulating generation sources, specifically hydropower in Norway. These flexible hydropower plants and pump storage plants allow compensating the inflexibility of wind power generation (e.g., in Denmark), which cannot easily follow load changes. Through the wholesale market, the Nord Pool can absorb and make use of excess wind electricity generation originating in Denmark, through complementary generation sources. This allows the Nord Pool to integrate a larger share of wind energy (e.g., Kopsakangas-Savolainen and Svento, 2013).

Box 14.1 | Regional cooperation on renewable energy in the Energy Community

The Energy Community extends the EU internal energy market to South East Europe and beyond, based on a legally binding framework. The Energy Community Treaty (EnCT) establishing the Energy Community entered into force on 1 July 2006 (Energy Community, 2005). The Parties to the Treaty are the European Union, and the Contracting Parties Albania, Bosnia and Herzegovina, Croatia, Former Yugoslav Republic of Macedonia, Montenegro, Serbia, the United Nations Interim Administration Mission in Kosovo (UNMIK), Moldova and Ukraine. The Energy Community treaty extended the so-called '*acquis communautaire*', the body of legislation, legal acts, and court decisions, which constitute European law, to the contracting parties. As a result, contracting parties are obliged to adopt and implement several EU directives in the areas of electricity, gas, environment, competition, renewable energies, and energy efficiency. In the field of renewable energy, the EU acquis established the adoption of the EU directives on electricity produced from renewable energy sources and on biofuels. As a further step, in 2012, the Energy Community adopted the EU RES Directive 2009/28/EC (Energy Community, 2012). This allows contracting parties to use the cooperation mechanisms (statistical transfers, joint projects, and joint support schemes) foreseen by the RES directive under the same conditions as the EU member states.

Analyses of the implementation of the *acquis* on renewables in the energy community (EIHP, 2007, p. 2007; Energy Community, 2008; IEA, 2008; IPA and EPU-NTUA, 2010) found that progress in implementing the EU directives has been dissimilar across Contracting Parties, among others due to the heterogeneity between these countries in institutional capacity, know-how, and pace of implementation of policies and regulatory frameworks (Energy Community, 2010; Mihajlov, 2010; Karakosta et al., 2011; Tešić et al., 2011; Lalic et al., 2011). Still, economic and political ties between South East Europe and the European Union and the prospect of contracting parties to become EU member states have contributed to the harmonization of legal, policy, and regulatory elements for RES (Renner, 2009, p. 20). Through the legally binding Energy Community Treaty, the European Union has exported its legislative frameworks on RES and EE to a neighboring region. Their further implementation, however, requires strengthening national and regional institutional capacity, developing regional energy markets and infrastructure, and securing financing of projects.

In Africa there are five main power pools, namely the Southern Africa Power Pool (SAPP), the West African Power Pool (WAPP), the East African Power Pool (EAPP), the Central African Power Pool (CAPP), and the Comité Maghrébin de l'Electricité (COMELEC). The SAPP, for example, includes 12 countries: Botswana, Lesotho, Malawi, South Africa, Swaziland, Zambia, Zimbabwe, Namibia, Tanzania, Angola, Mozambique, and Democratic Republic of the Congo. Its generation mix is dominated by coal-based power plants from South Africa, which has vast coal resources and the largest generation capacity within SAPP. Other resources available in the SAPP are hydropower from the northern countries and, to a lower extent, nuclear power, and gas and oil plants (Economic Consulting Associates (ECA), 2009; ICA, 2011). Overall the scale of trade within these power pools is small, leading to continued inefficiencies in the distribution of electricity generation across the continent (Eberhard et al., 2011). One of the driving forces in SAPP is supplying rapid demand growth in South Africa with hydropower generated in the northern part of the SAPP region. This way, the power pool can contribute to switching from coal to hydropower (ICA, 2011; IRENA, 2013). African power pools and related generation and transmission projects are financed through different sources, including member contributions, levies raised on transactions in the pool and donations and grants (Economic Consulting Associates (ECA), 2009). To the extent that financial sources are grants or loans from donor countries or multi-lateral development banks, there exists the possibility to tie financing to carbon performance standards imposed on electricity generation and transmission infrastructure projects.

Regional gas grids

Regional gas grids offer similar opportunities for mitigation (see Chapter 7). In particular, they allow the replacement of high-carbon coal-fired and diesel generation of electricity by gas-fired plants. Such gas grids are developing in East Asia linking China with gas exporting countries as well as in Eastern Europe, again linking gas exporters in Eastern Europe and Central Asia with consumers in Western Europe with the EU taking a coordinating role (Victor, 2006).

Regional cooperation on hydropower

Regional cooperation on hydropower may enable opportunities for GHG-emissions reduction for geographically close countries by exploiting hydropower power potential in one country and exporting electricity to another, by joint development of a transboundary river system (van Edig et al., 2001; Klaphake and Scheumann, 2006; Wyatt and Baird, 2007; Grumbine et al., 2012), or by technology cooperation and transfer to promote small hydropower (UNIDO, 2010; Kumar et al., 2011; Kaunda et al., 2012). The development of hydropower potential, however, needs to comply with stringent environmental, social and economic sustainability criteria as it has important ramifications for development and climate change in the affected regions (Kumar et al., 2011). In addition, there are difficult economic, political, and social issues regarding water sharing, upstream and downstream impacts, and other development objectives. Given its vulnerability to droughts and other impacts of climate change, hydropower development requires careful planning, including provisions for complementary electricity generation sources (Zarsky, 2010; Nyatichi Omambi et al., 2012)

Regional cooperation on energy efficiency standards and labelling

Standards and labels (S&L) for energy-efficient products are useful in accelerating market transformation towards more energy-efficient technologies. Energy-efficiency S&L programs help, for instance, reducing consumption of fossil fuels (e.g., diesel) for electricity generation. Also, when applied to biomass-based cook stoves, S&L help decreasing the use of traditional biomass for cooking (Jetter et al., 2012). Standards and labelling programs at a regional-scale provide critical mass for the creation of regional markets for energy efficiency and, therefore, incentives to equipment manufacturers. They are also useful in reducing non-tariff barriers to trade (NAEWG, 2002). Examples of existing S&L regional programs are the European Energy Labelling directive, first published as Directive 92/75/EEC by the European Commission in 1992 (European Commission, 1992) and subsequently revised (Directive 2010/30/EU; European Commission, 2010), to harmonize energy-efficiency S&L throughout EU member states and harmonization efforts on energy-efficiency S&L between the U.S, Canada, and Mexico as a means to reduce barriers to trade within the North American Free Trade Agreement (NAFTA), (NAEWG, 2002; Wiel and McMahon, 2005; Geller, 2006). Currently, several regional S&L initiatives are being developed, such as the Economic Community of West African States (ECOWAS) regional initiative on energy-efficiency standards and labelling (ECREEE, 2012a), and the Pacific Appliance Labelling and Standards (PALS) program in Pacific Island Countries (IIEC Asia, 2012).

14.4.2.3 Climate change cooperation under regional trade agreements

International trade regulation is particularly relevant as mitigation and adaptation policies often depend on trade policy (Cottier et al., 2009; Hufbauer et al., 2010; Aerni et al., 2010). On the one hand, trade liberalization induces structural change, which can have a direct impact on emissions of pollutants such as GHGs. On the other hand, regional trade agreements (RTAs), while primarily pursuing economic goals, are suitable to create mechanisms for reducing emissions and establish platforms for regional cooperation on mitigation and adaptation to climate change. In parallel to provisions on elimination of tariff and non-tariff trade barriers, the new generation of RTAs contains so called WTO-X provisions, which promote policy objectives that are not discussed at the multilateral trade negotiations (Horn et al., 2010). In particular, they offer the potential to refine criteria for distinctions made on the basis of process and production methods (PPMs), which are of increasing importance in addressing the linkage of trade and environment and of climate change mitigation in particular.

Regional trade agreements have flourished over the last two decades. As of December 2013, the World Trade Organization (WTO) acknowledged 379 notifications of RTAs to be in force(WTO, 2013), half of which went into force only after 2000. This includes bilateral as well as multilateral agreements such as, e.g., the EU, the NAFTA, the Southern Common Market (MERCOSUR), the Association of Southeast Asian Nations (ASEAN) and the Common Market of Eastern and Southern Africa (COMESA). Regional trade agreements increasingly transgress regional relations and encompass transcontinental preferential trade agreements (PTAs).

According to the economic theory of international trade, PTAs foster trade within regions and amongst member countries (trade creation) and they are detrimental to trade with third parties since trade with non-member countries is replaced by intraregional trade (trade diversion). Although the impacts of trade creation and trade diversion have not been analyzed theoretically with respect to their environmental impacts, conclusion by analogy implies that the effects on pollution-intensive and green industries can be positive or negative depending on the patterns of specialization. Most empirical studies look at NAFTA and find mixed evidence on the environmental consequences of regional trade integration in North America (Kaufmann et al., 1993; Stern, 2007). The effects of NAFTA on Mexico turn out to be small. Akbostancı et al. (2008) look at the EU-Turkey free trade agreement and find weak evidence that the demand for dirty imports declined slightly. A study including 162 countries that were involved in RTAs supports the view that regional trade integration is good for the environment (Ghosh and Yamarik, 2006). Among empirical studies looking at the effects of trade liberalization in general, Antweiler et al. (2001), Frankel and Rose (2005), Kellenberg (2008) and Managi et al. (2009) indicate that freer trade is slightly beneficial to the environment. As shown in Section 14.3.4, carbon embodied in trade is substantial and it has been increasing from 1990 to 2008 (Peters et al., 2011).

Trade liberalization in major trade regions has fostered processes that are relevant to climate change mitigation via the development of cooperation on climate issues. (Dong and Whalley, 2010, 2011) look at environmentally motivated trade agreements and find that their impacts, albeit positive, are very small. Many PTAs contain environmental chapters or environmental side-agreements, covering the issues of environmental cooperation and capacity building, commitments on enforcement of national environmental laws, dispute settlement mechanisms regarding environmental commitments, etc. (OECD, 2007). In the case of NAFTA, the participating countries (Canada, Mexico, and the United States) created the North American Agreement on Environmental Cooperation (NAAEC). The NAAEC established an international organization, the Commission for Environmental Cooperation (CEC), to facilitate collaboration and public participation to foster conservation, protection, and enhancement of the North American environment in the context of increasing economic, trade, and social links among the member countries. Several factors, such as the CEC's small number of actors, the opportunities for issue linkage, and the linkage between national and global governance systems have led to beneficial initiatives; yet assessments stress its limitations and argue for greater interaction with other forms of climate governance in North America (Betsill, 2007). The Asia-Pacific Economic Forum (APEC) provides an example of how trade-policy measures can be used to promote trade and investment in environmental goods and services. In 2011, APEC leaders reaffirmed to reduce the applied tariff rate to 5 % or less on goods on the APEC list of environmental goods by the end of 2015 (APEC, 2011). Although the legal status of these political declarations is non-binding, this 'soft law' can help to define the standards of good behavior of a 'well-governed state' (Dupuy, 1990; Abbott and Snidal, 2000).

Recent evidence suggests that environmental provisions in RTAs do affect CO_2 emissions of member countries (Baghdadi et al., 2013). Member countries of RTAs that include environmental harmonization policies converge in CO_2 emissions per capita, with the gap being 18 % lower than in countries without an RTA. On the other hand, member countries of RTAs not containing such an environmental agreement tend to diverge in terms of CO_2 emissions per capita. Moreover, the authors find that membership in an RTA *per se* does not affect average CO_2 emissions significantly whereas environmental policy harmonization within an RTA has a very small (0.3 %) but significant effect on reducing emissions. Thus, regional agreements with environmental provisions lead to slightly lower average emissions in the region and a strong tendency for convergence in those emissions.

There is a potential to expand PTA environmental provisions to specifically cover climate policy concerns. One of the few existing examples of enhanced bilateral cooperation on climate change under PTAs relates to the promotion of capacity building to implement the CDM under the Kyoto Protocol provided for in Article 147 of the Japan-Mexico Agreement for the Strengthening of the Economic Partnership. Holmes et al. (2011) argue that PTAs can include provisions on establishment of ETSs with mutual recognition of emissions allowances (i. e., linking national ETSs in a region) and carbon-related standards. In promoting mitigation and adaptation goals, PTAs can go beyond climate policy cooperation provisions in environmental chapters and make climate protection a crosscutting issue. Obligations to provide know-how and transfer of technology, as well as concessions in other areas covered by a PTA can provide appropriate incentives for PTA parties to accept tariff distinctions based on PPMs (Cosbey, 2004). Although PTAs constitute their own regulatory system of trade relations, the conclusion of PTAs, the required level of trade liberalization, and trade measures used under PTAs are subject to WTO rules (Cottier and Foltea, 2006). While trade measures linked to emissions is a contentious issue in the WTO (Bernasconi-Osterwalder et al., 2006; Holzer, 2010; Hufbauer et al., 2010; Conrad, 2011), the use of carbon-related trade measures under PTAs provides greater flexibility compared to their application in normal trade based on the most-favored nation (MFN) principle. Particularly, it reduces the risk of trade retaliations and the likelihood of challenge of a measure in the WTO dispute settlement (Holzer and Shariff, 2012).

While concerns are expressed in the literature about the coherence between regional and multilateral cooperation (Leal-Arcas, 2011), it is also recognized that PTAs could play a useful role in providing a supplementary forum for bringing together a number of key players (Lawrence, 2009) and fostering bilateral, regional, and trans-regional environmental cooperation (Carrapatoso, 2008; Leal-Arcas, 2013). With the current complexities of the UNFCCC negotiations, PTAs with their negotiation leverages and commercial and financial incentives can facilitate achievement of climate policy objectives. They can also form a platform for realization of mitigation and adaptation policies elaborated at a multilateral level (Fujiwara and Egenhofer, 2007).

14.4.2.4 Regional examples of cooperation schemes where synergies between adaptation and mitigation are important

Referring to potential regional actions to integrate adaptation and mitigation, Burton et al. (2007) point out the need to incorporate adaptation in mitigation and development policies. An integrated approach to climate change policies was considered and large-scale mitigation opportunities at the national and regional level were identified, indicating that scaling up could be realized through international initiatives (Kok and De Coninck, 2007).The UNFCCC Cancun agreements include mandates for multiple actions at the regional level, in particular related to adaptation and technology (UNFCCC, 2011). Some authors also underlined the importance of the linkage between adaptation and mitigation at the project level, in particular where the mitigative capacity is low and the need for adaptation is high. This linkage facilitates the integration of sustainable development priorities with climate policy, as well as the engagement of local policymakers in the mitigation agenda (Ayers and Huq, 2009). Section 4.6 underlines the large similarities and the complementarities between mitigative and adaptive capacities.

Opportunities of synergies vary by sector (Klein et al., 2007). Promising options can be primarily identified in sectors that can play a major role in both mitigation and adaptation, notably land use and urban planning, agriculture and forestry, and water management (Swart and Raes, 2007). It has been stated that forest-related mitigation activities can significantly reduce emissions from sources and increase CO_2 removals from sinks at a low cost. It was also suggested that those activities can be designed promoting synergies with adaptation and sustainable development (IPCC, 2007). Adaptation measures in the forestry sector are essential to climate change mitigation, for maintaining the forest functioning status addressing the negative impacts of climate change ('adaptation for forests'). They are also needed due to the role that forests play in providing local ecosystem services that reduce vulnerability to climate change ('adaptation for people') (Vignola et al., 2009; Locatelli et al., 2011). Information and multiple examples on interactions between mitigation and adaptation that are mutually reinforcing in forests ecosystems and agriculture systems are provided in Section 11.5.

Examples where integration of mitigation and adaptation processes are necessary include REDD+ activities in the Congo Basin, a region where there are well-established cooperation institutions to deal with common forest matters, such as the Central Africa Forest Commission (COMIFAC) and the Congo Basin Forest Partnership (CBFP). Some authors consider that the focus is currently on mitigation, and adaption is insufficiently integrated (Nkem et al., 2010). Other authors have suggested designing an overarching environmental road map or policy strategy. The policy approaches for implementing REDD+, adaptation, biodiversity conservation and poverty reductions may arise from them (Somorin et al., 2011).

The Great Green Wall of the Sahara, launched by the African Union, is another example to combine mitigation and adaptation approaches to address climate change. It is a priority action of the Africa-EU Partnership on Climate (European Union, 2011). The focus of the initiative is adaptation and mitigation to climate change through sustainable land management (SLM) practices. These practices are increasingly recognized as crucial to improving the resilience of land resources to the potentially devastating effects of climate change in Africa (and elsewhere). Thus, it will contribute to maintaining and enhancing productivity. SLM practices, which are referred in Section 14.3.5 of this report, also contribute to mitigate climate change through the reduction of GHG emissions and carbon sequestration (Liniger et al., 2011).

There may, however, also be significant differences across regions in terms of the scope of such opportunities and related regional cooperative activities. At present there is not enough literature to assess these possible synergies and tradeoffs between mitigation and adaptation in sufficient depth for different regions.

14.4.3 Technology-focused agreements and cooperation within and across regions

A primary focus of regional climate agreements surrounds the research, development, and demonstration (RD&D) of low-carbon energy technologies, as well as the development of policy frameworks to promote the deployment of such technologies within different national contexts (Grunewald et al., 2013). While knowledge-sharing and joint RD&D agreements related to climate change mitigation are possible in bilateral, regional, and larger multilateral frameworks (de Coninck et al., 2008), regional cooperation mechanisms may evolve as geographical regions often exhibit similar challenges in mitigating climate change. In some cases these similarities serve as a unifying force for regional technology agreements or for cooperation on a particular regionally appropriate technology.

Other regional agreements do not conform to traditional geographically defined regions, but rather may be motivated by a desire to transfer technological experience across regions. In the particular case of technology cooperation surrounding climate change mitigation, regional agreements are frequently comprised of countries that have experience in developing or deploying a particular technology, and countries that want to obtain such experience and deploy a similar technology. While many such agreements include countries from the North sharing such experience with countries from the South, it is increasingly common for agreements to also transfer technology experiences from North to North, or from South to South. Other forms of regional agreements on technology cooperation, including bilateral technology cooperation agreements, may serve political purposes such as to improve bilateral relations, or contribute to broader development assistance goals. Multilateral technology agreements, such as those facilitated under the UNFCCC, the Montreal Protocol, the IEA, and the GEF, are not included in the scope of this chapter as they are discussed in Chapter 13.

While there has been limited assessment of the efficacy of regional agreements, when available such assessments are reviewed below.

14.4.3.1 Regional technology-focused agreements

Few regional technology-focused agreements conform to traditional geographically defined regions. One exception is the Energy and Climate Partnership of the Americas (ECPA), which was initiated by the United States, and is a regional partnership among Western hemisphere countries to jointly promote clean energy, low-carbon development, and climate-resilient growth (ECPA, 2012). Argentina, Brazil, Canada, Chile, Colombia, Costa Rica, Dominica, Mexico, Peru, Trinidad, and Tobago, and the United States as well as the Inter-American Development Bank (IDB) and the Organization of American States (OAS) have announced initiatives and/or are involved in ECPA-supported projects. They focus on a range of topics, including advanced power sector integration and cross border trade in electricity, advancing renewable energy, and the establishment of an Energy Innovation Center to serve as a regional incubator for implementation and financing of sustainable energy innovation (ECPA, 2012). The ECPA could provide a model for other neighboring countries to form regionally coordinated climate change partnerships focused on technologies and issues that are of common interest within the region.

While not explicitly focused on climate, the Regional Innovation and Technology Transfer Strategies and Infrastructures (RITTS) program provides an interesting example of a regionally coordinated technology innovation and transfer agreement that could provide a model for regional technology cooperation. RITTS reportedly helped to develop the EU's regional innovation systems, improve the efficiency of the support infrastructure for innovation and technology transfer, enhance institutional capacity at the regional level, and promote the exchange of experiences with innovation policy (Charles et al., 2000).

The ASEAN is a particularly active region in organizing initiatives focused on energy technology cooperation that may contribute to climate change mitigation. ASEAN has organized the Energy Security Forum in cooperation with China, Japan, and Korea (the ASEAN+3) that aims to promote greater emergency preparedness, wider use of energy efficiency and conservation measures, diversification of types and sources of energy, and development of indigenous petroleum (Philippine Department of Energy Portal, 2014). The Forum of the Heads of ASEAN Power Utilities/Authorities (HAPUA) includes working groups focused on electricity generation, transmission, and distribution; renewable energy and environment; electricity supply industry services; resource development; power reliability and quality; and human resources (Philippine Department of Energy Portal, 2014). ASEAN's Center on Energy (ACE) (previously called the ASEAN-EC Energy Management Training and Research Center) was founded in 1990 as an intergovernmental organization to initiate, coordinate, and facilitate energy cooperation for the ASEAN region, though it lacks a mandate to implement actual projects (Kneeland et al., 2005; UNESCAP, 2008; Poocharoen and Sovacool, 2012). In addition, the European Commission partnered with the ASEAN countries in the COGEN 3 initiative, focused on promoting cogeneration demonstration projects using biomass, coal, and gas technologies (COGEN3, 2005). Regional energy cooperation in the ASEAN region has been mainly motivated by concerns about security of energy supply (Kuik et al., 2011) and energy access (Bazilian et al., 2012a), an increasing energy demand, fast-rising fossil fuel imports, and rapidly growing emissions of GHGs and air pollutants (USAID, 2007; UNESCAP, 2008; Cabalu et al., 2010; IEA, 2010b; c). As a result, some policies have translated into action on the ground. For example, during the APAEC 2004–2009, the regional 10 % target to increase the installed renewable energy-based capacities for electricity generation was met (Kneeland et al., 2005; Sovacool, 2009; ASEAN, 2010; IEA, 2010c).

The APEC also has an Energy Working Group (EWG) that was launched in 1990 to maximize the energy sector's contribution to the region's economic and social well-being, while mitigating the environmental effects of energy supply and use (APEC Secretariat, 2012).

The ECOWAS regional energy program aims to strengthen regional integration and to boost growth through market development to fight poverty (ECOWAS, 2003, 2006). The ECOWAS Energy Protocol includes provisions for member states to establish energy-efficiency policies, legal and regulatory frameworks, and to develop renewable energy sources and cleaner fuels. It also encourages ECOWAS member states to assist each other in this process. The ECOWAS has recently expanded further energy access initiatives, which were launched by The Regional Centre for Renewable Energy and Energy Efficiency (ECREEE, 2012a; b).

There are also examples of institutions that have been established to serve as regional hubs for international clean energy technology cooperation. For example, the Asia Energy Efficiency and Conservation Collaboration Center (AEEC), which is part of the Energy Conservation Center of Japan, promotes energy efficiency and conservation in Asian countries through international cooperation (ECCJ/AEEC, 2011). One of the longest-established institutions for promoting technology transfer and capacity building in the South is the Asian and Pacific Center for Transfer of Technology (APCTT), based in New Delhi, India. Founded in 1977, APCTT operates under the auspices of the United Nations Economic and Social Commission for Asia and the Pacific to facilitate technology development and transfer in developing countries of the region, with special emphasis on technological growth in areas such as agriculture, bioengineering, mechanical engineering, construction, microelectronics, and alternative energy generation (Asia-Pacific Partnership on Clean Development and Climate, 2013).

14.4.3.2 Inter-regional technology-focused agreements

Some technology agreements have brought together non-traditional regions, or spanned multiple regions. For example, the Asia-Pacific Partnership on Clean Development and Climate (APP) brought together Australia, Canada, China, India, Japan, Korea, and the United States. These countries did not share a specific geography, but had common interests surrounding mitigation technologies, as well as a technology-oriented approach to climate change policy. The purpose of the APP was to build upon existing bilateral and multilateral initiatives, although it was perceived by some to be offered forth by the participating nations as an alternative to the Kyoto Protocol (Bäckstrand, 2008; Karlsson-Vinkhuyzen and Asselt, 2009; Lawrence, 2009; Taplin and McGee, 2010). The APP was a public-private partnership that included many active private sector partners in addition to governmental participants that undertook a range of projects across eight task forces organized by sector. Initiated in 2006, the work of the APP was formally concluded in 2011, although some projects have since been transferred to the Global Superior Energy Performance Partnership (GSEP) under the Clean Energy Ministerial. This includes projects from the sectoral task forces on power generation and transmission, cement, and steel (US Department of State, 2011; Clean Energy Ministerial, 2012). One study reviewing the implementation of the APP found that a majority of participants found the information and experiences exchanged within the program to be helpful, particularly on access to existing technologies and know-how (Okazaki and Yamaguchi, 2011; Fujiwara, 2012). The APP's record on innovation and access to newer technologies was more mixed, with factors such as limited funding and a lack of capacity for data collection and management perceived as barriers (Fujiwara, 2012). As discussed in Section 13.6.3, it may also have had a modest impact on governance (Karlsson-Vinkhuyzen and Asselt, 2009; McGee and Taplin, 2009) and encouraged voluntary action (Heggelund and Buan, 2009).

Another technology agreement that brings together clean energy technology experience from different regions is the Clean Energy Ministerial (CEM). The CEM convenes ministers with responsibility for clean energy technologies from the world's major economies and ministers from a select number of smaller countries that are leading in various areas of clean energy (Clean Energy Ministerial, 2012). The first CEM meeting was held in Washington in 2010. The 23 governments participating in CEM initiatives are Australia, Brazil, Canada, China, Denmark, the European Commission, Finland, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Norway, Russia, South Africa, Spain, Sweden, the United Arab Emirates, the United Kingdom, and the United States. These participant governments account for 80 % of global GHG emissions and 90 % of global clean energy investment (Clean Energy Ministerial, 2012).

A smaller agreement that focused on a broad range of mitigation technologies, the Sustainable Energy Technology at Work (SETatWork) Program, was comprised of two years of activities that ran from 2008 to 2010. SETatWork developed partnerships between organizations in the EU, Asia, and South America focused on implementing the EU ETS through identifying CDM project opportunities and transferring European technology and know-how to CDM host countries (European Commission, 2011a).

Other inter-regional technology cooperation initiatives and agreements focus on specific technology areas. For example, multiple initiatives focus on the development or deployment of carbon dioxide capture and storage (CCS) technologies, including the Carbon Sequestration Leadership Forum (CSLF), the European CCS Demonstration Project Network, The Gulf Cooperation Council CCS Strategic Workshop, and the Global Carbon Capture and Storage Institute.

14.4.3.3 South-South technology cooperation agreements

There are increasingly more examples of technology cooperation agreements among and between developing countries, often in the context of broader capacity building programs or agreements to provide financial assistance. One example is the Caribbean Community Climate Change Centre; which coordinates the Caribbean region's response to climate change and provides climate change-related policy advice and guidelines to the Caribbean Community (Caribbean Community Climate Change Center, 2012). Larger countries such as China and Brazil have taken an active role in promoting South-South cooperation. For example, China has served as a key donor to the UNDP Voluntary Trust Fund for the Promotion of South-South Cooperation, and United Nations Educational, Scientific and Cultural Organization (UNESCO) is working with the China Science and Technology Exchange Centre, which is part of China's Ministry of Science and Technology, to develop a network for South-South cooperation on science and technology to Address Climate Change (United Nations Development Programme: China, 2005; UNESCO Bejing, 2012). The Brazilian Agricultural Research Corporation has established several programs to promote agricultural and biofuel cooperation with Africa, including the Africa-Brazil Agricultural Innovation Marketplace, supported by Brazilian and international donors (Africa-Brazil Agricultural Innovation Marketplace, 2012).

Other South-South programs of cooperation that do not focus on climate change explicitly still may encourage climate related technology cooperation. For example, the India, Brazil, South Africa (IBSA) Trust Fund implements South-South cooperation for the benefit of LDCs, focusing on identifying replicable and scalable projects that can be jointly adapted and implemented in interested developing countries as examples of best practices in the fight against poverty and hunger. Projects have included solar energy programs for rural electrification and other projects with potential climate change mitigation benefits (UNDP IBSA Fund, 2014).

14.4.3.4 Lessons learned from regional technology agreements

A review of regional climate technology agreements reveals a complex landscape of cooperation that includes diversity in structure, focus, and effectiveness. While all of the regional agreements discussed above vary in their achievements, the strength of the regional organization or of the relationships of the members of the partnership also vary substantially. This has a direct implication for the effectiveness of the cooperation, and for any emissions reductions that can be attributed to the program of cooperation.

Well-coordinated, regionally based organizations, such as ASEAN, have served as an effective platform for cooperation on clean energy, because such programs build upon a strong, pre-existing regional platform for cooperation. Since most regional organizations coordinate regional activity rather than govern it, most of these regional energy and climate technology agreements focus on sharing information and knowledge surrounding technologies, rather than implementing actual projects, though there are exceptions. Since many countries are involved in multiple regional agreements, often with a similar technical focus, it can be difficult to attribute technology achievements to any specific agreement or cooperation initiative.

Because of the large number of intra-regional climate technology agreements with different types of membership structures and motivations, it is very difficult to draw general lessons from these types of initiatives. Since intra-regional technology agreements rarely build upon existing regional governance structures, their efficacy depends both on the commitment of the members, as well as the resources committed. The prominence of regionally coordinated agreements in other arenas, including environmental protection and trade, suggests that regions will play an increasingly important role in climate-related cooperation in the future. Experience with regional climate cooperation thus far suggests that building upon pre-existing regional groupings and networks, particularly those with strong economic or trade relationships, may provide the best platform for enhanced regional climate change cooperation.

14.4.4 Regional mechanisms for investments and finance

14.4.4.1 Regional and sub-regional development banks and related mechanisms

Regional institutions, including the regional multilateral development banks and the regional economic commissions of the United Nations, play an important role in stimulating action and funding for mitigation activities (see Section 16.5.1.2 for a discussion of specific regional institutions). Development finance institutions channeled an estimated 76.8 billion USD_{2010} in 2010/2011 (Buchner et al., 2011).

Appropriate governance arrangements at the national, regional, and international level are an essential pre-requisite for efficient, effective, and sustainable financing of mitigation measures (see Chapter 16). The Report of the Secretary-General's High-Level Advisory Group on Climate Change Financing recommended that the delivery of finance for adaptation and mitigation be scaled up through regional institutions, given their strong regional ownership. It also found that regional cooperation provides the greatest opportunity for analyzing and understanding the problems of, and designing strategies for coping with, the impact of climate change and variability (United Nations, 2010).

There are few aggregated estimates of the split of finance by type of disbursement organization available (see Chapter 16). A regional breakdown of the recipients of Multilateral Development Bank (MDB) climate finance based on the OECD Creditor Reporting System (CRS) database shows that recipients are primarily located in Asia (26 %), Latin America and the Caribbean (23 %) and Europe/Commonwealth of Independent States region (19 %) (Buchner et al., 2011).

14.4.4.2 South-South climate finance

There are limited data available to accurately quantify South-South climate finance flows, and many studies have pointed to a need for more accessible and consistent data (Buchner et al., 2011). One study that tracked overall development assistance from countries that are not members of the OECD Development Assistance Committee (DAC) estimated flows of 9.66 billion to 12.88 billion USD_{2010} (9 to 12 billion USD_{2006}) and projected that these flows would surpass 15 billion USD by 2010 (ECOSOC, 2008; Buchner et al., 2011). Brazil, India and China, the 'emerging non-OECD donors', are playing an increasingly important role in the overall aid landscape, and these countries also have programs to provide climate-related assistance to developing countries (Buchner et al., 2011). The share of GEF contributions that come from developing countries was estimated to total 56.6 million USD_{2010} (52.8 million USD_{2006}) (Ballesteros et al., 2010).

14.5 Taking stock and options for the future

A key finding from this chapter is that currently there is a wide gap between the potential of regional cooperation to contribute to a mitigation agenda and the reality of modest to negligible impacts to date. As shown in the discussion on climate-specific as well as climate-relevant regional cooperation, the ability to use existing regional cooperation for furthering a mitigation agenda, by pursuing a common and coordinated energy policy, embodying mitigation objectives in trade agreements in urbanization and infrastructure strategies, and developing and sharing technologies at the regional level, is substantial. In principle, in many regions the willingness to cooperate on such an agenda is substantial. In the absence of an increasingly elusive global agreement, such regional cooperation may provide the best alternative to furthering an ambitious mitigation agenda. Also, if a global agreement emerges, such regional cooperation could prove vital for its implementation.

At the same time, the reality is one of very low mitigation impacts to date. Even in areas of deep integration where multiple instruments for mitigation have been put into place, progress on mitigation has been slower than anticipated. This is largely related to a political reluctance to pursue the multiple policy instruments with sufficient rigor. The challenge will be to drastically increase the ambition of existing instruments while carefully considering the positive and negative interactions between these different policies. For regions where deep regional integration is not present yet, the experience from the EU suggests that only after a substantial transfer of sovereignty to regional bodies can an ambitious mitigation be pursued. Such a transfer of sovereignty is unlikely in most regions where the regional cooperation processes are still in early stages of development. Alternatively, regional cooperation on mitigation can build on the substantial good-will within regions to develop voluntary cooperation schemes in the fields outlined in the chapter that also further other development goals, such as energy security, trade, infrastructure, or sustainable development. Whether such voluntary cooperation will be sufficient to implement ambitious mitigation measures to avoid the most serious impacts of climate change remains an open question.

14.6 Gaps in knowledge and data

While there is clear evidence from the theoretical and empirical literature that regional mechanisms have great potential to contribute to mitigation goals, there are large gaps in knowledge and data related to the issues covered in this chapter. In particular, there are gaps in the literature on:

- The quantitative impact of regional cooperation schemes on mitigation, especially in terms of quantifying their impact and significance. While some of the mechanisms, such as the EU-ETS are well-studied, many other cooperation mechanisms in the field of technology, labelling, and information sharing have hardly been analyzed at all.

- The factors that lead to the success or failure of regional cooperation mechanisms, including regional disparities and the mismatch between capacities and opportunities within and between regions. This research would be useful to determine which cooperation mechanisms are suitable for a particular region at a given stage of development, resource endowment, a given level of economic and political cooperation ties, institutional and technical national capacities and heterogeneity among the participating countries.

- Synergies and tradeoffs between mitigation and adaptation. In addition, it would be important to understand more about capacity barriers for low-carbon development at the regional level, including on the costs of capital and credit constraints. There is also very little peer-reviewed literature assessing the mitigation potential and actual achievements of climate-relevant regional cooperation agreements (such as trade, energy, or infrastructure agreements).

- The empirical interaction of different policy instruments. It is clear that regional policies interact with national and global initiatives, and often there are many regional policies that interact within the same regions. Not enough is known to what extent these many initiatives support or counteract each other.

14.7 Frequently Asked Questions

FAQ 14.1 How are regions defined in the AR5?

This chapter examines supra-national regions (i. e., regions in between the national and global level). Sub-national regions are addressed in Chapter 15. There are several possible ways to classify regions and different approaches are used throughout the IPCC Fifth Assessment Report (AR5). In most chapters, a five-region classification is used that is consistent with the integrated models: OECD-1990, Middle East and Africa, Economies in Transition, Asia, Latin America and the Caribbean. Given the policy focus of this chapter and the need to distinguish regions by their levels of economic development, this chapter adopts regional definitions that are based on a combination of economic and geographic considerations. In particular, this chapter considers the following 10 regions: East Asia (China, Korea, Mongolia) (EAS); Economies in Transition (Eastern Europe and former Soviet Union) (EIT); Latin America and Caribbean (LAM); Middle East and North Africa (MNA); North America (USA, Canada) (NAM); South-East Asia and Pacific (PAS); Pacific OECD-1990 members (Japan, Australia, New Zealand) (POECD); South Asia (SAS); sub-Saharan Africa (SSA); Western Europe (WEU). These regions can readily be aggregated to other regional classifications such as the regions used in scenarios and integrated assessment models (e. g., the so-called Representative Concentration Pathways (RCP) regions), commonly used World Bank socio-geographic regional classifications, and geographic regions used by WGII. In some cases, special consideration will be given to the cross-regional group of Least Developed Countries (LDCs), as defined by the United Nations, which includes 33 countries in SSA, 5 in SAS, 8 in PAS, and one each in LAM and MNA, and which are characterized by low incomes, low human assets, and high economic vulnerability.

FAQ 14.2 Why is the regional level important for analyzing and achieving mitigation objectives?

Thinking about mitigation at the regional level matters for two reasons. First, regions manifest vastly different patterns in their level, growth, and composition of GHG emissions, underscoring significant differences in socio-economic contexts, energy endowments, consumption patterns, development pathways, and other underlying drivers that influence GHG emissions and therefore mitigation options and pathways [14.3]. We call this the 'regional heterogeneity' issue.

Second, regional cooperation, including the creation of regional institutions, is a powerful force in global economics and politics—as manifest in numerous agreements related to trade, technology cooperation, transboundary agreements relating to water, energy, transport, and so on. It is critical to examine to what extent these forms of cooperation have already had an impact on mitigation and to what extent they could play a role in achieving mitigation objectives [14.4]. We call this the 'regional cooperation and integration issue'.

Third, efforts at the regional level complement local, domestic efforts on the one hand, and global efforts on the other hand. They offer the potential of achieving critical mass in the size of the markets required to make policies, for example, on border tax adjustment, work, in creating regional smart grids required to distribute and balance renewable energy.

FAQ 14.3 How do opportunities and barriers for mitigation differ by region?

Opportunities and barriers for mitigation differ greatly by region. On average, regions with the greatest opportunities to bypass more carbon-intensive development paths and leapfrog to low-carbon development are regions with low lock-in, in terms of energy systems, urbanization, and transport patterns. Poorer developing regions such as sub-Saharan Africa, as well as most Least Developed Countries, fall into this category. Also, many countries in these regions have particularly favorable endowments for renewable energy (such as hydropower or solar potential). At the same time, however, they are facing particularly strong institutional, technological, and financial constraints to undertake the necessary investments. Often these countries also lack access to the required technologies or the ability to implement them effectively. Given their urgent need to develop and improve energy access, their opportunities to engage in mitigation will also depend on support from the international community to overcome these barriers to invest in mitigation. Conversely, regions with the greatest technological, financial, and capacity advantages face much-reduced opportunities for low-cost strategies to move towards low-carbon development, as they suffer from lock-in in terms of energy systems, urbanization, and transportation patterns. Particularly strong opportunities for low-carbon development exist in developing and emerging regions where financial and institutional capacities are better developed, yet lock-in effects are low, also due to their rapid planned installation of new capacity in energy and transport systems. For these regions, which include particularly Latin America, much of Asia, and parts of the Middle East, a reorientation towards low-carbon development paths is particularly feasible. [14.1, 14.2, 14.3]

FAQ 14.4 What role can and does regional cooperation play to mitigate climate change?

Apart from the European Union (with its Emissions Trading Scheme and binding regulations on energy and energy efficiency), regional cooperation has, to date, not played an important role in furthering a mitigation agenda. While many regional groupings have developed initiatives to directly promote mitigation at the regional level—primarily through sharing of information, benchmarking, and cooperation on technology development and diffusion—the impact of these initiatives is very small to date. In addition, regional cooperation agreements in other areas (such as trade, energy, and infrastructure) can influence mitigation indirectly. The effect of these initiatives and policies on mitigation is currently also small, but there is some evidence that trade pacts that are accompanied by environmental agreements have had some impact on reducing emissions within the trading bloc. Nonetheless, regional cooperation could play an enhanced role in promoting mitigation in the future, particularly if it explicitly incorporates mitigation objectives in trade, infrastructure, and energy policies and promotes direct mitigation action at the regional level. With this approach regional cooperation could potentially play an important role within the framework of implementing a global agreement on mitigation, or could possibly promote regionally coordinated mitigation in the absence of such an agreement. [14.4]

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15

National and Sub-national Policies and Institutions

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Executive Summary

Since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), there has been a marked increase in national policies and legislation on climate change, however, these policies, taken together, have not yet achieved a substantial deviation in emissions from the past trend. Many baseline scenarios (those without additional policies to reduce emissions) show GHG concentrations that exceed 1000 ppm CO_2eq by 2100, which is far from a concentration with a likely probability of maintaining temperature increases below 2 °C this century. Mitigation scenarios suggest that a wide range of environmentally effective policies could be enacted that would be consistent with such goals. This chapter assesses national and sub-national policies and institutions to mitigate climate change in this context. It assesses the strengths and weaknesses of various mitigation policy instruments and policy packages and how they may interact either positively or negatively. Sector-specific policies are assessed in greater detail in the individual sector chapters (7–12). Major findings are summarized as follows. [Section 15.1]

The design of institutions affects the choice and feasibility of policy options as well as the sustainable financing of climate change mitigation measures (*limited evidence, medium agreement*). By shaping appropriate incentives, creating space for new stakeholders in decision making, and by transforming the understanding of policy choices, institutions designed to encourage participation by representatives of new industries and technologies can facilitate transitions to low-emission pathways, while institutions inherited unchanged from the past can perpetuate lock-in to high-carbon development paths. [15.2, 15.6]

There has been a considerable increase in national and sub-national mitigation plans and strategies since AR4 (*medium evidence, high agreement*). These plans and strategies are in their early stages of development and implementation in many countries, making it difficult to assess whether and how they will result in appropriate institutional and policy change, and thus, their impact on future emissions. However, to date these policies, taken together, have not yet achieved a substantial deviation in emissions from the past trend. Theories of institutional change suggest they might play a role in shaping incentives, political contexts, and policy paradigms in a way that encourages emissions reductions in the future. [15.1, 15.2]

Sector-specific policies have been more widely used than economy-wide, market-based policies (*medium evidence, high agreement*). Although economic theory suggests that economy-wide market-based policies for the singular objective of mitigation would generally be more cost-effective than sector-specific policies, political economy considerations often make economy-wide policies harder to design and implement than sector-specific policies. Sector-specific policies may also be needed to overcome sectoral market failures that price policies do not address. For example, building codes can require publicly funded energy efficient investments where private investments would otherwise not exist. Sector approaches also allow for packages of complementary policies, as, for example, in transport, where pricing policies that raise the cost of carbon-intensive forms of private transport are more effective when backed by public investment in viable alternatives. [15.1, 15.2, 15.5, 15.8, 15.9]

Direct regulatory approaches and information measures are widely used, and are often environmentally effective, though debate remains on the extent of their environmental impacts and cost effectiveness (*medium evidence, medium agreement*). Examples of regulatory approaches include energy efficiency standards; examples of information programmes include labelling programmes that can help consumers make better-informed decisions. While such approaches often work at a net social benefit, the scientific literature is divided on whether such policies are implemented with negative private costs to firms and individuals. Since AR4 there has been continued investigation into 'rebound' effects that arise when higher efficiency leads to lower energy prices and greater consumption. There is general agreement that such rebound effects exist, but there is low agreement in the literature on the magnitude. [3.9.5, 8.3, 9.7.2.4, 15.5.4, 15.5.5]

Fuel taxes are an example of a sector-specific policy and are often originally put in place for objectives such as revenue—they are not necessarily designed for the purpose of climate change mitigation (*high confidence*). In Europe, where fuel taxes are highest, they have contributed to reductions in carbon emissions from the transport sector of roughly 50 % for this group of countries. The short-run response to higher fuel prices is often small, but long-run price elasticities are quite high, or roughly −0.6 to −0.8. This means that in the long run, 10 % higher fuel prices correlate with 7 % reduction in fuel use and emissions. In the transport sector, taxes have the advantage of being progressive or neutral in most countries and strongly progressive in low-income countries. [15.5.2]

Reduction of subsidies to fossil energy can result in significant emission reductions at negative social cost (*high confidence*). [15.5.2] Although political economy barriers are substantial, many countries have reformed their tax and budget systems to reduce fuel subsidies that actually accrue to the relatively wealthy, and utilized lump-sum cash transfers or other mechanisms that are more targeted to the poor. [15.5.3]

Cap and trade systems for greenhouse gases are being established in a growing number of countries and regions (*limited evidence, medium agreement*). Their environmental effect has so far been limited because caps have either been loose or have not yet been binding. There appears to have been a tradeoff between the political feasibility and environmental effectiveness of these programmes, as well as between political feasibility and distributional equity in the allocation of permits. Greater environmental effectiveness through a tighter cap may be combined with a price ceiling that makes for political feasibility. [15.5.3]

Carbon taxes have been implemented in some countries and—alongside technology and other policies—have contributed to decoupling of emissions from gross domestic product (GDP) (*high confidence*). Differentiation by sector, which is quite common, reduces cost-effectiveness that arises from the changes in production methods, consumption patterns, lifestyle shifts, and technology development, but it may increase political feasibility, or be preferred for reasons of competitiveness or distributional equity. In some countries, high carbon and fuel taxes have been made politically feasible by refunding revenues or by lowering other taxes in an environmental fiscal reform. [15.2, 15.5.2, 15.5.3]

Adding a mitigation policy to another may not necessarily enhance mitigation (*high confidence*). For instance, if a cap and trade system has a sufficiently stringent cap, then other policies such as renewable subsidies have no further impact on total emissions (although they may affect costs and possibly the viability of more stringent future targets). If the cap is loose relative to other policies, it becomes ineffective. This is an example of a negative interaction between policy instruments. Since other policies cannot be 'added on' to a cap-and-trade system, if it is to meet any particular target, a sufficiently low cap is necessary. A carbon tax, on the other hand, can have an additive environmental effect to policies such as subsidies to renewables. [15.7]

There is a distinct role for technology policy as a complement to other mitigation policies (*high confidence*). Properly implemented technology policies reduce the cost of achieving a given environmental target. Technology policy will be most effective when technology-push policies (e.g., publicly funded research and development (R&D)) and demand-pull policies (e.g., governmental procurement programmes or performance regulations) are used in a complementary fashion (*robust evidence, high agreement*). [15.6] While technology-push and demand-pull policies are necessary, they are unlikely to be sufficient without complementary framework conditions. Managing social challenges of technology policy change may require innovations in policy and institutional design, including building integrated policies that make complementary use of market incentives, authority and norms (*medium evidence, medium agreement*). [15.6.5].

Since AR4, a large number of countries and sub-national jurisdictions have introduced support policies for renewable energy such as feed-in tariffs (FIT) and renewable portfolio standards (RPS). These have promoted substantial diffusion and innovation of new energy technologies such as wind turbines and photovoltaic (PV) panels, but have raised questions about their economic efficiency, and introduced challenges for grid and market integration (7.12, 15.6).

Worldwide investment in research in support of climate change mitigation is small relative to overall public research spending (*medium evidence, medium agreement*). The effectiveness of research support will be greatest if it is increased slowly and steadily rather than dramatically or erratically. It is important that data collection for programme evaluation be built into technology policy programmes, because there is very little empirical evidence on the relative effectiveness of different mechanisms for supporting the creation and diffusion of new technologies. [15.6.2, 15.6.5]

Public finance mechanisms reduce risks that deter climate investments (*high confidence*). The future value of carbon permits created by an economic instrument such as cap and trade may, for example, not be accepted as sufficiently secure by banks. Government public finance mechanisms to reduce risks include debt and equity mechanisms, carbon finance, and innovative grants. [15.12]

Government planning and provision can facilitate shifts to less energy and GHG-intensive infrastructure and lifestyles (*high confidence*). This applies particularly when there are indivisibilities in the provision of infrastructure as in the energy sector (e.g., for electricity transmission and distribution or district heating networks); in the transport sector (e.g., for non-motorized or public transport), and in urban planning. The provision of adequate infrastructure is important for behavioural change (*medium evidence, high agreement*) [15.5.6].

Successful voluntary agreements on mitigation between governments and industries are characterized by a strong institutional framework with capable industrial associations (*medium evidence, medium agreement*). The strengths of voluntary agreements are speed and flexibility in phasing measures, and facilitation of barrier removal activities for energy efficiency and low emission technologies. Regulatory threats, even though the threats are not always explicit, are also an important factor for firms to be motivated. There are few environmental impacts without a proper institutional framework *(medium evidence, medium agreement).* [15.5.5]

Synergies and tradeoffs between mitigation and adaptation policies may exist in the land-use sector (*medium evidence, medium agreement*). For other sectors such as industry and power, the connections are not obvious. [15.11]

The ability to undertake policy action requires information, knowledge, tools, and skills, and therefore capacity building is central both for mitigation and to the sustainable development agenda (*medium evidence, high agreement*). The needs for capacity building include capacity to analyze the implications of climate change; capacity to formulate, implement, and evaluate policies; capacity to take advantage of external funding and flexible mechanisms; and capacity to make informed choices of the various capacity building modalities. [15.10]

Mainstreaming climate change into development planning has helped yield financing for various climate policy initiatives (*medium evidence, medium agreement*). Among developing and some least developed countries, an emerging trend is the establishment of national funding entities dedicated to climate change. While diverse in design and objectives, they tap and blend international and national sources of finance, thereby helping to improve policy coherence and address aid fragmentation. Financing adaptation and mitigation in developing countries is crucial from the viewpoint of welfare and equity (*medium evidence, high agreement*). [15.12]

Gaps in knowledge: The fact that various jurisdictions produce various policy instruments influenced by co-benefits and political economy and that they interact in complex manners makes it difficult to evaluate the economic and environmental effectiveness of individual policy instrument as well as policy package of a nation. Most importantly, it is not known with certainty how much an emission reduction target may cost to the economy in the real world in comparison to the 'first best' optimal solution estimated by economic models in other chapters in this report. Costs may be under-stated or over-stated.

15.1 Introduction

This chapter assesses national and sub-national mitigation policies and their institutional settings. There has been a marked increase in national policies and legislation on climate change since the AR4 with a diversity of approaches and a multiplicity of objectives (see Section 15.2). However, Figure 1.9 of Chapter 1 suggests that these policies, taken together, have not yet achieved a substantial deviation in emissions from the past trend. Limiting concentrations to levels that would be consistent with a likely probability of maintaining temperature increases below 2 °C this century (scenarios generally in the range of 430–480 ppmv CO_2eq) would require that emissions break from these trends and be decreased substantially. In contrast, concentrations exceed 1000 ppmv CO_2eq by 2100 in many baseline scenarios (that is, scenarios without additional efforts to reduce emissions).

The literature on mitigation scenarios provides a wide range of CO_2 shadow price levels consistent with these goals, with estimates of less than USD 50/tCO_2 in 2020 in many studies and exceeding USD 100/tCO_2 in others, assuming a globally-efficient and immediate effort to reduce emissions. These shadow prices exhibit a strongly increasing trend thereafter. Policies and instruments are assessed in this light.

Section 15.2 assesses the role of institutions and governance. Section 15.3 lays out the classification of policy instruments and packages, while 15.4 discusses the methodologies used to evaluate policies and institutions. The performance of various policy instruments and measures are individually assessed in Sections 15.5 and 15.6.

The two main types of economic instruments are price instruments, that is, taxes and subsidies (including removal of subsidies on fossil fuels), and quantity instruments—emission-trading systems. These are assessed in Sections 15.5.2 and 15.5.3 respectively. An important feature of both these instruments is that they can be applied at a very broad, economy-wide scale. This is in contrast to the regulation and information policies and voluntary agreements which are usually sector-specific. These policies are assessed in Sections 15.5.4, 15.5.5, and 15.5.7. Government provision and planning is discussed in 15.5.6. The next section, 15.6, provides a focused discussion on technology policy including research and development and the deployment and diffusion of clean energy technologies. In addition to technology policy, longer-term effects of the policies assessed in Section 15.5 are addressed in Section 15.6.

Both these sections, 15.5 and 15.6, bring together lessons from policies and policy packages used at the sectoral level from Chapters 7 (Energy), 8 (Transport), 9 (Buildings), 10 (Industry), 11 (Agriculture, Forestry and Land Use) and Chapter 12 (Human Settlements, Infrastructure, and Spatial Planning).

The following sections further assess the interaction among policy instruments, as they are not usually used in isolation, and the impacts of particular instruments depend on the entire package of policies and the institutional context. Section 15.7 reviews interactions, both beneficial and harmful, that may not have been planned. The presence of such interactions is in part a consequence of the multi-jurisdictional nature of climate governance as well as the use of multiple policy instruments within a jurisdiction. Section 15.8 examines the deliberate linkage of policies across national and sub-national jurisdictions.

Other key issues are further discussed in dedicated sections. They are: the role of stakeholders including non-governmental organizations (NGOs) (15.9), capacity building (15.10), links between adaptation and mitigation policies (15.11), and investment and finance (15.12). Gaps in knowledge are collected in 15.13.

15.2 Institutions and governance

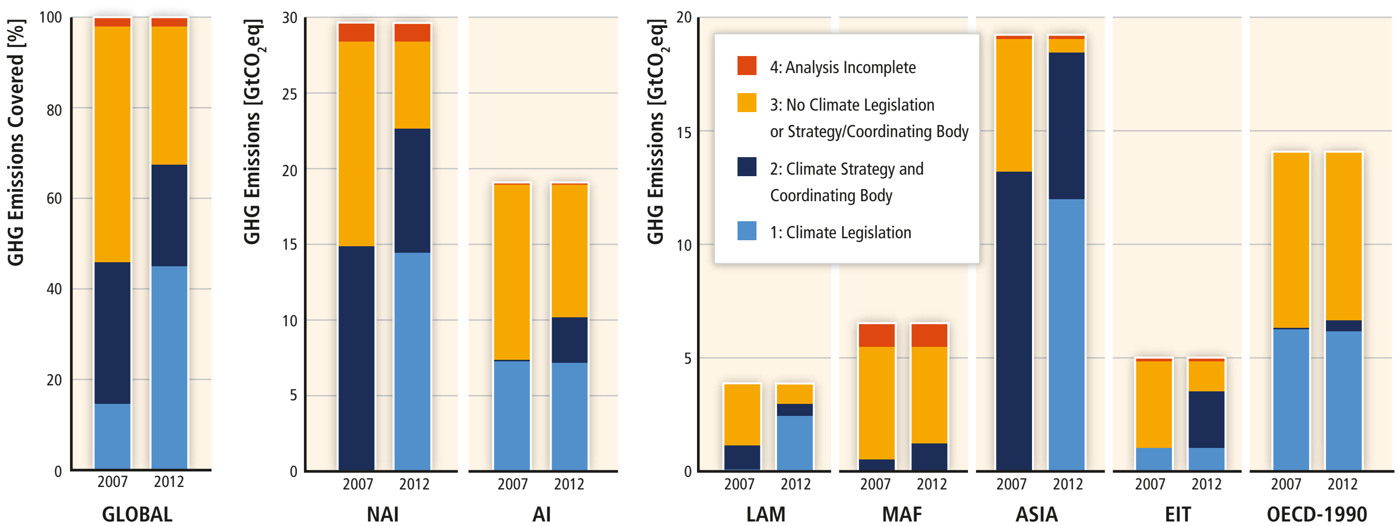
15.2.1 Why institutions and governance matter

Institutions and processes of governance (see Annex 1: Glossary for definitions) shape and constrain policy-making and policy implementation in multiple ways relevant for a shift to a low carbon economy. First, institutions—understood as formal rules and informal norms—set the incentive structure for economic decision making (North, 1991), influencing, for example, decisions about transportation investments, and behavioural decisions relevant to efficient energy use. Second, institutions shape the political context for decision making, empowering some interests and reducing the influence of others (Steinmo et al., 1992; Hall, 1993). Harrison (2012) illustrates this with respect to environmental tax reform in Canada. Third, institutions can also shape patterns of thinking and understanding of policy choices—through both normative and cognitive effects (Powell and DiMaggio, 1991). These effects can result in dominant policy paradigms—ideas, policy goals, and instruments—that favour some actions and exclude others from consideration (Radaelli and Schmidt, 2004). For example, existing energy systems are likely to remain in place without appropriate institutional change (Hughes, 1987) and changes in discourse, which would perpetuate existing technologies and policies and lock out new ones (Unruh, 2000; Walker, 2000). More generally, a mismatch between social-ecological context and institutional arrangements can lead to a lack of fit and exert a drag on policy and technological response (Young, 2002).

15.2.2 Increase in government institutionalization of climate mitigation actions

There has been a definite increase since AR4 in formal governmental efforts to promote climate change mitigation. These efforts are diverse in their approach, scale, and emphasis, and take the form of legislation, strategies, policies, and coordination mechanisms. Many of these are relatively recent, and often in the design or early implementation stage. As a result, it is premature to evaluate their effectiveness and there is insufficient literature as yet that attempts to do so. Since global greenhouse gas emissions have continued to increase in recent years (Chapter 5 and Section 15.1), it will be important to closely monitor this trend to evaluate if policies and institutions created are sufficiently strong and effective to lead to the reductions required to stabilize global temperature, for instance, at the 2 °C target. This section reviews national centralized governmental actions, while 15.2.3 discusses sectoral actions and 15.2.5 examines the roles of other stakeholders including non-state actors.

A review of climate legislation and strategy in almost all United Nation (UN) Member States shows that there has been a substantial increase in these categories between 2007 and 2012 (Dubash et al., 2013) (See Figure 15.1). Dubash et al. (2013) define climate legislation as mitigation-focused legislation that goes beyond sectoral action alone, while climate strategy is defined as a non-legislative plan or framework aimed at mitigation that encompasses more than a small number of sectors, and that includes a coordinating body charged with implementation. International pledges are not included. By these definitions, 39 % of countries, accounting for 73 % of population and 67 % of greenhouse gas emissions, were covered by climate law or strategies in 2012, an increase from 23 % of countries, 36 % of population, and 45 % of emissions in 2007. There are also strong regional differences,



	GLOBAL 2007	GLOBAL 2012	NAI 2007	NAI 2012	AI 2007	AI 2012	LAM 2007	LAM 2012	MAF 2007	MAF 2012	ASIA 2007	ASIA 2012	EIT 2007	EIT 2012	OECD-1990 2007	OECD-1990 2012
1	7 (15%)	22 (44%)	0 (0%)	14 (49%)	7 (38%)	7 (38%)	0 (2%)	2 (63%)	0 (0%)	0 (0%)	0 (0%)	12 (62%)	1 (20%)	1 (20%)	6 (44%)	6 (44%)
2	15 (30%)	11 (23%)	15 (50%)	8 (28%)	0 (0%)	3 (16%)	1 (28%)	1 (13%)	1 (8%)	1 (19%)	13 (69%)	6 (34%)	0 (0%)	3 (50%)	0 (0%)	0 (3%)
3	25 (52%)	15 (30%)	14 (46%)	6 (19%)	12 (61%)	9 (46%)	3 (70%)	1 (23%)	5 (76%)	4 (65%)	6 (30%)	1 (3%)	4 (76%)	1 (26%)	8 (55%)	7 (53%)
4	1 (3%)	1 (3%)	1 (4%)	1 (4%)	0 (1%)	0 (1%)	0 (0%)	0 (0%)	1 (16%)	1 (16%)	0 (1%)	0 (1%)	0 (3%)	0 (3%)	0 (0%)	0 (0%)

Figure 15.1 | National climate legislation and strategies in 2007 and 2012.* Reproduced from Dubash et al., (2013). In this figure, climate legislation is defined as mitigation-focused legislation that goes beyond sectoral action alone. Climate strategy is defined as a non-legislative plan or framework aimed at mitigation that encompasses more than a small number of sectors, and that includes a coordinating body charged with implementation. International pledges are not included, nor are sub-national plans and strategies. The panel shows proportion of GHG emissions covered.

* Number of countries and GHG emissions covered (NAI: Non Annex I countries (developing countries), AI: Annex I countries (developed countries), LAM: Latin America, MAF: Middle East and Africa, ASIA: Asia, EIT: Economies in Transition, OECD-1990: OECD of 1990)

with Asia and Latin America recording the fastest rate of increase. Taken as a block, in 2012, 49 % of current emissions from the developing world regions of Asia, Africa, and Latin America were under climate law and 77 % of emissions were under either law or strategy, while for the developed world regions of Organisation for Economic Co-operation and Development 1990 Countries OECD-1990 and Economies in Transition (EIT) the equivalent numbers are 38 % and 56 %. Finally, while the number of countries with climate legislation increased marginally from 18 % to 22 % over this period, the number of countries with climate strategies increased from 5 % to 18 %, suggesting many more countries are adopting a strategy-led approach. (For regional aggregations see Annex II.2)

Climate legislation and strategies follow a wide diversity of approaches to operationalization and implementation. The imposition of carbon prices is one approach widely discussed in the literature (See Section 15.5) but less frequently implemented in practice. Examples include the European Union's Emissions Trading Scheme (ETS) (See Section 14.4.2) or setting of carbon taxes (see Section 15.5.2). One study of the 19 highest emitting countries finds that six have put in place some form of carbon price, while 14 have put in place both regulation and other economic incentives for greenhouse gas mitigation (Lachapelle and Paterson, 2013). Common explanations for this variation are in terms of the novelty of emissions trading (although emissions trading has been in practice implemented much more widely than carbon taxation), the legitimacy problems faced by emissions trading (Paterson, 2010), or political contestation over increased taxation (see for example Laurent (2010), on the French case, Jotzo (2012) for Australia or Jagers and Hammar (2009), for evidence that popular support for carbon taxes in Sweden depend on how it is framed in popular debate), and lobbying by fossil-fuel or energy-intense industry lobbies (Bailey et al., 2012; Sarasini, 2013).

More generally speaking, policy instruments have often been sector-specific. Economy-wide instruments, even when implemented, have had exemptions for some sectors, most commonly those most exposed to international trade. The exemptions have arisen because national policies have been developed under the strong influence of sectoral policy networks (Compston, 2009) and many stakeholders therein—including firms and NGOs—influence the policy to promote their interests (Helm, 2010). This phenomenon undermines the overall cost-effectiveness of climate policy (Anthoff and Hahn, 2010) although it may help further other objectives such as equity and energy security (see Section 15.7).

Another approach follows a model of national-level target backed by explicit creation of institutions to manage performance to that target. In China, for example, a 'National Leading Group on Climate Change' in June 2007, housed in the apex National Development and Reform Commission and chaired by the premier (Tsang and Kolk, 2010a) coordinates the achievement of targets set in the subsequent National Climate Change Programme. The Chinese examples illustrate a broader point emerging from a cross-country study that implementation of climate legislation and plans are, in at least some cases, drawing powerful finance and planning departments into engagement with climate change (Held et al., 2013).

Another approach is to establish dedicated new climate change bodies that are substantially independent of the executive and that seek to coordinate existing government agencies through a variety of levers. The leading example of this approach is in the UK, where a dedicated Climate Change Committee analyzes departmental plans and monitors compliance with five-year carbon budgets (U.K., 2008; Stallworthy, 2009). Instead of direct executive action, as in the Chinese case, this approach relies on analysis, public reporting, and advice to government. Following the UK example, Australia has established an independent Climate Change Authority to advise the government on emission targets and review effectiveness of its Carbon Pricing Mechanism (Keenan et al., 2012).

15.2.3 Climate change mitigation through sectoral action

While there is no systematic study of implementation of climate plans, case study evidence suggests that these plans are frequently operationalized through sectoral actions. There are a variety of ways through which national plans interface with sectoral approaches to mainstream climate change. In some cases, there is a formal allocation of emissions across sectors. For example, in Germany, mitigation efforts were broken down by sectors for the period between 2008 and 2012, with the national 'Allocation Act 2012' specifying emissions budgets for sectors participating in the EU ETS as well as the remaining sectors (Dienes, 2007; Frenz, 2007). More typically, climate mainstreaming occurs through a sector by sector process led by relevant government departments, as in France (Mathy, 2007), India (Dubash, 2011; Atteridge et al., 2012), and Brazil (da Motta, 2011a; La Rovere et al., 2011).

In some cases, the sectoral process involves a role for stakeholders in engagement with government departments. In France, sectoral approaches are devised at the central level through negotiation and consultation between multiple ministries, experts, business, and NGOs. According to at least one analysis, this approach risks a dilution of measures through the influence of lobbies that may lose from mitigation actions (Mathy, 2007). In Brazil, sector specific approaches are developed by sectoral ministries complemented by a multi-stakeholder forum to solicit views and forge consensus (Hochstetler and Viola, 2012; Viola and Franchini, 2012; Held et al., 2013a).

In some cases, climate change considerations bring about changes in long-standing patterns of sector governance. In South Africa, for example, the Copenhagen pledge led to a process of reconsidering South Africa's integrated resource plan for electricity to include carbon reduction as one among multiple criteria (Republic of South Africa, 2011). In India, the establishment of national sectoral 'missions' had the effect of creating new institutional mechanisms in the case of the National

Solar Mission, or of raising the profile and importance of particular ministries or departments as in the example of the Bureau of Energy Efficiency (Dubash, 2011). In other cases, climate mainstreaming was facilitated by prior political shifts in governance of a sector. Brazil's climate approach particularly emphasizes the forest sector (da Motta, 2011b; La Rovere, 2011). Progress on the Brazilian plan was enabled by prior domestic political consensus around a far-reaching Forest Code (Hochstetler and Viola, 2012).

15.2.4 Co-Benefits as a driver of mitigation action

The importance of co-benefits—both development gains from climate policy and climate gains from development policy—emerge as a particularly strong rationale and basis for sectoral action. As Table 6.7 shows, an inventory of sectoral action on climate change (drawn from Chapter 7–12) is linked to a wide range of co-benefits and adverse side-effects, encompassing economic, social, and environmental effects. Table 15.1 provides a roadmap for the co-benefits and adverse side-effects from sectoral mitigation measures most prominently discussed across Chapters 7 to 12. They are listed in three columns: economic, social, and environmental. Each column shows the range of effects on objectives or concerns beyond mitigation discussed in Chapters 7.12 for that category. For example, energy security is categorized in the column of 'economic' and addressed in Section 7.9, 8.7, 9.7, 10.8, 11.13.6, and 12.8.

This perception is reinforced by comparative case studies and specific country studies. A comparative study finds that co-benefits is an important driving force for mitigation policies across large, rapidly industrializing countries (Bailey and Compston, 2012a), a finding that is supported by country level studies. India's National Action Plan on Climate Change (NAPCC), for example, is explicitly oriented to pursuit of co-benefits, with mitigation understood to be the secondary benefit emerging from development policies. The linkage between energy security and mitigation is particularly important to winning broader political support for action on mitigation (Dubash, 2011; Fisher, 2012). A similar trend is apparent in China (Oberheitmann, 2008), where provincial implementation of targets is enabled by linking action to local motivations, notably for energy efficiency (Teng and Gu, 2007; Richerzhagen and Scholz, 2008a; Qi et al., 2008; Tsang and Kolk, 2010b; Kostka and Hobbs, 2012). Tsang and Kolk (2010a) go so far as to say that Chinese leaders essentially equate climate policy with energy conservation. Kostka and Hobbs (2012) identify three ways in which this alignment of global and local objectives happens: interest bundling, through which objectives of political institutions are tied to local economic interests; policy bundling, to link climate change with issues of local political concern; and framing in ways that play to local constituencies.

The concept of 'nationally appropriate mitigation actions' (NAMAs) has a conceptual connection to the idea of co-benefits. Nationally appropriate mitigation actions are intended to be mitigation actions that are 'nationally appropriate' in the sense that they contribute to development outcomes. Therefore, NAMAs provide a possible mechanism for connection of national policies and projects to the global climate regime, although the mechanisms through which this will be accomplished are yet to be fully articulated (see Box 15.1). Another, related mechanism is the explicit formulation in many countries of 'low emissions development strategies' that seek to integrate climate and development strategies (Clapp et al., 2010).

15.2.5 Sub-national climate action and interaction across levels of governance

In many countries, the formulation and implementation of national mitigation approaches are further delegated to sub-national levels, with differing levels of central coordination, depending on national contexts and institutions. Comparative analysis of cross-country climate action is insufficiently developed to allow generalization and explanation of different approaches to climate policy.

Table 15.1 | Roadmap for the assessment of potential co-benefits and adverse side-effects from mitigation measures for additional objectives in the sector chapters (7–12). For overview purposes, only those objectives and concerns are shown that are assessed in at least two sectors. For a broader synthesis of the literature assessed in this report, see Section 6.6.

Effect of mitigation measures on additional objectives or concerns		
Economic	**Social**	**Environmental**
Energy security (7.9, 8.7, 9.7, 10.8, 11.13.6, 12.8)	Health impact (e.g., via air quality and noise) (5.7, 7.9, 8.7, 9.7, 10.8, 11.7, 11.13.6, 12.8)	Ecosystem impact (e.g., via air pollution) (7.9, 8.7, 9.7, 10.8, 11.7, 11.13.6/7, 12.8)
Employment impact (7.9, 8.7, 9.7, 10.8, 11.7, 11.13.6)	Energy/mobility access (7.9, 8.7, 9.7, 11.13.6, 12.4)	Land-use competition (7.9, 8.7, 10.8, 11.7, 11.13.6/7)
New business opportunity/economic activity (7.9, 11.7, 11.13.6)	(Fuel) Poverty alleviation (7.9, 8.7, 9.7, 11.7, 11.13.6)	Water use/quality (7.9, 9.7, 10.8, 11.7, 11.13.6)
Productivity/competitiveness (8.7, 9.7, 10.9, 11.13.6)	Food security (7.9, 11.7, 11.13.6/7)	Biodiversity conservation (7.9, 9.7, 11.7, 11.13.6)
Technological spillover/innovation (7.9, 8.7, 10.8, 11.3, 11.13.6)	Impact on local conflicts (7.9, 10.8, 11.7, 11.13.6)	Urban heat island effect (9.7, 12.8)
	Safety/disaster resilience (7.9, 8.7, 9.7, 10.8, 12.8)	Resource/material use impact (7.9, 8.7, 9.7, 10.8, 12.8)
	Gender impact (7.9, 9.7, 11.7, 11.13.6)	

Box 15.1 | Nationally Appropriate Mitigation Actions (NAMAs)

The Bali Action Plan (BAP), (1/CP.13; UNFCCC, 2007) states that developing countries are called on to take NAMAs supported and enabled by technology and finance. For example, NAMAs could be articulated in terms of national emissions intensity or trajectories, sectoral emissions, or specific actions at sectoral or sub-sectoral levels. As of June 2013, 57 parties had submitted NAMAs to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat.

The design of mechanisms to link NAMAs to global support lead to some complex tradeoffs. For example, large scale sectoral NAMAs provide the least scope for leakage (decreased emissions in one sector is undermined by increased emissions in another part of the economy) and the lowest measurement costs (Jung et al., 2010). However, designing NAMAs around transaction costs might run counter to designing them for targeted focus on national development priorities. Exploring the extent of this tradeoff and managing it carefully will be an important part of implementing NAMAs.

Much of the writing on NAMAs is focused on the challenges of linking national actions to the international climate framework. Conceptual challenges involved in linking NAMAs to the UNFCCC process include the legal nature of NAMAs (van Asselt et al., 2010), financing of NAMAs, and associated concerns of avoiding double counting (Cheng, 2010; Jung et al., 2010; van Asselt et al., 2010; Sovacool, 2011a) and measurement, reporting, and verification of NAMAs (Jung et al., 2010; Sterk, 2010; van Asselt et al., 2010).

While NAMAs pertain particularly to the developing world, co-benefits based arguments are also used in developed countries. In the United States, Gore and Robinson (2009) argue that expansion of municipal scale action is articulated in the form of co-benefits, and is driven by network-based communication and citizen initiative. In Germany, several benefits in addition to climate change have been attributed to the policy for energy transition or 'Energiewende,' including security of energy supply and industrial policy (Lehmann and Gawel, 2013).

In some federal systems, national target setting by the central government is followed by further allocation of targets to provinces, often through nationally specific formulae or processes. For example, in the case of Belgium, Kyoto targets were re-allocated to the regional level through a process of negotiation, followed by the preparation of regional climate plans to implement regional targets (Happaerts et al., 2011). Ultimately, since agreement could not be reached on regional targets to meet the national Kyoto targets, the approach relied on offsets were explicitly internalized as part of the national approach to meeting Kyoto targets. In China, national action is defined and monitored by the central government in consultation with provinces, and implementation is delegated to provinces. Targets set in the subsequent National Climate Change Programme as part of the 11th Five Year Plan were implemented through a mechanism of provincial communiqués to track compliance with the target, and provincial leading groups to implement the target (Teng and Gu, 2007; Qi et al., 2008; Tsang and Kolk, 2010b; Held et al., 2011a; Kostka and Hobbs, 2012). A range of policy mechanisms were used to implement this target, such as differential energy prices based on energy efficiency performance, promotion of energy audits, and financial incentives for performance (Held et al., 2011b). Subsequent revised targets have been set for the 12th Five Year Plan.

Other countries represent intermediate cases between central control and decentralization. India has developed a mix of national policies through its National Action Plan on Climate Change, responsibility for which rests with central government ministries, and State Action Plans on Climate Change to be developed and implemented by states (Dubash et al., 2013). While they are predominantly focused on implementing national level directives, there is also sufficient flexibility to pursue state-level concerns, and some states have created new mechanisms, such as the establishment of a Climate Change department in the state of Gujarat, and the establishment of a green fund in Kerala (Atteridge et al., 2012). In France, the EU objectives were adopted as national goals, and through national legislation, all urban agglomerations over 50,000 are required to prepare 'Climate and Energy Territorial Plans' to meet these goals and, additionally, to address adaptation needs (Assemblée Nationale, 2010). Since all other planning processes related to issues such as transport, building, urban planning, and energy have to conform to and support these objectives, this approach provides a powerful mechanism to mainstream climate change into local public planning. These plans also form a framework around which private voluntary action can be organized. In Germany, while the federal government initiates and leads climate action, the states or 'Länder' have a veto power against central initiatives through representation in the upper house of parliament (Weidner and Mez, 2008). In addition, however, the Länder may also take additional action in areas such as energy efficiency measures, renewable energy development on state property and even through state-wide targets (Biedermann, 2011).

In some cases, sub-national jurisdictions seem to be attempting to compensate for the lack of political momentum at the national level (Schreurs, 2008; Dubash, 2011). In the United States, for example, although progress at the federal level has been slow and halting, there have been multiple efforts at sub-national scales, through unilateral and coordinated action by states, judicial intervention, and municipal-scale action (Carlarne, 2008; Rabe, 2009, 2010; Posner, 2010). There are examples of states joining together in creating new institutional mechanisms, such as the Regional Greenhouse Gas Initiative (RGGI) among Northeastern states in the United States to institute an emissions trading programme, and the Western Climate Initiative (WCI) between California and several Canadian provinces, although both these initiatives have also failed to live up to their original promise (Mehling and Frenkil, 2013). Climate policy in the state of California, with its new cap and trade programme, is particularly worth noting both because of the size of its economy and because California has a history as a pioneer of environmental innovation (Mazmanian et al., 2008; Farrell and Hanemann, 2009).

As detailed further in Section 15.8, cities are particularly vibrant sites of sub-national action in some countries, often operating in networks and involving a range of actors at multiple scales (Betsill and Bulkeley, 2006; Gore and Robinson, 2009). For example, in the Netherlands, the central government has established a programme that provides subsidies to municipalities to undertake various measures such as improvements in municipal buildings and housing, improved traffic flow, sustainable energy, and so on (Gupta et al., 2007). In Brazil, important cities such as Rio de Janeiro and São Paulo have taken specific measures that go beyond national policies. For example, a 2009 São Paulo law (No. 13.798) commits the state to undertake mandatory economy-wide GHG emission reduction targets of 20 % by 2020 from 2005 levels (Lucon and Goldemberg, 2010). In the United States, over 1000 cities and municipalities have committed to reaching what would have been the US Kyoto target as part of the Conference of Mayors' Climate Protection Agreement (Mehling and Frenkil, 2013).

Sub-national action on climate change is a mix of bottom-up experimentation and the interaction of top-down guidance with local implementation action. In some cases, countries have set in place explicit mechanisms for coordination of national and sub-national action, such as in China and India, but there is insufficient evidence to assess the effectiveness of these mechanisms. More typical is relatively uncoordinated action and experimentation at sub-national level, particularly focused on cities. These issues are discussed further in Section 15.8.

15.2.6 Drivers of national and sub-national climate action

National and sub-national actions are related to domestic political institutions, domestic politics, international influences, and ideational factors. Based on data from industrialized countries, a comparative political analysis suggests that proportional representation systems such as those in many EU nations are more likely than first past the post systems to give importance to minority interests on environmental outcomes; systems with multiple veto points, such as the US system, afford more opportunities for opponents to block political action; and in federal systems powerful provinces with high compliance costs can block action, as seems to have occurred in Canada (Harrison and Sundstrom, 2010). Lachapelle and Paterson (2013) use quantitative analysis to substantiate the argument about proportional representation and systems with multiple veto points. They also show that presidential-congressional systems find it systematically more difficult to develop climate policy than parliamentary systems.

These are, however, only general tendencies: the specific details of country cases, as well as the possibility of multiple and interacting causal factors, suggests the need for caution in predicting outcomes based on these factors.

In particular, national domestic political factors are also salient. Electoral politics, operating through pressure for action from domestic constituents, is a determinant of action as is the cost of compliance (Harrison and Sundstrom, 2010). The role of climate change in electoral strategies developed by political parties may also play a role in climate governance, although evidence for this effect is available only for developed countries (Carter, 2008; Fielding et al., 2012; Bailey and Compston, 2012a). For example, the compliance costs of carbon pricing were the subject of direct electoral competition between Australia's major political parties in the 2007 and 2010 general elections (Rootes, 2011; Bailey et al., 2012). The presence of substantial co-benefits opportunities and re-framing policy around these opportunities can also influence domestic politics in favour of climate action (Held et al., 2013b); (Bailey and Compston, 2012a). Finally, the 'type' of state—liberal market, corporatist or developmental—can shape outcomes (Lachapelle and Paterson, 2013). For example, somewhat counter-intuitively corporatist states (e.g., Germany, South Korea) are more likely to have introduced carbon pricing than states with liberal market policy traditions (e.g., the United States, Canada). Conversely, liberal market economies are more likely, as are developmental states (e.g., China), to focus on R&D as a principal policy tool (on the United States, see notably Macneil (2012). These patterns reflect powerful institutional path dependencies and incentives facing actors promoting climate policy in particular countries (Macneil, 2012).

International pressures are also important in explaining state action. Diplomatic pressure, changes in public and private finance that emphasize mainstreaming climate change, and a general trend toward higher fossil-fuel energy prices all are associated with increasing climate action (Held et al., 2013b).

Finally, based on comparative case studies, various ideational factors such as national norms around multilateralism, perceptions of equity in the global climate regime (Harrison and Sundstrom, 2010), and ideas put forward by scientists, international organizations and other voices of authority can also shift domestic politics (Held et al., 2013b).

15.2.7 Summary of institutions and governance

The evidence on institutional change and new patterns of climate governance is limited, as many countries are in the process of establishing new institutions and systems of governance. However, several trends are visible. First, there is a considerable increase in government led institutionalization of climate action through both legislation and policy since AR4. The factors driving these changes include international pressures, scope for co-benefits, and changing norms and ideas. The specifics of national political systems also affect country actions. Second, evidence from national cases illustrates considerable diversity in the forms of action. While there are only a few cases of nationally led economy wide carbon price setting efforts, more common are sectoral approaches to climate change mitigation or delegated action to sub-national levels, often embedded within national climate policy frameworks. Third, the promise of 'co-benefits' is often an important stated reason for climate policies and their framing. Fourth, there is a profusion of activity at sub-national levels, particularly urban areas, much of which is only loosely coordinated with national actions. Finally, the diversity of approaches appears to be strongly driven by local institutional and political context, with legislative and policy measures tailored to operate within the constraints of national political and institutional systems.

15.3 Characteristics and classification of policy instruments and packages

This section presents a brief and non-exhaustive description of the main policy instruments and packages, using the common classification set by Chapter 3.8. Most of these instruments will be assessed with the common evaluation criteria set by Chapter 3 (see Section 15.5) in most of the remaining parts of this chapter. As indicated in Section 15.2, these instruments are introduced within an institutional context that obviously influences their design and implementation.

15.3.1 Economic instruments

Economic instruments are sometimes termed 'market-based' approaches because prices are employed in environmental and climate policies. Economic instruments for climate change mitigation include taxes (including charges and border adjustments), subsidies and subsidy removal, and emissions trading schemes. Taxes and subsidies are known as price instruments since they do not directly target quantities, while emissions trading schemes, especially cap-and-trade schemes (see below), are known as quantity instruments. This distinction can be important, as seen in Sections 15.5.3.8, 15.7.3.2, and 15.7.3.4.

Taxes and charges are ideally defined as a payment for each unit of GHG released into the atmosphere. In the climate context, they are usually unrelated to the provision of a service and are thus known as taxes rather than charges. They can be levied on different tax bases, whereas tax rates, given the global and uniform characteristics of the taxed emissions, usually do not show spatial variation (OECD, 2001). In the last years, many taxes on GHG or energy have devoted part of their revenues to the reduction of other distortionary taxes (green tax reforms), although other revenue uses are now playing an increasing role (Ekins and Speck, 2011).

Border tax adjustments are related instruments that intend to solve the dysfunctions of variable climate change regulations across the world. Although some authors highlight that they could alleviate the problem of leakage and a contribute to a wider application of mitigation policies (Ismer and Neuhoff, 2007), others emphasize that they do not constitute optimal policy instruments and could even increase leakage (Jakob et al., 2013) or cause potential threats to fairness and to the functioning of the global trade system (e.g., Bhagwati and Mavroidis, 2007).

*Subsidie*s to low GHG products or technologies have been applied by a number of countries but, contrary to the previous revenue-raising/neutral economic instruments, they demand public funds. In some countries there are 'perverse' subsidies lowering the prices of fossil fuels or road transport, which bring about a higher use of energy and an increase of GHG emissions. Therefore, *subsidy reduction or removal* would have positive effects in climate change and public-revenue terms and is therefore treated as an instrument in its own right (OECD, 2008).

In 'cap-and-trade' *emissions trading systems* regulators establish an overall target of emissions and issue an equivalent number of emissions permits. Permits are subsequently allocated among polluters and trade leads to a market price. The allocation of emission permits can be done through free distribution (e.g., grandfathering) or through auctioning. In 'baseline and credit' emissions trading systems, polluters may create emission reduction credits (often project-based) by emitting below a baseline level of emissions (Stavins, 2003).

15.3.2 Regulatory approaches

Regulations and standards were the core of the first environmental policies and are still very important in environmental and climate policies all around the world. They are conventional regulatory approaches that establish a rule and/or objective that must be fulfilled by the polluters who would face a penalty in case of non-compliance with the norm. There are several categories of standards that are applicable to climate policies, mainly:

- *Emission standards*, which are the maximum allowable discharges of pollutants into the environment, and which can also be termed as performance standards;
- *Technology standards* that mandate specific pollution abatement technologies or production methods (IPCC, 2007); and
- *Product standards* that define the characteristics of potentially polluting products (Gabel, 2000).

15.3.3 Information policies

A typical market failure in the environmental domain is the lack, or at least asymmetric nature, of relevant information among some firms and consumers. Good quality information is essential for raising public awareness and concern about climate change, identifying environmental challenges, better designing and monitoring the impacts of environmental policies, and providing relevant information to inform consumption and production decisions. Examples of information instruments include eco-labelling or certification schemes for products or technologies and collection and disclosure of data on GHG emissions by significant polluters (Krarup and Russell, 2005).

15.3.4 Government provision of public goods and services and procurement

A changing climate will typically be a 'public bad' and actions and programmes by governments to counteract or prevent climate change can thus be seen as 'public goods'. There are many examples where public good provision may be an appropriate form of mitigation or adaptation. Examples include physical and infrastructure planning, provision of district heating or public transportation services (Grazi and van den Bergh, 2008), and funding and provision of research activities (Metz, 2010). Moreover, the removal of institutional and legal barriers that promote GHG emissions (or preclude mitigation) should be included in this policy type. Afforestation programmes and conservation of state-owned forests are an important example.

15.3.5 Voluntary actions

Voluntary actions refer to actions taken by firms, NGOs, and other actors beyond regulatory requirement. Voluntary agreements represent an evolution from traditional mandatory approaches based on conventional or economic regulations and intend to provide further flexibility to polluters. They are based on the idea that, under certain conditions, polluters can decide collectively to commit themselves to abatement instead of, or beyond the requirements of regulation. Voluntary agreements, sometimes known as long-term agreements, can be developed in different ways; in most cases the voluntary commitment is assumed as a consequence of an explicit negotiation process between the regulator and the pollutant. In other cases a spontaneous commitment may be viewed as a way to avoid future mandatory alternatives from the regulator (Metz, 2010). Finally, there are cases where the regulator promotes standard environmental agreements on the basis of estimation of costs and benefits to firms (Croci, 2005).

15.4 Approaches and tools used to evaluate policies and institutions

15.4.1 Evaluation criteria

Several criteria have been usually employed to assess the effects of climate change policies and these have been laid out in Section 3.7. The criteria that have been used are environmental effectiveness, economic effectiveness (cost-effectiveness and economic efficiency), distributional equity and broader social impacts, and institutional, political, and administrative feasibility and flexibility. Political and institutional feasibility are not only a separate criterion, but also need to be taken into account when judging other criteria such as economic effectiveness. It would be misleading to show that a tax would have been more cost-effective than, for example, a regulation if it would never have been feasible to implement the tax at a sufficiently high level to have the same effect as that regulation.

15.4.2 Approaches to evaluation

One can evaluate the effect of policy instrument x on a set of variables y that matter for the evaluation criteria either through modelling or through ex-post empirical measurement. For any evaluation based solely on modelling, it will never be possible to know whether all important aspects of the relationship between x and the y's are captured appropriately by the model. For this reason, it is highly desirable to have ex-post empirical analysis to evaluate a policy instrument. In order to measure the effect of a policy instrument, one must compare the observed y's in the presence of x with the 'but-for' or 'counterfactual' value of the y's defined as their estimated likely value but for the implementation of x.

Statistical methods can be used to attempt to control for the evolution of the world in the absence of the policy. The most reliable basis for estimating counterfactual developments is to build programme evaluation into the design of programmes from their inception (Jaffe, 2002). If the planning of such evaluation is undertaken at the beginning of a programme, then data can be developed and maintained that greatly increase the power of statistical methods to quantify the true impact of a programme by controlling for but-for developments.

Statistical analyses capture only those policy effects that can be and have been measured quantitatively. Qualitative analyses and case studies complement statistical analyses by capturing the effects of policies and institutions on other aspects of the system, and the effect of institutional, social and political factors on policy success (e.g., Bailey et al., 2012).

Of course, data for ex-post evaluation is not always available, and even where it is, it is very challenging to capture all aspects of the situation empirically. Therefore, there will always be a role for models to elucidate the structure of policy effects, and to estimate or put bounds on the magnitude of effects. Such models can be purely analytical/theoretical, or they can combine empirical estimates of certain parameters with a model structure, as in 'bottom-up' models where many small effects are estimated and cumulated, or in simulation models, which combine an analytical/theoretical structure with numerical estimates of parameters of the model. Many such models are 'partial equilibrium,' meaning they capture the particular context of interest but ignore impacts on and feedback from the larger system. There are also computable 'general equilibrium' (CGE) models that allow for interactions between the context of the policy focus and the larger system, including overall macroeconomic impacts and feedbacks see for example, Bohringer et al., (2006).

'Experimental economics' uses a laboratory setting as a 'model' of a real-world process, and uses 'experimental subjects' responses in that setting as an indicator of likely real-world behaviour (Kotani et al., 2011). With any model, results are truly predictive of real-world results only to the extent that the model—be it theoretical, simulation or experimental—captures adequately the key aspects of the real world in the experiment.

15.5 Assessment of the performance of policies and measures, including their policy design, in developed and developing countries taking into account development level and capacity

15.5.1 Overview of policy implementation

In this section we assess the performance of a series of policy instruments and measures, starting with economic instruments (taxes in 15.5.2, emissions trading in 15.5.3), regulatory approaches (15.5.4), information programmes (15.5.5), government provision of public goods (15.5.6) and voluntary agreements (15.5.7). We assess aspects of these and other policies in Section 15.6 on technology and R&D policy, and in Section 15.7 that deals with interactions between policies.

Many policy instruments are in principle capable of covering the entire economy. However, as mentioned in Section 15.2, in practice the instruments are often targeted to particular sectors or industries. This partly reflects the fact that certain barriers or market failures are specific to or more pronounced in certain sectors or industries. Furthermore, some policies may cover only part of the economy as a result of the ability of special interests to exempt some sectors or industries (Compston, 2009), (Helm, 2010).

Broader coverage tends to promote greater cost-effectiveness. However, on fairness grounds there is an argument for partly or fully exempting certain industries in order to maintain international competitiveness, particularly when the threat to competitiveness comes from other nations that have not introduced climate policy and would gain competitive advantage as a result.

Table 15.2 brings together policy instruments discussed in sector chapters (Chapters 7 to 12). Two broad themes emerge from this survey. First, while policies that target broad energy prices—taxes or tradable allowances are clearly applicable across all sectors—a wide range of other policy approaches are also prevalent, which enable policy design that addresses sector specific attributes. For example, in the buildings sector regulatory instruments are an important tool. In the absence of a building code enforcing enhanced efficiency, an energy price signal alone might be insufficient to induce a builder to invest in an energy efficient building that they plan to sell or rent. Building and product standards also increase investor certainty thereby reducing costs. Similarly, the transport sector relies not only on pricing policies but also on government provision of infrastructure and regulation that guides urban development and modal choices. The industry sector faces information and other barriers to investment in efficiency, which can be overcome by audits and other information based programmes. In Agriculture, Forestry, and Other Land Use (AFOLU), government regulation to protect forests and set the conditions for REDD+ (Reducing Emissions From Deforestation and Forest Degradation) plays a substantial role, as do certification programmes for sustainable forestry.

Sector-specific policies often exist alongside broader ones. In energy supply, broad-based GHG emissions pricing has often been supplemented by specific price- and quantity-based mechanisms (such as feed-in-tariffs (FITs) and portfolio standards) and underpinned by sufficient regulatory stability (including non-discriminatory access to electricity and gas networks). In industry, relatively broad tax exemptions may be combined with mandatory audits, with the former helping 'level the playing field' and providing the impetus for action, and the latter addressing an information barrier; thus each instrument addresses a separate market failure or barrier. The implementation of multiple policy instruments within a single sector can promote cost-effectiveness when the two instruments address distinct market failures. On the other hand, multiple instruments can work against cost-effectiveness when the two instruments fail to address different market failures and thus are simply redundant. This issue is discussed further in Section 15.7 below.

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Table 15.2 | Sector Policy Instruments.

Policy Instruments	Energy (See 7.12)	Transport (See 8.10)	Buildings (See 9.10)	Industry (See 10.11)	AFOLU (See 11.10)	Human Settlements and Infrastructure (See 12.5)
Economic Instruments—Taxes (Carbon taxes may be economy-wide)	• Carbon taxes	• Fuel taxes • Congestion charges, vehicle registration fees, road tolls • Vehicle taxes	• Carbon and/or energy taxes (either sectoral or economy wide)	• Carbon tax or energy tax • Waste disposal taxes or charges	• Fertilizer or Nitrogen taxes to reduce nitrous oxide	• Sprawl taxes, impact fees, exactions, split-rate property taxes, tax increment finance, betterment taxes, congestion charges
Economic Instruments—Tradable Allowances (May be economy-wide)	• Emissions trading (e.g., EU ETS) • Emission credits under the Kyoto Protocol's Clean Development Mechanism (CDM) • Tradable Green Certificates	• Fuel and vehicle standards	• Tradable certificates for energy efficiency improvements (white certificates)	• Emissions trading • Emission credits under CDM • Tradable Green Certificates	• Emission credits under CDM • Compliance schemes outside Kyoto protocol (national schemes) • Voluntary carbon markets	• Urban-scale Cap and Trade
Economic Instruments—Subsidies	• Fossil fuel subsidy removal • Feed-in-tariffs for renewable energy • Capital subsidies and insurance for 1st generation Carbon Dioxide Capture and Storage (CCS)	• Biofuel subsidies • Vehicle purchase subsidies • Feebates	• Subsidies or tax exemptions for investment in efficient buildings, retrofits and products • Subsidized loans	• Subsidies (e.g., for energy audits) • Fiscal incentives (e.g., for fuel switching)	• Credit lines for low carbon agriculture, sustainable forestry.	• Special Improvement or Redevelopment Districts
Regulatory Approaches	• Efficiency or environmental performance standards • Renewable Portfolio Standards for renewable energy • Equitable access to electricity grid • Legal status of long-term CO_2 storage	• Fuel economy performance standards • Fuel quality standards • GHG emission performance standards • Regulatory restrictions to encourage modal shifts (road to rail) • Restriction on use of vehicles in certain areas • Environmental capacity constraints on airports • Urban planning and zoning restrictions	• Building codes and standards • Equipment and appliance standards • Mandates for energy retailers to assist customers invest in energy efficiency	• Energy efficiency standards for equipment • Energy management systems (also voluntary) • Voluntary agreements (where bound by regulation) • Labelling and public procurement regulations	• National policies to support REDD+ including monitoring, reporting and verification • Forest law to reduce deforestation • Air and water pollution control GHG precursors • Land-use planning and governance	• Mixed use zoning • Development restrictions • Affordable housing mandates • Site access controls • Transfer development rights • Design codes • Building codes • Street codes • Design standards
Information Programmes		• Fuel labelling • Vehicle efficiency labelling	• Energy audits • Labelling programmes • Energy advice programmes	• Energy audits • Benchmarking • Brokerage for industrial cooperation	• Certification schemes for sustainable forest practices • Information policies to support REDD+ including monitoring, reporting and verification	

Policy Instruments	Energy (See 7.12)	Transport (See 8.10)	Buildings (See 9.10)	Industry (See 10.11)	AFOLU (See 11.10)	Human Settlements and Infrastructure (See 12.5)
Government Provision of Public Goods or Services	• Research and development • Infrastructure expansion (district heating/cooling or common carrier)	• Investment in transit and human powered transport • Investment in alternative fuel infrastructure • Low emission vehicle procurement	• Public procurement of efficient buildings and appliances	• Training and education • Brokerage for industrial cooperation	• Protection of national, state, and local forests. • Investment in improvement and diffusion of innovative technologies in agriculture and forestry	• Provision of utility infrastructure such as electricity distribution, district heating/cooling and wastewater connections, etc. • Park improvements • Trail improvements • Urban rail
Voluntary Actions			• Labelling programmes for efficient buildings • Product eco-labelling	• Voluntary agreements on energy targets or adoption of energy management systems, or resource efficiency	• Promotion of sustainability by developing standards and educational campaigns	

15.5.2 Taxes, charges, and subsidy removal

15.5.2.1 Overview

Taxes on carbon (together with emissions trading systems) are economic instruments. In the presence of rational consumers, firms, and complete markets, they achieve any given level of emissions reduction in the least costly way possible. Economic instruments like carbon taxes are attractive because of their simplicity and broad scope covering all technologies and fuels (Section 3.8) and thus evoking the cost-minimizing combination of changes to inputs in production and technologies to changing behaviour as manifested in consumption choices and lifestyles. This is the reason they have the potential to be more efficient than directly regulating technology, products, or behaviour.[1] To minimize administrative costs, a carbon tax can be levied 'upstream' (at the points of production or entry into the country). Finally, unlike an emissions trading system that requires new administrative machinery, a tax can piggyback off existing revenue collection systems.

Despite these attractive properties, carbon taxes are not nearly as prevalent a policy instrument as one might expect. As yet, the Scandinavian countries, the Netherlands, the UK, and the Canadian province of British Columbia are the only large jurisdictions with significant and fairly general carbon taxes of at least USD 10/tCO_2.[2] The reasons for this are not entirely clear. It may be that a carbon tax, unlike a narrower sectoral regulation, attracts more hostile lobbying from fossil fuel interests[3] for whom the stakes it creates are high (Hunter and Nelson, 1989; Potters and Sloof, 1996; Goel and Nelson, 1999; Godal and Holtsmark, 2001; Skjærseth and Skodvin, 2001; Kolk and Levy, 2002; van den Hove et al., 2002b; McCright and Dunlap, 2003; Markussen and Svendsen, 2005; Pearce, 2006; Beuermann and Santarius, 2006; Deroubaix and Lévèque, 2006; Pinkse and Kolk, 2007; Bridgman et al., 2007; Bjertnæs and Fæhn, 2008; Blackman et al., 2010; Sterner and Coria, 2012). Secondly, the payments required by a tax are transparent, unlike the less visible costs of regulations. The general public, not being aware of the above-mentioned efficiency properties of a tax, may be less likely to accept such an instrument (Brännlund and Persson, 2010). Third, policy may be driven by perceived risks to competitiveness and employment as well as the distribution of costs rather than on considerations of pure efficiency (Decker and Wohar, 2007). Finally, a set of institutional path dependencies may have led to a favouring of emissions trading systems over taxes, including a post-Kyoto preference for emissions trading in key bureaucracies, supported by creation of supportive industry and other associations (Skjærseth and Wettestad, 2008; Paterson, 2012).

Countries that have sizeable general carbon taxes are fewer still—mainly a few Northern European countries. The carbon tax in Sweden is 1100 SEK or USD165/tCO_2, which is an order of magnitude higher than the price of permits on the EU emissions trading scheme (ETS) market or than the carbon taxes discussed in many other countries. Such high taxes typically have some exemptions motivated by the fact that other (competing) countries have no (or low) taxes. Sweden, for example, exempted the large energy users who participate in the EU ETS from also paying the carbon tax on the grounds that there would otherwise be a form of 'double' taxation (See 15.5.2.4 for a more thorough discussion).

[1] If psychological or institutional barriers to adoption or other market failures are the main factor impeding choice then regulations or other instruments may be an efficient complement or stand-alone instrument to deal with this (see Section 15.4).

[2] Australia has a fixed fee hybrid system sometimes described as a tax that will be converted into an ETS.

[3] These can be either producers (for instance of fossil fuels) or users of energy, ranging from energy intensive industries to truck drivers.

Although general carbon taxes are so far uncommon, there are many policies that have similar effects but (for political reasons) avoid using the words 'carbon' and/or 'tax', (Rabe and Borick, 2012). Taxes on fuels, especially transport fuels are very common. While narrower in scope, they nevertheless cover a significant fraction of emissions in many countries. They can be interpreted as sectoral carbon taxes; in some countries this is clearly stated as an objective of fuel taxes, in others it is not. Fuel taxes may be politically easier to implement in some countries since (private) transport is hardly subject to international competition and hence leakage rates are low. A large share of all revenues from environmentally related taxes in fact come from fuel taxes, which were introduced in various countries, beginning with Europe and Japan, though they are also common in low income, oil-importing countries. One of their main stated purposes is to finance road building, although additional arguments include reducing expensive imports, government revenue raising, and reducing environmental impacts. Irrespective of the motivation, the effect of carbon taxes on fuel is to raise prices to consumers and restrict demand (see Section 15.5.2.2). Fuel taxes are important for climate change mitigation since the transport sector represents a large and increasing share of carbon emissions (27 % of global energy-related CO_2 emissions in 2010—see Section 8.1). Theory, simulation, and empirical studies all suggest strongly that taxing fuel is a lower cost method of reducing emissions compared to policies such as fuel efficiency mandates, driving restrictions, or subsidies to new technologies[4] (Austin and Dinan, 2005). However, consumers who buy vehicles may be unable to correctly internalize the long-run savings of more fuel-efficient vehicles. This would be considered a 'barrier' and would provide motivation for having fuel efficiency standards in addition to fuel taxes (see Section 15.5.4).

Variation in fuel prices is generated by subsidies as well as taxes. Fossil fuel subsidies are prevalent in many countries, being most common in oil and coal producing countries. According to the International Monetary Fund (IMF) (2013), the Middle East and North Africa region accounts for around 50 % of global energy subsidies. In 2008, fossil fuel subsidies—for transport fuels, electricity, tax breaks for oil and gas production, and for research and development into coal generation, exceeded USD_{2010} 489.1 billion globally (IEA/OECD, 2011). A more recent estimate by the IMF (2013) puts the figure at USD_{2010} 469.5 billion or 0.7 % of global GDP in 2011. This is a pre-tax estimate and includes petroleum products, electricity, natural gas, and coal. A large share is in the fossil fuel exporting countries. After factoring in negative externalities, through corrective taxes, the IMF reports USD_{2010} 1.85 trillion in implicit subsidies. This figure assumes damages corresponding to a USD 25/t social cost on carbon, consistent with United States Interagency Working Group on Social Cost of Carbon (2010). 'Advanced economies' make up 40 % of the global post-tax estimate. Reviewing six major studies that estimate fossil fuel subsidies, Ellis (2010) notes that removal of such subsidies would increase the aggregate GDP in OECD and non-OECD countries in the "range from 0.1 per cent in total by 2010 to 0.7 per cent per year to 2050 (Ellis, 2010)." The studies reviewed include both modelling and empirical exercises.

15.5.2.2 Environmental effectiveness and efficiency

Assessing the environmental effectiveness of carbon taxation is not straightforward because multiple instruments and many other factors co-evolve in each country to produce policy mixes with different outcomes in terms of emissions. For example, energy taxes varying by sector have been prominent in the Nordic countries since the 1970s with carbon taxes being added on in the early 1990s. Ex-post analyses have found varying reductions in CO_2 emission from carbon taxes in Norway, Sweden, Denmark, and Iceland, compared to business-as-usual (see Andersen (2004) for an extensive review of these studies and their estimation techniques).

The UK's Climate Change Levy (CCL), introduced in 2001 on manufacturing plants and non-residential energy users (offices, supermarkets, public buildings, etc.), has had a strong impact on energy intensity (Martin et al., 2011). Electricity use, taxed at a rate of about 10 %, declined by over 22 % at plants subject to the levy as compared to plants that were eligible to opt out by entering into a voluntary agreement to reduce energy use. There was no evidence that the tax had any detrimental effect on economic performance or led plants to exit from the industry (Martin et al., 2011).

From 1990 to 2007, the CO_2 equivalent emissions in Sweden were reduced by 9 % while the country experienced an economic growth of +51 %. In Sweden, with the highest carbon tax (albeit with exemptions for some industrial sectors), there was a very strong decoupling of carbon emissions and growth with reductions in carbon intensity of GDP of 40 % (Johansson, 2000; Hammar et al., 2013). Per capita emissions in Denmark were reduced by 15 % from 1990 to 2005; the experience in Scandinavia, the UK, and the Netherlands was similar (Enevoldsen, 2005; Enevoldsen et al., 2007), (Bruvoll and Larsen, 2004), (Cambridge Econometrics, 2005), (Berkhout et al., 2004; Sumner et al., 2011; Lin and Li, 2011). Of course, many factors may be at play, and these differences cannot be attributed solely to differences in taxation. Overall, the evidence does suggest that carbon taxes, as part of an environmental tax reform, lead to abatement of GHG emissions, generate revenue for the government, and allow reductions in income tax threatening employment. Theory strongly suggests that if a tax is implemented then it would also be cost effective, but it is for natural reasons hard to demonstrate this empirically at the macro level.

There is much more evidence available on the environmental efficacy of fuel as compared to carbon taxation. In the short run, consumers may be locked into patterns of use by habit, culture, vehicle characteristics, urban infrastructure, and architecture. The short-run response to higher fuel prices is indeed often small—price elasticity estimates range between –0.1 to –0.25 for the first year. However long-run price elasticities are quite high: approximately –0.7 or a range of –0.6 to

[4] See also Section 15.12 on climate finance.

–0.8. This range is the average found by surveys of hundreds of studies that use both market based variations in fuel price as well as policy induced variations and exploit both temporal and cross-sectional variations in the data; the individual study estimates range substantially more depending on countries or regions covered, time period, method and other factors (Oum, 1989; Goodwin, 1992; Graham and Glaister, 2002; Goodwin et al., 2004). In the long run, therefore, 10 % higher fuel prices will ultimately lead to roughly a 7 % reduction in fuel use and emissions. Income elasticities are about 1, which means that 5 % growth in income gives 5 % growth in emissions. If instead a 2 % reduction is desired there is a 7 % gap between the 5 % increase and the –2 % desired and a 10 % increase in fuel price every year would be needed to achieve such a reduction in emissions with a 5 % growth in income.

The long-run effects of transport fuel taxation have been large. Sterner (2007) shows that in Europe, where fuel taxes have been the highest, they have contributed to reductions in CO_2 emissions from transport by 50 % for this group of countries. The whole Organisation for Economic Co-operation and Development (OECD) would have had 30 % higher fuel use had not the European Union and some other members imposed high fuel taxes (i. e., if all the OECD countries had instead chosen as low fuel taxes as in the United States). Similarly, the OECD could have decreased fuel use by more than 35 % if all member countries would have chosen as high taxes as the United Kingdom. The accumulated difference in emissions over the years leads to a difference in several ppm in CO_2 concentration, presumably making fuel taxes the policy that has had the largest actual impact on the climate up till now (Sterner, 2007).

The environmental effect of a fuel tax is illustrated in Figure 15.2, where the fitted curve is from a log-linear regression of the emission intensity of liquid fuels on the price of diesel. The cross-country variation in diesel prices is mostly due to variation in taxes (and in some cases, subsidies). Figure 15.2 suggests that the effect of a change in the price of a fuel on emissions is greater at low prices. This is intuitive, since fuel will be consumed wastefully when it is cheap, allowing for greater demand reductions when the price rises.

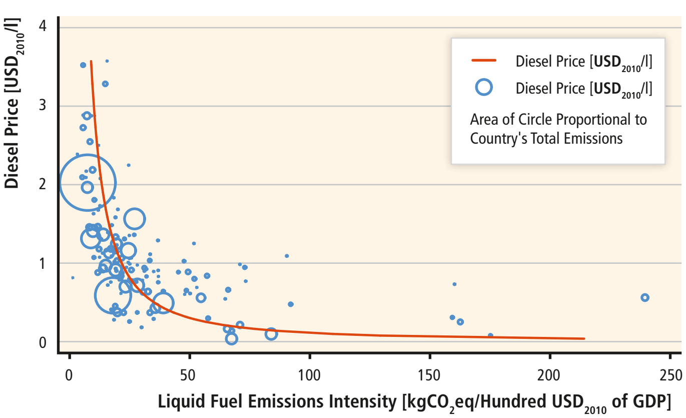

Figure 15.2 | The impact of average diesel prices across the world on the emissions intensity of liquid fuels.

Though there are few clean experiments, the market continuously creates 'quasi-experiments' which are analogous to the introduction of policies. Increased fuel prices in the USA in 2008, for instance, led to a shift in the composition of vehicles sold, increasing fuel-efficiency, while also reducing miles travelled (Ramey and Vine, 2010; Aldy and Stavins, 2012).

Other price instruments that have been used in the transport sector are congestion charges, area pricing, parking fees, and tolls on roads or in cities. These have been used to reduce congestion; emission reduction is a co-benefit. The USD_{2010} 15.4 congestion fee in London led to reductions in incoming private cars by 34 % when introduced. Overall congestion was also estimated to have been reduced by 30 %, and emissions fell (Leape, 2006). The smaller (USD_{2010} 2.6) congestion fee in Stockholm reduced total road usage by 15 % (Johansson et al., 2009).

Reducing subsidies to fossil energy will have a significant impact on emissions. Removing them could reduce world GHG emissions by 10 % at negative social cost by 2050 (Burniaux and Chateau, 2011).The IMF calculates that the removal of these subsidies induce a 15 % reduction in global energy related carbon emissions or 5 billion tCO_2 in absolute terms and concludes that the post-tax estimate of USD_{2010} 1.85 trillion in subsidies is 'likely to underestimate' energy subsidies due to the assumptions made, hence the impact on carbon emissions is likely to be higher. Ellis (2010) reports a range of effects from just a few percent to 18 % by 2050 depending on the size of the subsidy reduction.

Recognizing the potential impact of a reduction in subsidies to fossil fuels, the G20 and APEC blocks agreed in 2009 to phase out inefficient fossil fuel subsidies in all countries (G20 Leaders, 2009).

In China, the energy saving policies adopted in 1991, the 1998 Law on Energy Conservation, and the 2004 Medium and Long Term Specific Schema on Energy Saving, led to higher energy prices and explain half the decline in energy intensity of Chinese industries between 1997 and 1999, while R&D accounted for only 17 % of the decline (Fisher-Vanden et al., 2006; Yuan et al., 2009).

15.5.2.3 Distributional incidence and feasibility

Although fuel taxes have often been criticized for being regressive (that is, for imposing a proportionally higher burden on the poor), this is not always the case. There are large variations in distributional impacts both within and between social groups the effects range from regressive or progressive (Rausch et al., 2010, 2011); see also 6.3.5.2.

Studies of the distributional incidence of fuel taxes show that they may be neutral or weakly regressive (before revenue recycling) in rich countries, but they are generally progressive in poor countries. In many least developed and developing countries such as India, Indonesia, China, and many African countries, the progressivity of fuel taxes is in fact quite strong. In Europe they are approximately neutral (Sterner, 2012). Carbon taxation can sometimes have regressive effects prior to recycling revenue, but recycling can make the poorest households better off. Generally, the degree of progressivity can be selected depending on the method of recycling revenues. The environmental taxation gives rise to government income that can be allocated in ways that either benefit the poor or any other group giving a considerable range of options for how progressive or regressive the politicians want to make the overall package (Bureau, 2011).

The distributional effects of other taxes vary significantly. Kerosene taxes in developing countries are regressive since kerosene is used predominantly by the poor (Younger et al., 1999; Gangopadhyay et al., 2005; Datta, 2010). This regressivity may also apply to taxes on electricity or coal. The distributional effects of a more general carbon tax will depend on the mode of implementation with respect to different fuels and sectors and typically be more complex than for a single fuel, since the potential substitution possibilities are many. Results vary, but for instance, Hassett et al. (2009) finds a carbon tax to be regressive in the USA, showing that the cost is about 3.74 % for the poorest decile four times the effect on the highest decile. In India, on the other hand, a carbon tax would be progressive (Datta, 2010). The pro- or regressivity of carbon taxes will vary between countries but can also be affected by design, as shown for instance by Fullerton et al., (2012) or Sterner and Coria (2012).

The assertion that fuel taxes are regressive is often used as an argument and can make fuel taxes politically difficult to implement even if not true. Feasibility is however not tied in any simple way to income distribution effects. If a tax is progressive, this does not necessarily increase feasibility since this means that the interests of influential groups are affected, which may be a much bigger impediment to feasibility (Datta, 2010). Fear of social unrest may hold up subsidy removal. Protests over reduced petrol subsidies are common; for example, recently riots erupted in Nigeria when President Jonathan Goodluck tried to eliminate very costly petrol subsidies with only partial success. Some countries such as Iran and Indonesia have recognized that fuel subsidies actually accrue to the relatively wealthy and managed to successfully reduce the subsidies without much unrest, by making sure that revenues saved are spent fairly—for instance through general lump-sum cash transfers (Coady et al., 2010; Atashbar, 2012; Sterner, 2012; Aldy and Stavins, 2012).

15.5.2.4 Design issues: exemptions, revenue recycling, border adjustments

As mentioned above in 15.5.2.1, despite the attractive efficiency properties of a broad carbon tax, and even its progressivity in many circumstances, it may face political resistance. To have a big effect on emissions a tax must be high. Carbon and fuel taxes have often been initially resisted, but once introduced it seems the fee level has often been increased, (Sumner et al., 2011b). Another factor may be a path dependency since the taxes reduce the use of fossil fuel and lower fuel use means less opposition to fuel taxes, (Hammar et al., 2004). This path dependency may be the rationale for raising the fuel or carbon taxes slowly and steadily as done by the Conservative government in the UK with the Fuel Price Escalator starting in 1993, a policy that was continued under the successor Labour government for several years.

An emissions tax involves a transfer from economic agents to the state, namely the tax revenue from the residual emissions that are not abated. Private parties have to make this transfer in addition to bearing the cost of actually reducing emissions. There are a number of approaches to designing a tax (or fee) so that the transfer does not take place and resistance from incumbent polluters is reduced.

One approach is simply to exempt certain carbon-intensive industries—such as heavy industry in Sweden, as mentioned earlier. Such policies with incomplete coverage are less cost efficient than general policies (Montgomery, 1972 and Chapter 6.3.5.1). This lack of efficiency applies not only to carbon emissions—it applies even more broadly to agriculture, forestry and to other climate gases such as methane or nitrous oxide (Bosetti et al., 2011). However, narrow sectoral policies may be politically more feasible due to concerns about international competitiveness, the structure of winners and losers, and consequent lobbying (Holland et al., 2011).

A related approach that tries to avoid the loss of coverage is to exempt some firms from taxes conditional on their undertaking emission reduction commitments. In Denmark, for example, companies signing an energy savings agreement with the government received a 25 % tax reduction (OECD, 2001; Agnolucci, 2009; Sumner et al., 2011; Ekins and Speck, 2011; Aldy and Stavins, 2012). Similarly, in the UK some firms may sign Climate Change Agreements (CCA) to reduce emissions that exempt them from the CCL. This experience offers a cautionary tale: on average the agreements did not require firms to reduce emissions beyond what they would have done anyway (Martin et al., 2011). Conditional exemptions amount to unconditional ones if the conditions are lax.

Yet another approach to avoiding a large transfer to the state is to recycle all or part of the tax revenue. In the Canadian province of British Columbia, revenue from the broad carbon tax of USD_{2010} 29.1/tCO_2 is fully rebated to the general population via income tax cuts and transfers to low-income people who do not pay income tax. British Columbia raised the tax gradually in increments of USD_{2010} 4.8/tCO_2 annually to its current level (Jaccard, 2012).

Sometimes revenues are recycled to firms in emission-intensive industries. Again, this relies on identifying the recipients, so it is usually confined to a few sectors with the attendant disadvantages mentioned above. Refunded emission payments and other combinations of taxes and subsidies may be designed to be neutral so that, for example, the industry pays the cost of abatement but does not pay a tax for the allowed or reference level of pollution (Fischer, 2011). One expression of this is fees, which are collected in environmental funds and subsequently used in ways that benefit the polluters. An example from NO_x emissions in Sweden is that a refunded emission payment may be politically more acceptable and thus environmentally more effective than simply a tax. Since the fee is refunded (in proportion to output), there is considerably less resistance to the fee and it can be set much higher than what would have been acceptable for a pure tax. Norway has pioneered another instrument for NO_x emissions—taxes are refunded to cover abatement expenses. This implies a combination of a tax on emissions with a subsidy on abatement. Experience shows that a lower fee can achieve the same result with this instrument design as a tax (Fischer, 2011). Norway is considering promoting similar solutions for carbon emissions (Hagem et al., 2012). The drawback of such schemes for reducing carbon emissions is that their sectoral nature reduces coverage and raises costs.

Abatement subsidies have also been financed out of general revenues. Abatement subsidies need to be financed through tax revenues. The taxes needed to finance the subsidies in general involve a marginal excess burden. This deadweight loss is an extra cost of subsidies relative to emissions taxes. Furthermore, there is an efficiency penalty due to their sectoral nature. If applied to firms, subsidies may create perverse incentives to enter or to fail to exit from, a polluting industry, and raise costs (Polinsky, 1979). Perhaps for such reasons, they are seen in residential and commercial sectors, for instance, tax breaks are provided for building insulation or refurbishing. There are also white certificates and innovative financing schemes that allow loans to be repaid as part of electricity bills (See Section 9.10 for further discussion).

Another reason for tax exemptions is to avoid a loss of competitiveness in industries exposed to foreign competition that is not subject to taxation or equivalent policies. A pure tax (at a high level) may incentivize industries to move to neighbouring countries. This is known as 'leakage', since emissions `leak' to jurisdictions not subject to taxation. It is generally hard to find decisive empirical evidence of carbon leakage, though this may be partly because high carbon taxes have not been tried in any significant way for trade-exposed sectors. As discussed in Chapter 5, some simulations suggest that there could be sizeable effects (Elliott et al., 2010). Though the overall effects of border tax adjustment on leakage are subject to debate (see Jakob et al., 2013), a recent model comparison suggests that full border tax adjustments would moderately decrease leakage rates from on average from on average 12 to 8 % (Bohringer et al., 2012). Border tax adjustments are taxes levied on imported goods that impose equivalent taxes on emissions `embedded' in the goods. Aichele and Felbermayr (2011) find that sectoral carbon imports for a committed (i.e., taxed) country from an uncommitted exporter are approximately 8 % higher than if the country had no commitments and that the carbon intensity of those imports is about 3 % higher. When measurement of embedded emissions is uncertain, border tax adjustments can be criticized for introducing trade barriers in environmental guise (Holmes et al., 2011).

Leakage can also occur intertemporally. As shown by Sinn (2008, 2012), a carbon tax might not only encourage demand in other areas. There may also be a perverse supply side reaction (referred to as the Green Paradox) increasing the current supply of fossil fuels in anticipation of rising carbon taxes. Subsequent research (Gerlagh, 2011; Hoel, 2012) has shown that, strictly speaking, this only applies to very simplified and special models with complete exhaustion of all fossil fuels (which would lead to very drastic climate change) and also only to models in which the carbon tax actually starts low and rises faster than the discount rate. A number of conclusions can be drawn from the debate: (1) generally, the supply side should not be neglected; (2) if a tax is used, there are arguments for making it high rather than low and fast-growing; and most importantly, (3) instruments used need to cover as many countries and sources as possible. It may be difficult to find a single optimal tax, and it may be necessary, rather to formulate a tax rule that will decide how the tax rate is to be updated (Kalkuhl and Edenhofer, 2013).

15.5.3 Emissions trading

15.5.3.1 Overview of emissions trading schemes

Over the past three decades, emissions trading, or cap and trade, has evolved from just a textbook idea (Dales, 1968) to its current role as a major policy instrument for pollution control. Earlier experiences with emissions trading include schemes such as the California RECLAIM Program and the US Acid Rain Program (Tietenberg, 2006; Ellerman et al., 2010).

But since the start of the EU carbon trading system (See Section 14.4.2), several countries and sub-national jurisdictions (e.g., New Zealand, Australia, California, northeastern United States, Quebec, South Korea, Tokyo, and five cities and seven provinces in China) have also put in place or proposed trading schemes to control their carbon emissions. This section provides a brief overview of the literature (see further Perdan and Azapagic, 2011; Aldy and Stavins, 2012) and draws lessons for the design of carbon trading programmes.

15.5.3.2 Has emissions trading worked?

We begin by assessing environmental effectiveness. There were three GHG cap-and-trade programmes that were operational[5] by 2012 (Newell et al. 2013). The EU ETS, reviewed in 14.4.2, is by far the largest. Emissions are estimated to have fallen by 2–5 % relative to business-as-usual in the first pilot phase from 2005–2007 (Ellerman, Convery, De Perthuis, et al., 2010). Similarly, Egenhofer et al., (2011) attribute

5 California and Quebec started recently in 2013, as did Australia with its 'fixed-price' or tax period; trading starts 2014 and S Korea starts even later. None of these can be evaluated empirically at present.

reduction of emission intensity by 3.35 % per year in 2008–2009, in contrast to only 1 % in 2006–2007, to the EU ETS. Permit prices have fallen to around USD 10–15 in 2012 (Newell et al., 2013). Section 14.4.2 concludes that environmental effectiveness has been compromised to a large extent by a structurally lenient allocation of permits that was driven by the necessity for institutional and political feasibility.

The Regional Greenhouse Gas Initiative (RGGI), (see 15.5.3.3) has been ineffective since the cap has never been binding and is not expected to become so for several years (Aldy and Stavins, 2012). The third, much smaller, New Zealand ETS, appears to have had a small impact on emissions (Bullock, 2012). The last of the emissions trading schemes in GHGs, the Clean Development Mechanism (CDM), was an offset programme, not a cap-and-trade scheme. Section 13.13.1.2 finds that there are many challenges when it comes to additionality, baseline definition and leakage but possibly some advantages from the viewpoint of generating income in developing countries.

This experience shows that it is has been very difficult to get a cap-and-trade programme for GHGs enacted with a cap tight enough to have a significant environmental effect, at least initially. Other programmes (notably for the whole USA) that have been suggested have not made it through the political process. It is unclear to what extent this issue is peculiar to ETSs but there is a similar if not stronger opposition to the other major economic instrument, carbon taxation. One of the advantages claimed for an ETS is a greater option of allocating rights to appease opponents of a tax scheme. Hence there is a tradeoff between feasibility, distributional effects, and environmental effectiveness at least in the short run. Older non-GHG cap-and-trade programmes such as the SO_2 and leaded petrol phase-out programmes in the United States have been environmentally effective (Tietenberg, 2006; Schmalensee and Stavins, 2013).[6] It may be that any policy instrument stringent enough to have a significant environmental effective programme may have faced opposition in the particular circumstances. One possible lesson for design may be to build a price ceiling into any proposed cap-and-trade programme. In that case, the concern that a tight cap would lead to very high costs, would be alleviated and may make it politically feasible to have a somewhat more ambitious cap (Aldy and Stavins, 2012).

Cost-effectiveness is the main economic rationale for using emissions trading as opposed to simpler regulation. The experience with regard to GHG programmes is too limited to draw any conclusions yet. As in many of the earlier markets, cost savings in the US Acid Rain Program—an allowance trading system established in 1995 to control SO_2 emissions from coal-fired plants in the continental United States—were substantial (Carlson et al., 2000; Ellerman et al., 2000). Cost savings in this programme came not only from equalizing marginal costs across affected electric utility units on a period-by-period basis but also from equalizing (present value) marginal costs intertemporally as firms have saved current permits for future use in what is known as banking of permits. According to (Ellerman and Montero, 2007), the use of banking has been substantial and remarkably close to what would be expected in a well-functioning market. Recently, the price has collapsed to zero also in this market as the Environmental Protection Agency (EPA) has used other instruments to push for further reductions.

Banking has also been responsible for a large part of the significant cost savings in the US Lead Phasedown Program, a trading scheme established in 1982 to provide refineries with flexibility to gradually remove lead from gasoline. In addition to banking, cost savings in this program were driven by dynamic efficiencies, i.e., the faster adoption and/or development of more efficient refining technologies (Kerr and Newell, 2003). In contrast, dynamic efficiency has played a minor role in explaining cost savings in the US SO_2 allowance program (e.g., Ellerman et al., 2000; Fowlie, 2010; Kumar and Managi, 2010).

The introduction of a price on carbon through either a carbon tax or cap-and-trade can have substantial distributional consequences. Extensive analyses of these effects have been conducted in the US context. Burtraw et al. (2009) illustrate in the context of a trading programme that the outcome for the average household will depend much more importantly on the use of the value associated with emissions allowances than with the actual stringency of the regulation. For example, lump sum dividends or some kinds of tax reform can be progressive. Similarly Hassett et al. (2009) find that the degree of regressivity is much reduced when a lifetime measure of income is used. Parry (2004) shows in an analytical framework that emissions trading can be regressive, especially if implemented with free allocation to incumbent emitters (grandfathering). Bovenberg et al. (2005) find that profits can be maintained throughout the economy by freely allocating less (sometimes considerably less) than 25 % of pollution permits, with the rest auctioned. These considerations are very similar for tax or cap-and-trade systems. Granting greater than this quantity for free would lead to windfall profits. In simulation modelling of the US electricity market, Burtraw and Palmer (2008) find that it would be sufficient to allocate just 6 % of the allowances to the electricity industry to offset costs under a CO_2 trading programme because a majority of costs are borne by consumers; greater allocation would again lead to windfall profits. Hassett et al. (2009) examine regional effects and find them not to be very significant. Blonz et al. (2012) show that even if programmes are regressive, social safety nets, which adjust automatically to inflation, generally protect low-income groups in the United States, and middle income groups may be most vulnerable.

It should be noted that the experience with emissions trading, whether for greenhouse gases or other, non-climate-related pollutants, has been wholly in high-income countries. Coria and Sterner (2010) describe some success for air pollution in a middle income country like

[6] Note that there is literature (e.g., Lohmann, 2008) much less enthusiastic about the concept of emissions trading for reasons of justice and environmental integrity, among others, and more so after the current collapse of carbon prices in the EU-ETS (Lohmann, 2008).

Chile but it is unclear to what extent these can be transferred to developing countries.

15.5.3.3 Sector coverage and scope of the cap

A key component in a trading scheme is establishing the pollutants (e.g., greenhouse gases) and entities that will be regulated. There are several factors that may affect this decision: (1) the quality and cost of emissions measurement and verification, (2) the ability to target sectors with the greatest mitigation potential, (3) the ability to broaden the coverage to unlock low-cost mitigation opportunities, (4) the political and institutional feasibility of including certain sectors, and (5) the interactive effects the cap may have with other policies.

In most trading schemes, the affected sources are relatively large emitting sources whose emissions have been closely monitored (smaller sources are often regulated with alternative instruments). This applies to the earlier programmes (e.g., Acid Rain, RECLAIM, Lead Phasedown)[7] but also in carbon markets. In other words, there are few cases in which the point of obligation has been upstream, i.e., different than the emitting point. The trading scheme in Australia, launched in 2012, covered 373 entities comprising approximately 60 % of Australia's GHG emissions. Electricity generation, industrial processes, fugitive emissions, and non-legacy waste are under permit liability (Clean Energy Regulator, 2012). Small-scale stationary fossil fuel use (especially gas) is covered by upstream permit liability on fuel distributors. Liquid fuels used in aviation/shipping and synthetic GHGs are subject to an equivalent carbon price through changes to existing taxes. Agriculture and forestry can produce offset credits (Macintosh and Waugh, 2012; Caripis et al., 2012).[8]

Coverage in the carbon-trading scheme in New Zealand, is the most comprehensive and covers all GHGs and all sectors. It has expanded in stages from the forestry sector (in January 2008) to fossil fuels and industrial emissions (in July 2010), and will cover the waste sector in May 2014. The agricultural sector must report emissions since January 2012 but a decision on when it will face surrender obligations has not yet been made. This is the only national emissions trading scheme to include forestry, and is intended to shift land-use change decisions towards greater carbon sequestration and less deforestation (Karpas and Kerr, 2011; Adams and Turner, 2012). Coverage is also scheduled to expand in stages in the recently launched carbon market in California (Hanemann, 2009). In the first compliance period, which runs from 2013–2014, electricity generating and industrial facilities that exceed 25,000 tonnes of CO_2eq per year will be obligated to abide by the agreement; the second period (2015–2017) adds distributors of transportation, natural gas, and other fuels; and the third period (2018–2020) adds transportation fuels (CARB, 2011). All major sources will be covered over time, which will represent an equivalent of 85 % of California's GHG emissions (CARB, 2011). Offset projects are foreseen in forestry management, urban forestry, dairy methane digesters, and the destruction of ozone-depleting substances.

There are other carbon markets that are less ambitious in scope. The trading scheme in Tokyo, launched in April 2012, includes 300 industrial facilities—which in total consume at least 1,500 kl of crude oil equivalent per annum—and a combined 1,000 commercial and institutional buildings. In aggregate, this is equivalent to only 20 % of Tokyo's total CO_2 emissions (Partnership for Market Readiness, 2012). Though the programme may be limited in scope, it is one of the first programmes in the world to address emissions from urban buildings, which can be quite significant (Nishida and Hua, 2011). The Regional Greenhouse Gas Initiative (RGGI), a cap-and-trade programme initiated in 2009 and that covers nine Northeast and Mid-Atlantic states in the United States (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont), only regulates CO_2 emissions from power plants.

15.5.3.4 Setting the level of the cap

The cap defines the stringency of the trading scheme. Naturally, the permit prices also depend on many circumstances such as the economic growth. In many of the trading programmes reviewed above, the caps appear however to have been set below what would lead to efficient levels of abatement—since the allowance prices (the marginal abatement costs) have ended up below most estimates of the marginal environmental benefits from abatement. The RECLAIM Program which covers NO_x and SO_2 is an example as are the acid rain and lead phase-out programmes. It should be noted, however, that to varying extents, carbon trading programmes include mechanisms to tighten the cap gradually.

Caps in the carbon markets have slower reductions maybe because of higher short-term mitigation costs. In the Australian scheme, there is no cap on emissions during the initial so-called 'fixed-price phase' (2012–2014) but a price that rises from AUS 23.00 per tonne in 2012/2013 to AUS 25.40 in 2014/2015. The fixed price scheme, has many of the characteristics of a tax and offered advantages in the specific political circumstances that failed to agree on an emissions target but not on a price (Jotzo et al., 2012) hence preferring implicitly uncertainty on emissions rather than on the price (Jotzo and Betz, 2009; Jotzo and Hatfield-Dodds, 2011; Pearce, 2012). The fixed price period naturally established a price signal and provided time for important elements of the flexible price period to be implemented, such as an auction platform. Starting with the first flexible-price phase (2015–2018), the government will set annual caps for five-year peri-

[7] An exception is the market for particulates established in Santiago-Chile in 1992 for industrial sources (Montero et al., 2002). The trading commodity was not actual emissions, which were difficult to monitor on a daily basis, but a firm's maximum capacity to emit.

[8] For more see Section 7A of the National Greenhouse and Energy Reporting Act 2007 (National Greenhouse and Energy Reporting Act 2007, 2007). The carbon market in South Korea, to start in 2015, will cover around 450 large facilities and about 60 % of the country's GHG emissions (Kim, 2011).

ods, extending the cap by one year every year. A default cap (associated to a GHG emissions reduction of 5 % from 2000 levels by 2020) will apply in the event the parliament cannot agree on a cap (CAUS, 2012).

New Zealand, on the other hand, has operated within the Kyoto cap for 2008–2012 by requiring every unit of emission to be matched by a Kyoto unit at the end of the Protocol's true-up period. For 2012 and forward, the government has proposed legislative amendments to introduce a domestic cap and remove the requirement to back domestic emission with Kyoto units (NZME, 2013).

The cap in the California scheme is set in 2013 at about 2 % deviating under the projected level for 2012, and then drops about 2 % in 2014 and about 3 % from 2015 to 2020 on an annual basis (4 % of allowances will be held in reserve to contain costs). The Regional Greenhouse Gas Initiative has introduced a 'soft' fixed cap from 2009 to 2014 to decline by 2.5 % per year. Economic growth and natural gas prices have been lower than expected, so it is unlikely that the cap becomes binding by 2020 (Aldy and Stavins, 2012).[9]

15.5.3.5 Allocations

Permits have been allocated either by auction, or have been given away for free. In the latter case, allocation has been proportional to past emissions or output (i. e., grandfathered) or proportional to current output. Earlier programmes relied almost exclusively on grandfathering. The SO_2 allowance programme allocated less than 3 % of the total cap, through revenue-neutral auctions; mainly to provide an earlier and more reliable price signal to participants (Ellerman, Convery, De Perthuis, et al., 2010). Some of the recent carbon markets also provide free allocations because of concerns about emissions-intensive trade-exposed industries. In fact, the programme in New Zealand considers a very limited amount of auctioning (although increasing over time) unlike RGGI, which allocates the vast majority of permits through auctions (the softer cap in RGGI may explain the difference). Australia and California are somewhere in the middle in terms of auctioning, roughly 50 % and 80 % respectively.

The Californian and Australian schemes also make explicit output-based (free) allocation rules for energy-intensive, trade-exposed sectors, where recent production determines firm-level allocation. The Australian experience on this matter has also shown the influence that industry lobby groups can have in policy design (Garnaut, 2008; Pezzey et al., 2010) and how politically involved this can become (Macintosh et al., 2010).

15.5.3.6 Linking of schemes

Linking occurs when a trading scheme allows permits from another trading programme to be used to meet domestic targets. Such linkages can be mutually beneficial as they can improve market liquidity and lower costs of compliance. However, these benefits need to be weighed against challenges like losing unilateral control over domestic design and being subject to international price movements. Linking, however, involves certain tradeoffs in terms of exposure to international prices and loss of flexibility to unilaterally change features in the domestic design once links are established. International linkage of trading schemes might be simpler than harmonizing carbon taxes through international agreements (Karpas and Kerr, 2011). There is however, not general agreement on this point; to the contrary, agreements on taxes might avoid the most contentious baseline issues see for instance Nordhaus (2007).

The experience with linking is limited because carbon markets are relatively recent. One example of a linking process is the ongoing collaboration, since 2007, between California and the Canadian province of Quebec, which will both place compliance obligations on large emitters under their trading schemes beginning in January 2013 and continue negotiations for a full linking of the two schemes later on in 2013 (CARB, 2011). Another example is the announcement in 2013 of an Australia-EU ETS link by 2018 preceded by a transition phase in which Australian installations can use EU-Allowances for compliance from 2015 on. Interestingly, Australia is also exploring ways for establishing links with schemes in South Korea and California, which, de facto, would create links between all these trading schemes.[10] We do not yet know if linking schemes without prior commitment on overall caps will facilitate or complicate future negotiations on the caps.

15.5.3.7 Other design issues: banking, offsets, leakage, price volatility and market power

There are additional, important, aspects of policy design on which we can only briefly touch here. Unlike borrowing, banking of permits for future use is a feature used in many trading schemes with good results in terms of cost savings and environmental benefits (i. e., absence of emission spikes and acceleration of emission reductions). A well-documented example is the US SO_2 allowance programme (Ellerman and Montero, 2007). A dramatic example of volatility is given by the RECLAIM programme where in the summer of 2000 permit prices that began under USD 5,000 per ton of NO_x increased abruptly in price to almost USD 45,000, leading to a relaxation of the cap see Metcalf (2009). Offsets, the possibility of using emission credits outside the capped sectors either domestically or internationally (e. g., CDM or REDD), is another design feature common in most trading

[9] There is a proposal from the RGGI states, however, to reduce the cap in 45 % by 2020 (Regional Greenhouse Gas Initiative, Inc., 2013).

[10] The firm intentions of New Zealand and Australia about linking their systems came to a sudden end after the latter announced it was linking its system to the EU ETS.

schemes but of much concern because of the well-known tension between cost-effectiveness and additionality. One way to somewhat assuage this tension is to move away from a project-based crediting approaches (e.g., CDM) to scaled-up approaches—to the level of the sector, jurisdiction or country. Offset provisions, if well designed, can also help alleviate the 'leakage' problem of moving emissions from capped to uncapped sectors. An alternative design option to address leakage might be to use output-based allocation rules although this will raise concerns related to output subsidy. Another problem is market power specific to permit trading which has been the subject of much research since the work of Hahn (1984). It seems, however, that market power is less of a problem than anticipated (Liski and Montero, 2011), also confirmed by findings from laboratory experiments (Sturm, 2008).

15.5.3.8 Choice between taxes and emissions trading

Regarding the choice between taxes and tradable permits, longstanding economic theory (Weitzman, 1974; Hoel and Karp, 2001, 2002; Newell and Pizer, 2003) suggests that in the presence of uncertainty about the marginal cost of emission reduction, for a stock pollutant like CO_2, a carbon tax is more economically efficient than a tradable permit system. According to the Weitzman intuition, a tax is preferred since the benefits curve is fairly flat for a stock pollutant (this result could be changed in the presence of a major threshold effect). The reason is essentially that when there is a negative shock to the cost of emission reduction, as has been the case in the EU following the economic slowdown that began in 2008, cost efficiency calls for doing more abatement, with less being done at other times when the abatement cost is higher. This is achieved with a tax, but not with a cap that is fixed in each period. The slump in the carbon price in the EU ETS is thus suggestive of a loss of cost-effectiveness.

In the very long run there may be more uncertainty about the level of an optimal tax than about a quantity target and policymakers may then prefer to legislate a long-run abatement target in a cap-and-trade system. As seen above, this can entail short-run efficiency losses and it would be desirable to allow flexibility with regard to annual caps that would add up to the long run target, but concerns about credibility mean that such flexibility must be severely limited. As shown in Chapter 2 (Section 2.6.5), there is a literature on regulatory uncertainty that shows extra costs deriving from the hesitancy by investors in the face of all regulatory uncertainty but in particular perhaps, when it comes to cap-and-trade systems.

To prevent a large loss of efficiency in a cap-and trade-system, and to avoid exceptionally high price volatility that deters investment, price floors and ceilings can be used, although care would be needed in design to avoid breaching the integrity of the cap. Banking and borrowing of permits (see Section 15.5.3) are another means of providing intertemporal flexibility in abatement as are the availability of credit reserves or of offsets.

As explained in Section 15.7, a tax can be used in conjunction with other policy instruments while a cap-and-trade system either renders the other policies environmentally irrelevant or is itself rendered environmentally irrelevant by them. This is a major concern when decision making takes place at several levels.

As discussed in Section 15.5.2.4, the issues of intertemporal (and spatial) leakage discussed in the green paradox literature would appear to give preference to cap and trade over taxes but this is partly a simplification. The green paradox mainly exists in oversimplified models and poorly designed tax schemes. There are however, lessons from this literature concerning design details. For example, one might prefer high taxes that grow slowly to low taxes that rise very fast, and one might be careful with too much flexibility, particularly borrowing in permit systems. Kalkuhl and Edenhofer (2013) compares four policies, (1) a conventional Pigouvian carbon tax, (2) a carbon tax rule (that adjusts the tax level dependent on GHG concentrations), a permit trade (3) with or (4) without banking and borrowing) in the context of a (weak) green paradox setting with respect to three different criteria: the informational burden for the government, the commitment problem of the government, and the robustness of the policy with respect to deviations in behaviour (discount rate) by agents in the economy. They find that a tax and a trading scheme without banking and borrowing have high informational requirements. The ETS with banking and borrowing shifts the timing problem of carbon emissions to the private sector, but does not work well if these have different discount rates from the regulator. The flexible tax rule or an ETS with restricted banking and borrowing can lead to an optimal allocation even in this case, but then again the informational requirements for the regulator are daunting.

One of the attractions of emissions trading schemes appears to have been that they may meet with less opposition from industry, which can be allocated permits for free. Taxation is often resisted by lobbies and sometimes for constitutional reasons. Taxation is also resisted by those who want a smaller government—in which case environmental fiscal reform (raising carbon taxes while lower other taxes) may be more acceptable. Another argument that has been made in favour of an ETS is that it may be easier to link permit schemes across borders than to agree on common taxes. Harmonization is advantageous, since it reduces costs (15.7). There is however, no general agreement on this. Some analysts believe the opposite, that it will be easier to link taxation systems within an international agreement (Helm, 2003; Nordhaus, 2007; Jaffe et al., 2009; Metcalf and Weisbach, 2011) and (15.8.1). Finally, linking cap-and-trade systems would automatically involve financial transfers between countries. These might be a benefit for low-income countries if they can be carbon-efficient and maybe less controversial than negotiated side payments but this hinges on agreement concerning the various country targets.

Finally taxes, unlike an emission-trading scheme, do not require a new institutional infrastructure to keep track of ownership of emissions allowances. This consideration may be especially important in developing countries.

15.5.4 Regulatory approaches

15.5.4.1 Overview of the implementation of regulatory approaches

As discussed in Section 15.2, economy-wide carbon pricing, though widely discussed in the literature, has been rarely implemented. Those policies that have been implemented have often been sector-specific, and have often fallen in the category of a regulatory approach. Regulatory approaches are used across sectors, usually alongside other policies, as can be seen in Table 15.2. For example, Renewable Portfolio Standards (RPS), and energy efficiency standards may be combined with fuel subsidy reduction in the energy sector (Chapter 7). In the transport sector, vehicle efficiency and fuel quality standards are used alongside government provision of mass transit, and fuel taxes (Chapter 8). In the building sector, a number of complementary policies, such as appliance standards, labelling, and building codes are employed, along with tax exemptions for investment in energy-efficient buildings (9.9). In the industrial sector, energy audits for energy-intensive manufacturing firms are also regularly combined with voluntary or negotiated agreements and energy management schemes. Information programmes are the most prevalent approach for energy efficiency, followed by economic instruments, regulatory approaches and voluntary actions (10.11).

Several of these regulatory approaches often contain market-like features so that the distinction between regulatory approaches and economic instruments is not always sharp. Renewable Portfolio Standards programmes often, for example, allow utilities to satisfy their obligations by purchasing renewable energy credits from other producers, while feed-in tariffs involve both regulations and subsidies for renewable energy. Low-carbon fuel standards also sometimes incorporate market-like features including trading among suppliers.

Regulatory approaches play the following roles in mitigation policy. First, they directly limit greenhouse gas emissions by specifying technologies or their performance. Second, in sectors such as AFOLU (see Chapter 11) and urban planning (see Chapters 8 and 12) in which much activity is strongly influenced by government planning and provision, regulations that take climate policy into account are clearly important. These are discussed in further in Section 15.5.6. Third, regulations such as RPS can promote the diffusion and innovation of emerging technologies, a role that is examined in Section 15.6. Fourth, regulations may remove barriers for energy efficiency improvement. These may arise when firms and consumers are hindered by the difficulty of acquiring and processing information about energy efficient investments, or have split incentives as in landlord-tenant relationships.

Regulatory approaches have been criticized, both for being environmentally ineffective, and more strongly, for lack of cost-effectiveness, as the governments have limited information and may make governmental failures in intervention (Helm, 2010; see also Section 3.8.2). Some are opposed to the regulations on libertarian philosophical grounds (Section 3.10.1.1). In what follows, we assess the environmental and cost effectiveness of regulatory approaches, largely focusing on short-run effects of energy efficiency policies that have been extensively studied. Long-run effects acting through technology development are assessed in Section 15.6. There is insufficient literature on distributional incidence and feasibility to underpin an assessment of these dimensions.

15.5.4.2 Environmental effectiveness of energy efficiency regulations

Several prospective studies reviewed by Gillingham, Newell, and Palmer (2006) and one large ex-post study of US energy efficiency standards for appliances (Meyers et al., 2003) found substantial energy savings. Such savings have also been found in the building sector across countries (Section 9.10) in a study of best-practice building codes and other standards. Recently, econometric studies in the United States have also found energy reductions from building codes (Aroonruengsawat, 2012; Jacobsen and Kotchen, 2013). These studies also reported significant energy savings and related CO_2 reduction. Fuel economy standards for vehicles have also been successful in reducing fuel consumption in many countries (Anderson et al., 2011). Generally speaking, energy efficiency policies that address market failure can result in energy savings (7.10, 8.10, 9.10, Table 9.8, 10.10). Some case studies however, identified weak environmental effectiveness due to lack of implementation. Such examples were found for building codes and energy management systems.

Rebound effects need to be taken into account in interpreting these findings of environmental effectiveness of energy efficiency regulations. The rebound effect refers to the increase in energy consumption induced by a fall in the cost of using energy services as a result of increased energy efficiency. For detailed general discussion on rebound effects, see Sections 3.9.5 and 5.6.2. For sector-specific studies of rebound effects, see Section 9.6.2.4 for building sector and Chapter 8 for transport sector. With regard to appliance standards and fuel-economy regulations in the United States, environmental effects remain large even when taking the rebound effect into account (Gillingham et al., 2006; Anderson et al., 2011). More generally, direct rebound effects (within the regulated sector as a result of the fall in the cost of energy services) are commonly found to be in the range of 10 %–30 % in various sectors in developed countries, and higher in developing countries (Sorrell et al., 2009; Gillingham et al., 2013). Indirect rebound effects, which result from increased economic growth resulting from the fall in the cost of energy services, can be much larger. Reviewing claims of rebound effects in excess of 100 %, Dimitropoulos (2007) concluded that although the evidence base and methodologies were weak, the possibility of significant rebound effects could not be dismissed. A recent review suggests that total rebound effects are unlikely to exceed 60 % (Gillingham et al., 2013).

While the scale of the rebound effect varies, its presence suggests that complementary policies that include carbon pricing are called for so that mitigation is not compromised. Some countries, such as the UK, have begun to account for a direct rebound effect in energy policies (Maxwell et al., 2011).

Regulations such as emissions standards have also been criticized on the ground that they are less flexible than incentive-based approaches and may even provide perverse incentives and increase emissions under certain conditions like treating new units more stringently than old ones (Burtraw et al., 2010). Yet, recent modelling that incorporates institutional features of various policies in the United States, including the capacity to adjust the stringency of a regulation or a cap/tax, suggests that emissions standards may be more effective than cap and trade in reducing overall emissions (Burtraw and Woerman, 2013).

15.5.4.3 Cost effectiveness of energy efficiency regulations

Regulatory approaches are often implemented in contexts in which market failures or barriers to adoption of energy-efficient technologies exist. There is a considerable sectoral literature showing that energy efficiency regulations have been implemented at negative costs to firms and individuals, meaning that their value to consumers exceeded programme costs on average. In the transport sector, fuel economy standards have been shown to produce net cost savings over the life of the vehicle (Chapter 8.10). In the building sector, a range of energy efficiency policies including appliance standards and building codes have been found to have negative private costs (Table 9.8), (Gillingham et al., 2006, 2009a). In the industrial sector, a number of case studies on energy management systems and energy audit systems show that they have been cost effective (Chapter 10.10).

The cost effectiveness of such regulations has been the subject of heated debate. Economic theory points to the following circumstances in which regulations may be implemented with negative private costs. Buyers may have less information about the efficiency and cost of a device than sellers. They may not be able to assess the energy savings from an appliance even after using it. This can lead to a situation in which low-efficiency devices drive more expensive high-efficiency models out of the market. Efficiency standards in this setting can improve consumer welfare by reducing the informational asymmetry between buyers and sellers (Akerlof, 1970; Leland, 1979; Goulder and Parry, 2008). When competition is imperfect and sellers compete on both quality (efficiency) and price, then a minimum quality standard eliminates low-quality sellers from the market enhancing price competition among high-quality goods. This can make all consumers better off (Ronnen, 1991). Split incentives, as in landlord-tenant relationships, can lead to economically inefficient devices persisting in the market, absent intervention. For more details, see Box 3.10.

Individuals working in small workplaces often find it difficult to acquire and analyze information on energy efficiency (see 2.6.5.3 on human behaviour on energy efficiency). As a consequence, those individuals are prone to rely on intuition to make decisions. In many cases, analyzing the minimum cost actions given the price signal is too challenging, and thus cognitive costs may result in some consumers simply not taking operating (energy) costs into account at all while making their purchase decisions (Section 3.10.1.1). (Allcott, 2011) exhibits this case in a recent survey of US car buyers, 40 % of whom were shown not to consider fuel costs in their purchasing decision. This kind of consumer decision making can lead sellers to offer—and consumers to buy—less energy efficient products than if consumers could more easily compute the operating costs. Section 9.8 indicates that such barriers to energy efficiency are significant in the building sector. Regulation and information measures can help overcome these barriers.

Large firms have more resources than individuals to assess information on energy efficiency, and so may be more sensitive to carbon pricing. However, firms, especially small and medium enterprises, also face the barriers such as split incentive and lack of information. Governments may employ regulations (and information measures) to help correct this by implementing energy efficiency standards for equipment. See 3.10.1.2 for more on behaviour of firms on energy efficiency.

Although both the theory and empirical evidence detailed above show that policy interventions to remove barriers can have negative costs to firms and individuals, it has been argued that unaccounted labour and opportunity costs borne by governments, firms, and individuals involved in policy design and implementation process, as well as loss of amenity (for example, fuel economy standards may undermine other functions of cars, such as speed, safety, quality of air conditioning, and audio sets), result in understatement of regulatory costs. Such unaccounted costs are called 'hidden costs' (Box 3.10).

On the other hand, an ex-post evaluation of expected and realized costs of environmental regulations in the United States found that estimates of the unit cost of regulations by the regulator were overstated just as often as they were understated, while total costs were more frequently overstated (Harrington et al., 2000). Furthermore, Gillingham et al. (2006) note that in the United States, "even if unaccounted-for costs of appliance standards were almost equal to those measured, and actual energy savings only roughly half of those estimated, appliance standards still would yield positive net benefits on average" (Gillingham et al., 2006b). There may also be hidden benefits of regulations, (Sorrell, 2009), such as improved amenities and 'free drivers' (which would occur if nonparticipants were induced to invest in energy efficiency because others in the programme made such investments) induced by regulation (Gillingham et al., 2006). In conclusion, while it is clear that opportunities do exist to improve energy efficiency at negative private cost by regulations, the literature is divided as to what extent such negative private cost opportunities exist.

It is the social rather than the private costs of regulations, however, that are more relevant for public policy. This means that externalities need to be taken into account and co-benefits of policies, such as local air pollution reduction, would ideally be valued and subtracted from costs. Such externalities can be large. Muller, Mendelsohn, and Nordhaus (2011) found that the external costs of coal-fired utilities in the United States exceeded value-added in that sector. These and other costs and benefits have to be taken into account when evaluating policies.

15.5.5 Information measures

Information measures have been widely used in all sectors. To take typical examples, energy efficiency labelling for home electric appliances and thermal insulation of buildings, as well as carbon footprint certificates and public awareness initiatives are implemented in the building sector (9.10). Energy management systems, as well as government-assisted energy audits, either mandatory or voluntary, are used in the building, industry, and energy sectors (7.10, 9.10, 10.10). Mandatory reporting of GHG emissions is common for firms in the power and industrial sectors (7.10, 10.10), while labelling of automobile fuel economy is used in the transport sector (8.10). Sustainability certificate programmes are used in the forestry sector (11.10).

Regarding the environmental and economic effectiveness, a number of case studies in the building sector are shown for the energy efficiency labelling for home electric appliance, building label and certificates, energy audit programmes, and awareness raising campaign to stimulate behavioural change (see 9.10, Table 9.8). For energy efficiency, the role of information measures is the same with regulatory approaches, that is, to address market failure such as lack of information and split incentives. For details of the market failure and role of information measures, see Section 15.5.4.

While some studies mentioned above reported high economic and environmental effectiveness, the results are mixed in general, reflecting the wide diversity of the information measures, and it is not appropriate to draw a general conclusion. Note that some policy instruments, such as energy management systems and energy audit in the industrial sector that may fall either in regulatory approach and information measures, are also covered in the section on regulatory approach above.

Since information programmes typically provide information and leave it to firms or consumers to take appropriate action, those actions will usually only be taken spontaneously, or if they are perceived to have negative private costs economically. The discussion of hidden costs/benefits and rebound effects parallels that of regulatory approach, are covered in Section 15.5.4.

It should be noted that the role of information measure has been mostly supplementary to other policy instruments such as obligatory standards or much wider policy package as detailed in sector specific policy chapter (7.10, 8.10, 9.10, 10.10, 11.10). For example, energy efficiency labelling is often followed by energy efficiency standard as a single policy package. This also makes difficult to estimate the impacts of the information measure alone.

15.5.6 Government provision of public goods or services, and procurement

While formal assessment is difficult, it is clear that public provision and planning can and have played a prominent role in the mitigation of climate change at the national and sub-national levels, and in a wide range of industries including energy, transport, agriculture, forestry, and others. At the national level, government provision or funding is crucial for basic research into low and zero-emission technologies (see Section 15.7).

In the energy sector, the provision and planning of infrastructure, whether for electricity transmission and distribution or district heating networks, interconnectors, storage facilities, etc., is complementary to the development of renewable energy sources such as wind and solar energy (7.6.1.3). A modal shift from air to rail transport also requires public planning or provision by national and local governments as a part of the policy mix and in best-case scenarios could reduce associated emissions by 65–80 % (8.4.2).

Urban planning that incorporates climate change mitigation can have a major impact on emissions (Chapter 12); therefore, municipal governments have a very important role to play. Since mitigation policies have many co-benefits at the local level, including reduced local pollution and congestion, and improved quality of urban space, cities have an interest in mitigation policies in addition to the largely external climate benefits they provide. Land-use and transport policies can considerably influence the share of non-motorized transport, public transport, and associated emissions (8.4.2.3). Buildings and associated energy supply infrastructure are very long-lasting (9.4.5) so public planning to encourage the rapid adoption of new low-carbon technologies and avoid lock-in to high-emission infrastructure assumes importance. Such planning would need to take into account transport pricing relative to land prices, building, parking, and other zoning regulation, city-wide district heating and cooling systems, and green areas (see Section 12.5, and Baeumler et al., 2012). Capacity building at the municipal level may be needed for incorporating climate change mitigation and its co-benefits into the planning process, especially in developing countries (see Section 15.10.3).

Government planning and infrastructure provision can complement a carbon or fuel tax, addressing additional market failures that increase the quantity response to the price instrument by making substitution towards less energy and carbon-intensive lifestyles easier to implement. Conversely, whether or not a public transit system will generate sufficient demand to be economical depends on whether private transit (and its climate externalities) is suitably priced. By contrast, as noted below in Section 15.8, a tradable permit system for emissions would be a substitute, rather than a complement for emission reduction through public provision. In conjunction with a tradable permit system, local actions would affect the cost of reducing emissions, but not overall emissions themselves. This raises the possibility that local governments may be de-motivated to integrate mitigation in their planning if they are located in a national or international jurisdiction with a tradable permit system. In that case, their actions would not be 'additional' in GHG emission reduction, rather they would reduce the cost of meeting the overall cap. Furthermore, the cost reduction would not be captured entirely by the residents of the local jurisdiction in which the actions took place.

Since most of the world's forests are publicly owned, provision of sequestration services as part of forest conservation is largely in the public sector. Forest protected areas make up 13.5 % of the worlds' forests, and 20.8 % for tropical lowland evergreen broadleaf forests (rainforests) (Schmitt et al., 2009). During the period 2000–2005, strictly protected forest areas experienced 70 % less deforestation than all tropical forests (Campbell et al., 2008), but impact studies must also control for 'passive protection' (protected areas being located in remote and inaccessible areas), and 'leakage' (more deforestation outside the protected area). The understanding of how protected areas can contribute to forest conservation, and thereby be a means of climate change mitigation, has advanced much since AR4, due to better spatial data and methods.

Andam et al. (2008) find substantial passive protection for protected areas in Costa Rica. While a simple comparison suggests that protected areas reduce deforestation by 65 %, the impact drops to 10 % after controlling for differences in location and other characteristics. Gaveau et al. (2009) estimate the difference between deforestation rates in protected areas and wider areas in Sumatra, Indonesia during the 1990s to be 58.6 %; this difference falls to 24 % after propensity score matching which accounts for passive protection. In a global study, also using matching techniques, Joppa and Pfaff (2011) finds that for about 75 % of the countries, protected areas reduce forest conversion, but that in 80 % of these controlling for land characteristics reduces the impact by 50 % or more. Thus, an emerging consensus is that protected areas reduce deforestation (Chomitz et al., 2007), even though protection is not perfect, and there is a medium to high degree of passive protection. Estimates of leakage are more challenging, as the channels of leakage are diverse and harder to quantify.

Local governance of forests can be an effective way of reducing emissions from deforestation and forest degradation, as at least some of the public goods provided by forest are included in the decision making process. A meta-analysis of 69 cases of community forest management finds that 58 % of these were successful in meeting ecological sustainability criteria, e.g., 'improved forest condition' (Pagdee et al., 2006). Similarly, using data from 80 different forest management units in 10 countries, a study found positive correlation between greater devolved authority at the local level with higher levels of carbon sequestration (Chhatre and Agrawal, 2009). However, a study analyzing forest cover of central Himalaya in India that controls for confounders reports no statistically significant results (in forest cover) between village and state-managed forests, even though the costs per hectare are seven folds greater for the state-managed forests (Somanathan et al., 2009).

Where property rights are insecure, strengthening land rights is often put forward as a way to contain deforestation, though the effects are ambiguous. It is argued that the lack of tenure rights can discourage investment in land and increase soil exhaustion. This would, in turn, lead to greater incentives to deforest to compensate for the lost productivity due to degradation. Unclear tenure can also lead to unproductive and violent land conflicts (Alston et al., 2000). However, by increasing the value of land clearing, policies that strengthen private property rights over land could increase deforestation (Angelsen, 1999).

15.5.7 Voluntary actions

It has become quite common for major firms, either individually or in alliance with others, to commit to mitigation of climate change as part of their corporate social responsibility through emission cuts at their offices and facilities, technological research, development, and sales of climate friendly equipment (See IPCC, 2007). Non-government organizations also initiate voluntary actions (See Section 15.9).

This section focuses on voluntary agreements that are convened by industries in association with government. Voluntary agreements have been developed in very different ways in different nations, depending on their institutional and corporate culture background. In what follows the literature will be reviewed according to the three categories provided by Pinkse and Kolk (2009).

15.5.7.1 Government-sponsored voluntary programmes for firms

Government-sponsored programmes for firms, where participation is completely voluntary and there are no penalties for not participating in the agreement, have been implemented in several countries, including the United States and Australia. The United States EPA led voluntary programmes foster partnerships with industry and the private sector at large by providing technical support among other means (US EPA, 2013).

Ex-post case studies on the environmental and economic effectiveness have been scarce compared to the wide range of activities. Where available, they have been critical of this type of programme. Several studies say little reduction was achieved (see Brouhle et al. (2009) analyzing a voluntary programme in the US metal-finishing industry) or the impacts were short lived, as was the case for the US Climate Wise Program (Morgenstern et al., 2007). See also Griffiths et al. (2007) and Lyon and Maxwell (2004) who conclude the US Climate Leaders programme had little effect on firm behaviour.

15.5.7.2 Voluntary agreements as a major complement to mandatory regulations

Voluntary agreements (VAs) often form a part of a larger climate policy approach that contains binding policies such as a carbon tax or a cap-and-trade programme. Voluntary agreements conducted jointly with mandatory regulations have been widely implemented in Europe (Rezessy and Bertoldi, 2011).

This approach allows the regulated industries to use the voluntary agreement as a partial fulfilment of the mandatory regulation. For example, through participation in the CCA in the UK, energy intensive industrial sectors established targets to improve energy efficiency and the companies that met such targets received an 80 % discount from the CCL (Price et al., 2008). Likewise, the Dutch government ensured industries participating in Long-Term Agreements (LTA) were not subject to additional government policies regulating CO_2 emission reductions or energy conservation and that the new energy tax would not be levied on the participating industries. In both cases participants established a long term plan to save energy and reduce CO_2, and implemented energy management systems (Price et al., 2008; Stenqvist and Nilsson, 2012).

Some studies found that the voluntary agreements were environmentally and economically effective. Bressers et al. (2009) found positive results in terms of ambition, compliance, goal attainment and behavioural change. They also acknowledged the efficiency advantages of flexibility in phasing technical measures. Ekins and Etheridge (2006) analyzed the UK CCA and found that, while the targets were not very stringent and were generally achieved in advance of the set date, the CCAs appeared to have catalyzed energy savings by increasing awareness. This allowed the net environmental benefits to exceed what would have been achieved by levying a flat tax without rebates and CCAs while also generating economic gains for the companies under the CCAs (Ekins and Etheridge, 2006).

Rezessy and Bertoldi (2011) assessed the effectiveness of voluntary agreements in nine EU member countries. In cases where there is cooperative culture between governmental entities and the private sector, VAs can have some beneficial effects compared to legislation. They include willingness by the industry, sharing of information, flexibility in phasing measures, and fine-tuned solutions to individual industries. They emphasized that by engaging signatories in energy audits, consumption monitoring, energy management systems and energy efficiency project implementation, the voluntary agreements helped overcome the barrier for energy efficiency improvement in a systematic manner. Nevertheless, they also noted that the VAs had been criticized for lenient targets, deficiencies in monitoring, and difficulty in establishing the additionality. There are other critical studies. Bohringer and Frondel (2007) argued that they found little evidence that the commitment of the German cement industry was effective, due to weak monitoring. Martin et al. (2011) concluded that the CCL had strong negative environmental impacts. Voluntary agreement between the European Commission and the car industry which set a mid-term target of 25 % reduction on CO_2 emissions from automobiles by 2008 completely failed (Newell and Paterson, 2010).

15.5.7.3 Voluntary agreements as a policy instrument in governmental mitigation plan

Voluntary agreements may be used as a major policy instrument with wide coverage and political salience in a governmental mitigation plan. This type of voluntary agreement has been implemented in Japan and Taiwan, province of China.

The Japanese Voluntary Action Plan (VAP) by Keidanren (Japan Business Federation) was initiated in 1997. The plan, led by Keidanren and joined by 114 industrial associations, covered about 80 % of GHG emissions from Japan's industrial and energy transformation sectors. The plan is embedded in the regulatory culture in which the government constantly consults with industrial associations. It was reviewed annually in governmental committees, and an independent third party committee was also established to monitor its implementation; the included industries were required to be accountable with their environmental performance constantly. Industrial groups and firms established energy and GHG management systems, exchanged information, being periodically reviewed and acted to improve energy efficiency and cut GHG emissions. Several industry sectors raised the ambition levels with stricter targets during the course of VAP, once they achieved original targets (Tanikawa, 2004; Akimoto, 2012; Uchiyama et al., 2012; Yamaguchi, 2012). An econometric analysis found that voluntary actions by the manufacturing sector led to significant energy efficiency investments (Sugino and Arimura, 2011).

Two successful case studies in VAP have been reported. In cutting stand-by power by electric appliances, three major industrial associations announced 2001 the target to limit stand-by power less than 1 W for all electric appliances to be met by 2003. It was possible for them to commit to the ambitious targets—ambitious in terms of the level of target (1 W), wide coverage of appliances, and early timing of goal—exactly because it was voluntary, not mandatory. In contrast, other countries that took a regulatory approach have implemented much weaker targets at later dates, and the coverage of appliances had been small. By 2003, almost all appliances met the target on time in Japan. Also, semiconductor industrial associations committed to cut

Perfluorocarbons (PFC) emissions in 1998 and succeeded in reduction by 58 % by 2009 (Wakabayashi, 2013).

Chen and Hu (2012) analyzed the voluntary GHG reduction agreements of six different industrial sectors, as well as the fluorinated gases (F-gas) reduction agreement of the semiconductor and liquid crystal display (LCD) industries in Taiwan, province of China. They found that the plan launched in 2005 was largely successful.

15.5.7.4 Synthesis

The voluntary agreements have been successful particularly in countries with traditions of close cooperation between government and industry (IPCC, 2007; Rezessy and Bertoldi, 2011; Akimoto, 2012; Yamaguchi, 2012).

Successful voluntary agreements are characterized by a proper institutional framework. This framework consists of, first, capable and influential industrial associations that serve as an arena for information exchange and development of common expectation among industries. Second, governmental involvement in implementation review is crucial. Third, accompanying measures such as technical assistance and subsidies for energy audits and equipment can also be instrumental. Finally, regulatory threats, even if they are not explicitly articulated, are an important motivating factor for firms to be active in the voluntary agreements.

The key benefits of voluntary agreements are: 1) quick planning and actions when technological solutions are largely known but still face uncertainties; 2) flexibility in phasing technical measures; 3) facilitating coordination and information exchange among key stakeholders that are crucial to removing barriers to energy efficiency and CO_2 reductions; and 4) providing an opportunity for 'learning by doing' and sharing experiences.

However, several voluntary agreements have been criticized for not bringing about significant environmental impacts due to their limited scope or lack of proper institutional framework to ensure the actions to be taken (see Sections 15.5.7.2 and 15.5.7.3).

As cross-national evaluations, Morgenstern and Pizer (2007) reviewed voluntary environmental programmes in the United States, Europe, and Japan and found average reductions in energy use and GHG emissions of approximately 5 % beyond baselines. Borck and Coglianese (2009) argued that, as an alternative to regulatory approaches, voluntary agreements may effectively achieve small environmental goals at comparatively low cost.

The major role of voluntary agreements is to facilitate cooperation among firms, industrial associations, and governments in order to find and implement low cost emissions reduction measures. Such a role is important because large mitigation potential exists, yet it is hampered by formidable barriers such as lack of information and coordination among actors. In such context the voluntary agreements can play an important role as part of a policy package.

15.5.8 Summary

This section has reviewed a range of policy instruments. Among the four policy evaluation criteria, literature is rich for economic and environmental effectiveness. The distributional incidence of taxes has been studied quite extensively, much less is known about other policy instruments. Political and institutional feasibility was also discussed as a design issue of economic instruments. The reasons for which sector specific policy instruments such as regulations and information measures have higher political feasibility than economy-wide economic instruments were briefly discussed in Section 15.2, but there is a dearth of literature really analyzing this issue.

Basic economics suggests that one instrument—e.g., a price on carbon—would be most cost effective in dealing with the market failure associated with the release of greenhouse gases. The presence of other market failures, however, means that one instrument is insufficient for dealing comprehensively with issues related to the climate problem. We have seen in Section 15.5.4 that there are cognitive and institutional factors that imply barriers to market response to carbon prices. Therefore, regulatory approaches, information programmes, voluntary agreements, and government provision may serve as a complement to pricing policy as a way to remove barriers, thereby saving the money of firms and individuals and reducing social costs. There are strong separate arguments for a technology policy to correct for the externality implied by insufficient protection of property rights, as detailed in Section 15.6. Furthermore, because carbon-pricing policy is often lacking or insufficient for political reasons in nations, various policy instruments are playing substitutive role (see Section 8.10 for examples of the transport sector).

In several sectors such as transport, urban planning and buildings, energy, and forestry, government planning and provision of infrastructure is important, even crucial, for achieving emission reductions in a cost-effective manner. Absent the appropriate infrastructure, the costs of achieving significant emission reduction might be prohibitive.

As discussed in Section 15.2 and this section, real-world politics tend to produce various policy instruments and differentiated carbon price across sectors owing to politics. Those policy instruments may positively interact as illustrated above, but may also negatively interact. Such interactions will be further detailed in Sections 15.7 and 15.8. Policymakers face the challenge to understand how the policy package is constructed in their nation and must harmonize various policy instruments so that they interact synergistically.

Box 15.2 | National and sub-national policies specific to least developed countries (LDCs)

A number of developing countries have developed legislative and regulatory frameworks to measure and manage GHG emission (Box 15.1). These frameworks or strategies can be a part of larger development plans that aim to shift the economy to a low carbon and climate resilient trajectory. These plans can serve an important signaling function by aiding coordination of government agencies and stakeholders in addition to providing the government's commitment to a low-carbon policy framework (Clapp et al., 2010).

There are pre-requisites to develop these low carbon development strategies. Achieving this policy 'readiness' entails assembling the technical knowledge and analytical capacity, legal and institutional capacity, and engagement of stakeholders in the process (Aasrud et al., 2010; van Tilburg et al., 2011). Capacity building is also a continuous process that aims to improve strategies over time to enhance low carbon outcomes. Readiness for market-based instruments increases mitigative capacity in general and enables implementation and monitoring of mitigation policies (Partnership for Market Readiness, 2011). Due to tremendous variation in capacity across countries, sufficient flexibility to allow these strategies to evolve over time is needed (Clark et al., 2010; van Tilburg et al., 2011).

Evidence from CDM projects indicates that capacity building is necessary but not sufficient to allow countries to attract CDM projects. Targeted measures like support for Designated National Authorities have shown to be successful (Okubo and Michaelowa, 2010). In addition, CDM projects have been an important mechanism for creating awareness about climate change mitigation, and have served as an indirect link between cap-and-trade systems around the world (Michaelowa, 2013). Some developing country beneficiaries of CDM are also moving towards implementing longer-term national mitigation policies. For an assessment of the Clean Development Mechanism, please refer to Chapter 13 (13.13.1.2) and Chapter 16 (16.8) for the technology component.

Climate change mitigation has also been pursued through a co-benefits approach (See Section 15.2). Increasing access to energy services is an important priority for policymakers in developing countries (Chapter 4). An estimated 1.3 billion of the world's people have no access to electricity and roughly three billion rely on highly polluting and unhealthy traditional solid fuel for household heating and cooking (IEA, 2012; Pachauri et al., 2012, p. 19) (see Section 14.3.2.1). In the short term, policies may address use of climate-friendly technologies like solar lighting alternatives to kerosene lamps (Lam et al., 2012), and gasifier cook stoves (Grieshop et al., 2011), while longer term policies may address more comprehensive approaches such as universal grid connectivity. Chapter 6 (Section 6.6.2.3) and Chapter 16 (Box 16.3 in Section 16.8) use global scenario results to conclude that universal basic energy access can be achieved without significantly increasing GHG emissions.

One option particularly relevant for developing countries is a repeal of regressive subsidies given to fossil fuel based energy carriers, together with suitable compensating income transfers so as not to limit energy access or increase poverty (see Section 15.5.2). In some developing countries, subsidies to fossil fuels are slowing penetration of less expensive renewables. For example subsidies to natural gas result in an incremental levelized cost of wind power in Egypt of an estimated 88 % (Schmidt et al., 2012). Care must also be taken to ensure transparency and to clearly demonstrate that the savings that accrue from the removal of subsidies will be used to benefit the poor.

15.6 Technology policy and R&D policy

15.6.1 Overview of the role of technology policy and R&D policy

As discussed in Chapter 3.11, there are market failures associated with research, technology development, and technology diffusion that are distinct from and interact with the market failures associated with environmental harm of human activities such as anthropogenic climate change. There is therefore a distinct role for technology policy in climate change mitigation, which is complementary to the role of policies aimed directly at reducing current GHG emissions, which are discussed in Section 15.5 above.

Public policies and institutions affect the rate and direction of technological change at all points in the chain from the invention, to innovation, to adoption and diffusion of the technology, and unaddressed market failures or barriers at any stage in the chain can limit policy effectiveness (Nemet, 2013). The innovation systems literature stresses that technology development and deployment are driven by both technology push (forces that drive the development of technologies and innovation such as R&D funding and tax breaks for R&D, patents), and demand pull forces that increase the market demand for technologies such as technology subsidies and standards (Gallagher et al., 2012; Wilson et al., 2012).

Technology systems may create path dependencies in the innovation process. The current dominance of the carbon-based system creates incentives to improve carbon technology rather than non-carbon. This has been observed in private (Aghion et al., 2012) as well as public institutions (Unruh, 2000) exemplified by fossil fuel subsidies (OECD, 2013). Escaping carbon lock-in is essentially a problem of coordination (Rodrik, 2007; Kretschmer, 2008), which can be facilitated by public policy that addresses technology-push, demand-pull, and framework conditions in a complementary fashion (Nemet, 2013).

This section addresses the generic issues that arise in the implementation of policies intended specifically to foster the development and implementation of low-GHG technologies. It begins by discussing technology policy instruments in three overarching categories: 1) the patent system and other forms of intellectual property (IP); 2) public funding of research, tax subsidies for firms engaging in R&D; and 3) various policies designed to foster deployment of new technologies. It then moves on to discuss the impact of environmental policy on technological change in general, technological change in a broader social framework often termed an 'enabling environment' together with interactions across various elements of innovation systems, and finally the importance of incorporating programme evaluation into the design of technology policy.

15.6.2 Experience with technology policy

15.6.2.1 Intellectual property

Public policy towards IP inherently involves a tradeoff between the desire to create incentives for knowledge creators and developers, and the desire to have new knowledge used as widely as possible once it is created (Hall, 2007). It is therefore crucial to analyze the extent to which IP protection such as patents, will foster climate change mitigation, by encouraging the creation and development of new GHG-reducing technologies, versus the extent to which it will hamper mitigation by raising the cost and limiting access to such new technologies as are developed. Intellectual Property policy will affect climate change mitigation both through its effects on the creation of new technology and on the international transfer of mitigation technology. The first of these mechanisms will be considered here; the effect of IP policy on technology transfer is discussed in Chapter 13.9.

In general, the empirical evidence that IP protection stimulates innovation is limited to the chemical and pharmaceutical sectors, and to developed economies (Park and Ginarte, 1997). It is unclear to what extent IP protection is relevant to the development of the kind of technologies that would mitigate climate change in advanced and middle income countries, and it appears unlikely to be relevant to indigenous technology development in the poorest countries (Hall and Helmers, 2010).[11]

The Trade Related Intellectual Property Rights (TRIPS) agreement generally commits all countries to create and enforce standard IP protections, but it does allow for the possibility of exceptions to standard patent regulations for public policy reasons (World Trade Organization, 1994). Hence a major policy issue related to climate change is the extent to which developing countries will be compelled within the TRIPS framework to enforce strong IP protection relative to GHG-reducing technologies, or whether an exception or exceptions will develop for these technologies on public policy grounds (Derclaye, 2008; Rimmer, 2009).

Because the evidence that strong IP protection increases domestic innovation is almost entirely limited to specific sectors in the developed world, it is unclear whether maintenance of strong IP protection in less developed countries will increase those countries' indigenous creation or adaptation of GHG-reducing technologies. As discussed in Chapter 13, however, the evidence does suggest that the presence of an effective IP regime is a factor in fostering technology transfer into a country.

15.6.2.2 Public funding of research and development

Public funding of research and development may address specific market failures related to innovation (as discussed in Chapter 3.11), but may also help to compensate for barriers to private investment that may result from long lifetimes of incumbent technologies leading to lengthy transition times from one system/technology to another (Fouquet and Pearson, 2006; Fouquet, 2010), uncertainty about future levelized costs of capital or discount rates (Nemet, 2013), or the lack of guarantee on the success of an investment (Mazzucato, 2013; Nemet, 2013).

Public research expenditures that have the potential to foster the long-run development of GHG-mitigating technology come under a number of different common public research expenditure categories, including environment, agriculture, materials, and others. There are no widely accepted data that attempt to identify and sum up public expenditures across different categories that potentially relate to mitigation technologies. Much discussion about the potential for technological change to mitigate GHG emissions revolves around reducing and eliminating use of fossil fuels, and the largest single category of public research expenditure related to mitigation is energy research, discussed in Chapter 7.12.2.

Public energy-related research expenditures among the International Energy Agency (IEA) countries currently comprise about 5 % of total public R&D spending in those countries, less than half the share of

[11] There are however other relevant examples for instance of indigenous knowledge in developing countries being valuable when it comes to biodiversity and pharmaceuticals.

such research in total public research spending in 1980. Gallagher et al. (2012) report an increase in public funding for energy-technologies among IEA member countries in the 2000s but also find a continued prominence of funding for nuclear and fossil fuel technologies. A similar trend has been noted for non-IEA members like Brazil, China India, Mexico, Russia, and South Africa (Gallagher et al., 2012). A gradual but steady increase in this share is a major policy option for fostering the long-run development of GHG-reducing technologies (Jaffe, 2012).

The U.S. National Research Council (NRC) evaluated Federal Energy research, development, and demonstration (RD&D) investments in energy efficiency and fossil energy for the period 1978–2000. The NRC found that these investments "yielded significant benefits (economic, environmental, and national security-related), important technological options for potential application in a different (but possible) economic, political, and/or environmental setting, and important additions to the stock of engineering and scientific knowledge in a number of fields" (U.S. National Research Council, 2001). In terms of overall benefit-cost evaluation, the NRC found that the energy efficiency programmes produced net realized economic benefits that 'substantially exceeded' the investment in the programmes. For the fossil energy programmes, the net realized economic benefits were less than the cost of the programmes for the period 1978–1986, but exceeded the cost of the programmes for 1986–2000 (U.S. National Research Council, 2001). Japanese technology RD&D programmes for renewable energy and energy efficiency, known as Sunshine program and Moonlight program since 1974, were also found to be both economically and environmentally effective (Kimura, 2010).

In the short run, the availability of appropriately trained scientists and engineers is a constraint on a country's ability to increase its research output (Goolsbee, 1998) (See also Jensen and Thomson, 2013). This factor combines with short-run adjustment costs in laboratory facilities to make rapid ramp-up in research in a particular area likely to be cost-ineffective, as found to occur, for example, as a result of the doubling of US health research (Cockburn et al., 2011). Therefore, sustained gradual increases in research are likely to be more effective than short-run rapid increases. In the long run, it is possible to expand the supply of scientific and technical labour available to perform energy-related research. This can occur through training that occurs when publicly funded research is carried out at universities and other combined research and teaching institutions, and/or via direct public funding of training. Success at increasing the technical workforce has been found to be a crucial factor in the long-run benefits of health-related research in the United States (Cockburn et al., 2011).

15.6.2.3 Policies to foster or accelerate deployment and diffusion of new technologies

In addition to fostering technology development through research, many policies seek to foster the deployment of GHG-mitigating technologies in households and firms. Such deployment policies could be thought of as a form of abatement policy, to the extent that they reduce emissions relative to what would occur with the use of previous technologies. But the more fundamental reason for public policy to foster technology deployment is that deployment feeds back and enhances subsequent improvement of the technology over time (Jaffe and Stavins, 1994; Henkel and Hippel, 2005; Jaffe, 2012). For example, publicly funded research certainly played a role in the digital revolution, but active government involvement as an early purchaser was also crucial (Mowery, 2011). Purchases were made of products meeting stated technical specifications, and this approach has helped move products down the learning curve, eventually allowing civilian versions to be sold competitively.

Market failure in the deployment of new technologies is often illustrated via an image of a 'Valley of Death' between small scale or prototype developments and successful commercialization, in which the need for substantial increase in the scale of investment combines with uncertainty about technical reliability, market receptiveness and appropriability to stall or slow deployment (Grubb, 2004; Nemet, 2013, p. 112). A variety of demand-pull public policies can operate to carry technology deployment through the Valley of Death.

As laid out in Table 15.2, economic instruments such as subsidies, regulatory approaches, information programmes, government provision of public goods and services, as well as voluntary actions are common across sectors. The targeted technologies include low-emission vehicles such as hybrid cars in the transport sector (8.10), efficient electric appliances such as light-emitting diodes (LED) in the building sector (9.10), and advanced industrial equipment (11.10). Feed-in-tariffs are used for renewable in the power sector (7.10). Quantity requirement are also common, including RPSs in the power sector (7.10), biofuel mandates in the transport sector (8.10). Information programmes such as labelling of home electric appliance may be used to promote the sales of new, low emission technologies (9.10).

Since AR4, a large number of countries and sub-national jurisdictions have introduced support policies for renewable energy. These have promoted substantial diffusion and innovation of new energy technologies such as wind turbines and photovoltaic panels, though many renewable energy (RE) technologies still need policy support, if their market shares are to be increased (see 7.5.3, 7.6.1, 7.8.2, and Chapter 11 Bioenergy Annex).

Chapter 7 (citing the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN)) argued that "…some feed in tariffs have been effective and efficient at promoting RE electricity, mainly due to the combination of long-term fixed price or premium payments, network connections, and guaranteed purchase of all RE electricity generated". Feed-in-tariffs have been effective in promoting renewables in Germany and other nations (Couture and Gagnon, 2010; Ragwitz and Steinhilber, 2013). It is also argued that the flexibility of FITs can incorporate economic and technological changes (Klobasa et al., 2013) and encourage dynamic innovation (Mitchell et al., 2006). Proving dynamic efficiency in the narrow economic sense is more complicated, although Jaffe et al., (2005) have explored this in a somewhat positive light.

There are different views on FITs, especially in relation to their cost-effectiveness. Some criticize FIT of having 'failed to harness market incentives' because it is not statically cost effective (i.e., it supports photovoltaics in addition to wind energy, although the former is more expensive than the latter) (Frondel et al., 2008, 2010) . Schmalensee (2012), using a simple model, argues that while FITs shift risk away from investors in renewable energies, they may not reduce the risk to society as a whole. In a paper for the European Union, Canton and Linden (2010) argue that feed-in premiums are preferable to FITs if internal market distortions are to be avoided.

With the increasing market shares of intermittent generation, new challenges have to be addressed in respect to grid and market integration such as capacity constraints, demand spikes, back up capacity, and transmission. A reform of market design, including flexible demand side pricing, is proposed to make the system more flexible so it can react to the new challenges (See 7.10 and SSREN Chapter 8 for details (Sims et al., 2012).

A theme that runs through many of the sectoral deployment policy discussions is the importance of information, and the relationship between incomplete information and risk. Uncertainty about the physical and economic performance of new technologies is a major factor limiting their diffusion, so policies that address information issues may be complementary with economic incentives or regulatory approaches.

Many nations, including Germany, Spain, China, India, among others, have implemented ambitious deployment programmes for renewables consisting of capacity targets, FIT, and so forth (Jänicke, 2012), resulting in rapid capacity expansion and lower costs of technologies. Such progress may result in economic and environmental efficiency in the long run at the global scale (Kalkuhl et al., 2013). Ondraczek (2013) identifies awareness among consumers as a critical element in market development in Kenya and Tanzania and finds evidence for a 'virtuous cycle' between dissemination and awareness. Friebe et al. (2013) emphasize the need for including pre and post-sales services to sustain the uptake of solar home systems. Glemarec (2012) highlights the role for public-private partnerships to deliver energy access but underlines the need for public investment in capacity and market development.

Many developing countries face a somewhat different set of choices in encouraging technology deployment because of the dominance of state-owned or other monopoly enterprises in the energy sector. Liu and Kokko (2010) evaluate the factors related to the significant growth of wind power in China, and conclude that administrative rules stipulating levels of wind usage have been more effective than incentives operating through the pricing system. Pegels (2010) describes the introduction of a renewable FIT guaranteed for 20 years in South Africa, but notes that it is unclear what effect this will have on the investment decisions of the monopolist electricity supplier.

15.6.3 The impact of environmental policy instruments on technological change

There is some empirical literature assessing the impact of generic environmental policy instruments (discussed in the previous section) on technological change. For surveys, see Newell (2010) and Popp et al. (2010b). Jaffe and Palmer (1997), looking across industries in the United States., found that more stringent regulation was associated with higher R&D expenditures (controlling for industry fixed effects), but did not find any impact on industry patents. Lanjouw and Moody (1996) did find that across the United States, Germany, and Japan, patenting rates were correlated at the industry level with pollution control expenditures.

A number of studies have looked at the impact of energy prices on energy-saving technological change. These effects can be seen as indicative of the possible consequences of GHG policies that increase the effective price of emitting GHG. Popp (2002) found that rising energy prices increased the rate of patenting with respect to alternative energy sources and energy efficiency, with more than one-half the effect coming within five years of energy price changes. Newell (1999) found that rising energy prices increased the efficiency of the menu of household appliances available for purchase in the United States. The Norwegian carbon tax appears to have triggered technology innovation in the form of carbon dioxide storage in the Sleipner gas field (Sumner et al., 2011). Fuel taxes moved auto industry innovation towards more efficient technologies (Aghion et al., 2012), and the EU ETS moved the firms most affected by its constraints towards low-carbon innovation (Calel and Dechezleprêtre, 2012).

At a theoretical level, there are arguments why incentive-based policies such as carbon taxes or tradable permits are more conducive to innovation than regulatory approaches (Popp, Newell, et al., 2010b). After the 1990 Clean Air Act Amendments in the United States implemented a tradable permit programme for sulphur dioxide, Popp (2003) found that the rate of patenting on techniques for sulphur removal increased, and Lange and Bellas (2005) found that both capital and operating expenditures for scrubbers were reduced. In a survey of research on the effects of tradable permit systems on technology innovation and diffusion, Bellas (2011) concluded "The general result is that tradable permit programs have improved the pollution control technology compared to the previous regulation used." Sterner and Turnheim (2009) find similarly that the very high fee on NO_x in Sweden has led to a rapid process of both innovation and technology diffusion for abatement technologies.

More recently, a few studies have explored the effect of renewable energy policies on energy innovation. Johnstone et al. (2010) found that policy had a significant impact on patent applications for renewable technologies, with different policy instruments being effective for different technologies. Popp et al. (2010a) found that the link between greater patenting and investment in specific technologies is weak, but there does seem to be an association between policy and investment.

15.6.4 The social context of technological transitions and its interaction with policy

The central insight from the empirical literature is that both technology push and demand pull policies are required to be most effective (Nemet, 2009). A 'virtuous cycle' (IEA, 2003; Edenhofer et al., 2012) can occur, derived from learning from combined technology push and market pull whereby as 'learning' from market demand feeds back in to research and development, the improved product leads to more market demand and reduced costs. This virtuous technology and market cycle has been extended to include a third cycle of policy learning (Jänicke, 2012) whereby as learning from a successful policy occurs across the innovation chain, it can also be fed back into the process.

A technology policy will be more effective if it addresses multiple aspects such as institutions, regulations and standards, political models, laws, social norms and preferences, individual behaviours, skills, and other characteristics. This idea was originally developed and encapsulated in the UNFCCC definition of an 'enabling environment' (UNFCCC, 2001).[12] This general intention to match up specific technology requirements with the system situation in which they develop has been called framework conditions (Grubb, 2004), enabling environment (Edenhofer et al., 2012; Johansson et al., 2012), enabling factors (Nemet, 2013), and complementary innovations (Grubb et al., 2014).

There is a literature base that explores technology transitions and the implications of multilevel interactions across social and technological elements (e.g., Geels, 2011; Meadowcroft, 2011; Foxon, 2011). Three social challenges are raised as especially salient to social management when attempting to alter the technological system: (1) the size and visibility of transfers and assets created; (2) the predictability of pressure to expand the focus of the policies to broaden the social benefits; and (3) the potential for market incentives and framings of environmental issues to undermine normative motivational systems (Parson and Kravitz, 2013). Managing these social challenges may require innovations in policy and institutional design, including building integrated policies that make complementary use of market incentives, authority, and norms (Foxon, 2011; Gallagher et al., 2012; Parson and Kravitz, 2013). Doing so will reduce the risk of market incentives failing to achieve behavioural change and recognizes that incentives and norms have to be integrated to achieve sustainability transitions.

[12] Enabling environment is defined as: "the component of the framework [that] focuses on government actions such as fair trade policies, removal of technical, legal and administrative barriers to technical transfer, sound economic policy, regulatory frameworks and transparency, all of which create an environment conducive to private and public sector technology transfer" (UNFCCC, 2001).

15.6.5 Building programme evaluation into government technology programmes

Evaluation of government programmes to foster new energy technologies has been hampered by a lack of complete and consistent evaluation data at the programme level (U.S. National Research Council, 2001). This problem is common to many government technology programmes. Proper evaluation requires that data on project selection and project performance be collected as programmes commence and maintained after they are completed (Jaffe, 2002). Wider use of such evaluation methods would allow experience with relative effectiveness of different programmes to be used to improve outcomes over time. While the above argument applies to all governmental policy in general, it is particularly important for technology development programmes that may be vulnerable to governmental failure related to the picking and choosing of technologies under high uncertainty (Helm, 2010).

15.6.6 Summary of technology policy and R&D policy

There is a distinct role for technology policy in climate change mitigation. This role is complementary to the role of policies aimed directly at reducing current GHG emissions (15.6.1).

The availability of new technologies is crucial for the ability to realistically implement stringent carbon policies. Technology policy will be most effective when all aspects of the innovation/deployment chain are addressed in a complementary fashion (see Section 15.6.1). Investment depends on the willingness of a variety of actors to manage the balance between the risks and rewards in each step of the chain, and government decisions are crucial to this balance.

Evidence suggests that the presence of an effective IP regime increases domestic innovation. However, as evidence is almost entirely limited to specific sectors in the developed world, it is unclear whether strong IP protection in less developed countries will increase those countries' indigenous creation or adaptation of mitigation technologies (15.6.2.1).

Worldwide investment in research in support of climate change mitigation is small relative to overall public research spending. The effectiveness of research support will be greatest if it is increased steadily rather than dramatically or erratically (15.6.3).

A wide range of policy approaches is prevalent across sectors, which enable policy design that addresses sector- and technology-specific attributes. These policies are often designed as complementary sets of policies, or policy packages (15.5.1 and 15.6.2.3).

Complementary framework conditions, or an enabling environment, may complement a package of technology-push and demand-pull policies (15.6.4). Managing social challenges of technology policy change may require innovations in policy and institutional design, including building integrated policies that make complementary use of market incentives, authority and norms (15.6. 4).

It is important that data collection for programme evaluation be built into technology policy programmes (15.6.5), because there is very little empirical evidence on the relative effectiveness of different mechanisms for supporting the creation and diffusion of new technologies.

15.7 Synergies and tradeoffs among policies

This section discusses interactions between policies with different main objectives as well as between differing climate policies with the same objective. Section 15.7.2 discusses relationships between policies with different principal objectives—for example, between climate policy and development policy. The next two sections consider interactions between climate policies. Section 15.7.3 describes interactions between different climate policies at different levels of government, and 15.7.4 takes up interactions between climate policies enacted at the same level of government. The interactions in 15.7.3 and 15.7.4 reflect the absence of policy coordination, and they affect the environmental and economic outcomes. Deliberate linking of policies is discussed in Section 15.8.

15.7.1 Relationship between policies with different objectives

Governments throughout the world have enacted various policies to support the mitigation of climate change, which is the central objective of climate policy. However, the implementation of mitigation policies and measures can have positive or negative effects on additional objectives—and vice versa. To the extent these side-effects are positive, they can be deemed 'co-benefits'; if adverse and uncertain, they imply risks.[13] The co-benefits of climate policy are primary benefits of policies with other main objectives. Social development is a primary benefit of development policy, since such development is the main objective. Similarly, enhanced energy security, technological development, and reduced air pollution are primary benefits of energy security, technological development, and air-pollution policies, respectively. To the extent that these other policies (with other objectives) lead to mitigation, such mitigation is a co-benefit of these other policies.

[13] Co-benefits and adverse side-effects describe effects in non-monetary units without yet evaluating the net effect on overall social welfare. Please refer to the glossary in Annex I for definitions and to Chapters 3.6.3 and 4.8 for a discussion of how the concept of co-benefits relates to welfare and sustainable development, respectively.

Although there is growing interest in research on mitigation as a co-benefit (see Sections 1.2.1 and e.g., Kahn Ribeiro and de Abreu, 2008), the great majority of the literature assessed in other chapters focuses on the co-effects of sectoral mitigation measures (Chapters 7.9, 8.7, 9.7, 10.8, 11.7, 11.13.6, and 12.8) or transformation pathways (Section 6.6) on additional objectives. Table 15.1 in Section 15.2.4 provides a roadmap for the assessment of those co-benefits and adverse side-effects on the many objectives examined in various chapters of this report and highlights that the effects on energy security and air pollution as well as the associated reductions in health and ecosystem impacts are discussed in all sector chapters. For example, stringent mitigation results in reduced combustion of fossil fuels with major cuts in air pollutant emissions significantly below baseline scenarios (see 6.6.2.1 and, e.g., ApSimon et al., 2009) for a discussion of policy interaction in Europe); by increasing the diversity of energy sources and reducing energy imports in most countries, mitigation often results in energy systems that are less vulnerable to price volatility and supply disruptions (see 6.6.2.2 and, e.g., Lecuyer and Bibas, 2011) for a discussion of policy interaction in Europe).

According to recent scenario studies assessed in Chapter 6.6.2.7, stringent climate policies would significantly reduce the costs of reaching energy security and/or air pollution objectives globally. Recent literature assessed in Chapters 6.6.2.3, 7.9.1 and 16.8 finds that increasing access to modern energy services may not conflict with mitigation objectives—and vice versa.

There are two important advantages to coordinating separate policies and their various benefits. By coordinating policies, the various benefits and costs can be considered in an integrated fashion, which offers information helpful to determining how to achieve the objectives at low cost (see 6.6.2.7). In addition, coordinating policies can improve political feasibility. The concept of 'mainstreaming' climate policy refers to the linking of climate policy with other policy efforts, particularly policy efforts that have broad recognition. The prospects for successful climate policy can be enhanced through such mainstreaming (Kok and de Coninck, 2007).

Development frameworks at international or national levels, or by sector, may include mainstreaming as a key element. For it to be effective, climate change mitigation needs to be mainstreamed in appropriate national and sector planning processes to widen development goals within national and sectoral contexts. For developing countries, such integration of mitigation into development planning can reduce problems of cooperation and coordination that may arise across different levels of government (Tyler, 2010).

Mitigation plans can be embedded in national policy-making processes to align economic and social development with mitigation actions. For example, in China, the National Leading Group on Climate Change is part of the National Development and Reform Commission, the principal national planning body (see Section 15.2.2.2).

Limited institutional capacity in developing countries presents the most significant barrier to mainstreaming of mitigation policies. This includes a lack of knowledge and/or expertise in climate change issues, a lack of (or weak) oversight and/or enforcement. Developing countries aiming to mainstream and implement climate change mitigation policies must; 1) encourage awareness on the topic; 2) establish related training programmes; 3) ensure an adequate level of finance for enforcement; and 4) enhance coordination between ministries (Ellis et al., 2009).

15.7.2 Interactions between climate policies conducted at different jurisdictional levels

Climate policy has been conducted at various jurisdictional levels: international, national, regional (state or provincial), and local (municipal). Important interactions can occur across jurisdictional levels. Some interactions are beneficial, reinforcing the intended effects; others are problematic, interfering with the planned objectives. Sound policymaking requires attention to these interactions.

15.7.2.1 Beneficial interactions

Policies introduced by a local jurisdiction sometimes reinforce the goals of efforts undertaken at a higher jurisdictional level. In particular, a sub-national policy can enhance cost-effectiveness if it addresses market failures that are not confronted by a national climate policy. Thus, for example, as seen in Sections 15.5.4 and 15.5.6, an RPS in the electricity sector and an R&D subsidy could usefully complement a national emissions pricing policy.

The connections between instruments that deal with climate change and those that deal with congestion or local pollution also present an opportunity to policymakers, but they are very different since the latter vary depending on the socioeconomic context, technology, fuel, and vehicle use (Parry et al., 2007; Oikonomou and Jepma, 2008; Vanderschuren et al., 2010; Parry, 2013). For example, urban planning implemented jointly with fuel or carbon taxes can help fast growing developing countries minimize resource waste by avoiding urban sprawl. Policies incentivizing more dense urban architecture combined with the appropriate infrastructure for modern public transport can be an important complement to energy taxation. Such policies can be supported (and possibly financed) by fuel taxes if the policymaker wants to discourage citizens from making private decisions that are incompatible with this broader vision; policy combinations for this sector are discussed in greater detail in Chapter 8. Conversely, subsidizing fuels and taking a hands-off urban planning approach can result in urban sprawl and a growth in private automobile use along with growth in resulting emissions.

Local-level action can also be a good source of information by allowing experimentation. In the United States, environmental policies by the federal government have a history of evolving out of successful policy 'experiments' undertaken by states (Goulder and Stavins, 2011; Shobe and Burtraw, 2012). Thus, an appealing feature of local-level actions are their ability to try out policy options not currently in place at the higher jurisdictional level; the higher jurisdiction may have more confidence in introducing a policy subsequently if it already has a successful track record at the more local level.

Finally, local policies can produce beneficial strategic interactions. If national policy is insufficiently stringent, a stringent state/province or even municipal policy may create pressure on the national government to increase its own policy's stringency. Goulder and Stavins (2011) cite the example of California, which repeatedly increased the stringency of its local air pollution standards and was repeatedly followed by the federal government increasing Clean Air Act regulations' stringency. Similarly, Lucon and Goldemberg (2010) note the importance of São Paulo's GHG-reducing policies in influencing other local and even regional governments in Brazil.

15.7.2.2 Problematic interactions

Policies introduced at different levels sometimes interact in ways that compromise or weaken the intended environmental or economic impacts.

One particular difficulty that may arise is the problem of emissions leakage. This can occur, for example, when a climate policy introduced at a lower jurisdictional level is 'nested' within a cap-and-trade programme implemented at a higher jurisdictional level. Consider the case where a cap-and-trade programme exists at the national level, and where a sub-national authority introduces a new policy intended to reduce its own (sub-national) emissions beyond what would result from the national programme alone. The sub-national jurisdiction's efforts might indeed yield reductions within that jurisdiction, but facilities in other sub-national jurisdictions covered by the cap-and-trade programme will now use these allowances leading to higher emissions in these jurisdictions completely compensating the abatement effort in the more stringent jurisdiction. Since overall emissions at the higher level are determined by the given national-level cap, the effort by the sub-national jurisdiction does not succeed in reducing nationwide: it just causes emissions leakage—offsetting increases in emissions elsewhere in the nation. The national cap effectively prevents sub-national jurisdictions from achieving further emissions reductions (Goulder and Stavins, 2011; Shobe and Burtraw, 2012).

The issue applies to the United Kingdom's efforts to reduce emissions through a carbon tax on the power sector (electricity generators). The generators are required to pay the tax on every unit of carbon emissions while also being subject to the EU ETS cap on overall emissions. While the tax may lead to greater reduction in carbon emissions by the generators in the UK, the impact on overall emissions in the EU might be negligible, since overall European emissions are largely determined by the Europe-wide cap under the EU ETS. On this, see (Böhringer et al., 2008; Sartor and Berghmans, 2011; Goulder, 2013)

This leakage problem can be avoided when the lower-level jurisdiction's programme is nested within a carbon tax programme, rather than emissions cap, at the higher level. In this case, the sub-national policies generally are not environmentally irrelevant. The reduced emissions in the sub-national jurisdiction do not lead to a fall in the emissions price (the carbon tax) at the national level; hence there are no offsetting increases in emissions in jurisdictions outside the jurisdiction introducing the more stringent policy (De Jonghe et al., 2009; Fankhauser et al., 2010; Goulder and Stavins, 2011). This can be an important advantage of a carbon tax over a cap-and-trade system.

15.7.3 Interactions between policies conducted at the same jurisdictional level

Interactions also can arise when different policy instruments are introduced at the same jurisdictional level. These interactions can be beneficial or problematic in terms of the cost-effectiveness of reducing greenhouse gas emissions.

15.7.3.1 Beneficial interactions

The potential for cost-reducing interactions is greatest when the different instruments address different market failures. A fundamental principle of public policy is that the most cost-effective outcome results when there are as many policy instruments as the number of market failures involved, with each instrument focusing mainly on a different market failure (Tinbergen, 1970).

Climate policy is meant to address one market failure in particular—the climate-change-related externalities associated with GHGs. As seen in Section 15.6, another important market failure applies in the market for innovation: because new knowledge can spill over to third parties, innovators often cannot capture all of the social benefits from the new knowledge they create. Introducing two policy instruments, for example, emissions pricing to address the emissions externality, and a subsidy to R&D to address the innovation market failure, can lower the costs of achieving given emissions reductions. In addition to helping reduce emissions by encouraging fuel-switching and a reduction in demand, emissions pricing can help spur innovation. Likewise, the R&D subsidy can promote invention of low-carbon technologies, thereby helping to curb emissions. Hence the interactions of the two policies are beneficial. Although each of the two policies might to some degree affect both of the market failures, emissions pricing is particularly well focused on the first, while the R&D policy sharply addresses the second. Using two instruments helps achieve emissions reductions at the lowest cost. In this connection, Fischer and Newell (2004) and Oikonomou et al. (2010) find that a policy combination including a price on GHG emissions and renewable energy subsidies achieves emissions reductions at significantly lower cost than either of these policies alone. Schneider and Goulder (1997) obtain a similar result for the combination of carbon tax and R&D subsidy.

As noted already in Section 15.5.4.1, several studies (Greene, 1998; Goulder and Parry, 2008; Gillingham et al., 2009b) argue that there is a market failure associated with consumer purchases of durable energy-using equipment (automobiles, refrigerators, etc.), according to which consumers systematically underestimate their own future gains from purchasing more energy efficient durables. To the extent that this market failure is significant, the combination of emissions pricing and a second instrument (for example, an energy-efficiency standard for appliances) to address this additional market failure could lead to beneficial interactions and promote cost-effectiveness.

Some studies suggest a market failure associated with reliance on crude oil, claiming that reliance on oil produces an 'economic vulnerability externality', given the possibility of supply disruptions on the world oil market (Jones et al., 2004). Under these circumstances, the combination of emissions pricing (to address the climate change externality) and a tax on oil consumption (to address the vulnerability externality) can be a cost-effective way of dealing with both climate change and economic vulnerability. Several authors (e.g., Nordhaus, 2009), emphasize that the vulnerability to world oil price changes is largely a function of the share of overall oil consumption in GDP, rather than the share of consumed oil that comes from imports. This suggests that the vulnerability externality is best addressed through a tax on oil consumption rather than a tax on imported oil.

15.7.3.2 Problematic interactions

Multiple policies at the same jurisdictional level also can yield problematic interactions. This can happen when multiple policies only address the same market failure. Consider the situation where a given jurisdiction attempts to reduce greenhouse gases through both emissions pricing and another policy such as a performance standard (a limit on the ratio of emissions per unit of production). Economic theory claims that, absent market failures and other barriers, emissions pricing tends to promote a highly cost-effective outcome by promoting equality in the marginal costs of emissions-abatement across all the facilities that face the given price of emissions (the carbon tax or the price of emissions allowances). If, in addition, facilities face a performance standard, then this added policy approach either is redundant or it compromises cost-effectiveness.

It is redundant if meeting the performance standard would involve marginal abatement costs lower than the emissions price. In this event, cost-minimizing firms would be induced to meet or exceed this standard by the emissions price alone: there is no need for the standard. On the other hand, if the performance standard entails a cost per unit of abatement that is significantly higher than the emissions price, then this requirement sacrifices cost-effectiveness. Relying on emissions pricing alone would have promoted emissions reductions by the facilities that can achieve those reductions at the least cost. Thus it would likely have led to a situation where the more expensive technology approach was not employed. Hence in this case the combination of emissions pricing and the performance standard does not promote cost-effectiveness.

Emissions price policies interact with other policies differently depending on whether the emissions price policy involves a quantity limit (as is the case under cap and trade) or a stipulated emissions price (as is the case under an emissions tax). In the presence of a cap-and-trade programme, introducing an additional instrument such as a performance standard might yield no further reductions in overall emissions (Burtraw and Shobe, 2009; Fankhauser et al., 2010). The reason is that overall emissions are determined by the overall cap or number of allowances in circulation. The problem is formally very similar to the difficulty described in Section 15.7.3 above, where in the presence of a national cap-and-trade programme an effort by a sub-national jurisdiction to achieve further emissions reductions is likely to have difficulty achieving that goal. In contrast, introducing a performance standard in the presence of an emissions tax can in fact lead to a reduction in overall emissions. The price of emissions—the emissions tax—does not change when the performance standard causes a reduction in emissions. For this reason the reduction caused by the performance standard does not lead to a compensating increase in emissions elsewhere. Overall emissions fall.

For similar reasons, the same difficulty arises when a carbon tax is introduced in the presence of a cap-and-trade programme at the same jurisdictional level (Fischer and Preonas, 2010).

Nevertheless, as suggested above, the combination of emissions pricing and some other policy could be justified in terms of cost-effectiveness to the extent that the latter policy directly addresses a second market failure that emissions pricing does not directly confront.

It is important to recognize that the notion of a 'market failure' pertains only to the criterion of economic efficiency. Another important public policy consideration is distributional equity. Concerns about distributional equity can justify supplementing a given policy instrument with another in order to bring about a more equitable outcome. This may be desirable even if the multiplicity of instruments reduces cost-effectiveness.

15.8 National, state and local linkages

15.8.1 Overview of linkages across jurisdictions

In the last few years, an increasing number of sub-national administrations across the world have been active in the design and application of climate policies. Section 15.2 has reported some of these experiences, whereas Section 15.7 has dealt with some of the interactions that may arise with the simultaneous use of climate policy instruments by several jurisdictions. This section goes back a little and is basically interested in the allocation of climate policy responsibilities across the different levels of government that usually exist in most countries (central, provincial, and local administrations). Although such allocation involves the use the policy types described in Section 15.4, the emphasis here will not be on instrument use in itself, as this was already covered in Sections 15.5 to 15.7. The objective of this section is to examine the theoretical backing for such practical applications and to extract lessons that may be useful for future sub-national applications and even for the design and implementation of national and supra-national mitigation policies. When dealing with the reasons for and guidelines for the 'vertical' allocation of responsibilities among jurisdictions that co-exist in a country, the theory of fiscal federalism (economic federalism) offers valuable insights. In short, that the responsibility for public decision making over a particular issue (e.g., allocation of public goods, economic stabilization, or distribution) should be given to the jurisdictional level that could better manage it. In this sense, fiscal federalism contends that the central government should have the basic responsibility for functions whose national extension would render ineffective and inefficient a sub-national approximation, including 'national' public goods (Oates, 1999).

15.8.2 Collective action problem of sub-national actions

Given the global and public good nature of climate change, its jurisdictional allocation should actually be at the highest possible level. A sub-global allocation, as observed in Chapter 13, would lead other jurisdictions that are not active in climate change mitigation to benefit without paying the costs, i.e., in a free-riding fashion (Kousky and Schneider, 2003). Empirically, case studies found that climate policies tended to be less intrusive at sub-national level. While co-benefits with local development were pursued, policies that might incur costs to local economy were avoided in prefectures in Japan (Aoki, 2010). The costs for a sub-national administration may be actually beyond those of pure mitigation, as climate policies implemented by a jurisdiction might bring about leakage, (see the glossary in Annex I for a definition) (Kruger, 2007; Engel, 2009). Moreover, the 'reshuffling' that may be associated to sub-national policies may reduce their environmental effectiveness (Bushnell et al., 2008). As a consequence, climate change mitigation would be provided in a sub-optimal level with sub-national allocation of responsibilities.

15.8.3 Benefits of sub-national actions

Yet, even if the central government has a major responsibility in this area, this does not preclude the allocation of mitigation responsibilities within a federation, as observed in citizen's attitudes on this matter (Lachapelle et al., 2012). But even within the theory of fiscal federalism there are other reasons that may justify sub-national action in this field. First, as noted by Edenhofer et al. (2013), the exploitation of heterogeneous sub-national preferences for mitigation would lead to efficiency gains. This is actually one of the reasons for the decentralization theorem, a centrepiece of fiscal federalism, which in fact justifies sub-national allocation of certain public goods.

Moreover, decentralization can contribute to policy innovation by providing an opportunity to experiment with different approximations. Indeed, there might be potential gains from learning by doing in policy terms without imposing large costs on an entire country or the world with untried options (Oates, 2002). Sub-national governments could also choose to be leaders in the development of climate policies to obtain potential economic gains that are associated to 'first movers' (Jänicke and Jacob, 2004) and may provide guidance and incentives to other jurisdictions to follow them (Bulkeley and Castán Broto, 2012). Besides, as they tend to be smaller, sub-national governments may be able to adapt to new situations in a swifter manner and therefore may have a greater flexibility to modify existing climate policies or to define new ones (Puppim de Oliveira, 2009; Galarraga et al., 2011).

Other general approaches to federalism, such as cooperative and democratic federalism, may also provide reasons for sub-national involvement in this area (Inman and Rubinfeld, 1997). On the one hand, cooperative federalism argues for allocating pure public goods to the local level, counting on the power of inter-jurisdictional bargaining to improve allocations. On the other hand, democratic federalism incorporates sub-national representation in central decision making on public goods. In any case, federal structures may be crucial for the transmission of mitigation policies because most sub-national governments are now responsible for matters that have huge effects on GHG emissions, namely: land use planning, building codes, waste management, traffic infrastructure and management, and public transport (Collier and Löfstedt, 1997; Bulkeley and Betsill, 2005; Doremus and Hanemann, 2008). But sub-national governments also have direct policies aimed at GHG mitigation, including: energy efficiency programmes, educational efforts, green procurement standards, partnership agreements with local businesses, or tree planting (Schreurs, 2008).

Yet another reason for a sub-national role in climate policies is beyond the standard collective action approach. By indicating that externality-correcting regulations and global agreements are not the only pace to tackling climate change problems, Ostrom (2010) suggested a polycentric approach in which mitigation activities are undertaken by multiple (public and private) units at diverse scales. The prevalence of sub-national actions in the field, contentious to other approaches, may be actually a proof of polycentrism in the area (Byrne et al., 2007; Sovacool, 2011b). The polycentric approach could be seen as a reinterpretation of the findings of the federalism literature, as actions should involve many different agents in a reinforcing manner.

Finally, further issues may explain sub-national allocation. Local authorities, for instance, may be more effective in reducing GHG emissions from some sources such as waste and transport, as this may provide significant co-benefits to local citizens (Kousky and Schneider, 2003). Moreover, sub-central administrations are usually closer to the places and citizens impacted by climate change. Even though climate change is a global phenomenon, the nature of its impacts and severity varies significantly across locations so some sub-national governments have reasons to be more protective than national or supranational administrations (Andreen, 2008). This is also the case of adaptation, where sub-national authorities can better manage challenges such as flood risk, water stress, or 'climate proofing' of urban infrastructure (Corfee-Morlot et al., 2009). In all the preceding situations, sub-national governments may tailor actions and policies to people's needs, with an easier identification of priorities and difficulties as they are closer to citizens than more centralized administrations (Lindseth, 2004; Galarraga et al., 2011).

15.8.4 Summary

As in other environmental areas (Dalmazzone, 2006), there is theoretical backing for the allocation of climate-related policies to sub-national levels of government, although there are several limiting factors to a widespread reliance on these administrations. A federal structure that provides coordination and enables an easier transmission of climate policies throughout the agents of the economy is likely to increase the effectiveness of actions against climate change. Moreover, the lessons learned in the design and application of climate policies at different jurisdictional levels could be used in a global setting.

15.9 The role of stakeholders including NGOs

This section considers the role of stakeholders and civil society in developing and delivering concrete mitigation action and focuses on how stakeholders impact policy design and implementation. The range of stakeholders is immense given the extent and complexity of climate change. Devising policy in an inclusive manner may be lengthy and politically challenging (Irvin and Stansbury, 2004), however adopting an inclusive approach to climate policy can bring advantages, notably through increasing the legitimacy of policy design, its durability and implementation (Lazo et al., 2000; Beierle, 2002; Dombrowski, 2010).

15.9.1 Advocacy and accountability

Some of the major functions and roles of NGOs can include raising public awareness, which often involves translating scientific and technical knowledge into actionable forms, lobbying, influencing business investment decisions, and monitoring and implementing agreements (Gulbrandsen and Andresen, 2004; Guay et al., 2004; Betsill and Corell, 2008; Newell, 2008; Dombrowski, 2010). Their domains of action also include engagement in sub-national and national policies and institutions as well as international processes like UNFCCC (Wapner, 1995; Lisowski, 2005). It is in these diverse forms that NGOs play a role in "connecting knowledge with responsibility" (Szarka, 2013) and promoting norms of accountability (Gough and Shackley, 2001; Newell, 2008).

Stakeholders can also affect when and how evidence of climate change translates into policies via the domestic political system (Social Learning Group, 2001). The differing results of the same scientific evidence, for instance, the political polarization in the United States versus more proactive and consensual attempts to find solutions in Europe (Skjærseth et al., 2013) demonstrate how stakeholder interests can filter scientific evidence.

Evidence also indicates that that some fossil fuel companies went further and promoted climate scepticism by providing financial resources to like-minded think-tanks and politicians (Antilla, 2005; Boykoff and Boykoff, 2007), although other fossil fuel companies adopted a more supportive position on climate science (van den Hove et al., 2002a). Differences in the attitudes of oil companies towards climate change are explained in part by domestic institutional contexts and management structures as well as the structure of assets or technologies of different energy companies (Rowlands, 2000; Kolk and Levy, 2002).

15.9.2 Policy design and implementation

Three factors have been considered important for lobbying success in policy design namely: how institutions shape the space for participation (Kohler-Koch and Finke, 2007), organizational resources (Eising, 2007), and the policy environment (Mahoney, 2008; Coen and Richardson, 2009).

In the case of the EU ETS, Skodvin et al. (2010) find that interest groups are able to limit "spectrum of politically feasible policy options." Instrument choice is a function of the extent of resources these interest groups control, the role of veto players in the political process, policy networks and entrepreneurs (Skjærseth and Wettestad, 2009; Skodvin et al., 2010; Braun, 2013; Skjærseth et al., 2013).

The role of business interests in supporting emissions trading as opposed to taxation, in the UK, has also been recognized (Bailey and Rupp, 2006; Nye and Owens, 2008). The political opposition to Australia's Carbon Pollution Reduction Scheme has been explained largely by the opposition of fossil fuel interests (Crowley, 2010, 2013; Macintosh et al., 2010; Bailey et al., 2012). Similarly, in New Zealand, the agriculture sector has played a major role in obtaining a transition period for the sector, use of an intensity-based accounting system, and free credits (Bullock, 2012). This has led to questions regarding the environmental effectiveness of the ETS (Bührs, 2008).

Stakeholders also affect policy durability, flexibility, and implementation. For example, European Climate Change Programme featured consultation processes that ensured policy credibility by having the buy-in of stakeholders. Similarly, the persistence of climate legislation in California has been explained by the stability of coalition groups supporting the legislation due to path dependence despite the economic downturn in contrast to the emerging coalition at the national level which broke down after economic shocks (Knox-Hayes, 2012).

15.9.3 Summary of the role of stakeholders

Early findings indicate the importance of institutions in creating spaces for stakeholder participation, the organizational resources of the stakeholders themselves, and the general policy environment as being critical factors that determine the effectiveness of stakeholder engagement. However, the degree to which policy design and implementation to mitigate climate change is dependent on stakeholder engagement is as yet under-researched and it must be stressed that the evidence base is thin and that these results primarily derive from case studies.

15.10 Capacity building

As national and sub-national governments around the globe confront the multifaceted challenge of climate change mitigation and adaptation, capacity is essential. According to the Agenda 21, building a country's capacity "encompasses the country's human, scientific, technological, organizational, institutional, and resource capabilities" (United Nations, 1992).

The priority for capacity building is strongly reflected in the Johannesburg Plan of Implementation (United Nations, 2002), where capacity building, especially for developing countries and countries with economies in transition, features prominently. It is also stressed in the UNFCCC's capacity building framework for developing countries (Decision 2/CP.7; UNFCCC, 2001). The goal of capacity building under this framework is "to strengthen particularly developing country parties, to promote the widespread dissemination, application and development of environmentally sound technologies and know-how, and to enable them to implement the provisions of the Convention. In addition, the COP under the UNFCCC requested the Subsidiary Body for Implementation to organize an annual in-session Durban Forum for in-depth discussion on capacity-building following COP-17" (Decision 2/CP.17; UNFCCC, 2011). The Durban Forum provides an opportunity for representatives from governments, UN organizations, intergovernmental and non-governmental organizations, academia, and the private sector to share ideas, experiences, and good practices on implementing capacity-building activities.

15.10.1 Capacity to analyze the implications of climate change

Climate change is a severe and major problem that has the potential to seriously derail poverty alleviation in a number of low income countries (Dell et al., 2009). Climate change will affect livelihood assets by impacting health, access to natural resources and infrastructure (Skoufias, 2012). It is also likely to erode agricultural productivity in tropical climates (Skoufias, 2012). Given that the implications of climate change differ so dramatically between countries, to inform climate negotiations and allow countries to realize the full extent of their adaptation needs, substantial capacity would be required to analyze the implications of climate change and to formulate country positions. So far, the academic capacity is geographically very skewed. For example, the International Social Science Council (ISSC) commissioned a bibliometric study on social science research on climate change and global environmental change in the period from 2000 until 2010. It found that OECD countries completely dominated this research and that the poorest countries, notably in Africa, hardly were visible at all in the statistics (Hackmann and St Clair, 2012).

15.10.2 Capacity to design, implement and evaluate policies

The design, implementation, and evaluation of national and sub-national climate policies necessitate in-country human capital. National governments and civil society require that climate policies be adapted to local economic, cultural, and social conditions to ensure their effectiveness and public support. To be politically acceptable, such work generally needs to be done by citizens of the country in which the policies are to be implemented. Political feasibility is mainly determined by policy design to improve environmental and economic effectiveness and distributional equity (Bailey and Compston, 2012b). A high level of scientific knowledge and analytical skills are required for such work. Capacity building allows the leadership to be sensitive to environmental constraints and encourages policymaking to meet the needs of the people within these parameters (United Nations, 1992).

Many studies analyze the technological options for achieving deep reductions in GHG emissions, however they do not necessarily reflect the need for capacity building. For example, while Pacala and Socolow (2004), through their 'stabilization wedges', increased the understanding of the technological options that could be deployed to reach stabilization targets, they did so without pointing out the capacity necessary to reach such a potential. These do however need local adaptation. Through the collaborative dialogue under the Durban Forum, key areas for capacity building on mitigation have emerged, including: low-carbon development strategies; NAMAs; Monitoring, Reporting and Verification; Technology Needs Assessments (TNAs); and mitigation assessments.

15.10.3 Capacity to take advantage of external funding and flexible mechanisms

Climate change, and the global policies to mitigate and adapt to it, also imply additional capacity challenges in order to take advantage of international funding and flexible mechanisms such as the CDM in the Kyoto Protocol, and REDD+. So far, the distribution of projects under flexible mechanisms has been very skewed towards countries with greater capacity. As an example, only 2.5 % of normal CDM projects have been hosted by African countries (Fenhann and Staun, 2010).

In the preparations for the UNFCCC Durban Forum on Capacity Building (UNFCCC, 2011) it was noted that capacity-building in developing countries should be improved by (1) ensuring consultations with stakeholders throughout the entire process of activities; (2) enhancing integration of climate change issues and capacity-building needs into national development strategies, plans and budgets; (3) increasing country-driven coordination of capacity-building activities; and (4) strengthening networking and information sharing among developing countries, especially through South-South and triangular cooperation.

15.10.4 Capacity building modalities

Capacity building is about equipping people, communities, and organizations with the tools, skills, and knowledge to address the challenges of climate change. It can be delivered through education, outreach, and awareness, but it can also be facilitated through peer learning, knowledge platforms, information exchanges, and technical assistance (Mytelka et al., 2012). The need for capacity building is large. Hundreds of thousands of scientists of various disciplines need to be trained globally in the coming decades as well as policymakers, civil servants, businessmen, and civil society. These needs are not limited to developing countries, as it is needed at all levels of society and in all regions of the world.

There are many different modalities. Since the 15th Conference of the Parties (COP-15), partnerships have formed at the international, national, and sub-national level aimed at climate readiness activities. Capacity building in the private sector is also important. Studies indicate that good management, trained workers, and clean manufacturing increase energy efficiency while reducing CO_2 emissions. Substantive carbon reductions can be achieved at zero or negative cost through improved workplace practices, optimized processes, and behavioural changes in production (Bloom et al., 2010). Even this requires human resources and capacity to be undertaken.

Capacity building requires a long time horizon, and this is particularly evident in education-poor countries. Building in-country academic programmes that can graduate well-trained masters and PhD students can take decades. When students graduate from such programmes it takes an additional 5–10 years of post-doctoral and junior faculty positions to build the experience and skills to contribute at a high international level (Sterner et al., 2012). Capacity building initiatives are therefore fragile and require continued support and nurturing by both national governments and international organizations. This may be one additional and important area for climate finance.

15.11 Links to adaptation

This section discusses links between national and sub-national policies and institutions for mitigation and adaptation. Links between adaptation and mitigation policies at the international level are discussed in Chapter 13, while adaptation in general is discussed in WGII. Adaptation will be needed because some climate change is inevitable (Chapter 5). Indeed, some governments have started to plan and implement policies aimed at tackling changes that are likely to take place or have taken place already (Aaheim et al., 2009). In the longer term, the level of adaptation needed will depend on the success of mitigation efforts and the resulting GHG concentrations, thus there is an obvious linkage between mitigation and adaptation. However, the level of adaptation needed will also depend on the climate response to any given GHG level, around which there is high uncertainty. Mitigation will help to reduce the uncertainty on future changes and is therefore helpful for planning adaptation.

It has been argued that mitigation and adaptation policies are related to each other (Smith and Olesen, 2010). This, however, is a controversial issue (Hamin and Gurran, 2009). Any given mitigation policy at the national or sub-national level is unlikely to have a significant effect on the global climate, so that the climatic consequences of that policy for the purpose of planning adaptation can usually be ignored. The direct side-effects of a mitigation policy for adaptation are more relevant. Examples of such direct effects are mainly in land use (discussed in Section 15.11.3 below) where synergies and tradeoffs between mitigation and adaptation policies may arise.

It is, of course, true that mitigation policies can have effects on adaptation across sectors. For example, carbon pricing can make air-conditioning more expensive, thus hindering adaptation to a warmer climate. However, this is simply one of many costs of a mitigation policy that will be taken into account while making policies. Conversely, adaptation to higher temperatures has led to increased electricity consumption for cooling (Gupta, 2012) that has to be taken into account while planning mitigation, but so do all changes in demand arising for other reasons such as income growth.

On the national scale, the approach to mitigation and adaptation differs between high or upper-middle income countries and low or lower-middle income countries due to the balance of responsibilities and the focus on mitigation versus adaptation.

The early national policy focus in high or upper-middle income countries was largely on mitigation. These policies were largely developed without in-depth consideration of adaptation linkages. Those high or upper-middle income countries that are developing national adaptation strategies and policies (e.g., see Bizikova et al., 2008; Stewart et al., 2009; Bedsworth and Hanak, 2010; Biesbroek et al., 2010) have shown limited consideration of the effects of adaptation policies on greenhouse gas emissions to date. Neufeldt et al. (2010) investigated the reasons for this disconnect in Europe and found it was due to a strong sectoral separation: sectors that were major emitters have been mitigation focused, and have received little attention on adaptation, whereas climate sensitive sectors such as agricultural, although a potential contributor to emission reductions, have focused on adaptation. They also report that adaptation policy and actions have lagged behind mitigation more generally, and the difference in timing also contributes to the separation of the two domains. This is now starting to change: Bruin et al. (2009) in the Netherlands considered the potential GHG emissions of adaptation measures as part of a national multi-criteria ranking of options.

To date, most of the national climate policy initiatives in low-income countries, especially in the LDCs, have focused on adaptation, notably through the National Adaptation Programme of Action (NAPAs). However, more recently there has been a shift with a number of national policy initiatives that aim to develop climate resilient, low carbon economies (also known as low-emission development strategies or green growth). These include Ethiopia's Climate Resilient Green Economy Vision (EPA Ethiopia, 2011) and Rwanda's Green Growth and Climate Resilience National Strategy for Climate Change and Low Carbon Development (Government of Rwanda, 2011). Given the importance of climate change in these highly vulnerable countries, these initiatives look to build climate resilience, but also recognize the benefits in advancing low carbon development. Research on the linkages between emission reductions and adaptation is still at an early stage and most of the synergies between adaptation and mitigation are centred on the agricultural and forestry sectors.

Some local activities, such as those regarding land-use decisions, have important implications for both mitigation (e.g., by means of carbon sequestration) and adaptation (e.g., by means of increasing resilience to climate change). Ravindranath (2007) explores the synergies between mitigation and adaptation in the forestry sector. As forests are highly vulnerable to climate change, but provide opportunities for mitigation (e.g., through afforestation), efforts to enhance carbon sequestration need to embed adaptation elements so that exposure to climate impacts can be addressed. Mitigation efforts through forest management regimes such as conservation areas and sustainable forestry contribute to adaptation. Conversely, adaptation efforts such as urban forestry and measures to conserve soil and water also have mitigation effects (Ravindranath, 2007).

Similar issues have emerged for the agricultural sector, with the focus on climate-smart agriculture. This focus recognizes the high vulnerability of agriculture as a climate-sensitive sector, but also addresses the fact that it is a major source of greenhouse gas emissions in developing economies. A number of options have been identified as potentially beneficial for mitigation and adaptation, including (McCarthy et al., 2011) soil and water conservation (including conservation agriculture, low or minimum tillage, vegetation strips, terraces, structures such as bunds contours, shade trees, tied ridges, small-scale water harvesting, compost production, cover crops, improved fallows, crop residues), agroforestry, and improved pasture and grazing management including restoration. These options generally are based on sustainable agricultural land management (SALM) practices. These practices reduce climate related risks in the form of rainfall variability and soil erosion, increase soil organic matter and soil fertility (thus increasing productivity), and reduce emissions by either reducing soil emissions or preventing other more emission intensive activities. More traditional measures to increase productivity, such as fertilizer use or increased irrigation, have the potential to increase greenhouse gas emissions because of the high energy intensity of fertilizer production and the energy use in water abstraction and pumping; however, they may still reduce land-use emissions by increasing the productivity and yields per hectare, as well we reduce future land-use pressures that may lead to deforestation (Chapter 11). However, as highlighted by McCarthy et al. (2011), many of these climate-smart options involve important opportunity or policy costs, higher risks, or may involve benefits that arise over longer time periods (e.g., improved soil function), or involve wider environmental benefits that are not immediately useful to farmers. They also frequently involve institutional, financial, and capacity barriers, and so may not happen autonomously.

Both the forest and agricultural sectors also link through to issues of rural land-use change and land planning/management, which can have synergistic effects on mitigation and adaptation (Pimentel et al., 2010), but which can also involve complex tradeoffs.

Overall, the emerging evidence suggests that while there may be a potential for synergistic mitigation and adaptation policy linkages in the agricultural and forest sectors, the translation of these policies through to implementation may well be challenging because of the different characteristics of mitigation and adaptation (e.g., the global public good nature of mitigation versus the local benefits from adaptation), because of the additional costs involved (e.g., involving higher capital costs or opportunity costs associated with synergistic options), because of institutional, technological or behavioural barriers, and because different actors maybe involved in mitigation and adaptation decisions, including the need to address cross-sectoral aspects.

15.12 Investment and finance

15.12.1 National and sub-national institutions and policies

The justification for investment and finance and the description of the various financial agreements have been elaborated in Chapter 13. Chapter 16 assesses in more detail the range of institutional arrangements for mitigation finance at the global, regional, national, and sub-national levels. This section concentrates on institutional mechanisms which parties to the UNFCCC, developed and developing countries, have been using or introducing to facilitate, tap, channel, and catalyze climate change investment and finance. It also briefly touches on some of the major policy directions and trends affecting mitigation finance and investments. Earlier sections of this chapter presented the variety of policy instruments available and being used both in developed and developing countries. Public finance is needed for subsidies and public provision (Sections 15.5.2 and 15.5.6). In this section we track the consequences with a view to the aggregate funding needed.

Without dedicated financial policy, other policy instruments alone may be insufficient to mobilize the large-scale investments needed to move the world away from its current high-emission path.

Recent case studies and some empirical evidence highlight the importance of targeted public finance to help catalyze and leverage private investment in some mitigation activities (CPI, 2012). For this purpose, governments have at their disposal a variety of mechanisms that include credit lines, bonds, guarantees, equity, venture capital, carbon finance, and grants (Maclean et al., 2008). These mechanisms exist and are effective mostly in developed and emerging economies (Kennedy and Corfee-Morlot, 2012).

In addition, a number of innovative mechanisms are being promoted in some developed countries with success. These include, 'property assessed financing districts' where residential and commercial property owners are provided with loans for renewable energy and energy efficiency, 'direct cash subsidies' to promote the installation of energy efficiency measures and renewable energy systems, 'power purchase agreements', and ESCOs—Energy Service Companies to implement performance-based energy efficiency projects (Ellingson et al., 2010).

National development banks are increasingly playing a critical role in leveraging public and private resources in both developed and developing countries. National development banks, which operate mainly domestically, have an advantage in accessing local financial markets and dealing with barriers that they understand better than others (Smallridge et al., 2013).

International financing for mitigation and adaptation has impacted the domestic climate discourse and has created incentives for sustainable development at national and local levels in developing countries (Metz and Kok, 2008). National and sub-national efforts to finance climate change often have an explicit link to international processes or support through the various mechanisms of the Convention and Kyoto Protocol or those encouraged to facilitate funding for developing countries such as bilateral and multilateral channels. Some of these mechanisms have led to significant investment in developing countries. An estimated USD 215.4 billion had been invested in 4832 Clean Development Mechanism projects by June 15, 2012 (UNFCCC, 2012). Similarly, the Global Environment Facility (GEF) estimates that since the start of its operations (1991–2013), it has leveraged over USD 27 billion for climate change projects (GEF, 2013).

A new trend is the establishment by several developing countries of funds and national funding entities dedicated to climate change. Table 16.2 lists some of these institutions, their objectives, governance, and sources of funding. The missions and objectives are diverse and their level of institutionalization varies from country to country. All are designed to tap and blend funding available from international and domestic sources—public and private—to catalyze climate investment in their country (Flynn, 2011).

National funding entities have the potential to help countries cope with the proliferation of funds and entities offering financial resources for mitigation activities (Glemarec, 2011; Smith et al., 2011). Increased fragmentation of international assistance has increased transaction costs for recipients while the multiplicity and competitive nature of sources has challenged national and sub-national capacities (Knack and Rahman, 2007; Anderson, 2012). Limited absorptive and human capacity resources do however present serious challenges. Evidence of the ability of national funding entities to ensure coherence between national institutions dedicated to climate change and cabinet entities such as the Ministry of Finance or the Office of the President relies on case studies and, currently, does not yet offer general conclusions (Thornton, 2010).

15.12.2 Policy change direction for finance and investments in developing countries

There have been some significant trends in recent years regarding climate finance and the actors involved. Three are particularly relevant for their impact on the way climate finance is being managed and who does the management.

First, financing climate objectives by mainstreaming climate change into development planning has been gaining ground. This is particularly the case of countries wanting to integrate adaptation strategies into their overall national strategy as a way to build resilience. It is also evident in some of the climate change action plans and strategies of some countries that are clearly linked to poverty reduction and national development objectives (Garibaldi et al., 2013). However, the benefits and costs of integrating climate change considerations into development planning may be difficult to attain in practice. The OECD (OECD, 2005) warns of 'mainstreaming overload' as climate change competes with other issues like governance and gender to be mainstreamed into development planning. Barriers to integrating climate and development objectives include: lack of human and institutional capacity and lack of coordination among line ministries (Knack and Rahman, 2007; Kok et al., 2008).

Second, is the growing recognition that financing climate actions can have large co-benefits. Investments in clean energy, for example, may result in improvement in health indicators as air pollution levels decrease. Similarly, investing in forest conservation may result in a reduction of GHG emissions from deforestation. Thus, the increasing interest in the concept of co-benefits or climate and development as 'win-win' outcomes. Reducing emissions has been seen as a by-product of reducing energy costs in the case of China (Richerzhagen and Scholz, 2008). Reducing emissions from deforestation and forest degradation is seen as another major opportunity to deliver both emissions reductions and livelihood benefits. However, Campbell (2009) and Adams and Hulme (2001) argue that the ability to define these win-win objectives is a major factor for success.

Third, the number of actors involved in climate finance and investment is growing. Climate change finance is no longer a monopoly of the public sector. There is now a multiplicity of actors from the private and business world whose level of financing exceeds that of the public sector several fold, particularly in the middle-income and emerging economies (Gomez-Echeverri, 2013). This development has the potential to address implementation gaps, generate greater participation from stakeholders, and encourage public-private partnerships that promote sustainable development (Pattberg, 2010).

Two areas of need emerge from the literature (Cameron, 2011; Zingel, 2011). First, attracting climate finance investments will require strengthening institutional and governance capacities at the national and sub-national levels in recipient countries. Specifically, the ability to formulate strategies and action plans, including policies and measures, formulate, assess and approve projects, demonstrate accountability and transparency to their own populations, as well as to the development partners to raise levels of investment confidence will be needed. Second, robust mechanisms are needed to ensure accountability. This would involve greater transparency in both donor and recipient countries. The role of civil society organizations and the media could be strengthened for good governance and accountability.

15.13 Gaps in knowledge and data

- Cross-country comparisons of institutional design options, particularly mechanisms for coordinating and mainstreaming climate and other related sector policies, are limited. Wider use of evaluation methods would allow for the understanding of relative effectiveness of different options and designs to be used to improve outcomes over time.

- Evaluating the economic and environmental effectiveness of individual policy instruments and packages is difficult as various jurisdictions produce policy instruments influenced by context-specific factors such as co-benefits and political economy considerations. As a result, the cost of committing to a target and the actions needed to meet it, are difficult to estimate. For example, fuel taxes in the transport sector are implemented for multiple purposes including energy security, congestion and pollution reduction, revenue for road construction, mitigation of climate change, and so forth. It is difficult to gauge the contribution of fuel taxes to mitigation efforts.

- While the distributional incidence of taxes has been studied quite extensively, much less is known about the distributional incidence of other policy instruments and packages. Similarly, knowledge gaps remain uneven across policy instruments on other criteria such as institutional, political, and administrative feasibility.

- The asymmetry of methodologies regarding 'negative cost' policies regarding regulation and information measures with case studies arguing for negative private and social cost polices while critiques basing results on economic theory and models has meant that conclusive results are not yet available.

- Understanding of the relative balance between demand pull and supply push policies needed to accelerate technological innovation remains an important gap. Data on global private investment in research and development is a major gap along in addition to public R&D figures in middle income and low-income countries.

- The valuation of co-benefits from emission reduction has been studied comprehensively in the United States (Muller et al., 2011), but much less is known about other countries. This is important because taking these co-benefits into account could significantly lower the cost of emission reduction, and perhaps offer negative costs, in several sectors.

15.14 Frequently Asked Questions

FAQ 15.1 What kind of evidence and analysis will help us design effective policies?

Economic theory can help with policy design at a conceptual level, while modelling can provide an ex-ante assessment of the potential impact of alternative mitigation policies. However, as theory and modelling tend to be based on sets of simple assumptions, it is desirable that they are complemented by ex-post policy evaluations whenever feasible. For example, theory and bottom up modelling suggest that some energy efficiency policies can deliver CO_2 emission reductions at negative cost, but we need ex-post policy evaluation to establish whether they really do and whether the measures are as effective as predicted by ex-ante assessments (Section 15.4).

As climate policies are implemented, they can generate an empirical evidence base that allows policy evaluation to take place. If evaluation is built into the design of a programme or policy from its inception, the degree of success and scope for improvement can be identified. Policies implemented at the sub-national levels provide sites for experimentation on climate policies. Lessons from these efforts can used to accelerate policy learning.

Much of the evidence base consists of case studies. While this method is useful to gain context-specific insights into the effectiveness of climate policies, statistical studies based on large sample sizes allow analysts to control for various factors and yield generalizable results. However, quantitative methods do not capture institutional, political, and administrative factors and need to be complemented by qualitative studies.

FAQ 15.2 What is the best climate change mitigation policy?

A range of policy instruments is available to mitigate climate change including carbon taxes, emissions trading, regulation, information measures, government provision of goods and services, and voluntary agreements (Section 15.3). Appropriate criteria for assessing these instruments include: economic efficiency, cost effectiveness, distributional impact, and institutional, political, and administrative feasibility (Section 15.5).

Policy design depends on policy practices, institutional capacity and other national circumstances. As a result, there is no single best policy instrument and no single portfolio of instruments that is best across many nations. The notion of 'best' depends on which assessment criteria we employ when comparing policy instruments and the relative weights attached to individual criteria. The literature provides more evidence about some types of policies, and how well they score against the various criteria, than others. For example, the distributional impacts of a tax are relatively well known compared to the distributional impacts of regulation. Further research and policy evaluation is required to improve the evidence base in this respect (Section 15.12).

Different types of policy have been adopted in varying degrees in actual plans, strategies, and legislation. While economic theory provides a strong basis for assessing economy-wide economic instruments, much mitigation action is being pursued at the sectoral level (Chapters 7–12). Sectoral policy packages often reflect co-benefits and wider political considerations. For example, fuel taxes are among a range of sectoral measures that can have a substantial effect on emissions even though they are often implemented for other objectives.

Interactions between different policies need to be considered. The absence of policy coordination can affect environmental and economic outcomes. When policies address distinct market failures such as the externalities associated with greenhouse gas emissions or the undersupply of innovation, the use of multiple policy instruments has considerable potential to reduce costs. In contrast, when multiple instruments such a carbon tax and a performance standard are employed to address the same objective, policies can become redundant and undermine overall cost effectiveness (Section 15.8.4.2).

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16

Cross-cutting Investment and Finance Issues

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Executive Summary

For the first time, an assessment report by the Intergovernmental Panel on Climate Change (IPCC) contains a chapter dedicated to investment and finance. These are the chapter's key findings:

Scientific literature on investment and finance to address climate change is still very limited and knowledge gaps are substantial; there are no agreed definitions for climate investment and climate finance. Quantitative data are limited, relate to different concepts, and are incomplete. Accounting systems are highly imperfect. Estimates are available for current total climate finance, total climate finance provided to developing countries, public climate finance provided to developing countries, and climate finance under the United Nations Framework Convention on Climate Change (UNFCCC), as well as future incremental investment and incremental cost for mitigation measures. Climate finance relates both to adaptation and mitigation, while under the scope of this chapter, estimates of future investment needs are presented only for mitigation. [Section 16.1]

Total climate finance for mitigation and adaptation is estimated at 343 to 385 billion USD (2010/11/12 USD) per year using a mix of 2010, 2011, and 2012 data, almost evenly being invested in developed and developing countries (*medium confidence*). The figures reflect the total financial flow for the underlying investments, *not the incremental investment*, i.e., the portion attributed to the emission reductions. Around 95 % of reported total climate finance is for mitigation (*medium confidence*). [16.2.1.1]

The total climate finance currently flowing to developing countries is estimated to be between 39 to 120 billion USD per year using a mix of 2009, 2010, 2011, and 2012 data (2009/2010/2011/2012 USD) (*medium confidence*). This range covers public and private flows for mitigation and adaptation. Public climate finance is estimated at 35–49 billion USD (2011/2012 USD) (*medium confidence*). Most public climate finance provided to developing countries flows through bilateral and multilateral institutions, usually as concessional loans and grants. Climate finance under the UNFCCC is funding provided to developing countries by Annex II Parties. The climate finance reported by Annex II Parties averaged nearly 10 billion USD per year from 2005 to 2010 (2005–2010 USD) (*medium confidence*). Between 2010 and 2012, the 'fast-start finance' (FSF) provided by some developed countries amounted to over 10 billion USD per year (2010/2011/2012 USD) (*medium confidence*). Estimates of international private climate finance flowing to developing countries range from 10 to 72 billion USD (2009/2010 USD) per year, including foreign direct investment as equity and loans in the range of 10 to 37 billion USD (2010 USD and 2008 USD) per year over the period of 2008–2011 (*medium confidence*). [16.2.1.1]

Emission patterns that limit temperature increase from pre-industrial level to no more than 2 °C require considerably different patterns of investment. A limited number of studies have examined the investment needs to transform the economy to limit warming to 2 °C. Information is largely restricted to energy use with global total annual investment in the energy sector at about 1200 billion USD. In the results for these scenarios, which are consistent to keeping carbon dioxide equivalent (CO_2eq) concentration in the interval 430–530 ppm until 2100, annual investment in fossil-fired power plants without carbon dioxide capture and storage (CCS) would decline by 30 (median: –20 % compared to 2010) (2 to 166) billion USD during the period 2010–2029, compared to the reference scenarios (*limited evidence, medium agreement*). Investment in low-emissions generation technologies (renewable, nuclear, and electricity generation with CCS) would increase by 147 (median: +100 % compared to 2010) (31 to 360) billion USD per year during the same period (*limited evidence, medium agreement*) in combination with an increase by 336 (1 to 641) billion USD in energy-efficiency investments in the building, transport, and industry sector (*limited evidence, medium agreement*), frequently involving modernization of existing equipment. Higher energy efficiency and the shift to low-emission energy sources contribute to a reduction in the demand for fossil fuels, thus causing a decline in investment in fossil fuel extraction, transformation, and transportation. Scenarios suggest that the average annual reduction of investment in fossil fuel extraction in 2010–2029 would be 116 (–8 to 369) billion USD (*limited evidence, medium agreement*). Such 'spillover' effects could yield adverse effects on economies, especially of countries that rely heavily on exports of fossil fuels. Model results suggest that deforestation could be reduced against current deforestation trends by 50 % with an investment of 21 to 35 billion USD per year (*low confidence*). Information on investment needs in other sectors in addition to energy efficiency, e.g., to abate process or non-CO_2 emissions is virtually unavailable. [16.2.2]

Resources to address climate change need to be scaled up considerably over the next few decades both in developed and developing countries (*medium evidence, high agreement*). Increased financial support by developed countries for mitigation (and adaptation) measures in developing countries will be needed to stimulate the increased investment. Developed countries have committed to a goal of jointly mobilizing 100 billion USD per year by 2020 in the context of meaningful mitigation action and transparency on implementation. The funding could come from a variety of sources—public and private, bilateral and multilateral, including alternative sources of finance. Studies of how 100 billion USD per year could be mobilized by 2020 conclude that it is challenging but feasible. [16.2]

Public revenues can be raised by collecting carbon taxes and by auctioning carbon allowances (*high confidence*). Putting a price on greenhouse gas (GHG) emissions, through a carbon tax or emissions trading, alters the rate of return on high- and low-carbon investments. It makes low-emission technologies attract more investment and at the same time it raises a considerable amount of revenue that can be used for a variety of purposes, including climate finance. These carbon-related sources are already sizeable in some countries

[16.2.1.2]. The consideration of alternative sources of public revenue like taxes on international bunker fuels has the potential to generate significant funds but is still in its infancy. Reducing fossil fuel subsidies would lower emissions and release public funds for other purposes [16.2.3].

Within appropriate enabling environments, the private sector, along with the public sector, can play an important role in financing mitigation (*medium evidence, high agreement*). Its contribution is estimated at 267 billion USD per year in 2010 and 2011 (2010/2011 USD) and at 224 billion USD (2011/2012 USD) per year in 2011 and 2012 on average, which represents around 74 % and 62 % of overall climate finance, respectively (*limited evidence, medium agreement*) [16.2.1]. In a range of countries, a large share of private sector climate investment relies on low-interest and long-term loans as well as risk guarantees provided by public sector institutions to cover the incremental costs and risks of many mitigation investments. In many countries, therefore, the role of the public sector is crucial in helping these private investments happen. The quality of a country's enabling environment—including the effectiveness of its institutions, regulations and guidelines regarding the private sector, security of property rights, credibility of policies and other factors—has a substantial impact on whether private firms invest in new technologies and infrastructures. Those same broader factors will probably have a big impact on whether and where investment occurs in response to mitigation policies [16.3]. By the end of 2012, the 20 largest emitting developed and developing countries with lower risk country grades for private sector investments covered 70 % of global energy-related CO_2 emissions (*low confidence*). This makes them attractive for international private sector investment in low-carbon technologies. In many other countries, including most least developed countries, low-carbon investment will often have to rely mainly on domestic sources or international public finance [16.4.2].

A main barrier to the deployment of low-carbon technologies is a low risk-adjusted rate of return on investment vis-à-vis high-carbon alternatives often resulting in higher cost of capital (*medium evidence, high agreement*). This is true in both developed and developing countries. Dedicated financial instruments to address these barriers exist and include inter alia credit insurance to decrease risk, renewable energy premiums to increase return, and concessional finance to decrease the cost of capital. Governments can also alter the relative rates of return of low-carbon investments in different ways and help to provide an enabling environment. [16.3, 16.4]

Appropriate governance and institutional arrangements at the national, regional, and international level need to be in place for efficient, effective, and sustainable financing of mitigation measures (*high confidence*). They are essential to ensure that financing to mitigate and adapt to climate change responds to national needs and priorities and that national and international activities are linked and do not contradict each other. An enabling environment at the national level ensures efficient implementation of funds and risk reduction using international resources, national funds, as well as national development and financial institutions. [16.5]

Important synergies and tradeoffs between financing mitigation and adaptation exist (*medium confidence*). Available estimates show that adaptation projects get only a minor fraction of international climate finance. Current analyses do not provide conclusive results on the most efficient temporal distribution of funding on adaptation vis-à-vis mitigation. While the uncertainties about specific pathways and relationships remain, and although there are different considerations on its optimal balance, there is a general agreement that funding for both mitigation and adaptation is needed. Moreover, there is an increasing interest in promoting integrated financing approaches, addressing both adaptation and mitigation activities in different sectors and at different levels. [16.6]

Increasing access to modern energy services for meeting basic cooking and lighting needs could yield substantial improvements in human welfare at relatively low cost (*medium confidence*). Shifting the large populations that rely on traditional solid fuels (such as unprocessed biomass, charcoal, and coal) to modern energy systems and expanding electricity supply for basic human needs could yield substantial improvements in human welfare for a relatively low cost; 72–95 billion USD per year until 2030 to achieve nearly universal access. [16.8]

16.1 Introduction

This is the first time an assessment report by the Intergovernmental Panel on Climate Change (IPCC) contains a chapter dedicated to investment and finance to address climate change. This reflects the growing awareness of the relevance of these issues for the design of efficient and effective climate policies.

The assessment of this topic is complicated by the absence of agreed definitions, sparse data from disparate sources, and limited peer-reviewed literature. Equity, burden sharing, and gender considerations related to climate change are discussed in other chapters, inter alia Sections 3.3 and 4.6.2. This chapter does not include a separate discussion of these considerations in relation to climate finance.

There is no agreed definition of climate finance (Haites, 2011; Stadelmann et al., 2011b; Buchner et al., 2011; Forstater and Rank, 2012). The term 'climate finance' is applied both to the financial resources devoted to addressing climate change globally and to financial flows to developing countries to assist them in addressing climate change. The literature includes multiple concepts within each of these broad categories (Box 1.1). The specific mitigation and adaptation measures whose costs qualify as 'climate finance' also are not agreed. The mea-

Box 16.1 | Different concepts, different numbers

Different concepts of climate finance are found in the literature. The corresponding values differ significantly.

Financial resources devoted to addressing climate change globally:

Total climate finance includes all financial flows whose expected effect is to reduce net GHG emissions and/or to enhance resilience to the impacts of climate variability and the projected climate change. This covers private and public funds, domestic and international flows, expenditures for mitigation and adaptation to current climate variability as well as future climate change. It covers the full value of the financial flow rather than the share associated with the climate change benefit; e. g., the entire investment in a wind turbine rather than the portion attributed to the emission reductions. The estimate by Buchner et al. (2012, 2013b) of current climate finance of 343 to 385 billion USD (2010/2011/2012 USD) per year using a mix of 2010, 2011, and 2012 data, corresponds roughly to this concept.

The *incremental investment* is the extra capital required for the initial investment for a mitigation or adaptation project in comparison to a reference project. For example, the investment in wind turbines less the investment that would have been required for the coal or natural gas-generating unit displaced. Since the value depends on the unknown investment in a hypothetical alternative, the incremental investment is uncertain. Incremental investment for mitigation and adaptation measures is not regularly estimated and reported, but estimates are available from models. It can be positive or negative. Many agriculture and reducing emissions from deforestation and forest degradation (REDD+) mitigation options that involve ongoing expenditures for labour and other operating costs rather than investments are excluded.

The *incremental costs* reflect the cost of capital of the incremental investment and the change of operating and maintenance costs for a mitigation or adaptation project in comparison to a reference project. It can be calculated as the difference of the net present values of the two projects. Many mitigation measures—such as energy efficiency, renewables, and nuclear—have a higher capital cost and lower operating costs than the measures displaced. Frequently the incremental costs are lower than the incremental investment. Values depend on the incremental investment as well as projected operating costs, including fossil fuel prices, and the discount rate. Models can estimate the incremental costs of energy supply and demand but data are not immediately available and aggregate estimates cannot be provided. Estimates are available for single-mitigation options (see, e. g., Chapter 7).

The *macroeconomic costs of mitigation policy* are the reductions of aggregate consumption or gross domestic product induced by the reallocation of investments and expenditures induced by climate policy. These costs do not account for the benefit of reducing anthropogenic climate change and should thus be assessed against the economic benefit of avoided climate change impacts. Models have traditionally provided estimates of the macroeconomic costs of climate policy (see Chapter 6).

Financial flows to developing countries to assist them in addressing climate change:

The *total climate finance flowing to developing countries* is the amount of the total climate finance invested in developing countries that comes from developed countries. This covers private and public funds for mitigation and adaptation. Estimates from a few studies suggest the current flow is between 39 and 120 billion USD per year (2009–2012 USD).

Public climate finance provided to developing countries is the finance provided by developed countries' governments and bilateral institutions as well as multilateral institutions for mitigation and adaptation activities in developing countries. Most of the funds provided are concessional loans and grants. Estimates suggest that public climate finance flows to developing countries were at 35 to 49 billion USD per year in 2011 and 2012 (2011/2012 USD).

Private climate finance flowing to developing countries is finance and investment by private actors in/from developed countries for activities in developing countries whose expected effect is to reduce net GHG emissions and/or to enhance resilience to the impacts of climate variability and the projected climate change.

Under the *United Nations Framework Convention on Climate Change (UNFCCC), climate finance* is not well-defined. Annex II Parties provide and mobilize funding for climate related activities in developing countries. Most of the funds provided are concessional loans and grants. The climate finance provided to developing countries reported by Annex II Parties averaged nearly 10 billion USD per year from 2005 to 2010 (2005–2010 USD). In addition, some developed countries promised FSF amounting to over 10 billion USD per year between 2010 and 2012 (2010/2011/2012 USD).

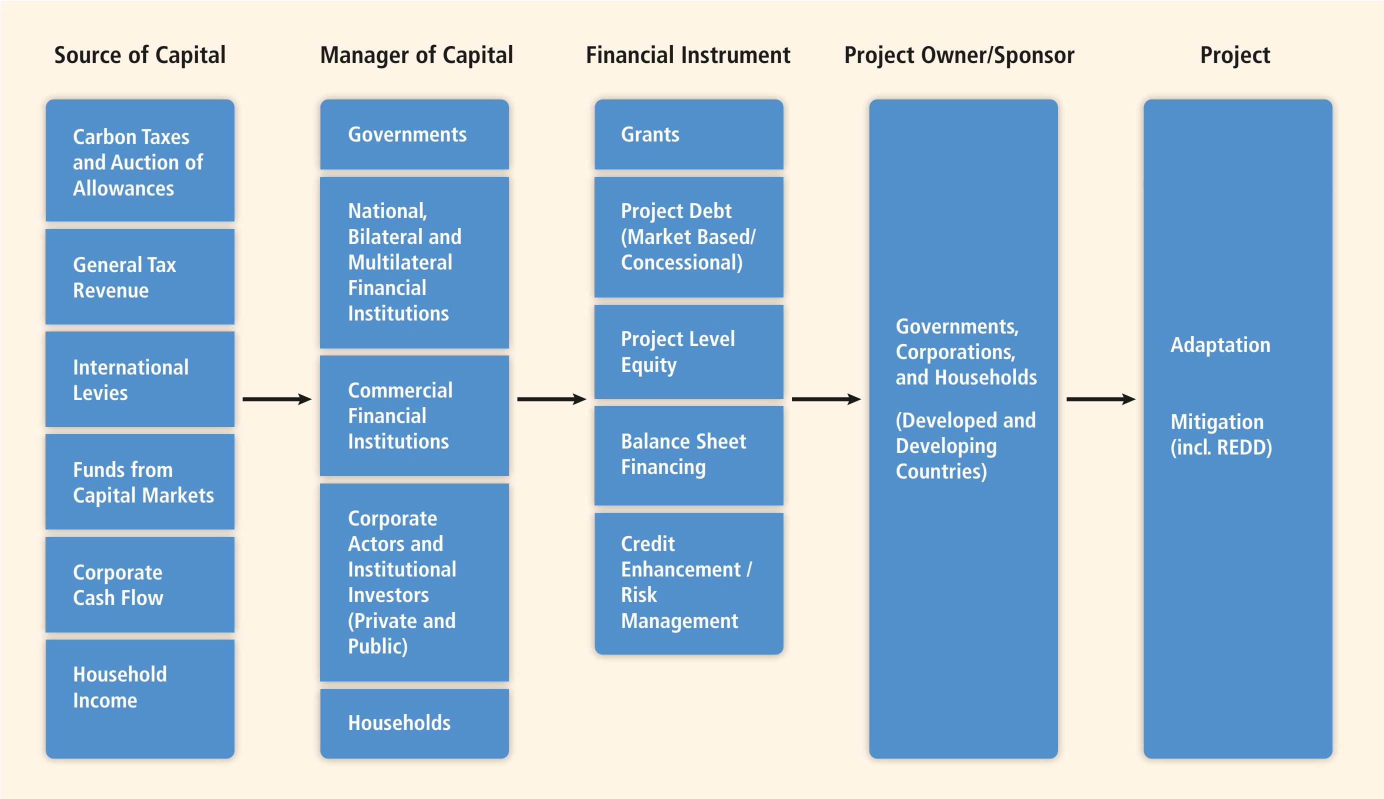

Figure 16.1 | Overview of climate finance flows. Note: Capital should be understood to include all relevant financial flows. The size of the boxes is not related to the magnitude of the financial flow.

sures included vary across studies and often are determined by the data available[1].

The rest of the chapter is structured as follows: Section 16.2 reviews estimates of current climate finance corresponding to the different concepts in Box 1, projections of global incremental investment and incremental costs for energy-related mitigation measures to 2030, and options for raising public funds for climate finance. Enabling factors that influence the ability to efficiently generate and implement climate finance are discussed in Section 16.3. Section 16.4 considers opportunities and key drivers for low-carbon investments. Institutional arrangements for mitigation finance are addressed in Section 16.5. Synergies and tradeoffs between financing mitigation and adaptation are discussed in Section 16.6. The chapter concludes with sections devoted to financing mitigation activities in developed (Section 16.7) and developing countries (Section 16.8) and a review of important gaps of knowledge (Section 16.9).

[1] Most of the financial flow data in this chapter originate from 2010, 2011, and 2012 and were published in USD. The exchange rates used by each source to convert other currencies to USD are not specified in the published sources. In these cases, the published USD figure has been maintained and the base year is similar to the year the commitment/investment/flow was announced/reported. If no base year is indicated, as for most monetary values in Section 16.2.2, the base year is 2010.

16.2 Scale of financing at national, regional, and international level in the short-, mid-, and long-term

16.2.1 Current financial flows and sources

Figure 16.1 provides an overview of climate finance and the terms used in this chapter. The term 'capital' is used because most climate finance involves an investment, but it should be understood to include all relevant financial flows[2]. One or more capital managers mobilize the required capital and invest it in an adaptation or mitigation project. Project owners or sponsors—governments, corporations, or households—implement a project using their own and other sources of capital. However, projects often obtain capital from multiple capital managers (Buchner et al., 2011, 2012; Jürgens et al., 2012). An instrument defines the financial agreement between a project owner/sponsor and a manager of capital. A project that obtains capital from sev-

[2] Terms that cover both capital and operating costs, such as 'financial resources' or 'funds' are cumbersome (sources/managers of financial resources) or potentially confusing ('funds' can also be institutions).

eral managers would use multiple instruments. The size of the boxes is not related to the magnitude of the financial flow.

Data on current climate finance, summarized below, indicate that most capital deployed is private—private corporations and households. That is not surprising since they dominate the economy in most countries.

Domestically, government funds are disbursed directly as financial incentives or tax credits, or through national financial institutions. Climate finance under the UNFCCC currently is provided mainly by the national governments of Annex II Parties. Climate finance from the budgets of these government flows through bilateral institutions being a national public entity, such as Japan International Cooperation Agency (JICA), Agence Française de Développement (AFD), Kreditanstalt für Wiederaufbau (KfW), or through multilateral institutions having several countries as shareholders, such as the World Bank, regional development banks, and multilateral climate funds.

There is no internationally agreed definition of mitigation and adaptation projects; for example, whether a high-efficiency gas-fired generating unit is a mitigation project or which capacity building activities help to address climate change. The relevant projects, and hence the scale of climate finance, depend upon the definition of mitigation and adaptation projects adopted. In practice, the definition varies across studies and is often determined by the data available.

16.2.1.1 Estimates of current climate finance

This section reviews estimates of current global total climate finance, total climate finance flowing to developing countries, public climate finance provided to developing countries and climate finance under the UNFCCC.

There is no comprehensive system for tracking climate finance (Clapp et al., 2012; Tirpak et al., 2012), therefore, estimates must be compiled from disparate sources of variable quality and timeliness, sources that use different assumptions and methodologies and have gaps and may occasionally duplicate coverage. Available data typically relate to commitments rather than disbursements, so the amount reported may not equal the amount received by the project owner during a given year. Changes in exchange rates further complicate the picture. For these and other reasons, estimates of current climate finance exhibit considerable uncertainties.

Global total climate finance is estimated at 343 to 385 billion USD per year for 2010/11 (2010/11 USD) and 356 to 363 billion USD per year for 2011/12 (2011/12 USD), with mitigation accounting for approximately 95 % of this amount (350 billion USD and 337 billion USD, respectively) (Buchner et al., 2012, 2013b). This estimate includes a mix of instruments, e.g., grants, concessional loans, commercial loans and equity, as well as the full investment in mitigation measures such as renewable energy generation technologies that also produce other goods or services[3]. The figures reflect new commitments by capital managers using a mix of 2010/11 and 2011/12 data, respectively. Private finance dominates the total, but its share declined from 74 % (267 billion USD) on average in 2010 and 2011 to 62 % (224 billion USD) on average in 2011 and 2012 (2010/2011 USD and 2011/2012 USD) (Buchner et al., 2012, 2013b). Investment in renewable generation technologies dominates the mitigation investment (Frankfurt School-UNEP Centre and BNEF, 2012).

Reasonably robust estimates of *total climate finance for individual countries* are available for only a few cases, for instance, for Germany (Jürgens et al., 2012). However, some institutions report on their financing commitments for climate and environment. Data from 19 development banks indicate that commitments of mitigation finance increased from 51 billion USD in 2011 to 65 billion USD in 2012 with commitments of adaptation finance rising from 6 to 14 billion USD over the same period (2011/2012 USD). Concessional funding provided by public development banks plays an important role in financing domestic climate projects, e.g., in Brazil, China, and Germany.

A growing number of developed and developing countries, including Bangladesh, Colombia, Indonesia, Nepal, Samoa, Tanzania, Uganda, and the United States as well as the European Commission, calculates the share of their annual budget devoted to climate change mitigation and adaptation often using a methodology known as a Climate Public Expenditure and Institutional Review (UNDP, 2013a). Country estimates range from 3–15 % of the national budget.

A few estimates of *total climate finance flowing to developing countries* are available. Clapp et al. (2012) estimate the total at 70–120 billion USD per year based on 2009–2010 data (2009/2010 USD). Data from Buchner et al. (2013a) suggest a net flow to developing countries of the order of 40 to 60 billion USD for 2010 and 2011 (2010/2011 USD).[4] For 2011 and 2012, North-South flows are estimated at 39 to 62 billion USD (2011/2012 USD) (Buchner et al., 2013b). Clapp et al. (2012) estimate the private investment at 37–72 billion USD (2009/2010 USD) per year based on 2009–2010 data and Stadelmann

[3] Methodology used by Buchner et al. (2012, 2013b): Finance flows are limited to 'climate-specific finance', capital flows targeting low-carbon, and climate-resilient development with direct or indirect mitigation or adaptation objectives/outcomes. The focus is on current financial flows (upfront capital investment costs and grants expressed as commitments, so risk management instruments are excluded). Data are for total rather than incremental investment because incremental investment requires assumptions on the baseline on a project-by-project basis. The data are for 'gross' investment, the full value of the investment, and reflect commitments because disbursement data is not widely available. The data are a mix of 2010 and 2011 data, and 2011 and 2012 data, respectively.

[4] Buchner et al. (2013) estimate that developed countries mobilized 213 to 255 billion USD climate finance per year during 2010 and 2011 while 160 to 208 billion USD climate finance had been committed to climate change projects in developed countries. Developing countries mobilized 120 to 141 billion USD climate finance per year during 2010 and 2011 and 162 to 202 billion USD had been committed to climate change projects in developing countries. Those figures suggest a net flow to developing countries of the order of 40 to 60 billion USD per year (2010/2011 USD).

et al. (2013) estimate foreign direct investment as equity and loans in the range of 10 to 37 billion USD per year based on 2008–2011 data (2010 USD and 2008 USD).

The investment in registered **Clean Development Mechanism (CDM**) projects is estimated at over 400 billion USD over the period 2004 to 2012 (2004–2012 USD) (UNEP Risø, 2013). Of that amount almost 80 billion USD was for projects registered during 2011 and 195 billion USD for projects registered during 2012 (2011 USD and 2012 USD). The majority of the investment in CDM projects is private. Renewable energy projects account for over 70 % of the total investment. The share of CDM renewable energy projects with some foreign investment has grown over time, representing almost 25 billion USD in 2011 (2011 USD) (Kirkman et al., 2013).[5]

Since 1999 almost 100 **carbon funds** with a capitalization of 14.2 billion USD have been established (Alberola and Stephan, 2010).[6] Carbon funds are investment vehicles that raise capital to purchase carbon credits (52 %) and/or invest in emission reduction projects (23 %). A fund may have only private investors (48 %), only public investors (29 %) or a mix of both (23 %) (Alberola and Stephan, 2010). Investment may be restricted to a specific region or project type (e.g., REDD+). Financial data, especially for private funds, is often confidential so the amount of finance provided to developing countries via carbon funds is not available. Scaling up data from 29 funds on the amount invested in projects suggests a maximum cumulative investment of 18 billion USD (1999–2009 USD) (Kirkman et al., 2013).

Public climate finance provided to developing countries was estimated at 35 to 49 billion USD per year in 2011 and 2012 (2011/2012 USD) (Buchner et al., 2013b).[7] These public funds flow mainly through bilateral and multilateral institutions[8]. Most of the climate finance is implemented by development banks, frequently involving the blending of government resources with their own funds. There are two main reporting systems for public support in place that are not fully comparable due to differences in respective methodologies.

The Organisation for Economic Co-operation and Development (OECD) Development Assistance Committee (DAC) reports the amount of official development assistance (ODA) committed bilaterally for projects that have climate change mitigation or adaptation as a 'principal' or 'significant' objective by its 23 member countries and the European Commission. The DAC defines ODA as those flows to countries on the DAC List of ODA Recipients and to multilateral institutions provided by official agencies or by their executive agencies. Resources must be used to promote the economic development and welfare of developing countries as a main objective and they must be concessional in character, meaning as grants or as concessional loans including a grant element of at least 25 %, calculated at a rate of discount of 10 %. The amount is the total funding committed to each project, not the share of the project costs attributable to climate change (OECD, 2013a). Researchers have questioned the accuracy of the project classification (Michaelowa and Michaelowa, 2011; Junghans and Harmeling, 2013). Bilateral commitments averaged 20 billion USD per year in 2010 and 2011 (2010/2011 USD) (OECD, 2013a) and were implemented by bilateral development banks or other bilateral agencies, provided to national government directly or to dedicated multilateral climate funds (Buchner et al., 2012, 2013b).

Seven multilateral development banks (MDBs)[9] reported climate finance commitments of about 24.1 and 26.8 billion USD in 2011 and 2012, respectively (2011/2012 USD). The reporting is activity-based allowing counting entire projects but also project components. Recipient countries include developing countries and 13 European Union (EU) member states. It covers grant, loan, guarantee, equity, and performance-based instruments, not requiring a specific grant element. The volume covers MDBs' own resources as well as external resources managed by the MDBs that are also reported to OECD DAC (such as contributions to the Global Environment Facility (GEF), Climate Investment Funds (CIFs), and Carbon Funds) (AfDB et al., 2012a; b, 2013).

Under the UNFCCC, climate finance is not well-defined. Annex II Parties committed to provide new and additional financial resources to cover the "agreed full incremental costs" of agreed mitigation measures implemented by developing countries (Article 4.3), to "assist the developing country Parties that are particularly vulnerable to the adverse effects of climate change in meeting costs of adaptation" (Article 4.4) and to cover the agreed full costs incurred by developing countries for the preparation of their national communications (Article 4.3) (UNFCCC, 1992). None of these terms are operationally defined (Machado-Filho, 2011). These commitments are reaffirmed by the Kyoto Protocol (UNFCCC, 1998, Art. 11). The Conference of Parties (COP) has agreed that funds provided to developing country Parties may come from a wide variety of sources, public, and private, bilateral and multilateral, including alternative sources (UNFCCC, 2010, para. 99).

Annex II Parties report the financial resources they provide to developing countries through bilateral and multilateral channels for climate

5 CDM projects sell emission reduction credits, Certified Emission Reductions (CERs), to developed country buyers, which provide a return to developed country investors.

6 United Nations Environment Program (UNDP) estimates that in addition up to 6000 private equity funds have been established for the purpose of funding climate change-related activities (UNDP, 2011).

7 Buchner et al. (2013b) count climate finance provided by bilateral finance institutions, multilateral finance institutions, government bodies, and climate funds as public flows. The difference between lower- and upper-bound results when taking the ownership structure of multilateral institutions into account and excluding all bilateral flows marked as having climate as 'significant' objective.

8 Ryan et al. (2012) estimate the annual average finance provided to developing countries for energy efficiency at 18.9 billion USD in 2010 from bilateral financial institutions and 4.9 billion USD from multilateral financial institutions over the period 2008–2011.

9 African Development Bank (AfDB), the Asian Development Bank (ADB), the European Bank for Reconstruction and Development (EBRD), the European Investment Bank (EIB), the Inter-American Development Bank (IDB), the World Bank (WB) and the International Finance Corporation (IFC).

change action to increase transparency about public flows of climate finance vis-à-vis expectations and needs. The latest summary of the Annex II reports on their provided climate finance indicates that they provided a total of 58.4 billion USD for the period 2005 through 2010, an average of nearly 10 billion USD per year (2005–2010 USD) (UNFCCC, 2011a).[10] Most of the funds provided are concessional loans and grants. In addition, a range of developed countries promised FSF of about 10 billion USD per year from 2010 to 2012 (2010/2011/2012 USD) (see Section 16.2.1.3).[11]

Operating entities of the financial mechanism of the UNFCCC deal with less than 10 % of the climate finance reported under the Convention, although that could change once the Green Climate Fund (GCF) becomes operational. Annex II Party contributions to the Trust Fund of the GEF, the Special Climate Change Fund (SCCF) and the Least Developed Countries Fund (LDCF) amounted to about 3.3 billion USD for 2005 through 2010, an average of less than 0.6 billion USD per year (2005–2010 USD) (UNFCCC, 2011a). Most of the funds are used for mitigation. The Adaptation Fund derives most of its funds from the sale of its share of the CERs issued for CDM projects[12].

16.2.1.2 Current sources of climate finance

Climate finance comes from the sources of capital shown in Figure 16.1 including capital markets, carbon markets, and government budgets. Most government funding comes from general revenue but some governments also raise revenue from sources—carbon taxes and auctioned GHG-emission allowances—that have mitigation benefits. Most corporate funding comes from corporate cash flow including corporate borrowing, often called balance-sheet finance (Frankfurt School-UNEP Centre, 2013).[13] Household funding comes from household income from wages, investments, and other sources. Governments, corporations, and households can all access capital markets to mobilize additional funds.

This section summarizes estimates of the revenue currently generated by carbon taxes and auctioned GHG-emission allowances. Fuel taxes, fossil fuel royalties, and electricity charges can be converted to CO_2eq charges but they are excluded here because they are usually implemented for different policy goals.

Carbon taxes generate about 7 billion USD in revenue annually mainly in European countries (2010/2011 USD).[14] Denmark, Finland, Germany, Ireland, Italy, Netherlands, Norway, Slovenia, Sweden, Switzerland, and the United Kingdom—generated about 6.8 billion USD in 2010 (2010 USD) and 7.3 billion USD (2011 USD) in 2011. India[15], Australia, and Japan introduced carbon taxes in July 2010, July 2012, and October 2012, respectively. In some countries, part or all of the revenue is dedicated to environmental purposes or reducing other taxes; none is earmarked for international climate finance.

Auctioned allowances, fixed price compliance options, and the international sale of surplus Assigned Amount Units (AAUs) generate about 2 billion USD per year for national governments (2010/2011 USD). Among the 30 countries participating in the EU emissions trading scheme, Austria, Germany, Hungary, Ireland, the Netherlands, Norway, and the United Kingdom auctioned some emission allowances during the second (2008–2012) phase (European Commission, 2012). Buchner et al. (2011, 2012) estimate auction revenue at 1.4 and 1.6 billion USD for 2010 and 2011 (2010/2011 USD). Germany has so far earmarked a portion of its auction revenue for international climate finance (Germany Federal Ministry for the Environment Nature Conservation and Nuclear Safety, 2012). New Zealand collected 1.25 and 1.42 million USD for 2010 (6 months) and 2011, respectively, from its fixed price compliance option of 10.8 USD per tonne of CO_2 (15 NZD) (New Zealand Ministry for the Environment, 2012).

Several eastern European countries (Estonia, Czech Republic, Poland, and Russia) sell surplus AAUs to generate revenue. Others such as Bulgaria, Latvia, Lithuania, Slovakia, and Ukraine, sell their surplus AAUs to fund Green Investment Schemes that support domestic emission reduction measures (Linacre et al., 2011).[16] Revenue rose from 276 million USD in 2008 (2008 USD) to 2 billion USD in 2009 (2009 USD) and then declined to less than 1.1 billion USD in 2010 (2010 USD) (Kossoy and Ambrosi, 2010; Linacre et al., 2011; Tuerk et al., 2013). Buchner at al. (2011, 2012) estimate the revenue at 580 and 240 million USD for 2010 and 2011, respectively (2010 and 2011 USD).

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[10] Although there is an agreed reporting format, the UNFCCC Secretariat notes that many data gaps and inconsistencies persist in the reporting approaches of Annex II Parties. The information is compiled by the UNFCCC Secretariat from Annex II national communications. The figures represent 'as committed' or 'as spent' currency over the 6 years. The procedures used by different countries and the Secretariat to convert currencies into USD are not known.

[11] Although COP took note of the ´fast start finance' (FSF) commitment in paragraph 95 of Decision 1/CP.16 (UNFCCC, 2010) and the funds committed have been reported annually to the UNFCCC, the FSF is not formally climate finance under the UNFCCC.

[12] Currently the only international levy is the 2 % of the CERs issued for most CDM projects provided to the Adaptation Fund. The Fund sells the CERs and uses the proceeds for adaptation projects in developing countries. Sale of CERs generated revenue of over 90 million USD for FY 2010 (2010/2011 USD) and over 50 million USD for FY 2011 (World Bank, 2012a). In December 2012 Parties agreed to extend the share of proceeds levy to the issuance of emission reduction unit (ERUs) and the first international transfers of AAUs (UNFCCC, 2012a, para. 21).

[13] General revenue includes revenue collected from all taxes and charges imposed by a government. Balance sheet finance means that a new investment is financed by the firm rather than as a separate project. The firm may seek external funding (debt and/or equity) but that funding is secured by the operations of the firm rather than the new investment.

[14] Revenue from taxes explicitly named carbon taxes in the OECD database of environmentally related taxes, available at http://www2.oecd.org/ecoinst/queries/index.htm.

[15] In India, the carbon tax is on coal only.

[16] The Green Investment Schemes are a source of climate finance for these countries.

16.2.1.3 Recent developments

Climate finance has been affected by the financial crisis of late 2008, the subsequent stimulus packages and the FSF commitment of 30 billion USD for 2010–2012 made by developed countries in December 2009 for climate action in developing countries.

The **financial crisis** in late 2008 reduced investment in renewable energy (Hamilton and Justice, 2009). In late 2008 and early 2009, investment in renewable generation fell disproportionately more than that in other types of generating capacity (IEA, 2009). Global investment in renewable energy fell 3 % during 2009 but rebounded strongly in 2010 and 2011. In developed countries, where the financial crisis hit hardest, investment dropped 14 % while renewable energy investment continued to grow in developing countries (Frankfurt School-UNEP Centre and BNEF, 2012).

In response to the financial crisis, Group of Twenty Finance Ministers (G20) governments implemented **economic stimulus packages** amounting to 2.6 trillion USD. Of that amount, 180 to 242 billion USD was low-carbon funding (2008 and 2009 USD) (IEA, 2009; REN21, 2010). The stimulus spending supported the rapid recovery of renewable energy investment by compensating for reduced financing from banks. Some countries facing large public sector deficits scaled down green spending when the economy started recovering (Eyraud et al., 2011).

At the UNFCCC in Copenhagen in 2009, developed countries committed to provide new and additional resources approaching 30 billion USD of **FSF** to support mitigation and adaptation action in developing countries during 2010–2012 (UNFCCC, 2009a). The sum of the announced commitments exceeds 33 billion USD (UNFCCC, 2011b, 2012b; c, 2013a)[17]. Japan, United States, United Kingdom, Norway, and Germany being the five biggest donors have reported commitments amounting to 27 billion USD (2010/2011/2012 USD). Nakooda et al. (2013) finds that around 45 % have been provided as grants and around 47 % in the form of loans, guarantees, and insurance. Approximately 61 % of the funds had been committed for mitigation, 10 % for REDD+, ,18 % for adaptation, 9 % for multiple objectives and for 2 % of the funding the purpose is unknown. The funders reported commitments to recipient country governments via bilateral channels (33 %), multilateral climate funds (20 %), recipient countries companies (12 %), and multilateral institutions (9 %). Data on actual disbursements is not available to date because of the multi-year time lag between commitment and disbursement.

The announced pledges triggered questions as to whether they were 'new and additional' as promised (Fallasch and De Marez, 2010; BNEF, 2011). Some countries explain the basis on which they consider their pledge to be 'new and additional'. Criteria have been proposed that indicate, when applied to the pledges, that proportions ranging from virtually none to almost all are new and additional (Brown et al., 2010; Stadelmann et al., 2010, 2011b). For Germany, Japan, the United Kingdom, and the United States annual FSF contributions were significantly higher than the 2009 expenditure related to climate activities in developing countries (Nakooda et al., 2013).

16.2.2 Future low-carbon investment

As noted in Chapter 6, the stabilization of GHG concentrations will ultimately require dramatic changes in the world's energy system, including a dramatic expansion in the deployment of low-carbon energy sources. This change will require significant shifts in global investment in the energy, land use, transportation, and infrastructure sector. The future investment flows summarized in this section are based on several large-scale analyses conducted over the past few years. For the most part these analyses explore scenarios to achieve specified temperature or concentration goals. Hence, the estimates of investment flows drawn from these studies should not be interpreted as forecasts, but rather, as some probable future states of the world.

Figure 16.2 presents estimates of baseline, i. e., current investment in energy supply sub-sectors as a reference for the following considerations. It illustrates the very substantial nature of investments in today's energy sector with global total annual investment at about USD_{2010} 1200 billion and very strong roles for investments in fossil fuel extraction, transmission and distribution (T&D), and electricity generation.

16.2.2.1 Investment needs

While a large number of studies and many modelling comparison exercises have assessed technological transformation pathways and the macroeconomic costs of transforming the global economy, only a handful of studies estimate the associated investment needs. Section 16.2.2.2 summarizes available estimates of investment needs under climate policy between 2010–2029 and 2030–2049, for the world as a whole and for non-OECD and OECD countries. Models and scenarios differ so the focus is on incremental investment, i. e., the differences in the estimated investment between the reference and mitigation scenarios.[18] It must also be noted that the model estimates crucially rely on assumptions about the future costs of technologies and of subsidies, on the possibility of nuclear phaseout in some countries, and on the mitigation policies already included in the reference scenarios.

Without climate policy, investments in the power sector would mainly be directed towards fossil fuels, especially in non-OECD countries that rely on low-cost coal power plants to supply their growing

[17] The information is compiled by the UNFCCC Secretariat from national reports on FSF. The figures represent 'as committed' currency over the three years. The procedures used by different countries and the Secretariat to convert currencies into USD are not known.

[18] Adaptation costs and economic losses from future climate change are not considered in any of these estimates.

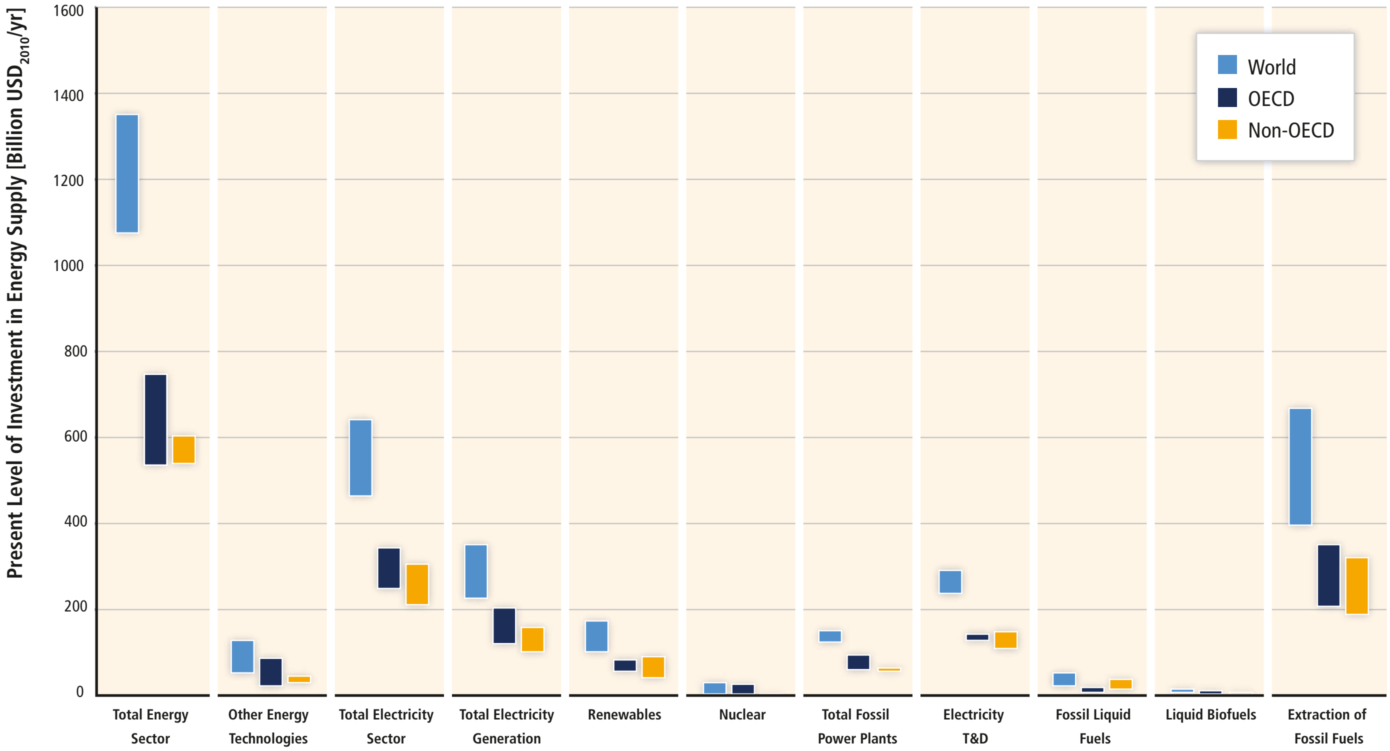

Figure 16.2 | Present level of investment in energy supply. Note: The bars indicate the minimum and maximum level of investments found in the literature. Ranges result from different sources of market information and differing definitions of the investment components to be included. Source: From McCollum et al. (2013) based on data from IEA World Energy Outlook 2011 (IEA, 2011) and GEA (Riahi et al., 2012).

demand for electricity. At the global level, fossil fuel-based power generation would require an average annual investment of 182 (95 to 234) billion USD in 2010–2029 and 287 (158 to 364) billion USD in 2030–2049;[19] the bulk of investments (roughly 80 %) goes to non-OECD countries.[20] There is greater uncertainty in models about the future of renewable and nuclear power without climate policy. Modelled global investment in renewable power generation is expected to increase over time from 123 (31 to 180) billion USD per year in 2010–2029 to 233 (131 to 336) billion USD over 2030–2049. Nuclear power generation would attract 55 (11 to 131) billion USD annually in 2010–2029 and 90 (0 to 155) billion USD per year in 2030–2049.

The **introduction of an emission reduction target** in the models abruptly changes the investment pattern. Figures 16.3 and 16.4 report the investment change for major power generation technologies, fossil fuel extraction, and for end-use energy efficiency, for emission scenarios compatible with a long-term target of keeping mean global temperature increase below 2 °C in 2100.[21] Although the policy targets are not identical, they are close enough to allow a broad comparison of results. The dispersion across estimated emission reductions over 2010–2029 and 2010–2049 is mainly due to differences in reference scenario emissions and because models choose different optimal emission trajectories among the many compatible with the long-term climate goal.

The results of an analysis of investment estimates in Figures 16.3 and 16.4 show that climate policy is expected to induce a major reallocation of investments in the power sector. Investments in fossil-fired power plants (without CCS) were equal to about 137 billion USD per year in 2010. Investment would decline by 30 (2 to 166) billion USD per year (about −20 % for the median) during the period 2010–2029, compared to the reference scenarios. Investment in low-emissions generation technologies (renewable, nuclear, and electricity generation with CCS) would increase by 147 (31 to 360) billion USD per year (about 100 % for the median) during the same period.

Based on a limited number of studies (McKinsey, 2009; IEA, 2011; Riahi et al., 2012), annual incremental investments until 2030 in energy-efficiency investments in the building, transport, and industry sector increase by 336 (1 to 641) billion USD. The only three studies with sectoral detail in end-use technologies show an increase of investments of 153 (57 to 228) billion USD for the building sector, 198 (98 to 344) billion USD for the transport sector, 80 (40 to 131) billion USD for the

19 The mean should not be considered as an expected value. It is not possible to attribute any probability distribution to models' outcomes. Therefore policymakers face pure uncertainty in face of future investment needs. The range is presented to provide information on the degree of uncertainty in the literature.

20 See captions of Figures 16.3 and 16.4 for a list of the studies surveyed.

21 Also in this case, the mean and median are used as synthetic indicators having no predictive power.

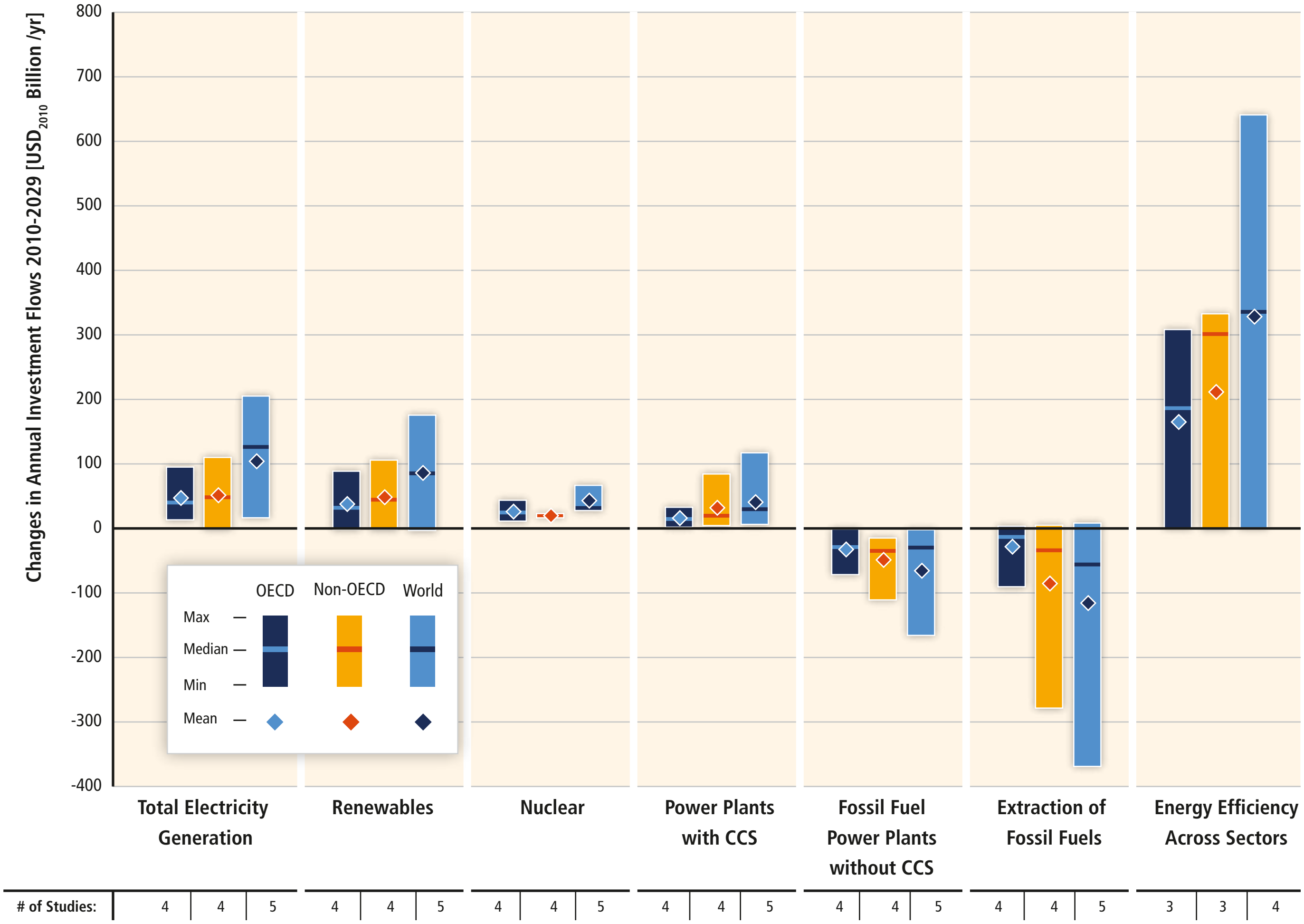

Figure 16.3 | Change of average annual investment in mitigation scenarios (2010–2029). Investment changes are calculated by a limited number of model studies and model comparisons for mitigation scenarios that stabilize concentrations within the range of 430–530 ppm CO_2eq by 2100 compared to respective average baseline investments. Note: The vertical bars indicate the range between minimum and maximum estimate of investment changes; the horizontal bar indicates the median of model results. Proximity to this median value does not imply higher likelihood because of the different degree of aggregation of model results, low number of studies available, and different assumptions in the different studies considered. The numbers in the bottom row show the total number of studies available in the literature. Sources: UNFCCC (2008). IEA (2011): 450 Scenario (450) relative to the Constant Policies Scenario (CPS). The CPS investment in CCS is also included under Coal and Gas (retrofitting); World investment in biofuels includes international bunkers; investment in solar photovoltaic (PV) in buildings is attributed to power plants in supply-side investment. Riahi et al. (2012): the Global Energy Assessment Mix scenario (GEA-Mix) relative to the GEA reference scenario. Carraro et al. (2012): 460 ppm CO_2eq in 2100 (t460) relative to reference scenario. McCollum et al. (2013): the Low Climate Impact Scenarios and Implications of Required Tight Emission Control Strategies (LIMITS), RefPol-450 scenario (2.8 W/m^2 in 2100) relative to the reference scenarios, mean of six models. McKinsey (2009): data obtained from Climate Desk, S2015 scenario with full technological potential, 100 % success rate, negative lever of costs, beginning of policy in 2015 | Regions: OECD, non-OECD, and World.

industry sector. Incremental investments in end-use technologies are particularly hard to estimate and the number of studies is limited (Riahi et al., 2012). Results should therefore be taken with caution.

While models tend to agree on the relative importance of investments in fossil and non-fossil power generation, they differ with respect to the mix of low-emission power generation technologies and the overall incremental investment. This is mainly due to different reference scenarios (e.g., population, economic growth, exogenous technological progress), and assumptions about (1) the structure of the energy system and the costs of reducing the energy intensity of the economy versus reducing the carbon intensity of energy, (2) the investment costs of alternative technologies over time, and (3) technological or political constraints on technologies. Limits to the deployment of some key technology options or the presence of policy constraints (e.g., delayed action, limited geographical participation) would increase investment needs (Riahi et al., 2012; McCollum et al., 2013).

Higher energy efficiency, technological innovation in transport, and the shift to low-emission generation technologies—all contribute to a drastic reduction in the demand for fossil fuels, thus causing a sharp decline in investment in fossil fuel extraction, transformation, and transportation. Scenarios from a limited number of models suggest that average annual investment reduction in 2010–2029 would be equal to 56 (–8 to 369) billion USD. The contraction would be sharper in 2030–2049, in the order of 451 (332 to 1385) billion USD per year.

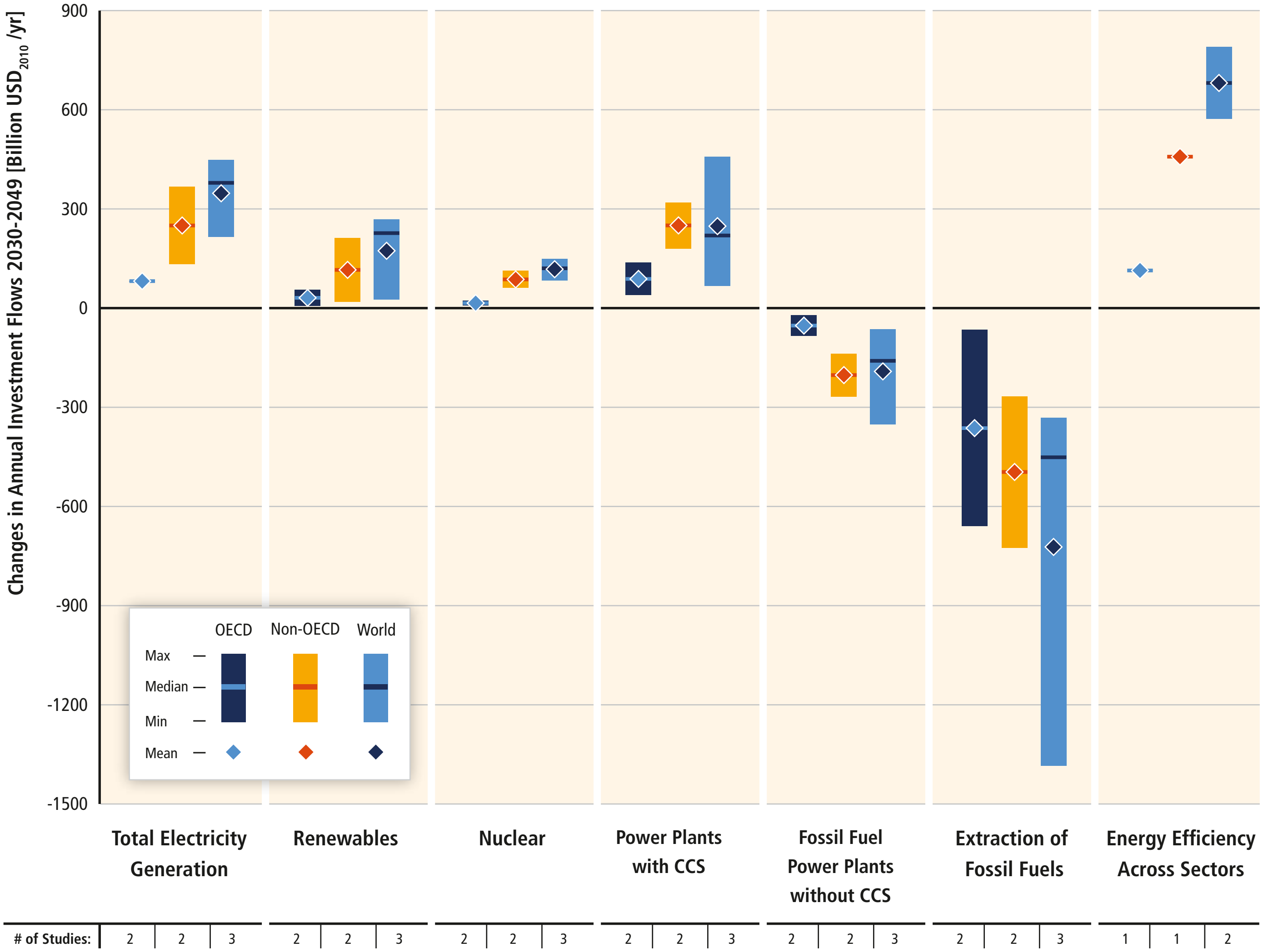

Figure 16.4 | Change of average annual investment in mitigation scenarios (2030–2049). Investment changes are calculated by a limited number of model studies and model comparisons for mitigation scenarios that stabilize concentrations within the range of 430–530 ppm CO_2eq by 2100 compared to respective average baseline investments. Note: The vertical bars indicate the range between minimum and maximum estimate of investment changes; the horizontal bar indicates the median of model results. Proximity to this median value does not imply higher likelihood because of the different degree of aggregation of model results, low number of studies available, and different assumptions in the different studies considered. The numbers in the bottom row show the total number of studies available in the literature. Sources: Riahi et al. (2012): the Global Energy Assessment Mix scenario (GEA-Mix) relative to the GEA reference scenario. Carraro et al. (2012): 460 ppm CO_2eq in 2100 (t460) relative to reference scenario. McCollum et al. (2013): the Low Climate Impact Scenarios and Implications of Required Tight Emission Control Strategies (LIMITS), RefPol-450 scenario (2.8 W/m^2 in 2100) relative to the reference scenarios, mean of six models. Regions: OECD, non-OECD, and World.

All models that provide data on investments for fossil fuel extraction show that overall investments in energy supply would decrease against the baseline trends in scenarios consistent with the 2 °C limit (IEA, 2011; Carraro et al., 2012; Riahi et al., 2012; McCollum et al., 2013).

According to a range of models, climate policy would thus substantially change the allocation of baseline energy investments rather than increase overall demand for energy investment.

Models with a separate consideration of energy-efficiency measures foresee the need for significant incremental investment in energy efficiency in the building, transport, and industry sector in addition to the reallocation of investment from high-carbon to low-carbon power supply.

There is wide agreement among model results on the necessity to ramp up investments in research and development (R&D) to increase end-use energy efficiency and to improve low-emission generation energy carriers and energy transformation technologies. Estimates of the additional funding needed for energy-related R&D range from 4.5 to 78 billion USD per year during 2010–2029 (UNFCCC, 2007; Carraro et al., 2012; McCollum et al., 2013) and from 115 to 126 billion USD per year in 2030–2049 (Carraro et al., 2012; Marangoni and Tavoni, 2013; McCollum et al., 2013). Because of the need for new low-carbon alternatives, investments in R&D are higher in case of nuclear phaseout and other technological constraints (Bosetti et al., 2011).

Land-use is the second largest source of GHG emissions and within land use, tropical deforestation is by far the largest source (see Chapters 5 and 11). Efforts to stabilize atmospheric concentrations of GHGs will require investments in land use change (LUC) as well as in the energy sector.

Kindermann et al. (2008) use three global forestry and land use models to examine the costs of reduced emissions through avoided deforestation over the 25 year period from 2005–2030.[22] The models' results suggest substantial emission reductions can be achieved. The models estimate that 1.6 to 4.3 $GtCO_2$ per year could be reduced for 20 USD tCO_2 with the greatest reductions coming from Africa followed by Central and South America and Southeast Asia. They also use the models to estimate the costs to reduce deforestation by between 10 % and 50 % of the baseline. Deforestation could be reduced by 10 % (0.3–0.6 $GtCO_2$ per year) over the 25-year period for an investment of 0.5 to 2.1 billion USD per year in forest preservation activities, and a 50 % reduction (1.5–2.7 $GtCO_2$ per year) could be achieved for an investment of 21.2 to 34.9 billion USD per year. This is comparable to what has been found by UNFCCC (2008) and McCollum et al. (2013).

Investment needs in other sectors commonly relate to energy-efficiency measures included above. Information on global or regional investment needs to abate process emissions or non-CO_2 emissions in sectors like the waste, petroleum, gas, cement, or the chemical industry is virtually unavailable. For instance, McKinsey (2009) does not provide information that could be separated from energy-efficiency measures in the sectors. An indicative estimate for the waste sector can be derived from Pfaff-Simoneit (2012) suggesting investment needs of approximately 10–20 billon USD per year if access to a modern waste management system were to be provided for an additional 100 million people per year.

16.2.2.2 Incremental costs

Incremental costs can be calculated for an individual project, a programme, a sector, a country, or the world as a whole. The incremental costs reflect the incremental investment and the change of operating and maintenance costs for a mitigation or adaptation project in comparison to a reference project. It can be calculated as the difference of the net present values of the two projects. Estimates of the incremental costs of mitigation measures for key sectors or the entire economy have been prepared for over 20 developing countries (Olbrisch et al., 2011). When estimates of both the incremental costs and the incremental investment are available, the former is generally lower because of the annualization of incremental investments for the calculation of incremental costs.

From an economic perspective, macroeconomic incremental costs can be defined as the lost gross domestic product (GDP). This measure provides an aggregate cost of the mitigation actions (estimates provided in Chapter 6), but it does not provide information on the specific micro-economic investments that must be made and costs incurred to meet the mitigation commitments. This distinction is important if international climate finance commitments will be implemented through institutions designed to provide financial support for specific investments and costs rather than macro-level compensation.

Other than on the project-level, investment needs are thus frequently only a fraction of incremental costs on the level of the macro-economy. This difference is largely due to reduced growth of carbon-constrained economies in many models. Adaptation costs and economic losses from future climate change, which are not considered in these estimates, should be lower for climate policy scenarios than in the reference scenario.

16.2.3 Raising public funding by developed countries for climate finance in developing countries

Comparison of the model estimates of future mitigation investment (Section 16.2.2) with the current level of global total climate finance (Section 16.2.1.1) indicates that global climate finance needs to be scaled up. Increased financial support by developed countries for mitigation (and adaptation) in developing countries will be needed to stimulate the increased investment. This section reviews possible sources of additional funds that could be implemented by developed country governments to finance mitigation in developing countries.

In December 2009, developed countries committed to a goal of mobilizing jointly 100 billion USD a year by 2020 to address the needs of developing countries in the context of meaningful mitigation actions and transparency on implementation. This funding will come from a wide variety of sources, public and private, bilateral and multilateral, including alternative sources of finance (UNFCCC, 2009a).[23] This goal has been recognized by the COP (UNFCCC, 2010, para. 98). This recognition does not change the commitments of Annex II Parties specified in Article 4 of the Convention to provide financial resources for climate-related costs incurred by developing countries.

Studies by the High-level Advisory Group on Climate Change Financing (AGF) (AGF, 2010) and the World Bank Group et al. (2011) at the request of G20 finance ministers have analyzed options for mobilizing 100 billion USD per year by 2020. The AGF concluded that it is challenging but feasible to reach the goal of mobilizing 100 billion USD

[22] The models used are the Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA) (Roktiyanskiy et al., 2007), the Generalized Comprehensive Mitigation Assessment Process Model (GCOMAP) (Sathaye et al., 2006), and the Global Timber Model (GTM) (Sohngen and Mendelsohn, 2003).

[23] There is currently no definition of which 'climate' activities count toward the 100 billion USD, what 'mobilizing' means, or even which countries are covered by this commitment (Caruso and Ellis, 2013).

Table 16.1 | Summary of potential sources of public funds for climate finance in 2020.

Option	Projected amount generated in 2020 (billion USD_{2010}/year)	Share assumed to be dedicated to international climate finance
1) Options that contribute to developed country national budgets, dependent on national decisions		
Domestic auctioned allowances	AGF: 125–250[b]; G20: 250	AGF: 2–10 %; G20: 10 %
Domestic carbon tax[c]	AGF: 250	AGF: 4 %
Phase out of fossil fuel subsidies	AGF: 8; G20: 40–60	AGF: 100 %; G20: 15–25 %
Higher fossil fuel royalties	AGF: 10	AGF: 100 %
Wires charge on electricity generation	AGF: 5	AGF: 100 %
2) Options that contribute to national budgets, dependent on international agreements		
Border carbon cost levelling	Grubb 2011: 5*	
Financial transactions tax	AGF: 2–27	AGF: 25–50 %
3) Funds collected internationally pursuant to an international agreement		
Extension of the 'share of proceeds'	AGF: 38–50	AGF: 2–10 %
Auctioning a portion of AAUs	AGF: 125–250[b]	AGF: 2–10 %
Carbon pricing for international aviation***,[a]	UNFCCC: 10–25**; AGF: 6; G20: 13	AGF: 25–50 %; G20: 33–50 %
Carbon pricing for international shipping***,[a]	UNFCCC: 10–15**; AGF: 16–19; G20: 26	AGF: 25–50 %; G20: 33–50 %

Notes: AGF, G20, and UNFCCC refer to estimates from AGF (2010), World Bank Group et al. (2011) and UNFCCC (2007), respectively. * = Date not specified; ** = 2006 USD; *** Could fall into category 2 depending upon the method of implementation; [a] The AGF and G20 estimates for international aviation and international shipping assume that a substantial fraction (30 to 50 %) of the global revenue is allocated to developing countries. [b] The AGF combines auctioned AAUs and auctioned domestic allowances, here half of the total is included in each category; [c] The AGF estimates revenue of 10 billion USD per 1 USD tax per tonne of CO_2, that is equivalent to potential revenue of 250 billion USD and a 4 % share for international climate finance as reported here. Sources: Compiled from AGF (2010), World Bank Group et al. (2011), UNFCCC (2007), and Grubb (2011).

annually for climate actions in developing countries. Both reports conclude that a mix of sources is likely to be required to reach the goal.

Both reports estimate the revenue that could be mobilized in 2020 by various options to finance climate action in developing countries in the context of a carbon price of 25 USD per tonne of CO_2eq in Annex II countries. The feasibility of the options was not assessed. For some options, only a fraction of the revenue was assumed to be available for international climate finance. Their estimates of the international climate finance that could be generated by each option, together with other estimates, where available, are summarized in Table 16.1. Only options to mobilize public funds and that yield mitigation benefits are included in the table; options for increased borrowing by multilateral institutions and mobilizing more private finance are excluded.

Virtually all of the options put a price on GHG emissions thus providing a mitigation benefit in addition to generating revenue. The options are grouped into the following categories (Haites and Mwape, 2013):

1. Options that contribute to developed countries national budgets, dependent on national decisions;
2. Options that contribute to national budgets, dependent on international agreements; and
3. Funds collected internationally pursuant to an international agreement.

Funds mobilized by options in the first two categories flow into national budgets, so the amount allocated for international climate finance depends on national decisions. In contrast, funds mobilized by options in the third category go directly to an international fund.

The AGF and G20 reports assume for many options that only small fraction of the total revenue mobilized is dedicated to international climate finance. Hence, these options would mobilize revenue to meet the international climate finance goal and at the same time mobilize substantial revenue for domestic use by Annex II governments. The domestic share of the revenue could be used by Annex II treasuries to reduce deficits and debt, or to reduce existing distortionary taxes and so help stimulate economic growth.

Global modelling estimates

Using integrated models, it is possible to estimate the potential carbon revenues when all emissions are taxed or all permits are auctioned. These estimates reflect a scenario in which all world regions commit to reduce GHG emissions using an efficient allocation of abatement effort, i.e., globally equal marginal abatement costs. Therefore, it should be used to gain insights rather than exact revenue forecasts.

From the analysis of scenarios already presented in this chapter (Carraro et al., 2012; Calvin et al., 2012; McCollum et al., 2013) it is possible to derive the following messages:

Carbon revenues are potentially large, in the order of up to 200 billion USD each in China, the European Union and the United States in 2030. At the global level, they could top 1600 billion USD in 2030.

Carbon revenues may peak in the mid-term and decline in the long-term, as decreasing emissions (the tax base) more than offset the increase in the carbon price (Carraro et al., 2012). In regions with lower marginal abatement costs, the tax base shrinks faster so carbon revenues fall faster. Fast-growing regions may see growing carbon revenues for several decades more.

Scenarios and/or regions in which absorption of emissions—e.g., by means of bioenergy with CCS—plays an important role may exhibit net negative emissions. This implies net reduction of carbon revenues so governments must finance net negative emissions using either the general budget or international funding (Carraro et al., 2012).

16.3 Enabling environments

This section highlights the importance of a supportive enabling environment in facilitating low-carbon investments. The concept of enabling environment is not clearly defined, so it has many different interpretations. One is government policies that focus on "creating and maintaining an overall macroeconomic environment" (UNCTAD, 1998).[24] Another (Bolger, 2000), interprets an 'enabling environment' as the wider context within which development processes take place, i.e., the role of societal norms, rules, regulations, and systems. This environment may either be supportive (enabling) or constraining.

According to Stadelmann and Michaelowa (2011), capacity building and enabling environment are separate but interrelated concepts. Capacity building targets knowledge and skills gaps, while the enabling environment for low-carbon business activities is "the overall environment including policies, regulations and institutions that drive the business sector to invest in and apply low-carbon technologies and services." According to this definition, the enabling environment has three main components: (1) the core business environment, which is relevant for all types of businesses, e.g., tax regime, labour market, and ease of starting and operating a business; (2) the broader investment climate, including education, financial markets, and infrastructure, which is partially low-carbon related, e.g., via climate change education or investments in electricity grids; and (3) targeted policies that encourage the business sector to invest in low-carbon technologies.

Capacity building can also be seen as a subcomponent of an enabling environment (UNFCCC, 2009b) as it aims to improve the enabling environment by overcoming market, human, and institutional capacity barriers. Support for capacity building can increase the probability that the recipient country will succeed in implementing mitigation policies, and hence may reduce the total funding needed (Urpelainen, 2010).

Reliability and predictability are important elements of an enabling environment. While stable and predictable government policies reduce uncertainty about expected return on investment, frequent and unpredictable changes to policies can undermine market efficiency (Blyth et al., 2007; Brunner et al., 2012). Predictability and stability require well-established legal institutions and rule of law. Institutional capacity across sectors and at various levels is also important (Brinkerhoff, 2004).

In their econometric examination, Eyraud et al. (2011) found that lowering the cost of capital is particularly effective in boosting investment in low-carbon activities. Hence, macro-economic factors and policy regulatory frameworks that are good for private investment as a whole are also important determinants of climate investment. Put differently, obstacles that impede private investment also hamper investment in low-carbon technologies. More elements related to the drivers of low-carbon investments, which are part of enabling environments, are found in the next sub-section.

16.4 Financing low-carbon investments, opportunities, and key drivers

Financing mitigation projects is, in principle, similar to financing any other investment. This section provides an overview of factors that attract private capital for low-carbon investments. First, different categories of capital managers and their key investment criteria are introduced. Next, challenges that hamper investors, such as investment risks and access to capital, are assessed. Finally, selected financial instruments used in low-carbon transactions are presented and discussed.

16.4.1 Capital managers and investment decisions

Mitigation measures often are financed through investments by several different capital managers (see Figure 16.1). It is crucial to understand the basic investment logic and the preferred financial instruments of each type of capital manager.[25] Box 16.2 characterizes some of the major types of capital managers.

Risk and return are crucial decision factors in any investment finance decision, including low-carbon activities. The higher the perceived risk,

[24] For enabling environments for technology transfer see McKenzie Hedger et al. (2000).

[25] For the different types of financing typically used, i.e., required, in the different stages of renewable technologies, such as R&D, commercialization, manufacturing, and sales, see Mitchell et al.(2011).

Box 16.2 | Types of capital managers relevant for investment and finance in low-carbon activities

Governments commit to mitigation measures to comply with international agreements and self-imposed targets. Their role as capital managers is limited to mitigation measures where they invest directly. In 2011 and 2012, the public sector provided on average 135 billion USD per year (2011/2012 USD) of public funding for climate finance, thereof 12 billion USD provided directly by government bodies[1] (Buchner et al., 2013b).

Public financial institutions include national, bilateral, multilateral, and regional finance institutions, as well as UN agencies and national cooperation agencies. These institutions invested 121 billion USD in mitigation and adaptation measures in 2012 (2012 USD), more than 50 % was provided as concessional loans (Buchner et al., 2013b).

Commercial financial institutions, such as banks, pension funds, life insurance companies, and other funds, manage over 71 trillion USD in assets. They can have long-time horizon investments diversified across asset classes with varying risk return profiles and investment tenors, sectors, and geographies (Inderst et al., 2012). The ability of institutional investors to invest in mitigation measures depends on their investment strategy, restrictions agreed upon with their clients, as well as the regulatory framework. Life insurance and pension funds are especially constrained by the latter (Glemarec, 2011). Their contribution was estimated at 22 billion USD in 2012 (2012 USD) (Buchner et al., 2013b).

Energy corporations including power and gas utilities, independent power producers, energy companies, and independent project developers can design, commission, and operate renewable energy projects. They provided approximately 102 billion USD (2012 USD) for climate finance in 2012 (Buchner et al., 2013b).

Non-energy corporations invest in mitigation measures to reduce their energy bills, meet voluntary commitments or comply with emission trading schemes. Altogether, they provided around 66 billion USD in 2012 for low-carbon investment (2012 USD) (Buchner et al., 2013b).

Households' investments are funded by income and savings supplemented by loans. In 2012, households provided around 33 billion USD for climate finance projects; 83 % of households' contributions were in developed countries, especially in Germany, Japan, and Italy (Buchner et al., 2013b).

[1] This estimate excludes financing by public financial institutions and by dedicated climate fund, the latter providing approximately 1.6 billion USD (2012 USD) in 2012 (Buchner et al., 2013b).

the higher the cost of capital and required return needing to be generated to cover the costs (i. e., higher risk results in a higher discount rate for cash flow) (Romani, 2009).

Equity and debt are basically the two basic types of finance. Both come at a certain cost, which is very sensitive to risk, i. e., risk premium or risk margin. The type of finance required depends on the type of activity, its development phase, and its application.

Project finance is usually the preferred financing approach for infrastructure or energy projects worth more than 21.4 million USD (UNEP, 2005). In this financing structure, debt and equity are paid back exclusively from the cash flows generated by the project and there is no recourse to the balance sheet (also call non-recourse finance); as opposed to balance-sheet financing, where all '*on-balance sheet*' assets can be used as collateral. In 2012, around 70 billion USD of project-level market rate debt went towards emission reduction (70 % provided by the public sector). Project-level equity was estimated at approximately 11 billion USD. However, the largest share of mitigation , 198 billion USD, consisted of balance-sheet financing (2012 USD) (Buchner et al., 2013b).

Risk profile, tenor (i. e., loan duration) and **size** are the primary criteria to characterize the financing demand. The total financing demand can be split into tranches with varying risk profiles (e. g., debt vs. equity) and varying tenors that match the characteristics of existing financing instruments. For renewable energy projects, higher cost of capital will increase start-up costs, which are generally front-loaded and higher per unit of capacity than for fossil fuel-based projects even if financing conditions are identical (Brunnschweiler, 2010). Lenders require a higher equity share if a project is perceived as risky. A typical project finance structure in an industrialized country consists of 10–30 % equity, whereas in developing countries this share tends to be higher (UNEP, 2007). However, equity tends to be scarce in many developing countries (see Section 16.4.2.2).

16.4.2 Challenges for low-carbon investment

Factors that reduce the relative attractiveness of implementing a low-carbon technology shall be considered as a challenge. Many factors pertaining to the general investment environment can have an enabling character or can act as a challenge (see Section 16.3). However, there are also low-carbon specific factors—especially in absence of a clear price signal for carbon emissions—that, if they remain, may keep the market penetration of these technologies to low percentages (Gillingham and Sweeney, 2011). The latter will be assessed in this subsection.

Challenges vary significantly within the different investment categories, dependent upon the investor and the type of activity. For instance, each group is faced with some additional typical financial challenges. Energy-efficiency measures, for instance, often face misaligned incentives between the asset owner, user, and lender. It is more complex for energy-efficiency projects to structure and share the underlying risks. In addition, energy savings are intangible as collateral (Hamilton and Justice, 2009; Ryan et al., 2012; Venugopal and Srivastava, 2012).

Investment risks: Investments in low-carbon activities face partly the same risks as other investments in the same countries analogous to the core and broader investment climate. These risks can be broadly grouped into political risks (e.g., political instability, expropriation, transfer risk, breach of contract, etc.) and macro-economic risks (e.g., currency risk, financial risks, etc.). In some developing countries, political and macro-economic risks represent a high barrier to investment (Ward et al., 2009; World Bank, 2011a; Venugopal and Srivastava, 2012).

There are also types of risks characteristic for low-carbon investments: **Low-carbon policy risks** are one type of these risks that concern the predictability, longevity, and reliability of policy, e.g., low-carbon regulations might change or not be enforced (Ward et al., 2009; Venugopal and Srivastava, 2012; Frisari et al., 2013). Private capital will flow to those countries, or markets, where regulatory frameworks and policies provide confidence to investors over the time horizon of their investment (Carmody and Ritchie, 2007).

Mitigation activities also face **specific technology and operational risk**. For relatively new technologies, these are related to performance of the technology (i.e., initial production and long-term performance), delay in the construction, and the risk of not being able to access affordable capital (see Section 16.4.2.2). Some low-carbon activities also tend to depend on an expected future development, e.g., steep learning curves for certain technologies. Operational risks include the credit quality of the counterparties, off-take agreements, especially in a scenario where the mitigation technology has a higher costs of production, supply chain scalability, unreliable support infrastructure, and maintenance costs (Jamison, 2010; Venugopal and Srivastava, 2012).

Moreover, risks may be overestimated due to limited information in markets that are undergoing a technological and structural transition (Sonntag-O'Brien and Usher, 2006) and the longer time frame used to assess the risk increases uncertainty. A lack of quantitative analytical methodologies for risk management may add to the perceived risk.

Return on investment: The basic challenge is to find a financing package that provides the debt and equity investors with a reasonable return on their investment given the perceived risks. Debt financiers have a strong interest in seeing that their loans are paid back and hence provide funds to less risky, proven technologies and established companies (Hamilton, 2010). It is estimated that in 2009 they required an average internal rate of return (IRR) of around 3 to 7 % above the London Interbank Offered Rate (LIBOR) reference interest rate, for renewable energy projects in industrialized countries. Venture capitalists, angel investors, and some foundations (through so-called programme-related investments) are situated on the other side of the financing continuum. They typically invest in new companies and technologies, and are willing to take higher risks while expecting commensurately larger returns. These investors may require an IRR of 50 % or higher because of the high chances that individual projects will fail. Private equity companies that invest in more established companies and technologies may still require an IRR of about 35 % (Hamilton and Justice, 2009). However, these typical IRRs have to be considered with care since they may vary according to the prevailing basis interest rates (i.e., the current LIBOR rate), perceived risks of the investment category and the availability of alternative investment opportunities. Many renewable energy projects, especially in developing countries where additional risk margins are added, are struggling to reach returns of this level to satisfy the expectations of financiers of equity and debt.

Cost of capital and access to capital: In many countries, there are imperfections in the capital market restricting the access to affordable long-term capital (Maclean et al., 2008). This is particularly the case in many developing countries where local banks are not able to lend for 15–25 years due to their own balance sheet constraints (Hamilton, 2010), e.g., to match the maturity of assets and liabilities.

Attracting sufficient equity is often critical for low-carbon activities, especially for renewable energy projects in developing countries (Glemarec, 2011). The equity base of a company is used to attract (leverage) mezzanine or debt finance especially in project finance investments. Since equity is last in the risk order and can be recovered only by means of sale of shares of the asset or its liquidation, return expectations are significantly higher than for debt or mezzanine finance. Often, equity is also the key limiting factor in the expansion of a low-carbon activity, e.g., through growth of a company, expansion into new markets, R&D, or multiplication of a project approach (UNEP, 2005).

Market and project size: Since the pre-investment costs vary disproportionally with the project size, smaller low-carbon projects incur much higher transaction costs than larger ones of conventional energy projects (Ward et al., 2009). These costs include feasibility and due diligence work, legal and engineering fees, consultants, and permitting costs. Hamilton (2010) finds that small low-carbon projects in developing countries seeking less than 10 million USD of debt are generally not attractive to an international commercial bank. Due to the higher transaction costs, small projects might also generate lower gross returns, even if the rate of return lies within the market standards (Sonntag-O'Brien and Usher, 2006).

There is basically no secondary market to raise debt for low-carbon projects. Hence, institutional investors, whose major asset class is bonds, lack opportunities to invest in low-carbon energy projects because they do not issue bonds or the issuance size is too small (Hamilton and Justice, 2009; Kaminker and Stewart, 2012). The minimum issuance size for investment grade bonds tends to be about 460 million USD, so few projects can achieve this standard (Veys, 2010). Many renewable energy projects need investment in the range of 70–700 million USD, with only a few big ones towards the upper end (Hamilton and Justice, 2009). In 2011, clean energy bonds amounted to only about 0.2 % of the global bond market (Kaminker and Stewart, 2012).

Tenor-risk combination: Capital markets tend to prefer a combination of long tenor with low risk and are willing to finance high risk only in the short term. Due to higher political and macro-economic instability in developing countries, investors are particularly reluctant to invest in projects with such a long investment horizon. Although pension funds and insurance companies are long-term investors, concerns about quality and reliability of cash flow projections, credit ratings of off-takers for power purchase agreements, short-term performance pressures, and financial market regulations often inhibit them from investing in long-term low-carbon assets (Kaminker and Stewart, 2012). Industrial firms also face constraints with extended payback periods, since they typically operate with a short-term horizon that requires rapid positive returns on investment (Della Croce et al., 2011). A significant positive consideration, however, is that low-carbon projects like waste heat, geothermal, wind, and solar have zero or negligible fuel price volatility risk.

Human resources and institutional capacity: The lack of technical and business capabilities at the firm, financial intermediary and regulatory level are significant barriers to harness low-carbon technologies, especially in many developing economies (Ölz and Beerepoot, 2010). In countries where private sector actors do not only own the low-carbon technology but are also predominately responsible for the diffusion of technologies in the market, capacity building efforts need to focus on these actors' ability to develop, fund, and deploy the respective technologies (Lall, 2002; Figueiredo, 2003; Mitchell et al., 2011).

16.4.3 Financial instruments

Policy instruments to incentivize mitigation activities are assessed in depth in Chapters 13, 14, and 15. Evidently a missing price signal for carbon emissions is a major obstacle for low-carbon investments. But not only in absence of such a price signal, other important measures can be applied to reduce critical barriers for low-carbon investment. Basic financial instruments are illustrated in Figure 16.1 and introduced in Section 16.4.1. This subsection focuses on three types of financial instruments with the following purposes: reducing risk, reducing the cost of capital, and providing access to capital, as well as enhancing cash-flows. Figure 16.5 illustrates in a simplified manner how these instruments can enhance market competitiveness of low-carbon projects. There is a growing literature on how the public sector can use these instruments to mobilize additional private finance, and can help to improve the risk-return profile of investments for low-carbon activities.

16.4.3.1 Reducing investment risks

Risk mitigation can play an essential part in helping to ensure that a successful project financing structure is achieved by transferring risk away from borrowers, lenders, and equity investors. Various instruments provided by private insurers, and by means of public mechanisms, can help to partially or fully reduce the exposure of investors to

Figure 16.5 | Instruments to enhance market competitiveness of low-carbon projects.

political risk, exchange rate fluctuations, business interruption, shortfalls in output, delays or damage during fabrication, construction, and operation of a product, project, and company (Marsh, 2006).

There is a wide portfolio of proven commercial- and government-supported risk mitigation products that can be instrumental in efficiently expanding low-carbon investment. Their allocation and application requires a substantial level of expertise, experience, and resources available in specialized insurance companies, export credit agencies, and selected commercial and development banks. Examples of such products are highlighted below. They signal the potential for expanded use of risk mitigation instruments to support low-carbon investment (Frisari et al., 2013).

Credit enhancements/guarantees, such as commercial credit insurance and government guarantees, usually cover part of the loan and reduce the loss incurred by a lender if the borrower is unable to repay a loan. The lender must still evaluate the creditworthiness and conditions of the loan, but these instruments can reduce the interest rate and improve the terms, thereby expanding the available credit or reducing the costs (Stadelmann et al., 2011a).

Trade credit insurance provides partial protection against certain commercial risks (e.g., counterparty default) and political risks (e.g., war and terrorism, expropriation, currency transfer, or conversion limitations) and other risks like non-honouring of sovereign financial obligations or breach of contract by sovereign actors (MIGA, 2012; OPIC, 2012). Such insurance is provided by commercial insurance companies and by governments to their manufacturers, exporters, or financiers.

Production and savings guarantees are typically provided to their clients by energy service companies (ESCOs) and large energy performance contracting (EPC) contractors. Only proven practices and technologies are eligible to receive these guarantees, covering both technical risk (from customer payment default due to non-performance attributable to the ESCO or EPC contractor), and comprehensive risk (defaults due to technical and financial creditworthiness of the customer) (IDB, 2011).

Local currency finance can be used if currency fluctuations are particularly risky for a project or company because a major investment is made in foreign currency and revenues are in local currency. Loans in local currency or risk management swaps to hedge foreign currency liability back into respective local currency can be provided by development finance institutions (IFC, 2013; TCX, 2013a). Structured funds like the Currency Exchange Fund (TCX) are dedicated to hedge these cross-border currency and interest rate mismatches (TCX, 2013b).

By the end of 2012, the 20 largest emitting developed and developing countries with lower risk country grades for private sector investments were producing 70 % of global energy-related CO_2 emissions (Harnisch and Enting, 2013). In investment-grade countries, risk mitigation instruments and access to long-term finance can be provided at reasonably low costs, and have the potential to mobilize substantial additional private sector mitigation investments. In other countries, low-carbon investment would have to rely mainly on domestic sources or international public finance.

16.4.3.2 Reducing cost of and facilitating access to capital

In many situations, mitigation measures imply additional or incremental investments. Independent of the specific role of equity or debt finance in these individual investments, and irrespective of potential future reductions of operating and maintenance costs, the level of these investments can be a severe barrier to the investment decisions of different investors (as outlined in Section 16.4.2).

Concessional or 'soft' loans are repayable funds provided at terms more favourable than those prevailing on the market including lower interest rates, longer tenor, longer grace period, and reduced level of collateral. Providers of concessional loans are typically development banks on behalf of governments. In international cooperation, concessional loans of varying degree and type have been established as main financing instruments to support public sector entities and local banks by bilateral and multilateral development banks (Maclean et al., 2008; Birckenbach, 2010; UNEP, 2010, 2011, 2012). In 2011, bilateral finance institutions, for instance, disbursed 73 % of their mitigation finance as concessional loans (UNEP, 2012). National finance institutions provided around 87 % of their climate funding in 2010/2011 via soft loans (Buchner et al., 2012).

Grants are non-repayable funds provided to a recipient for a specific purpose by a government, public financial institution or charity. Grants can play an important role in reducing up-front capital investment costs, and meeting viability gaps for projects that are more expensive than business-as-usual (Buchner et al., 2012).

Rebates provide immediate price reductions for purchase of an eligible product. Rebates can be structured to decline over time, encouraging early adopters and reflecting anticipated technology cost reductions (de Jager and Rathmann, 2008). Rebates are typically administered by retailers of respective products, in cooperation with a government agency.

Tax deductions or tax credits increase the after-tax cash flow for a specific investment. Hence, they can have a similar effect as soft loans by reducing the net annual payments for the amortization of a capital investment. They can be useful in enticing profitable enterprises to enter the market for renewable energies to reduce their tax liabilities. However, they require to be embedded in a country's tax system and a base in the tax code. Additionally, the specific level cannot be easily adapted to changed market conditions and will depend on the specific tax burden of the taxed entity (Wohlgemuth and Madlener, 2000).

Equity plays a critical role in financing a project and it is potentially attractive for governments to provide equity to companies or projects to support desirable activities. At the same time, limited expertise of the public sector in allocating capital in risky operations and in management of companies, and problems arising from the relationships of owners and regulators, are frequently cited as reasons against a broad public engagement as equity investor. In support of emission mitigation activities, a number of approaches have been successfully demonstrated. Because of the challenges discussed above, some public sector investors have decided to limit their equity investment to minority stakes and apply clear investment criteria to avoid crowding-out of private investors and to use defined exit strategies (IFC, 2009).

16.4.3.3 Enhancing cash flow

Nationally agreed **feed-in tariffs** (FITs) or **third-party guaranteed renewable energy premiums** for individual power purchase agreements provide a secure long-term cash-flow to operators of renewable energy systems—based on technology, system size, and project location. Debt and equity for a project can hence be secured due to the long duration, the guaranteed off-take of the electricity generated, and the grid access. Consequently, FITs do not only increase and stabilize the return, but also reduce the risks for developers, lenders, and investors. As a result, the cost of capital and required rate of return can be reduced as well (Cory et al., 2009; Kubert and Sinclair, 2011). The FITs for renewable energy have been implemented in a broad range of industrialized and developing countries (Fulton et al., 2010). The level of the FIT for a specific technology, region and time determines the effectiveness and efficiency of the programme, but it is difficult to establish the appropriate level up front and to adapt it as the market evolves and the technology matures.

CO_2 Offset-Mechanisms can also provide additional cash flow via the sales of credits to support the economics of a mitigation investment. Unlike renewable energy premiums, however, there is uncertainty about the future level of this payment stream. This has made many financiers hesitant to provide debt finance for these projects. Some MDBs, like the ADB have a provision to buy credits upfront contributing to investment capital and reducing uncertainty on the future cash-flows from the sale of carbon credits (ADB, 2011; Asian Development Bank, 2012).

16.5 Institutional arrangements for mitigation financing

Institutions are essential to channel climate finance to mitigation and adaptation measures (Stadelmann, 2013) and to ensure that the actions funded respond to national needs and priorities in an efficient and effective way.[26] Through institutions, knowledge is accumulated, codified, and passed on in a way that is easily transferable and used to build capacities, share knowledge, transfer technologies, help develop markets, and build enabling environments for effective climate investments. Without proper institutions, some actions and investments may remain simply as stand-alone projects with no lasting effects, or a one-off capital equipment supply rather than a transaction with a transfer of skills, know-how, full knowledge of the technology, and a contribution to a broader system of innovation and technological change (Ockwell et al., 2008).

16.5.1 International arrangements

Global arrangements for climate change mitigation finance are essential for several reasons. Most commonly cited is the fact that because the earth's climate is a public good, investing within borders is often not seen as beneficial to a particular country unless doing so becomes a collective effort (Pfeiffer and Nowak, 2006). The UNFCCC, among others, was established to address this dilemma and turn the global effort on climate change into a collective action that would be seen by all as beneficial to the whole (Burleson, 2007). Trusted institutions are needed to channel and implement the funding in an orderly and efficient process.

Funds that are part of the financial mechanism of the UNFCCC are subject to guidance from the COP. Until recently, these included only the GEF Trust Fund, the SCCF and the LDCF, all of which are administered by the GEF (see Section 16.2.1.1) (UNFCCC, 2013b). In 2010, the COP decided to establish the GCF to be designated as a new operating entity of the Financial Mechanism (UNFCCC, 2010). The GCF, that is currently being operationalized, is expected to become the main global fund to support climate action in developing countries, but it has not yet been capitalized. In addition, the Adaptation Fund has been established under the Kyoto Protocol.

The UNFCCC recognizes that funding for mitigation may come from a variety of sources and through a variety of channels beyond the financial mechanism, such as multilateral and bilateral institutions engaged in official development assistance. There has been an expansion in the number of public and private climate funds in the last decade. The UNDP estimates that over the last decade some 50 international public funds, 45 carbon market funds, in addition to 6000 private equity funds (set up largely independent of international climate policy) have been established for the purpose of funding climate change-related activities (UNDP, 2011). Some of these, such as CIFs are multi-donor funds administered by the World Bank but with their own governance and

[26] The term 'institution' in this context is defined narrowly to mean an established organization dedicated to facilitate, manage, or promote mitigation finance, as opposed to the broader meaning of the term commonly used in the study of the social sciences and used to mean a structure or mechanism of social order and cooperation governing the behaviour of individuals in society, e.g., the institutions of marriage or religion.

organizational structure. The CIFs were designed as an interim measure to demonstrate how scaled-up support can be provided and include a sunset clause linked to progress on the financial architecture under UNFCCC. They consist of two trust funds: the Clean Technology Fund (CTF), which promotes scaled-up financing for demonstration, deployment, and transfer of low-carbon technologies with significant potential for long-term GHG emissions savings, and the Strategic Climate Fund (SCF), under which are three separate initiatives for piloting transformational, scaled-up action on climate change (World Bank, 2011b; c). The pledges and contributions to the CIFs are recorded as ODA, and therefore constitute a multi-bilateral arrangement (World Bank, 2010).

The CDM and carbon funds are directly linked to emission. Prior to the decline of certificate prices, they played a central role in attracting climate investments. The CDM is one of three trading mechanisms created by the Kyoto Protocol that a developed country can use to help meet its national commitment. The CDM allows a developed country to use credits issued for emission reductions in developing countries. The other two mechanisms—Joint Implementation (JI) and International Emissions Trading (IET)—involve only developed countries with national commitments. The CDM is the largest of the mechanisms (UNFCCC, 2013c). Some of the carbon funds have been established by multilateral financial institutions. The World Bank established the first fund, the Prototype Carbon Fund, in 1999, and has since created several additional funds (World Bank, 2013).

There are several institutions promoting mitigation finance by private actors, which frequently combine financial power of up to several trillions. However, their scope of work differs considerably. Some of the major private sector institutions include inter alia the World Business Council on Sustainable Development (WBCSD) (WBCSD, 2013), the Climate Markets and Investment Association (CMIA) (CMIA, 2013), and the Global Investor Coalition on Climate Change (Global Investor Coalition on Climate Change, 2013).

Regional arrangements play an important role in fostering regional cooperation and stimulating action and funding. These regional institutions include the regional multilateral development banks and the regional economic commissions of the United Nations on the multilateral side.27 They are increasingly engaging in the promotion of mitigation and adaptation activities in their respective regions and establishing and helping to manage regional financing arrangements (Sharan, 2008). In the Asia and Pacific region, examples of regional financial arrangements to promote funding for mitigation activities include ADB´s Clean Energy Financing Partnership Facility, the Asia Pacific Carbon Fund, and the Future Carbon Fund. Other regional development banks have been equally active (Asian Development Bank, 2013a; b; c).

[27] Economic Commission for Latin America, Inter American Development Bank (IDB), Economic Commission for Africa (ECA), African Development Bank (AfDB), Economic Commission for Asia and the Pacific (ESCAP), Asian Development Bank (ADB), Economic Commission for Europe (ECE), European Bank for Reconstruction, and Development (EBRD).

Regional groupings such as the Economic Community for West African States (ECOWAS), the Association of Southeast Asian Nations (ASEAN), the Secretariat for Central American Economic Integration, Mercosur, Corporación Andina de Fomento, and the Andean Pact, to name just a few, have been actively promoting sub-regional integration of energy systems and cooperation in climate change activities in developing countries for some years. In the developed world, one of the best examples of these regional political groupings is the European Union, which has been very active in the area of climate change and in supporting activities in developing countries.

Bilateral cooperation arrangements are widely used by donor countries to provide funding to partner country governments and their implementing organizations. They frequently involve development banks and agencies with a proven track record in international cooperation. The three principal means to channel climate change funding bilaterally are (1) bilateral programmes for funding international cooperation in the energy, water, transport, or forestry, (2) dedicated funding windows established to target climate change funding open to a wider range of implementing institutions, and (3) new funds implemented by bilateral development institutions with their own governance structure. The OECD has established a framework for the implementation and reporting modalities that can be applied to all climate-relevant ODA and partially for other official flows (see OECD, (2013b) for agreed principles on statistics, effectiveness, evaluation, and the like). Officially supported export credits provided by export credit agencies on behalf of national governments are also covered by a respective OECD arrangement (OECD, 2013c).

Triangular cooperation arrangements are defined by the OECD as those involving a traditional donor, most likely a member of DAC, an emerging donor in the south (providers of South-South Cooperation), and the beneficiary countries or recipients of development aid (Fordelone, 2011). Although they have grown in number in recent years, triangular arrangements, and particularly those for climate change financing, are a relatively recent mode of development cooperation (ECOSOC, 2008). These arrangements have attracted a number of countries particularly for technology cooperation across sectors or specified industries. The rise of triangular arrangements has been driven by the growing role of middle-income countries and their increasing presence in providing development co-operation in addition to receiving it, and by the desire to experiment with other types of cooperation where the experience of developing countries can be brought to bear.

16.5.2 National and sub-national arrangements

The landscape of institutional arrangements for action on climate change is diverse. In many countries, actions on climate change are not clearly defined as such. Consequently, many of the national arrangements that exist to promote programmes and activities that contribute to mitigation do not appear in the literature as institutions dedicated to support climate finance.

In many countries, particularly in developed countries and in a few larger developing countries, finance for mitigation comes mainly from the private sector, often with public support through regulatory and policy frameworks and/or specialized finance mechanisms. Institutional arrangements and mechanisms that are successful in mobilizing and leveraging private capital tend to be more cost-effective in climate change mitigation, but some projects with low private investments (e.g., projects reducing industrial GHGs or projects owned by state-owned enterprises) are also among the most cost-effective (Stadelmann, 2013). The institutions and public finance mechanisms are diverse, but all aim to help commercial financial institutions to do this job effectively and efficiently. Many of the institutions support specialized public finance mechanisms such as dedicated credit lines, guarantees to share the risks of investments and debt financing of projects, microfinance or incentive funds, and schemes to mobilize R&D and technical assistance funds to build capacities across the sectors, including the private and commercial sectors (Maclean et al., 2008). National development banks play an important role in financing domestic climate projects in many countries especially by providing concessional funding (Smallridge et al., 2012; Höhne et al., 2012; IDFC, 2013).

Many developing countries, other than the larger ones, are trying to cope with the multiplicity of sources, agents and channels offering climate finance (Glemarec, 2011). These efforts take two forms.

One form is coordination of national efforts to address climate change by relevant government institutions. Very few developing countries have an institution fully dedicated to climate finance (Gomez-Echeverri, 2010). Rather, climate finance decisions involve multiple ministries and agencies often coordinated by the ministry of the environment. Involvement of ministries of foreign affairs and ministries of finance is becoming more common due to their engagement in international negotiations and the promise of increased resources under UNFCCC.

The second form is the establishment of specialized national funding entities designed specifically to mainstream climate change activities in overall development strategies. These institutions blend international climate funding with domestic public funds and private sector resources (Flynn, 2011). Table 16.2 lists examples of national funding entities. A common feature is the desire to allocate resources for activities that are fully mainstreamed to the national needs and priorities. To do this, the national funding entities seek to tap the numerous international sources of climate finance and supplement them with domestic resources. They are also expected to develop the governance and capacity requirements for 'direct access' to funds from the Adaptation Fund and the GCF.[28]

[28] Direct access means that an accredited institution in the recipient country may receive funds directly to implement a project. Currently, most international funding institutions insist that projects be implemented by a multilateral development bank or UN agency.

In many countries, sub-national arrangements are increasingly becoming an effective vehicle for advancing energy and climate change goals. These arrangements and the institutions that support them are being established to advance regional collaboration in areas of common interest and to benefit from greater efficiency and effectiveness through actions with greater geographical coverage (Setzer, 2009). For example, because of their population densities and economic activities, cities are major contributors to global GHG emissions, and as such they are major potential contributors to worldwide mitigation efforts (Corfee-Morlot et al., 2009). In recent years, there has been an increase in the number of networks and initiatives specifically dedicated to enhance the role of cities in the fight against climate change. As a result, these initiatives are potentially big contributors to mitigation efforts, but because of the lack of clear processes linking these initiatives to national and international climate change policy, their impact in broader policy frameworks is less certain (UN-Habitat, 2011). One possible opportunity for enhancing this linkage is through the new National Appropriate Mitigation Actions (NAMAs) being submitted by developing countries within the context of UNFCCC. The NAMA process agreed to at Bali provides an opportunity to incorporate sectoral policies with relevance to their cities (Li, 2011).

16.5.3 Performance in a complex institutional landscape

The institutional landscape for climate finance is becoming increasingly complex as interest of actors to enter the field of climate change finance and mitigation activities in developing countries increases. As in other international cooperation, there are discussions about effectiveness of climate finance (see OECD (2008) for politically agreed principles on aid effectiveness). Concerns have been raised about diverting attention and resources from development aid, i.e., ODA, such as health and education, the additionality of expanded funding for mitigation and adaptation (Michaelowa and Michaelowa, 2011), the difficulty of defining and measuring comparable results and achieving coherence with national priorities and development strategies, the lack of transparency, the fragmentation and duplication of efforts, and that the number of established funds may undermine the authority of the operating entities of the financial mechanism of the UNFCCC (Poerter et al., 2008). The proliferation of climate funds (HBF and ODI, 2013) and funding channels with their own governance procedures can create a substantial bureaucratic burden for recipients (Greene, 2004). Compounding these problems is the fragmentation of governance architectures that prevail in most developing countries (Biermann et al., 2009). Climate finance may be more effective if the operation of related institutions is streamlined and the capacity in developing countries to cope with the increasing number of these institutions is developed further. Evidence on the effectiveness of institutions to mainstream climate change mitigation and adaptation activities is currently lacking.

Table 16.2 | A sample of national funding entities in developing countries. Sources: Adapted from Gomez-Echeverri (2010), updated based on UNDP and World Bank (2012), Amazon Fund (2012), BCCRF (2012), CDMF (2012), ICCTF (2012), World Bank (2012b), UNDP (2013b).

Name, country, establishment	Description	Source of fund and operations	Governance
Amazon Fund, Brazil (2010)	Established to combat deforestation and promote sustainable development in the Amazon. Focus: adaptation and mitigation	Designed to attract national and private investment for Amazon rainforest projects as well as donations and earnings from non-reimbursable investments made	Managed by the Brazilian Development Bank (BNDES), a Guidance Committee composed of federal and state governments and civil society, and a Technical Committee
Bangladesh Climate Change Resilience Fund (BCCRF) (2010)	Established to provide support for the implementation of Bangladesh's Climate Change Strategy and Action Plan 2009–2018 and particularly vulnerable communities. Focus: adaptation and mitigation	Designed to attract funds from UNFCCC finance mechanisms, and direct donor support	Managed by a board composed of Ministers of Environment, Finance, Agriculture, Foreign Affairs, and Women and Children Affairs and disaster management, as well as donors and civil society organizations
China CDM Fund (CDMF) (2007)	Established jointly by Ministries of Finance, Foreign Affairs, Science and Technology, and National Development and Reform Commission (NDRC). Focus: mitigation	Funded by revenues generated from CDM projects in China, as well as grants from domestic and international institutions	Governed by the Board of the China CDM Fund that comprises representatives of seven line ministries, and managed and operated by a management centre affiliated with the Ministry of Finance
Indonesia Climate Change Trust Fund (ICCTF) (2010)	Established jointly by the National Development Planning Agency and Ministry of Finance to pool and coordinate funds from various sources to finance Indonesia's climate change policies and programmes	Currently funded by grants from development partners but designed for direct access to international climate funding and to attract private funding	The UNDP is an interim Trustee operating under a Steering Committee headed by the National Development Planning Agency that also includes donors and other line ministries
Guyana REDD Investment Fund (GRIF) (2010)	Established to finance activities under the Low Carbon Development Strategy of Guyana and to create an innovative climate finance mechanism. Focus: mitigation and adaptation	Designed to attract donor support. Operates under a performance-based funding modality, based on an independent verification of Guyana's deforestation and forest degradation rates and progress on REDD+ enabling activities	A Steering Committee with members of government and financial contributors chaired by the Government of Guyana, is the decision making and oversight body. The International Development Association (IDA) of the World Bank Group acts as Trustee and the partner entities provide operational services
Ethiopia Climate Resilient Green Economy Facility (2012)	Established to support country's vision of attaining a middle-income economy with low-carbon growth by 2020. Focus: mitigation and adaptation	Designed to mobilize, access, and blend both local and international public and private resources to support Ethiopia's Climate Resilience Green Economy Strategy	Governed by a Ministerial Steering Committee chaired by Ministry of Finance and Economic Development with an advisory body composed of development partners, multilateral organizations, national non-governmental organizations (NGOs), civil society, private sector, and academia

16.6 Synergies and tradeoffs between financing mitigation and adaptation

This section introduces a conceptual framework linking adaptation and mitigation in terms of financing and investment. Estimates of investments needed for mitigation are provided in Section 16.2.2, and for adaptation investments in the sectoral chapters of the Working Group II report. First, this section addresses the interactions of financing adaptation and mitigation in terms of their specific effectiveness and tradeoffs, as well as their competition for funding over time. Second, it discusses examples of integrated financing approaches.

16.6.1 Optimal balance between mitigation and adaptation and time dimension

Both mitigation and adaptation measures are necessary to effectively avoid harmful climate impacts. However, an assessment on whether, where, and which types of adaptation and mitigation measures and policies are substitutes or complements requires theoretical analysis and empirical evidence (Section 13.3.3). Investing in mitigation may reduce the need to invest in adaptation, and vice versa. Several authors have recognized that optimal mitigation and adaptation strategies should be jointly determined (Schelling, 1992; Kane and Shogren, 2000; Dellink et al., 2009; Bosello et al., 2010), including from the perspective of a global decision maker. The optimal balance of mitigation and adaptation depends on their relative costs, for any given profile of climate change impacts. To avoid inefficiencies, the socially discounted rate of return on resources invested in mitigation and adaptation should be equal. Therefore, mitigation and adaptation compete to attract investments. From the perspective of simple economic models, a reduction in the costs of mitigation should lead to more mitigation and less adaptation, and, according to this view, they are substitutes (Ingham et al., 2005).

From the perspective of development and climate studies (Tol, 2007; Ayers and Huq, 2009), climate change in most cases will impact the economy by reducing its production potential (part of the residual damage), and the level of impacts will depend on its efficiency, diversity, and vulnerability, as well as on how institutions are able to adapt.

On the other hand, policies to address mitigation and/or adaptation could promote the transfer of technologies and financial resources, and strengthen institutions and markets, which could lead to the enhancement of a country's productive capacity (Halsnæs and Verhagen, 2007).

Combined mitigation and adaptation strategies taking into account cost-effectiveness may involve economic tradeoffs. The optimal balance, including allocation of resources, should be determined taking into account possible co-benefits, which may be difficult to assess. Many actions that integrate mitigation and adaptation have enough co-benefits to make obvious sense of their immediate implementation (see Working Group II report), in spite of the fact that in many cases, assessment of their effective combination, cost-effectiveness, and tradeoffs requires improved information, improved capacities for analysis and action, and further policymaking (Wilbanks and Sathaye, 2007). Modelling of any direct interaction between adaptation and mitigation in terms of their specific effectiveness and tradeoffs would also be desirable (Wang and McCarl, 2011).

An analysis on the time composition (timing of mitigation and adaptation) of the optimal climate change strategy is also important to assess how to best allocate climate change funds. Emerging frameworks for assessing the tradeoffs between adaptation and mitigation include those from the point of view of risks and costs. People invest resources to reduce the risk they confront or create (Ehrlich and Becker, 1972; Lewis and Nickerson, 1989). Recent studies have used integrated assessment models to numerically calculate the optimal allocation of investments between mitigation and adaptation. They confirm the analytical insights of Kane and Shogren (2000) and suggest that investments in mitigation should anticipate investments in adaptation (Lecocq and Shalizi, 2007; de Bruin et al., 2009; Bosello et al., 2010). The reason for this is because climate and economic systems have inertia and delaying action increases the costs of achieving a given temperature target. These studies suggest that the competition between mitigation and adaptation funds extends over time.

By arguing "uncertainty on the location of damages reduces the benefits of 'targeted' proactive adaptation with regard to mitigation and reactive adaptation", some authors reinforce the idea that it is optimal to wait to invest in adaptation (Lecocq and Shalizi, 2007). For the above reasons, Carraro and Massetti (2011) suggest that the greatest share of the GCF should finance emissions reductions rather than adaptation in developing countries. Other authors propose a framework that could integrate into an optimization model not only mitigation and adaptation, but also climate change residual damages. In the light of the uncertain impacts of climate change, prioritizing mitigation measures is justified, on the basis of a precautionary approach. Adaptation actions "should be optimally designed, consistently with mitigation, as a residual strategy addressing the damage not accommodated by mitigation" (Bosello et al., 2010).

Wang and McCarl (2011) recognizes that, in terms of an overall investment shared between mitigation and adaptation, mitigation tackles the long-run cause of climate change while adaptation tackles the short-run reduction of damages and is preferred when damage stocks are small. Contrary to Bosello et al. (2010), they advocate that, instead of taking adaptation as a 'residual' strategy, well-planned adaptation is an economically effective complement to mitigation since the beginning and should occur in parallel. Thus, adaptation investment should be considered as an important current policy option due to the near-term nature of given benefits.

Moreover, the optimal balance of adaptation and mitigation measures and investments should be determined in function of the magnitude of climate change; "if mitigation can keep climate change to a moderate level, then adaptation can handle a larger share of the resulting impact vulnerabilities" (Wilbanks et al., 2007). While the uncertainties about specific pathways remain, and although there are different considerations on their optimal balance, there is a general agreement that funding for both mitigation and adaptation is needed.

16.6.2 Integrated financing approaches

Despite the lack of modelling of any direct interaction between adaptation and mitigation in terms of financing, there is an increasing interest in promoting integrated financing approaches, addressing both adaptation and mitigation activities in different sectors and at different levels. Although the GCF will have thematic funding windows for adaptation and mitigation, an integrated approach will be used to allow for cross-cutting projects and programmes (UNFCCC, 2011c, para 37).

The theoretical literature reviewed in Section 16.1.1 provides only general guidance on financing mitigation and adaptation measures. Analysis of specific adaptation and mitigation options in different sectors reveals that adaptation and mitigation can positively and negatively influence the effectiveness of each other (see also Working Group II report). Particular opportunities for synergies exist in some sectors (Klein et al., 2007), including agriculture (Niggli et al., 2009), forestry (Ravindranath, 2007; Isenberg and Potvin, 2010), and buildings and urban infrastructure (Satterthwaite, 2007).

Mitigation activities have global benefits while most adaptation activities benefit a smaller geographical area or population. Funding sources with a regional, national or sub-national perspective, therefore, will increasingly favour adaptation over mitigation measures (Dowlatabadi, 2007; Wilbanks and Sathaye, 2007). Thus the sources of climate finance available may yield a mix of mitigation and adaptation measures quite different from the global optimal mix. Additional studies "to understand the complex way in which local adaptation aggregates to the global level" are needed (Patt et al., 2009). Although the optimal mix cannot be determined precisely, the availability of international climate finance for both mitigation and adaptation is necessary to counteract such tendencies.

Taking into account the strong regional nature of climate change impacts, a regional financing arrangement will be more responsive and relevant than a global one, and may play an important role in adaptation (Sharan, 2008). Regional funding tools have made arrangements for financing adaptation activities in complement to mitigation measures: e.g., the Poverty and Environment Fund (PEF) of the Asian Development Bank promotes the mainstreaming of environmental and climate change considerations into development strategies, plans, programmes, and projects of the bank (ADB, 2003).

The AfDB acts as manager and coordinator of new funding for the Congo Basin forest ecosystem conservation and sustainable management (UNEP, 2008). According to the operational procedures by AfDB, to be eligible for financing under the Congo Basin Forest Fund (CBFF), project proposals and initiatives considered for funding should, among other things, aim at slowing the rate of deforestation, contribute to poverty alleviation, provide some contribution to climate stabilization and GHG emissions reduction, and may show environment, economic, and social risk assessment in addition to appropriate mitigation measures, as well as be supported by national strategies to combat deforestation while preserving biodiversity and promoting sustainable development (AfDB, 2009). See Section 14.3.2 for additional information on regional examples of cooperation schemes identifying synergies between mitigation and adaptation financing.

Many ongoing bilateral and multilateral development activities address mitigation and adaptation at the same time. A recent survey by Illmann et al. (2013) discusses examples from agriculture (conversion of fallow systems into continuously cultivated area; the reuse of wastewater for irrigation), forestry (reforestation with drought-resistant varieties; mangrove plantations), and from the energy sector (rural electrification with renewable energy, production of charcoal briquettes from agricultural waste). The study identifies significant potential to further mobilize these synergies within existing development cooperation programmes.

Another point of debate regarding synergies and tradeoffs between financing mitigation and adaptation relates to the conceptual framework that suggests allocating responsibility for international financing of adaptation based on the historical contribution of countries to climate change in terms of GHG emissions and their capacity to pay for the costs of adaptation at international level (Dellink et al., 2009). The provision of international climate finance, of course, raises other issues of equity and burden sharing, which are beyond the scope of this chapter.

16.7 Financing developed countries' mitigation activities

This and the next section consider the manner in which developed and developing countries may choose to finance the incremental investments and operating costs associated with GHG mitigation activities. It is fully recognized that a country's individual circumstances will in large part determine how financing is accomplished, and further, that individual national circumstances vary widely among members of the developed and developing country groups.

The manner in which developed countries finance their mitigation activities depends largely on the policies chosen to limit GHG emissions and the ownership of the sources of emissions. Policies and ownership also determine the distribution of the burdens posed by the financing needs, i.e., if it will be financed by households and firms through higher prices, taxes, or both.

In 2011 and 2012, on average, 177 billion USD of global climate finances were invested in developed countries (49 % of the global total climate finance) of which the vast majority (81 %) originated in the same country as the investment was undertaken (2011/2012 USD) (Buchner et al., 2013b). Due to the financial crisis investment in renewable energy in developed countries dropped 14 % in 2009 (Frankfurt School-UNEP Centre and BNEF, 2012), but saw a rapid recovery due to the green stimulus packages (IEA, 2009; REN21, 2010). The eight development banks of OECD countries that are members of the International Development Finance Club (IDFC) allocated 28 billion USD (2011 USD) and 33 billion USD (2012 USD) 'green'[29] finance to domestic projects in 2011 and 2012, respectively (Höhne et al., 2012; IDFC, 2013). Public climate finance was also directed to developing countries at a range of 35–49 billion USD per year for 2011 and 2012 (2011/2012 USD) (Buchner et al., 2013b).

Without climate policy, an estimated 96 (70–126) billion USD per year of investment in fossil power generation will occur in developed countries from 2010–2029; from 2030 to 2049, this figure increases to 131 (86–215) billion USD per year. In a climate policy scenario compatible with a 2 °C warming limit in 2100, OECD countries are expected to reduce investments in fossil power generation by 57 % (–2 to –89 %) during 2010–2029, but investments will drop by 90 % (–80 to –98 %) during 2030–2049. Investment in renewable power generation instead will increase by 86 % (58 to 116 %) during 2010–2029 and by 200 % (77 to 270 %) during 2030–2049 (based on IEA (2011), Carraro et al. (2012), Calvin et al. (2012) and McCollum et al. (2013), used in Section 16.2.2).

To date, public sourcing for climate finance originates primarily from general tax revenues. However, under ambitious stabilization targets, financial sources that yield mitigation benefits have the potential to generate high revenues that could be used for climate finance. Carbon taxes and the auctioning of emissions allowances carry the highest potential, a phaseout of fossil fuel subsidies, and a levy or emission trading scheme for international aviation and shipping emissions are

[29] 'Green' finance as reported by IDFC includes projects with other environmental benefits. Approximately 93 % (80 %) of the 'green' finance by IDFC in 2011 (2012) was climate finance (Höhne et al., 2012; IDFC, 2013).

estimated to generate considerable revenues as well (UNFCCC, 2007; AGF, 2010; World Bank Group et al., 2011).

Most developed countries offer a reasonably attractive core and broader enabling environment for climate investments. Developed countries, as do many emerging economies, combine substantial energy-related GHG emission reduction potential with low country risks. At the end of 2012, 29 out of 36 assessed developed countries fell into the group of lower risk country grade, producing 39 % of global fuel-related CO_2 emissions (Harnisch and Enting, 2013). Private finance can thus be the main source of low-carbon investment in these countries, however private actors are often dependent on public support through regulatory and policy frameworks and/or specialized finance mechanisms.

While macroeconomic and policy risk have been reasonably low in the past, low-carbon policy risks have affected investments in developed countries. In principle, risk-mitigation instruments and access to long-term finance can be provided at reasonably low cost. Suitable institutions exist to implement specialized public finance mechanisms to provide dedicated credit lines, guarantees to share the risks of investments, debt financing of projects, microfinance or incentive funds, and schemes to mobilize R&D and technical assistance funds for building capacities across the sectors. The institutions and types of public finance mechanisms in existence across countries are diverse but share the common aim of helping commercial financial institutions to effectively and efficiently perform this job (Maclean et al., 2008).

In 2012, the most widespread fiscal incentives were capital subsidies, grants, and rebates. They were in place in almost 90 % of high-income countries. In 70 % of the countries public funds were used to support renewable energy, e. g., public investment loans and grants. Feed-in tariffs were in place in 27 high-income countries at national or state level (75 % of all countries analyzed) (REN21, 2012).

16.8 Financing mitigation activities in and for developing countries including for technology development, transfer, and diffusion

Analogous to the previous section, this section outlines key assessment results for mitigation finance in and for developing countries, i. e., embracing domestic flows as well as financing provided by developed countries.

An estimated 51 % of the total global climate finance in 2011 and 2012, namely on average 182 billion USD per year, was invested in developing countries (2011/2012 USD). Thereof, 72 % was originating in the same country as it was invested) (Buchner et al., 2013b). The total climate finance flowing from developed to developing countries is estimated to be between 39 and 120 billion USD per year in 2011 and 2012 (2011/2012 USD). This range covers public and the more uncertain flows of private funding for mitigation and adaptation. Clapp et al. (2012) estimate the total at 70–120 billion USD per year based on 2009–2010 data. Data from Buchner et al. (2013a) suggest a net flow to developing countries for 2010 and 2011 of the order of 40 to 60 billion USD. North-South flows are estimated at 39 to 62 billion USD per year for 2011 and 2012 (2011/2012 USD) (Buchner et al., 2013b).

Public climate finance provided by developed countries to developing countries was estimated at 35 to 49 billion USD per year in 2011 and 2012 (2011/2012USD) (Buchner et al., 2013b). Multilateral and bilateral institutions played an important role in delivering climate finance to developing countries. Seven MDBs[30] reported climate finance commitments of about 24.1 and 26.8 billion USD in 2011 and 2012, respectively[31] (2011 and 2012 USD) (AfDB et al., 2012a; b, 2013). These institutions manage a range of multi-donor trust climate funds, such as the Climate Investment Funds, and the funds of the financial mechanism of the Convention (GEF, SCCF, LDCF). The GCF is expected to become an additional international mechanism to support climate activities in developing countries. Bilateral climate-related ODA commitments were at an average of 20 billion USD per year in 2010 and 2011 (2010/2011 USD) (OECD, 2013a)[32] and were implemented by bilateral development banks or bilateral agencies, provided to national government directly or to dedicated multilateral climate funds (Buchner et al., 2012). However, bilateral and multilateral commitments are not fully comparable due to differences between methodologies.

Climate projects in developing countries showed a higher share of balance-sheet financing and concessional funding provided by national and international development finance institutions than developed countries (Buchner et al., 2012). Domestic public development banks played an important role in this regard. The 11 non-OECD development

30 African Development Bank (AfDB), the Asian Development Bank (ADB), the European Bank for Reconstruction and Development (EBRD), the European Investment Bank (EIB), the Inter-American Development Bank (IDB), the World Bank (WB), and the International Finance Corporation (IFC).

31 The reporting is activity-based allowing counting entire projects but also project components. Recipient countries include developing countries and 13 EU member states. It covers grant, loan, guarantee, equity, and performance-based instruments, not requiring a specific grant element. The volume covers MDBs' own resources as well as external resources managed by the MDBs that might also be reported to OECD DAC (such as contributions to the GEF, CIFs, and Carbon Funds).

32 It covers total funding committed to projects that have climate change mitigation or adaptation as a 'principal' or 'significant' objective. The ODA is defined as those flows to countries on the DAC List of ODA Recipients and to multilateral institutions provided by official agencies or by their executive agencies. Resources must be used to promote the economic development and welfare of developing countries as a main objective and they must be concessional in character (OECD, 2013a).

Box 16.3 | Least Developed Countries' investment and finance for low-carbon activities

This box highlights key issues related to investment and finance for Least Developed Countries (LDCs), however some of these issues are certainly also relevant for other developing countries.

Climate change increased the challenges LDCs are facing regarding food, water, and energy that exacerbate sustainable development. Most LDCs are highly exposed to climate change effects as they are heavily reliant on climate-vulnerable sectors such as agriculture (Harmeling and Eckstein, 2012). Most of the LDCs, already overwhelmed by poverty, natural disasters, conflicts, and geophysical constraints, are now at risk of further devastating impacts of climate change. In turn, they contribute very little to carbon emissions (Baumert et al., 2005; Fisher, 2013).

At the same time, LDCs are faced with a lack of access to energy services and with an expected increase in energy demand due to the population and GDP growth. Of the 1.2 billion people without electricity in 2010, around 85 % live in rural areas and 87 % in Sub-Saharan Africa and Southern Asia. For cooking, the access deficit amounts to 2.8 billion people who primarily rely on solid fuels. About 78 % of that population lives in rural areas, and 96 % are geographically concentrated in Sub-Saharan Africa, Eastern Asia, Southern Asia, and South-Eastern Asia (Sustainable Energy for All, 2013) (see Section 14.3.2.1 for other estimates provided by the literature). By investing in mitigation activities in the early and interim stages, access to clean and sustainable energy can be provided and environmentally harmful technologies can potentially be leapfrogged. Consequently, needs for finance and investment are pressing both for adaptation and mitigation.

Regarding specific mitigation finance needs, there are no robust data for LDCs. It is estimated that shifting the large populations that rely on traditional solid fuels (such as unprocessed biomass, charcoal, and coal) to modern energy systems and expanding electricity supply for basic human needs could yield substantial improvements in human welfare for a relatively low cost (72–95 billion USD per year until 2030 to achieve nearly universal access) (Pachauri et al., 2013). For instance, in Bangladesh, the costs to provide a minimum power from solar home system's energy source to off-grid areas was around 285 USD per household (World Bank, 2012c). However, the very few country studies on mitigation needs and costs are not representative of the whole group of LDCs and are not comparable. Data on international and domestic private sector activities in LDCs are also lacking, as are data on domestic public flows. With respect to North-South flows, the OECD DAC reported that developed countries provided 730 million USD in mitigation related ODA to LDCs in the year 2011. Bangladesh received the highest share with 117 million USD, followed by Uganda and Haiti with more than 70 million USD (OECD, 2012).

Most LDCs have very few CDM projects that are also an important vehicle for mitigation (UNFCCC, 2012d; UNEP Risø, 2013). To improve the regional distribution of CDM projects, the CDM Executive Board has promoted the regulatory reform of CDM standards, procedures, and guidelines. Furthermore, stakeholder interaction has been enhanced and a CDM loan scheme has been established by UNFCCC to provide interest-free loans for CDM project preparation in LDCs (UNFCCC, 2012e).

Some LDCs are starting to allocate public funds to mitigation and adaptation activities, e.g., NAPAs or national climate funds (Khan et al., 2012). However, pressing financial needs to combat poverty favour other expenditures over climate-related activities.

Most LDCs struggle to provide an enabling environment for private business activities, a very common general development issue (Stadelmann and Michaelowa, 2011). It is noteworthy that among the 30 lowest-ranking countries in the World Bank's Doing Business Index, 23 countries are LDCs (World Bank, 2011a). Obstacles to general private business activities in turn hinder long-term private climate investments (Hamilton and Justice, 2009). Due to very high perceived risk in LDCs, risk premiums are very high. This is particularly problematic as low-carbon investments are very responsive to the cost of capital (Eyraud et al., 2011). In a challenging environment, it is difficult to implement targeted public policies and financial instruments to mobilize private mitigation finance. Moreover, the weakness of technological capabilities in LDCs presents a challenge for successful development and transfer of climate-relevant technologies (ICTSD, 2012).

To develop along a low-carbon growth path, LDCs rely on international grant and concessional finance. It is especially important to ensure the predictability and sustainability of climate finance for LDCs, as these countries are inherently more vulnerable to economic shocks due to their structural weaknesses (UNCTAD, 2010).

While all donors and development institutions provide mitigation finance to LDCs, there are some dedicated institutional arrangements, such as the LDCF and the SCCF under the Convention. Some LDCs have also implemented national funding institutions, e.g., Benin, Senegal, and Rwanda in the framework of the Adaptation Fund, or the Bangladesh Climate Change Resilience Fund.

While knowledge and data gaps regarding mitigation finance are generally higher in developing than in developed countries, they are even more severe in LDCs.

bank members of IDFC provided 44 billion USD of domestic 'green'[33] finance in 2011 and 2012 (2011 and 2012 USD) (Höhne et al., 2012; IDFC, 2013).

According to UNFCCC (2011a), Annex II countries provided an average of almost 10 billion USD per year of climate finance to developing countries. In 2009, developed countries committed to provide new and additional resources approaching 30 billion USD of 'FSF' to support mitigation and adaptation action in developing countries during 2010–2012. The sum of the announced commitments exceeds 33 billion USD (UNFCCC, 2011b, 2012b; c, 2013a). Data on the amount actually disbursed is not available. Some analyses question whether these funds were 'new and additional' (Brown et al., 2010; Stadelmann et al., 2010, 2011b).

There is limited robust information on the current magnitude of private flows from developed to developing countries. Clapp et al. (2012) estimate the private investment at 37–72 billion USD per year based on 2009–2010 data (2008/2009 USD) and Stadelmann et al. (2013) estimate foreign direct investment as equity and loans in the range of 10 to 37 billion USD (2010 and 2008 USD) per year based on 2008–2011 data.

In reference scenarios as well as in policy scenarios compatible with a 2 °C warming target in 2100, non-OECD countries absorb the greatest share of incremental investments in power generation technologies. Without climate policy, investments in the power sector are mainly directed towards fossil fuels. About 73 % (65 % to 80 %) of global investment in fossil power plants between 2010–2029, and 78 % (76 to 80 %) between 2030–2049, would flow into in the non-OECD because many developing countries rely on low-cost coal power plants to supply an ever-growing demand of electricity in the scenarios examined (based on IEA (2011), Carraro et al. (2012), Calvin et al. (2012), and McCollum et al. (2013) used in Section 16.2.2). In a climate policy scenario compatible with a 2 °C warming limit in 2100, non-OECD countries are expected to absorb 51 % (34 % to 66 %) of incremental average annual investment in renewables over 2010–2029, and 67 % (61 % to 73 %) over 2030–2049.

In tackling climate change, developing countries face different types and magnitudes of constraints. Out of the 149 assessed developing countries, only 37 were assigned lower risk country grades. These countries, being attractive for international private sector investment in low-carbon technologies, represent 38 % of global CO_2 emissions. However, the majority of developing countries currently exhibits higher country risk grades—reflecting less attractive international investment conditions—and finds it more difficult to attract foreign private investment (Harnisch and Enting, 2013). Moreover, the lack of technical capacity and training systems is a significant barrier for low-carbon investment in many developing economies (Ölz and Beerepoot, 2010). Between 2005 and 2009, developed countries provided 2.5 billion USD of ODA to support creation of general enabling environments in developing countries (2005–2009 USD) (Stadelmann and Michaelowa, 2011).

Since investment risks for low-carbon projects in developing countries are typically perceived to be higher than in developed countries, the cost of capital and the return requirements of investors are respectively higher. The IRR for general infrastructure in developing countries, for instance, is a median of 20 % compared to about 12 % in developed countries (Ward et al., 2009). Access to affordable long-term capital is limited in many developing countries (Maclean et al., 2008), where local banks are not able to lend for 15–25 years due to balance sheet constraints (Hamilton, 2010), such as the mismatch in the maturity of assets and liabilities. In addition, appropriate financing mechanism for end-users' up-take are also often missing (Derrick, 1998). Moreover, equity finance is scarce in many developed countries, increasing the dependence on project finance. Especially in low-income countries, project sponsors frequently rely on external assistance to cover project development costs for many investments because of their high risks and non-commercial nature (World Bank, 2011d).

Many developing countries use a range of incentives for investments in renewable energies (REs), especially fiscal incentives (OECD, 2013d). Public financing instruments to stimulate RE, such as public investment, loans, or grants, were in place in 57 % of the countries analyzed and FITs were established in 39 developing countries in 2012 (REN21, 2012). Carbon pricing has not yet widely been adopted by developing countries, apart from the non-perfect carbon price incentive via the CDM. However, currently new ETS are set up, planned, or under consideration in some developing countries such as China (provinces and cities), Kazakhstan, Ukraine, Chile, Brazil, and South Korea, but it will take time until such ETS will be fully operational and provide enough investment certainty (Kossoy et al., 2013).

Regional groupings such as the ECOWAS, the ASEAN, and the Mercosur, have been actively promoting sub-regional integration of energy systems and cooperation in climate change activities.

On the national level, there is an on-going attempt to cope with the multiplicity of sources, agents, and channels offering financial resources for climate action (Glemarec, 2011). Most developing countries rely on relevant ministries and agencies chaired by the ministry of the environment or finance to coordinate climate change finance (Gomez-Echeverri, 2010). Some developing countries are establishing national implementing entities and funds that mainstream climate change activities into overall development strategies. Often these institutions are designed to blend international funding with domestic and private sector resources (Flynn, 2011).

[33] 'Green' finance as reported by IDFC includes projects with other environmental benefits. Approximately 93 % (80 %) of the 'green' finance by IDFC in 2011 (2012) was climate finance (Höhne et al., 2012; IDFC, 2013).

16.9 Gaps in knowledge and data

Scientific literature on investment and finance for low-carbon activities is still very limited and knowledge gaps are substantive.

- **Common definitions and data availability**. To date there are no common definitions for central concepts related to climate finance or financial accounting rules. Neither are there complete or reasonably accurate data on current climate finance and its components, namely developed country sources or commitments, developing country sources or commitments, international flows, and private vs. public sources. The role of domestic and South-South flows and domestic investments in developing countries is also not adequately understood and documented. Frequently it is not possible to distinguish exactly between adaptation and development finance, since they are closely interconnected. Another difficult assessment is on the differences between funding under the ODA and 'new and additional' funds available. Important metrics like the high-carbon investment by sub-sector and region, the carbon intensity of new investments, downward deviations from reference emission pathways, or the cost-effectiveness of global mitigation investments are not tracked systematically.

- **Model outputs and approaches**. Only very limited model results exist for additional investments and incremental costs to abate CO_2 emissions in sectors other than energy supply, e.g., via energy efficiency in industry, buildings, and transport, as well as in other sectors like forestry, agriculture, and waste, or to mitigate process and non-CO_2 emissions in the petroleum and gas, cement, and chemical industry, or from refrigeration and air conditioning. Very limited analysis has been published that takes a globally consistent perspective of incremental investments and costs at the level of nation states and regions. This perspective could enrich the scientific discussion because global and regional netting approaches among sectors and sub-sectors may fall short of the complexity of real political decision making processes.

- A comprehensive and transparent treatment of investment and technology risks in energy models is not available. The impact of fuel price volatility on low-carbon investments is generally not considered. Reasonably robust quantitative results of the need for additional R&D for low-carbon technologies and practices and on the timing of these needs (infrastructure and technology deployment roadmaps) are not available. While there is literature on mitigation technology diffusion and transfer in general, it is not clear whether specific financial requirements to this end are different from finance for other mitigation activities.

- For the energy sector, there is no convergence on the order of magnitude of net incremental investment costs across its sub-sectors. Interactions of stringent climate policies with overall growth and investment of individual economies and the world economy as a whole are also not yet well understood.

- **Effectiveness and efficiency of climate finance.** Knowledge about enabling environments for effective deployment of climate finance in any country is insufficient. There is very limited empirical evidence to relate the concept of low-carbon activities to macro determinants from a cross-country perspective. More research is especially needed regarding determinants for mitigation investment in LDCs.

- There is only case-specific knowledge by practitioners on the selection and combination of instruments that are most effective at shifting (leveraging) private investment to mitigation and adaptation. There is no general understanding of what are the efficient levers to mobilize private investment and its potential in any country (since they will differ by investment and country).

- The effectiveness of different public climate finance channels in driving low-carbon development is insufficiently analyzed. Estimates of the incremental cost value of public guarantees, export insurances, and non-concessional loans of development banks would provide valuable insights. Little is known on determinants for an economically efficient and effective allocation of public climate finance. A comprehensive assessment of the interrelation between private and public sector actors in sharing incremental costs and risks of mitigation investments, for example, via concessional loans or guarantee instruments has not been undertaken yet.

- There is no agreement yet which institutional arrangements are more effective at which level (international—national—local) and for what investment in which sector. However, an understanding of the key determinants of this efficiency and of the nature of a future international climate policy agreement is needed first.

- **Balance between mitigation and adaptation finance and investment.** The optimal balance, including its time dimension, is a difficult exercise given the lack of modelling of any direct interaction between adaptation and mitigation in terms of their specific effectiveness and tradeoffs. A better-informed assessment of the effective integration of mitigation and adaptation, including tradeoffs and cost avoidance estimates, is needed. Moreover, there is limited research and literature to assess synergies and tradeoffs between and across sector-specific mitigation and adaptation measures from the specific financing and investment point of view.

16.10 Frequently Asked Questions

FAQ 16.1 What is climate finance?

There is no agreed definition of climate finance. The term 'climate finance' is applied both to the financial resources devoted to addressing climate change globally and to financial flows to developing countries to assist them in addressing climate change. The literature includes multiple concepts within each of these broad categories.

There are basically three types of metrics for **financial resources devoted to addressing climate change globally.** *Total climate finance* includes all financial flows whose expected effect is to reduce net greenhouse gas emissions and/or to enhance resilience to the impacts of climate variability and the projected climate change. This covers private and public funds, domestic and international flows, expenditures for mitigation and adaptation, and adaptation to current climate variability as well as future climate change. It covers the full value of the financial flow rather than the share associated with the climate change benefit; e.g., the entire investment in a wind turbine rather than the portion attributed to the emission reductions. The *incremental investment* is the extra capital required for the initial investment to implement a mitigation or adaptation measure, for example, the investment in wind turbines less the investment that would have been required for a natural gas generating unit displaced. Since the value depends on a hypothetical alternative, the incremental investment is uncertain. The *incremental costs* reflect the cost of capital of the incremental investment and the change of operating and maintenance costs for a mitigation or adaptation project in comparison to a reference project. It can be calculated as the difference of the net present values of the two projects. Values depend on the incremental investment as well as projected operating costs, including fossil fuel prices, and the discount rate.

Financial flows to assist developing countries in addressing climate change typically cover the following three concepts. The *total climate finance* flowing to developing countries is the amount of the total climate finance invested in developing countries that comes from developed countries. This covers private and public funds for mitigation and adaptation. *Public climate finance* provided to developing countries is the finance provided by developed countries' governments and bilateral institutions as well as multilateral institutions for mitigation and adaptation activities in developing countries. *Private climate finance flowing to developing countries* is finance and investment by private actors in/from developed countries for activities in developing countries. Under the UNFCCC, *climate finance* is not well-defined. Annex II Parties provide and mobilize funding for climate related activities in developing countries. Most of the funds provided are concessional loans and grants.

FAQ 16.2 How much investment and finance is currently directed to projects that contribute to mitigate climate change and how much extra flows will be required in the future to stay below the 2 °C limit?

Current climate finance was estimated at around 359 billion USD per year of which 337 billion USD per year was invested in mitigation using a mix of 2011 and 2012 data (2011/2012 USD). This covers the full investment in mitigation measures, such as renewable energy generation technologies that also produce other goods or services. Climate finance invested in developed countries amounted to 177 billion USD and in developing countries 182 billion USD (2011/2012 USD).

Climate policy is expected to induce a significant change in investment pattern in all scenarios compatible with a 2 °C limit. Based on data from a limited number of scenarios, there would need to happen a remarkable reallocation of investments in the power sector from fossil fuels to low-emissions generation technologies (renewable power generation, nuclear, and electricity generation with CCS). While annual investment in conventional *fossil-fired power plants without CCS* is estimated to decline by about 30 billion USD per year in 2010–2029 (i.e., by 20 % compared to 2010), annual investment in *low-emission generation technologies* is expected to increase by about 147 billion USD per year (i.e., by 100 % compared to 2010), over the same period.

Investment in *energy efficiency in the building, transport, and industry sector* would need to increase by several hundred billion USD per year from 2010–2029. Information on investment needs in other sectors, e.g., CO_2 to abatement processes or non-CO_2 emissions, is sparse.

Model results suggest that *deforestation* could be reduced against current deforestation trends by 50 % with an investment of 21 to 35 billion USD annually.

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Annexes

ANNEX

I

Glossary, Acronyms and Chemical Symbols

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Glossary

This glossary defines some specific terms as the Lead Authors intend them to be interpreted in the context of this report. Glossary **entries** (highlighted in bold) are by preference subjects; a main entry can contain ***subentries***, in bold and italic, for example, ***Primary Energy*** is defined under the entry **Energy**. Blue, italicized *words* indicate that the term is defined in the Glossary. The glossary is followed by a list of acronyms and chemical symbols. Please refer to Annex II for standard units, prefixes, and unit conversion (Section A.II.1) and for regions and country groupings (Section A.II.2).

Abrupt climate change: A large-scale change in the *climate system* that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems. See also *Climate threshold*.

Adaptability: See *Adaptive capacity*.

Adaptation: The process of adjustment to actual or expected *climate* and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected *climate* and its effects.[1]

Adaptation Fund: A Fund established under the *Kyoto Protocol* in 2001 and officially launched in 2007. The Fund finances *adaptation* projects and programmes in *developing countries* that are Parties to the *Kyoto Protocol*. Financing comes mainly from sales of *Certified Emissions Reductions (CERs)* and a share of proceeds amounting to 2 % of the value of CERs issued each year for *Clean Development Mechanism (CDM)* projects. The Adaptation Fund can also receive funds from government, private sector, and individuals.

Adaptive capacity: The ability of systems, *institutions*, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.[2]

Additionality: *Mitigation* projects (e.g., under the *Kyoto Mechanisms*), *mitigation policies*, or *climate finance* are additional if they go beyond a *business-as-usual* level, or *baseline*. Additionality is required to guarantee the environmental integrity of project-based offset mechanisms, but difficult to establish in practice due to the counterfactual nature of the *baseline*.

[1] Reflecting progress in science, this glossary entry differs in breadth and focus from the entry used in the Fourth Assessment Report and other IPCC reports.

[2] This glossary entry builds from definitions used in previous IPCC reports and the Millennium Ecosystem Assessment (MEA, 2005).

Adverse side-effects: The negative effects that a *policy* or *measure* aimed at one objective might have on other objectives, without yet evaluating the net effect on overall social welfare. Adverse side-effects are often subject to *uncertainty* and depend on, among others, local circumstances and implementation practices. See also *Co-benefits*, *Risk*, and *Risk tradeoff*.

Aerosol: A suspension of airborne solid or liquid particles, with a typical size between a few nanometres and 10 μm that reside in the *atmosphere* for at least several hours. For convenience the term aerosol, which includes both the particles and the suspending gas, is often used in this report in its plural form to mean aerosol *particles*. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence *climate* in several ways: directly through scattering and absorbing radiation, and indirectly by acting as cloud condensation nuclei or ice nuclei, modifying the optical properties and lifetime of clouds. Atmospheric aerosols, whether natural or anthropogenic, originate from two different pathways: emissions of primary *particulate matter (PM)*, and formation of secondary *PM* from gaseous *precursors*. The bulk of aerosols are of natural origin. Some scientists use group labels that refer to the chemical composition, namely: sea salt, organic carbon, *black carbon (BC)*, mineral species (mainly desert dust), sulphate, nitrate, and ammonium. These labels are, however, imperfect as aerosols combine particles to create complex mixtures. See also *Short-lived climate pollutants (SLCPs)*.

Afforestation: Planting of new *forests* on lands that historically have not contained *forests*. Afforestation projects are eligible under a number of schemes including, among others, *Joint Implementation (JI)* and the *Clean Development Mechanism (CDM)* under the *Kyoto Protocol* for which particular criteria apply (e.g., proof must be given that the land was not forested for at least 50 years or converted to alternative uses before 31 December 1989).

For a discussion of the term *forest* and related terms such as afforestation, *reforestation* and *deforestation*, see the IPCC Special Report on Land Use, Land-Use Change and Forestry (IPCC, 2000). See also the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).

Agreement: In this report, the degree of agreement is the level of concurrence in the literature on a particular finding as assessed by the authors. See also *Evidence*, *Confidence*, *Likelihood*, and *Uncertainty*.

Agricultural emissions: See *Emissions*.

Agriculture, Forestry and Other Land Use (AFOLU): Agriculture, Forestry and Other Land Use plays a central role for *food security* and *sustainable development (SD)*. The main *mitigation* options within AFOLU involve one or more of three strategies: *prevention* of emissions to the *atmosphere* by conserving existing *carbon pools* in soils or vegetation or by reducing emissions of *methane (CH_4)* and *nitrous*

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oxide (N_2O); *sequestration*—increasing the size of existing *carbon pools*, and thereby extracting *carbon dioxide (CO_2)* from the *atmosphere*; and *substitution*—substituting biological products for *fossil fuels* or energy-intensive products, thereby reducing CO_2 emissions. Demand-side measures (e.g., by reducing losses and wastes of food, changes in human diet, or changes in wood consumption) may also play a role. FOLU (Forestry and Other Land Use)—also referred to as *LULUCF (Land use, land-use change, and forestry)*—is the subset of AFOLU emissions and removals of *greenhouse gases (GHGs)* resulting from direct human-induced land use, land-use change and forestry activities excluding *agricultural emissions*.

Albedo: The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the albedo of soils ranges from high to low, and vegetation-covered surfaces and oceans have a low albedo. The earth's planetary albedo varies mainly through varying cloudiness, snow, ice, leaf area and land cover changes.

Alliance of Small Island States (AOSIS): The Alliance of Small Island States (AOSIS) is a coalition of small islands and low-lying coastal countries with a membership of 44 states and observers that share and are active in global debates and negotiations on the environment, especially those related to their vulnerability to the adverse effects of *climate change*. Established in 1990, AOSIS acts as an ad-hoc lobby and negotiating voice for small island development states (SIDS) within the United Nations including the *United Nations Framework Convention on Climate Change (UNFCCC)* climate change negotiations.

Ancillary benefits: See *Co-benefits*.

Annex I Parties/countries: The group of countries listed in Annex I to the *United Nations Framework Convention on Climate Change (UNFCCC)*. Under Articles 4.2 (a) and 4.2 (b) of the UNFCCC, Annex I Parties were committed to adopting national *policies* and *measures* with the non-legally binding aim to return their *greenhouse gas (GHG)* emissions to 1990 levels by 2000. The group is largely similar to the *Annex B Parties* to the *Kyoto Protocol* that also adopted emissions reduction targets for 2008–2012. By default, the other countries are referred to as *Non-Annex I Parties*.

Annex II Parties/countries: The group of countries listed in Annex II to the *United Nations Framework Convention on Climate Change (UNFCCC)*. Under Article 4 of the UNFCCC, these countries have a special obligation to provide financial resources to meet the agreed full incremental costs of implementing *measures* mentioned under Article 12, paragraph 1. They are also obliged to provide financial resources, including for the transfer of technology, to meet the agreed incremental costs of implementing *measures* covered by Article 12, paragraph 1 and agreed between *developing country* Parties and international entities referred to in Article 11 of the UNFCCC. This group of countries shall also assist countries that are particularly vulnerable to the adverse effects of *climate change*.

Annex B Parties/countries: The subset of *Annex I Parties* that have accepted *greenhouse gas (GHG)* emission reduction targets for the period 2008–2012 under Article 3 of the *Kyoto Protocol*. By default, the other countries are referred to as *Non-Annex I Parties*.

Anthropogenic emissions: See *Emissions*.

Assigned Amount (AA): Under the *Kyoto Protocol*, the AA is the quantity of *greenhouse gas (GHG)* emissions that an *Annex B country* has agreed to as its *cap* on its emissions in the first five-year commitment period (2008–2012). The AA is the country's total GHG emissions in 1990 multiplied by five (for the five-year commitment period) and by the percentage it agreed to as listed in Annex B of the *Kyoto Protocol* (e.g., 92 % for the EU). See also *Assigned Amount Unit (AAU)*.

Assigned Amount Unit (AAU): An AAU equals 1 tonne (metric ton) of *CO_2-equivalent emissions* calculated using the *Global Warming Potential (GWP)*. See also *Assigned Amount (AA)*.

Atmosphere: The gaseous envelope surrounding the earth, divided into five layers—the *troposphere* which contains half of the earth's atmosphere, the *stratosphere*, the mesosphere, the thermosphere, and the exosphere, which is the outer limit of the atmosphere. The dry atmosphere consists almost entirely of nitrogen (78.1 % volume mixing ratio) and oxygen (20.9 % volume mixing ratio), together with a number of *trace gases*, such as argon (0.93 % volume mixing ratio), helium and radiatively active *greenhouse gases (GHGs)* such as *carbon dioxide (CO_2)* (0.035 % volume mixing ratio) and *ozone (O_3)*. In addition, the atmosphere contains the GHG water vapour (H_2O), whose amounts are highly variable but typically around 1 % volume mixing ratio. The atmosphere also contains clouds and *aerosols*.

Backstop technology: *Models* estimating *mitigation* often use an arbitrary carbon-free technology (often for power generation) that might become available in the future in unlimited supply over the horizon of the *model*. This allows modellers to explore the consequences and importance of a generic solution technology without becoming enmeshed in picking the actual technology. This 'backstop' technology might be a nuclear technology, fossil technology with *Carbon Dioxide Capture and Storage (CCS)*, *solar energy*, or something as yet unimagined. The backstop technology is typically assumed either not to currently exist, or to exist only at higher costs relative to conventional alternatives.

Banking (of Assigned Amount Units): Any transfer of *Assigned Amount Units (AAUs)* from an existing period into a future commitment period. According to the *Kyoto Protocol* [Article 3 (13)], Parties included in Annex I to the *United Nations Framework Convention on Climate Change (UNFCCC)* may save excess AAUs from the first commitment period for compliance with their respective *cap* in subsequent commitment periods (post-2012).

Baseline/reference: The state against which change is measured. In the context of *transformation pathways*, the term 'baseline scenarios' refers to *scenarios* that are based on the assumption that no *mitigation policies* or *measures* will be implemented beyond those that are already in force and/or are legislated or planned to be adopted. Baseline scenarios are not intended to be predictions of the future, but rather counterfactual constructions that can serve to highlight the level of emissions that would occur without further *policy* effort. Typically, baseline scenarios are then compared to *mitigation scenarios* that are constructed to meet different goals for *greenhouse gas (GHG)* emissions, atmospheric concentrations, or temperature change. The term 'baseline scenario' is used interchangeably with 'reference scenario' and 'no policy scenario'. In much of the literature the term is also synonymous with the term 'business-as-usual (BAU) scenario,' although the term 'BAU' has fallen out of favour because the idea of 'business-as-usual' in century-long socioeconomic projections is hard to fathom. See also *Climate scenario*, *Emission scenario*, *Representative concentration pathways (RCPs)*, *Shared socio-economic pathways*, *Socio-economic scenarios*, *SRES scenarios*, and *Stabilization*.

Behaviour: In this report, behaviour refers to human decisions and actions (and the perceptions and judgments on which they are based) that directly or indirectly influence *mitigation* or the effects of potential *climate change* impacts (*adaptation*). Human decisions and actions are relevant at different levels, from international, national, and subnational actors, to NGO, tribe, or firm-level decision makers, to communities, households, and individual citizens and consumers. See also *Behavioural change* and *Drivers of behaviour*.

Behavioural change: In this report, behavioural change refers to alteration of human decisions and actions in ways that mitigate *climate change* and/or reduce negative consequences of *climate change* impacts. See also *Drivers of behaviour*.

Biochar: *Biomass* stabilization can be an alternative or enhancement to *bioenergy* in a land-based *mitigation* strategy. Heating *biomass* with exclusion of air produces a stable carbon-rich co-product (char). When added to soil a system, char creates a system that has greater abatement potential than typical *bioenergy*. The relative benefit of biochar systems is increased if changes in crop yield and soil emissions of *methane* (CH_4) and *nitrous oxide* (N_2O) are taken into account.

Biochemical oxygen demand (BOD): The amount of dissolved oxygen consumed by micro-organisms (bacteria) in the bio-chemical oxidation of organic and inorganic matter in wastewater. See also *Chemical oxygen demand (COD)*.

Biodiversity: The variability among living organisms from terrestrial, marine, and other *ecosystems*. Biodiversity includes variability at the genetic, species, and *ecosystem* levels.[3]

[3] This glossary entry builds from definitions used in the Global Biodiversity Assessment (Heywood, 1995) and the Millennium Ecosystem Assessment (MEA, 2005).

Bioenergy: *Energy* derived from any form of *biomass* such as recently living organisms or their metabolic by-products.

Bioenergy and Carbon Dioxide Capture and Storage (BECCS): The application of *Carbon Dioxide Capture and Storage (CCS)* technology to *bioenergy* conversion processes. Depending on the total lifecycle emissions, including total marginal consequential effects (from *indirect land use change (iLUC)* and other processes), BECCS has the potential for net *carbon dioxide* (CO_2) removal from the *atmosphere*. See also *Sequestration*.

Bioethanol: Ethanol produced from *biomass* (e.g., sugar cane or corn). See also *Biofuel*.

Biofuel: A fuel, generally in liquid form, produced from organic matter or combustible oils produced by living or recently living plants. Examples of biofuel include alcohol (*bioethanol*), black liquor from the paper-manufacturing process, and soybean oil.

First-generation manufactured biofuel: First-generation manufactured biofuel is derived from grains, oilseeds, animal fats, and waste vegetable oils with mature conversion technologies.

Second-generation biofuel: Second-generation biofuel uses non-traditional biochemical and thermochemical conversion processes and feedstock mostly derived from the lignocellulosic fractions of, for example, agricultural and forestry residues, municipal solid waste, etc.

Third-generation biofuel: Third-generation biofuel would be derived from feedstocks such as algae and energy crops by advanced processes still under development.

These second- and third-generation biofuels produced through new processes are also referred to as next-generation or advanced biofuels, or advanced biofuel technologies.

Biomass: The total mass of living organisms in a given area or volume; dead plant material can be included as dead biomass. In the context of this report, biomass includes products, by-products, and waste of biological origin (plants or animal matter), excluding material embedded in geological formations and transformed to *fossil fuels* or peat.

Traditional biomass: Traditional biomass refers to the biomass—fuelwood, charcoal, agricultural residues, and animal dung—used with the so-called traditional technologies such as open fires for cooking, rustic kilns and ovens for small industries. Widely used in *developing countries*, where about 2.6 billion people cook with open wood fires, and hundreds of thousands small-industries. The use of these rustic technologies leads to high pollution levels and, in specific circumstances, to *forest* degradation and *deforestation*. There are many successful initiatives around the world to make traditional biomass burned more efficiently and cleanly using efficient cookstoves and kilns. This last use of traditional biomass is sustainable and provides large health and economic benefits to local populations in *developing countries*, particularly in rural and peri-urban areas.

Modern biomass: All biomass used in high efficiency conversion systems.

Biomass burning: Biomass burning is the burning of living and dead vegetation.

Biosphere (terrestrial and marine): The part of the earth system comprising all *ecosystems* and living organisms, in the *atmosphere*, on land (terrestrial biosphere) or in the oceans (marine biosphere), including derived dead organic matter, such as litter, soil organic matter and oceanic detritus.

Black carbon (BC): Operationally defined *aerosol* species based on measurement of light absorption and chemical reactivity and/or thermal stability. It is sometimes referred to as soot. BC is mostly formed by the incomplete combustion of *fossil fuels*, *biofuels*, and *biomass* but it also occurs naturally. It stays in the *atmosphere* only for days or weeks. It is the most strongly light-absorbing component of *particulate matter (PM)* and has a warming effect by absorbing heat into the *atmosphere* and reducing the *albedo* when deposited on ice or snow.

Burden sharing (also referred to as Effort sharing): In the context of *mitigation*, burden sharing refers to sharing the effort of reducing the *sources* or enhancing the *sinks* of *greenhouse gases (GHGs)* from historical or projected levels, usually allocated by some criteria, as well as sharing the cost burden across countries.

Business-as-usual (BAU): See *Baseline/reference*.

Cancún Agreements: A set of decisions adopted at the 16th Session of the *Conference of the Parties (COP)* to the *United Nations Framework Convention on Climate Change (UNFCCC)*, including the following, among others: the newly established *Green Climate Fund (GCF)*, a newly established technology mechanism, a process for advancing discussions on *adaptation*, a formal process for reporting *mitigation* commitments, a goal of limiting *global mean surface temperature* increase to 2 °C, and an agreement on MRV—Measuring, Reporting and Verifying for those countries that receive international support for their *mitigation* efforts.

Cancún Pledges: During 2010, many countries submitted their existing plans for controlling *greenhouse gas (GHG)* emissions to the Climate Change Secretariat and these proposals have now been formally acknowledged under the *United Nations Framework Convention on Climate Change (UNFCCC)*. *Developed countries* presented their plans in the shape of economy-wide targets to reduce emissions, mainly up to 2020, while *developing countries* proposed ways to limit their growth of emissions in the shape of plans of action.

Cap, on emissions: Mandated restraint as an upper limit on emissions within a given period. For example, the *Kyoto Protocol* mandates emissions caps in a scheduled timeframe on the anthropogenic *greenhouse gas (GHG)* emissions released by *Annex B countries*.

Carbon budget: The area under a *greenhouse gas (GHG)* emissions trajectory that satisfies assumptions about limits on cumulative emissions estimated to avoid a certain level of *global mean surface temperature* rise. Carbon budgets may be defined at the global level, national, or sub-national levels.

Carbon credit: See *Emission allowance*.

Carbon cycle: The term used to describe the flow of carbon (in various forms, e.g., as *carbon dioxide*) through the *atmosphere*, ocean, terrestrial and marine *biosphere* and lithosphere. In this report, the reference unit for the global carbon cycle is GtC or $GtCO_2$ (1 GtC corresponds to 3.667 $GtCO_2$). Carbon is the major chemical constituent of most organic matter and is stored in the following major *reservoirs*: organic molecules in the *biosphere*, *carbon dioxide (CO_2)* in the *atmosphere*, organic matter in the soils, in the lithosphere, and in the oceans.

Carbon dioxide (CO_2): A naturally occurring gas, also a by-product of burning *fossil fuels* from fossil carbon deposits, such as oil, gas and coal, of burning *biomass*, of *land use changes (LUC)* and of industrial processes (e.g., cement production). It is the principal anthropogenic *greenhouse gas (GHG)* that affects the earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a *Global Warming Potential (GWP)* of 1. See Annex II.9.1 for GWP values for other GHGs.

Carbon Dioxide Capture and Storage (CCS): A process in which a relatively pure stream of *carbon dioxide (CO_2)* from industrial and energy-related *sources* is separated (captured), conditioned, compressed, and transported to a storage location for long-term isolation from the *atmosphere*. See also *Bioenergy and carbon capture and storage (BECCS)*, *CCS-ready*, and *Sequestration*.

Carbon dioxide fertilization: The enhancement of the growth of plants as a result of increased atmospheric *carbon dioxide (CO_2)* concentration.

Carbon Dioxide Removal (CDR): Carbon Dioxide Removal methods refer to a set of techniques that aim to remove *carbon dioxide (CO_2)* directly from the *atmosphere* by either (1) increasing natural *sinks* for carbon or (2) using chemical engineering to remove the CO_2, with the intent of reducing the atmospheric CO_2 concentration. CDR methods involve the ocean, land, and technical systems, including such methods as *iron fertilization*, large-scale *afforestation*, and *direct capture* of CO_2 from the *atmosphere* using engineered chemical means. Some CDR methods fall under the category of *geoengineering*, though this may not be the case for others, with the distinction being based on the magnitude, scale, and impact of the particular CDR activities. The boundary between CDR and *mitigation* is not clear and there could be some overlap between the two given current definitions (IPCC, 2012, p. 2). See also *Solar Radiation Management (SRM)*.

Carbon footprint: Measure of the exclusive total amount of emissions of *carbon dioxide (CO_2)* that is directly and indirectly caused by an activity or is accumulated over the life stages of a product (Wiedmann and Minx, 2008).

Carbon intensity: The amount of emissions of *carbon dioxide (CO_2)* released per unit of another variable such as *gross domestic product (GDP)*, output energy use, or transport.

Carbon leakage: See *Leakage*.

Carbon pool: See *Reservoir*.

Carbon price: The price for avoided or released *carbon dioxide (CO_2)* or *CO_2-equivalent* emissions. This may refer to the rate of a *carbon tax*, or the price of *emission permits*. In many *models* that are used to assess the economic costs of *mitigation*, carbon prices are used as a proxy to represent the level of effort in *mitigation policies*.

Carbon sequestration: See *Sequestration*.

Carbon tax: A levy on the carbon content of *fossil fuels*. Because virtually all of the carbon in *fossil fuels* is ultimately emitted as *carbon dioxide (CO_2)*, a carbon tax is equivalent to an emission tax on CO_2 emissions.

CCS-ready: New large-scale, stationary *carbon dioxide (CO_2)* point *sources* intended to be retrofitted with *Carbon Dioxide Capture and Storage (CCS)* could be designed and located to be 'CCS-ready' by reserving space for the capture installation, designing the unit for optimal performance when capture is added, and siting the plant to enable access to storage locations. See also *Bioenergy and Carbon Dioxide Capture and Storage (BECCS)*.

Certified Emission Reduction Unit (CER): Equal to one metric tonne of *CO_2-equivalent emissions* reduced or of *carbon dioxide (CO_2)* removed from the *atmosphere* through the *Clean Development Mechanism (CDM)* (defined in Article 12 of the *Kyoto Protocol*) project, calculated using *Global Warming Potentials (GWP)*. See also *Emissions Reduction Units (ERU)* and *Emissions trading*.

Chemical oxygen demand (COD): The quantity of oxygen required for the complete oxidation of organic chemical compounds in water; used as a measure of the level of organic pollutants in natural and waste waters. See also *Biochemical oxygen demand (BOD)*.

Chlorofluorocarbons (CFCs): A chlorofluorocarbon is an organic compound that contains chlorine, carbon, hydrogen, and fluorine and is used for refrigeration, air conditioning, packaging, plastic foam, insulation, solvents, or *aerosol* propellants. Because they are not destroyed in the lower *atmosphere*, CFCs drift into the upper *atmosphere* where, given suitable conditions, they break down *ozone (O_3)*. It is one of the *greenhouse gases (GHGs)* covered under the 1987 *Montreal Protocol* as a result of which manufacturing of these gases has been phased out and they are being replaced by other compounds, including *hydrofluorocarbons (HFCs)* which are GHGs covered under the *Kyoto Protocol*.

Clean Development Mechanism (CDM): A mechanism defined under Article 12 of the *Kyoto Protocol* through which investors (governments or companies) from developed (*Annex B*) *countries* may finance *greenhouse gas (GHG)* emission reduction or removal projects in developing (*Non-Annex B*) *countries*, and receive *Certified Emission Reduction Units (CERs)* for doing so. The *CERs* can be credited towards the commitments of the respective *developed countries*. The *CDM* is intended to facilitate the two objectives of promoting *sustainable development (SD)* in *developing countries* and of helping *industrialized countries* to reach their emissions commitments in a *cost-effective* way. See also *Kyoto Mechanisms*.

Climate: Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the *climate system*.

Climate change: Climate change refers to a change in the state of the *climate* that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the *atmosphere* or in *land use*. Note that the *United Nations Framework Convention on Climate Change (UNFCCC)*, in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. See also *Climate change commitment*.

Climate change commitment: Due to the thermal inertia of the ocean and slow processes in the cryosphere and land surfaces, the *climate* would continue to change even if the atmospheric composition were held fixed at today's values. Past change in atmospheric composition leads to a committed *climate change*, which continues for as long as a radiative imbalance persists and until all components of the *climate system* have adjusted to a new state. The further change in temperature after the composition of the *atmosphere* is held constant is referred to as the constant composition temperature commitment or simply committed warming or warming commitment. Climate change commitment includes other future changes, for example in the hydrological cycle, in extreme weather events, in extreme climate events, and in sea level change. The constant emission commitment is the committed climate change that would result from keeping *anthropogenic emissions* constant and the zero emission commitment is the climate change commitment when emissions are set to zero. See also *Climate change*.

Climate (change) feedback: An interaction in which a perturbation in one *climate* quantity causes a change in a second, and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced. In this Assessment Report, a somewhat narrower definition is often used in which the climate quantity that is perturbed is the *global mean surface temperature*, which in turn causes changes in the global radiation budget. In either case, the initial perturbation can either be externally forced or arise as part of internal variability.

Climate engineering: See *Geoengineering*.

Climate finance: There is no agreed definition of climate finance. The term 'climate finance' is applied both to the financial resources devoted to addressing *climate change* globally and to financial flows to *developing countries* to assist them in addressing *climate change*. The literature includes several concepts in these categories, among which the most commonly used include:

Incremental costs: The cost of capital of the *incremental investment* and the change of operating and maintenance costs for a *mitigation* or *adaptation* project in comparison to a reference project. It can be calculated as the difference of the net present values of the two projects. See also *Additionality*.

Incremental investment: The extra capital required for the initial investment for a *mitigation* or *adaptation* project in comparison to a reference project. See also *Additionality*.

Total climate finance: All financial flows whose expected effect is to reduce net *greenhouse gas (GHG)* emissions and/or to enhance *resilience* to the impacts of *climate variability* and the projected *climate change*. This covers private and public funds, domestic and international flows, expenditures for *mitigation* and *adaptation* to current *climate variability* as well as future *climate change*.

***Total climate finance flowing to developing countries*:**The amount of the *total climate finance* invested in *developing countries* that comes from *developed countries*. This covers private and public funds.

Private climate finance flowing to developing countries: Finance and investment by private actors in/from *developed countries* for *mitigation* and *adaptation* activities in *developing countries*.

Public climate finance flowing to developing countries: Finance provided by *developed countries'* governments and bilateral institutions as well as by multilateral institutions for *mitigation* and *adaptation* activities in *developing countries*. Most of the funds provided are concessional loans and grants.

Climate model (spectrum or hierarchy): A numerical representation of the *climate system* based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrizations are involved. Coupled Atmosphere-Ocean *General Circulation Models* (AOGCMs) provide a representation of the *climate system* that is near or at the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the *climate*, and for operational purposes, including monthly, seasonal and interannual *climate predictions*.

Climate prediction: A climate prediction or climate forecast is the result of an attempt to produce (starting from a particular state of the *climate system*) an estimate of the actual evolution of the climate in the future, for example, at seasonal, interannual, or decadal time scales. Because the future evolution of the *climate system* may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature. See also *Climate projection*, and *Climate scenario*.

Climate projection: A climate projection is the simulated response of the *climate system* to a scenario of future *emission* or concentration of *greenhouse gases (GHGs)* and *aerosols*, generally derived using *climate models*. Climate projections are distinguished from *climate predictions* by their dependence on the emission/concentration/*radiative forcing* scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized. See also *Climate scenario*.

Climate scenario: A plausible and often simplified representation of the future *climate*, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic *climate* *change*, often serving as input to impact models. *Climate projections* often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as the observed current *climate*. See also *Baseline/reference*, *Emission scenario*, *Mitigation scenario*, *Representative concentration pathways (RCPs)*, *Scenario*, *Shared socio-economic pathways*, *Socio-economic scenario*, *SRES scenarios*, *Stabilization*, and *Transformation pathway*.

Climate sensitivity: In IPCC reports, equilibrium climate sensitivity (units: °C) refers to the equilibrium (steady state) change in the annual *global mean surface temperature* following a doubling of the atmospheric *CO_2-equivalent concentration*. Owing to computational constraints, the equilibrium climate sensitivity in a *climate model* is sometimes estimated by running an atmospheric *general circulation model (GCM)* coupled to a mixed-layer ocean model, because equilibrium climate sensitivity is largely determined by atmospheric processes. Efficient models can be run to equilibrium with a dynamic ocean. The climate sensitivity parameter (units: °C $(W\ m^{-2})^{-1}$) refers to the equilibrium change in the annual *global mean surface temperature* following a unit change in *radiative forcing*.

The effective climate sensitivity (units: °C) is an estimate of the *global mean surface temperature* response to doubled *carbon dioxide (CO_2)* concentration that is evaluated from model output or observations for evolving non-equilibrium conditions. It is a measure of the strengths of the *climate feedbacks* at a particular time and may vary with forcing history and *climate* state, and therefore may differ from equilibrium climate sensitivity.

The transient climate response (units: °C) is the change in the *global mean surface temperature*, averaged over a 20-year period, centred at the time of atmospheric CO_2 doubling, in a *climate model* simulation in which CO_2 increases at 1 % yr^{-1}. It is a measure of the strength and rapidity of the surface temperature response to *greenhouse gas (GHG)* forcing.

Climate system: The climate system is the highly complex system consisting of five major components: the *atmosphere*, the hydrosphere, the cryosphere, the lithosphere and the *biosphere*, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the *atmosphere* and *land use change (LUC)*.

Climate threshold: A limit within the *climate system* that, when crossed, induces a non-linear response to a given forcing. See also *Abrupt climate change*.

Climate variability: Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the *climate* on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the *climate system* (internal variability), or to variations in natural or anthropogenic external forcing (external variability). See also *Climate change*.

CO_2-equivalent concentration: The concentration of *carbon dioxide (CO_2)* that would cause the same *radiative forcing* as a given mixture of CO_2 and other forcing components. Those values may consider only *greenhouse gases (GHGs)*, or a combination of GHGs, *aerosols*, and surface *albedo* changes. CO_2-equivalent concentration is a metric for comparing *radiative forcing* of a mix of different forcing components at a particular time but does not imply equivalence of the corresponding *climate change* responses nor future forcing. There is generally no connection between *CO_2-equivalent emissions* and resulting CO_2-equivalent concentrations.

CO_2-equivalent emission: The amount of *carbon dioxide (CO_2)* emission that would cause the same integrated *radiative forcing*, over a given time horizon, as an emitted amount of a *greenhouse gas (GHG)* or a mixture of GHGs. The CO_2-equivalent emission is obtained by multiplying the emission of a GHG by its *Global Warming Potential (GWP)* for the given time horizon (see Annex II.9.1 and WGI AR5 Table 8.A.1 for GWP values of the different GHGs). For a mix of GHGs it is obtained by summing the CO_2-equivalent emissions of each gas. CO_2-equivalent emission is a common scale for comparing emissions of different GHGs but does not imply equivalence of the corresponding *climate change* responses. See also *CO_2-equivalent concentration*.

Co-benefits: The positive effects that a *policy* or *measure* aimed at one objective might have on other objectives, without yet evaluating the net effect on overall social welfare. Co-benefits are often subject to *uncertainty* and depend on, among others, local circumstances and implementation practices. Co-benefits are often referred to as ancillary benefits. See also *Adverse side-effect*, *Risk*, and *Risk tradeoff*.

Cogeneration: Cogeneration (also referred to as combined heat and power, or CHP) is the simultaneous generation and useful application of electricity and useful heat.

Combined-cycle gas turbine: A power plant that combines two processes for generating electricity. First, fuel combustion drives a gas turbine. Second, exhaust gases from the turbine are used to heat water to drive a steam turbine.

Combined heat and power (CHP): See *Cogeneration*.

Computable General Equilibrium (CGE) Model: See *Models*.

Conference of the Parties (COP): The supreme body of the *United Nations Framework Convention on Climate Change (UNFCCC)*, comprising countries with a right to vote that have ratified or acceded to the convention. See also *Meeting of the Parties (CMP)*.

Confidence: The validity of a finding based on the type, amount, quality, and consistency of *evidence* (e.g., mechanistic understanding, theory, data, *models*, expert judgment) and on the degree of *agreement*. In this report, confidence is expressed qualitatively (Mastrandrea et al., 2010). See WGI AR5 Figure 1.11 for the levels of confidence and WGI AR5 Table 1.2 for the list of *likelihood* qualifiers. See also *Uncertainty*.

Consumption-based accounting: Consumption-based accounting provides a measure of emissions released to the *atmosphere* in order to generate the goods and services consumed by a certain entity (e.g., person, firm, country, or region). See also *Production-based accounting*.

Contingent valuation method: An approach to quantitatively assess values assigned by people in monetary (willingness to pay) and non-monetary (willingness to contribute with time, resources etc.) terms. It is a direct method to estimate economic values for *ecosystem* and environmental services. In a survey, people are asked their willingness to pay/contribute for access to, or their willingness to accept compensation for removal of, a specific environmental service, based on a hypothetical *scenario* and description of the environmental service.

Conventional fuels: See *Fossil fuels*.

Copenhagen Accord: The political (as opposed to legal) agreement that emerged at the 15th Session of the *Conference of the Parties (COP)* at which delegates 'agreed to take note' due to a lack of consensus that an agreement would require. Some of the key elements include: recognition of the importance of the scientific view on the need to limit the increase in *global mean surface temperature* to 2° C; commitment by *Annex I Parties* to implement economy-wide emissions targets by 2020 and *non-Annex I Parties* to implement *mitigation* actions; agreement to have emission targets of *Annex I Parties* and their delivery of finance for *developing countries* subject to Measurement, Reporting and Verification (MRV) and actions by *developing countries* to be subject to domestic MRV; calls for scaled up financing including a fast track financing of USD 30 billion and USD 100 billion by 2020; the establishment of a new *Green Climate Fund (GCF)*; and the establishment of a new technology mechanism. Some of these elements were later adopted in the *Cancún Agreements*.

Cost-benefit analysis (CBA): Monetary measurement of all negative and positive impacts associated with a given action. Costs and benefits are compared in terms of their difference and/or ratio as an indicator of how a given investment or other *policy* effort pays off seen from the society's point of view.

Cost of conserved energy (CCE): See *Levelized cost of conserved energy (LCCE)*.

Cost-effectiveness: A *policy* is more cost-effective if it achieves a goal, such as a given pollution abatement level, at lower cost. A critical condition for cost-effectiveness is that marginal abatement costs be equal among obliged parties. *Integrated models* approximate cost-effective solutions, unless they are specifically constrained to behave otherwise. Cost-effective *mitigation scenarios* are those based on a stylized implementation approach in which a single price on *carbon dioxide (CO_2)* and other *greenhouse gases (GHGs)* is applied across the globe in every sector of every country and that rises over time in a way that achieves lowest global discounted costs.

Cost-effectiveness analysis (CEA): A tool based on constrained optimization for comparing *policies* designed to meet a prespecified target.

Crediting period, Clean Development Mechanism (CDM): The time during which a project activity is able to generate *Certified Emission Reduction Units (CERs)*. Under certain conditions, the crediting period can be renewed up to two times.

Cropland management: The system of practices on land on which agricultural crops are grown and on land that is set aside or temporarily not being used for crop production (UNFCCC, 2002).

Decarbonization: The process by which countries or other entities aim to achieve a low-carbon economy, or by which individuals aim to reduce their carbon consumption.

Decomposition approach: Decomposition methods disaggregate the total amount of historical changes of a policy variable into contributions made by its various determinants.

Deforestation: Conversion of *forest* to non-forest is one of the major *sources* of *greenhouse gas (GHG)* emissions. Under Article 3.3 of the *Kyoto Protocol*, "the net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be sued to meet the commitments under this Article of each Party included in Annex I". Reducing emissions from deforestation is not eligible for *Joint Implementation (JI)* or *Clean Development Mechanism (CDM)* projects but has been introduced in the program of work under *REDD (Reducing Emissions from Deforestation and Forest Degradation)* under the *United Nations Framework Convention on Climate Change (UNFCCC)*.

For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation*, and deforestation see the IPCC Special Report on Land Use, Land-Use Change and Forestry (IPCC, 2000). See also the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).

Dematerialization: The ambition to reduce the total material inputs required to deliver a final service.

Descriptive analysis: Descriptive (also termed positive) approaches to analysis focus on how the world works or actors behave, not how they should behave in some idealized world. See also *Normative analysis*.

Desertification: Land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities. Land degradation in arid, semi-arid, and dry sub-humid areas is a reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, *forest*, and woodlands resulting from *land uses* or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as (1) soil erosion caused by wind and/or water; (2) deterioration of the physical, chemical, biological, or economic properties of soil; and (3) long-term loss of natural vegetation (UNCCD, 1994).

Designated national authority (DNA): A designated national authority is a national *institution* that authorizes and approves *Clean Development Mechansim (CDM)* projects in that country. In CDM host countries, the DNA assesses whether proposed projects assist the host country in achieving its *sustainable development (SD)* goals, certification of which is a prerequisite for registration of the project by the CDM Executive Board.

Developed/developing countries: See *Industrialized/developing countries*.

Development pathway: An evolution based on an array of technological, economic, social, institutional, cultural, and biophysical characteristics that determine the interactions between human and natural systems, including consumption and production patterns in all countries, over time at a particular scale.

Direct Air Capture (DAC): Chemical process by which a pure *carbon dioxide (CO_2)* stream is produced by capturing CO_2 from the ambient air.

Direct emissions: See *Emissions*.

Discounting: A mathematical operation making monetary (or other) amounts received or expended at different times (years) comparable across time. The discounter uses a fixed or possibly time-varying discount rate (> 0) from year to year that makes future value worth less today. See also *Present value*.

Double dividend: The extent to which revenue-generating instruments, such as *carbon taxes* or auctioned (tradable) *emission permits* can (1) contribute to *mitigation* and (2) offset at least part of the potential welfare losses of climate *policies* through recycling the revenue in the economy to reduce other taxes likely to cause distortions.

Drivers of behaviour: Determinants of human decisions and actions, including peoples' values and goals and the factors that constrain action, including economic factors and incentives, information access, regulatory and technological constraints, cognitive and emotional processing capacity, and social norms. See also *Behaviour* and *Behavioural change*.

Drivers of emissions: Drivers of emissions refer to the processes, mechanisms and properties that influence emissions through factors. Factors comprise the terms in a decomposition of emissions. Factors and drivers may in return affect *policies*, *measures* and other drivers.

Economic efficiency: Economic efficiency refers to an economy's allocation of resources (goods, services, inputs, productive activities). An allocation is efficient if it is not possible to reallocate resources so as to make at least one person better off without making someone else worse off. An allocation is inefficient if such a reallocation is possible. This is also known as the Pareto Criterion for efficiency. See also *Pareto optimum*.

Economies in Transition (EITs): Countries with their economies changing from a planned economic system to a market economy. See Annex II.2.1.

Ecosystem: A functional unit consisting of living organisms, their non-living environment, and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire *biosphere*. In the current era, most ecosystems either contain people as key organisms, or are influenced by the effects of human activities in their environment.

Ecosystem services: Ecological processes or functions having monetary or non-monetary value to individuals or society at large. These are frequently classified as (1) supporting services such as productivity or *biodiversity* maintenance, (2) provisioning services such as food, fiber, or fish, (3) regulating services such as *climate* regulation or carbon *sequestration*, and (4) cultural services such as tourism or spiritual and aesthetic appreciation.

Embodied emissions: See *Emissions*.

Embodied energy: See *Energy*.

Emission allowance: See *Emission permit*.

Emission factor/Emissions intensity: The emissions released per unit of activity. See also *Carbon intensity*.

Emission permit: An entitlement allocated by a government to a legal entity (company or other emitter) to emit a specified amount of a substance. Emission permits are often used as part of *emissions trading* schemes.

Emission quota: The portion of total allowable emissions assigned to a country or group of countries within a framework of maximum total emissions.

Emission scenario: A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., *greenhouse gases*, *aerosols*) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, *technological change*, *energy* and *land use*) and their key relationships. Concentration scenarios, derived from emission scenarios, are used as input to a *climate model* to compute *climate projections*. In IPCC (1992) a set of emission scenarios was presented which were used as a basis for the *climate projections* in IPCC (1996). These emission scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emission Scenarios (Nakićenović and Swart, 2000) emission scenarios, the so-called *SRES scenarios*, were published, some of which were used, among others, as a basis for the *climate projections* presented in Chapters 9 to 11 of IPCC (2001) and Chapters 10 and 11 of IPCC (2007). New emission scenarios for *climate change*, the four *Representative Concentration Pathways (RCPs)*, were developed for, but independently of, the present IPCC assessment. See also *Baseline/reference*, *Climate scenario*, *Mitigation scenario, Shared socio-economic pathways*, *Scenario*, *Socio-economic scenario*, *Stabilization*, and *Transformation pathway*.

Emission trajectories: A projected development in time of the emission of a *greenhouse gas (GHG)* or group of GHGs, *aerosols*, and GHG *precursors*.

Emissions:

Agricultural emissions: Emissions associated with agricultural systems—predominantly *methane (CH_4)* or *nitrous oxide (N_2O)*. These include emissions from enteric fermentation in domestic livestock, manure management, rice cultivation, prescribed burning of savannas and grassland, and from soils (IPCC, 2006).

Anthropogenic emissions: Emissions of *greenhouse gases (GHGs)*, *aerosols*, and *precursors* of a GHG or *aerosol* caused by human activities. These activities include the burning of *fossil fuels*, *deforestation*, *land use changes (LUC)*, livestock production, fertilization, waste management, and industrial processes.

Direct emissions: Emissions that physically arise from activities within well-defined boundaries of, for instance, a region, an economic sector, a company, or a process.

Embodied emissions: Emissions that arise from the production and delivery of a good or service or the build-up of infrastructure. Depending on the chosen system boundaries, upstream emissions are often included (e.g., emissions resulting from the extraction of raw materials). See also *Lifecycle assessment (LCA)*.

Indirect emissions: Emissions that are a consequence of the activities within well-defined boundaries of, for instance, a region, an economic sector, a company or process, but which occur outside the specified boundaries. For example, emissions are described as indirect if they relate to the use of heat but physically arise outside the boundaries of the heat user, or to electricity production but physically arise outside of the boundaries of the power supply sector.

Scope 1, Scope 2, and Scope 3 emissions: Emissions responsibility as defined by the GHG Protocol, a private sector initiative. 'Scope 1' indicates direct *greenhouse gas (GHG)* emissions that are from *sources* owned or controlled by the reporting entity. 'Scope 2' indicates indirect GHG emissions associated with the production of electricity, heat, or steam purchased by the reporting entity. 'Scope 3' indicates all other *indirect emissions*, i.e., emissions associated with the extraction and production of purchased materials, fuels, and services, including transport in vehicles not owned or controlled by the reporting entity, outsourced activities, waste disposal, etc. (WBCSD and WRI, 2004).

Territorial emissions: Emissions that take place within the territories of a particular jurisdiction.

Emissions Reduction Unit (ERU): Equal to one metric tonne of *CO_2-equivalent emissions* reduced or of *carbon dioxide (CO_2)* removed from the *atmosphere* through a *Joint Implementation (JI)* (defined in Article 6 of the *Kyoto Protocol*) project, calculated using *Global Warming Potentials (GWPs)*. See also *Certified Emission Reduction Unit (CER)* and *Emissions trading*.

Emission standard: An emission level that, by law or by *voluntary agreement*, may not be exceeded. Many *standards* use *emission factors* in their prescription and therefore do not impose absolute limits on the emissions.

Emissions trading: A market-based instrument used to limit emissions. The environmental objective or sum of total allowed emissions is expressed as an emissions *cap*. The *cap* is divided in tradable *emission permits* that are allocated—either by auctioning or handing out for free (grandfathering)—to entities within the jurisdiction of the trading scheme. Entities need to surrender *emission permits* equal to the amount of their emissions (e.g., tonnes of *carbon dioxide*). An entity may sell excess permits. Trading schemes may occur at the intra-company, domestic, or international level and may apply to *carbon dioxide (CO_2)*, other *greenhouse gases (GHGs)*, or other substances. Emissions trading is also one of the mechanisms under the *Kyoto Protocol*. See also *Kyoto Mechanisms*.

Energy: The power of 'doing work' possessed at any instant by a body or system of bodies. Energy is classified in a variety of types and becomes available to human ends when it flows from one place to another or is converted from one type into another.

Embodied energy: The *energy* used to produce a material substance or product (such as processed metals or building materials), taking into account *energy* used at the manufacturing facility, *energy* used in producing the materials that are used in the manufacturing facility, and so on.

Final energy: See *Primary energy*.

Primary energy: Primary energy (also referred to as energy *sources*) is the *energy* stored in natural resources (e.g., coal, crude oil, natural gas, uranium, and renewable sources). It is defined in several alternative ways. The International Energy Agency (IEA) utilizes the physical energy content method, which defines primary energy as *energy* that has not undergone any anthropogenic conversion. The method used in this report is the direct equivalent method (see Annex II.4), which counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy, but treats combustion energy as the energy potential contained in fuels prior to treatment or combustion. Primary energy is transformed into secondary energy by cleaning (natural gas), refining (crude oil to oil products) or by conversion into electricity or heat. When the secondary energy is delivered at the end-use facilities it is called final energy (e.g., electricity at the wall outlet), where it becomes usable energy in supplying *energy services* (e.g., light).

Renewable energy (RE): Any form of energy from solar, geophysical, or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. For a more detailed description see *Bioenergy*, *Solar energy*, *Hydropower*, *Ocean*, *Geothermal*, and *Wind energy*.

Secondary energy: See *Primary energy*.

Energy access: Access to clean, reliable and affordable *energy services* for cooking and heating, lighting, communications, and productive uses (AGECC, 2010).

Energy carrier: A substance for delivering mechanical work or transfer of heat. Examples of energy carriers include: solid, liquid, or gaseous fuels (e.g., *biomass*, coal, oil, natural gas, hydrogen); pressurized/heated/cooled fluids (air, water, steam); and electric current.

Energy density: The ratio of stored *energy* to the volume or mass of a fuel or battery.

Energy efficiency (EE): The ratio of useful *energy* output of a system, conversion process, or activity to its *energy* input. In economics, the term may describe the ratio of economic output to *energy* input. See also *Energy intensity*.

Energy intensity: The ratio of *energy* use to economic or physical output.

Energy poverty: A lack of access to modern *energy services*. See also *Energy access*.

Energy security: The goal of a given country, or the global community as a whole, to maintain an adequate, stable, and predictable *energy* supply. Measures encompass safeguarding the sufficiency of *energy* resources to meet national *energy* demand at competitive and stable prices and the resilience of the *energy* supply; enabling development and deployment of technologies; building sufficient infrastructure to generate, store and transmit *energy* supplies; and ensuring enforceable contracts of delivery.

Energy services: An energy service is the benefit received as a result of *energy* use.

Energy system: The energy system comprises all components related to the production, conversion, delivery, and use of *energy*.

Environmental effectiveness: A *policy* is environmentally effective to the extent by which it achieves its expected environmental target (e.g., *greenhouse gas (GHG)* emission reduction).

Environmental input-output analysis: An analytical method used to allocate environmental impacts arising in production to categories of final consumption, by means of the Leontief inverse of a country's economic input-output tables. See also Annex II.6.2.

Environmental Kuznets Curve: The hypothesis that various environmental impacts first increase and then eventually decrease as income per capita increases.

Evidence: Information indicating the degree to which a belief or proposition is true or valid. In this report, the degree of evidence reflects the amount, quality, and consistency of scientific/technical information on which the Lead Authors are basing their findings. See also *Agreement*, *Confidence*, *Likelihood* and *Uncertainty*.

Externality/external cost/external benefit: Externalities arise from a human activity when agents responsible for the activity do not take full account of the activity's impacts on others' production and consumption possibilities, and no compensation exists for such impacts. When the impacts are negative, they are external costs. When the impacts are positive, they are external benefits. See also *Social costs*.

Feed-in tariff (FIT): The price per unit of electricity (heat) that a utility or power (heat) supplier has to pay for distributed or renewable electricity (heat) fed into the power grid (heat supply system) by non-utility generators. A public authority regulates the tariff.

Final energy: See *Primary energy*.

Flaring: Open air burning of waste gases and volatile liquids, through a chimney, at oil wells or rigs, in refineries or chemical plants, and at landfills.

Flexibility Mechanisms: See *Kyoto Mechanisms*.

Food security: A state that prevails when people have secure access to sufficient amounts of safe and nutritious food for normal growth, development, and an active and healthy life.[4]

Forest: A vegetation type dominated by trees. Many definitions of the term forest are in use throughout the world, reflecting wide differences in biogeophysical conditions, social structure and economics. According to the 2005 *United Nations Framework Convention on Climate Change (UNFCCC)* definition a forest is an area of land of at least 0.05–1 hectare, of which more than 10–30 % is covered by tree canopy. Trees must have a potential to reach a minimum of 25 meters at maturity in situ. Parties to the Convention can choose to define a forest from within those ranges. Currently, the definition does not recognize different biomes, nor do they distinguish natural forests from plantations, an anomaly being pointed out by many as in need of rectification.

For a discussion of the term forest and related terms such as *afforestation*, *reforestation* and *deforestation* see the IPCC Report on Land Use, Land-Use Change and Forestry (IPCC, 2000). See also the Report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).

Forest management: A system of practices for stewardship and use of *forest* land aimed at fulfilling relevant ecological (including *biological diversity*), economic and social functions of the *forest* in a sustainable manner (UNFCCC, 2002).

Forestry and Other Land Use (FOLU): See *Agriculture, Forestry and Other Land Use (AFOLU)*.

Fossil fuels: Carbon-based fuels from fossil hydrocarbon deposits, including coal, peat, oil, and natural gas.

Free Rider: One who benefits from a common good without contributing to its creation or preservation.

[4] This glossary entry builds on definitions used in FAO (2000) and previous IPCC reports.

Fuel cell: A fuel cell generates electricity in a direct and continuous way from the controlled electrochemical reaction of hydrogen or another fuel and oxygen. With hydrogen as fuel the cell emits only water and heat (no *carbon dioxide*) and the heat can be utilized (see also *Cogeneration*).

Fuel poverty: A condition in which a household is unable to guarantee a certain level of consumption of domestic *energy services* (especially heating) or suffers disproportionate expenditure burdens to meet these needs.

Fuel switching: In general, fuel switching refers to substituting fuel A for fuel B. In the context of *mitigation* it is implicit that fuel A has lower carbon content than fuel B, e.g., switching from natural gas to coal.

General circulation (climate) model (GCM): See *Climate model*.

General equilibrium analysis: General equilibrium analysis considers simultaneously all the markets and feedback effects among these markets in an economy leading to market clearance. *(Computable) general equilibrium (CGE) models* are the operational tools used to perform this type of analysis.

Geoengineering: Geoengineering refers to a broad set of methods and technologies that aim to deliberately alter the *climate system* in order to alleviate the impacts of *climate change*. Most, but not all, methods seek to either (1) reduce the amount of absorbed *solar energy* in the *climate system* (*Solar Radiation Management*) or (2) increase net carbon *sinks* from the *atmosphere* at a scale sufficiently large to alter *climate* (*Carbon Dioxide Removal*). Scale and intent are of central importance. Two key characteristics of geoengineering methods of particular concern are that they use or affect the *climate system* (e.g., *atmosphere*, land or ocean) globally or regionally and/or could have substantive unintended effects that cross national boundaries. Geoengineering is different from weather modification and ecological engineering, but the boundary can be fuzzy (IPCC, 2012, p. 2).

Geothermal energy: Accessible thermal *energy* stored in the earth's interior.

Global Environment Facility (GEF): The Global Environment Facility, established in 1991, helps *developing countries* fund projects and programmes that protect the global environment. GEF grants support projects related to *biodiversity*, *climate change*, international waters, land degradation, the *ozone (O_3)* layer, and persistent organic pollutants.

Global mean surface temperature: An estimate of the global mean surface air temperature. However, for changes over time, only anomalies, as departures from a climatology, are used, most commonly based on the area-weighted global average of the sea surface temperature anomaly and land surface air temperature anomaly.

Global warming: Global warming refers to the gradual increase, observed or projected, in global surface temperature, as one of the consequences of *radiative forcing* caused by *anthropogenic emissions*.

Global Warming Potential (GWP): An index, based on radiative properties of *greenhouse gases (GHGs)*, measuring the *radiative forcing* following a pulse emission of a unit mass of a given GHG in the present-day *atmosphere* integrated over a chosen time horizon, relative to that of *carbon dioxide* (CO_2). The GWP represents the combined effect of the differing times these gases remain in the *atmosphere* and their relative effectiveness in causing *radiative forcing*. The *Kyoto Protocol* is based on GWPs from pulse emissions over a 100-year time frame. Unless stated otherwise, this report uses GWP values calculated with a 100-year time horizon which are often derived from the IPCC Second Assessment Report (see Annex II.9.1 for the GWP values of the different GHGs).

Governance: A comprehensive and inclusive concept of the full range of means for deciding, managing, and implementing *policies* and *measures*. Whereas government is defined strictly in terms of the nation-state, the more inclusive concept of governance recognizes the contributions of various levels of government (global, international, regional, local) and the contributing roles of the private sector, of nongovernmental actors, and of civil society to addressing the many types of issues facing the global community.

Grazing land management: The system of practices on land used for livestock production aimed at manipulating the amount and type of vegetation and livestock produced (UNFCCC, 2002).

Green Climate Fund (GCF): The Green Climate Fund was established by the 16th Session of the *Conference of the Parties (COP)* in 2010 as an operating entity of the financial mechanism of the *United Nations Framework Convention on Climate Change (UNFCCC)*, in accordance with Article 11 of the Convention, to support projects, programmes and *policies* and other activities in *developing country* Parties. The Fund is governed by a Board and will receive guidance of the COP. The Fund is headquartered in Songdo, Republic of Korea.

Greenhouse effect: The infrared radiative effect of all infrared-absorbing constituents in the *atmosphere*. *Greenhouse gases (GHGs)*, clouds, and (to a small extent) *aerosols* absorb terrestrial radiation emitted by the earth's surface and elsewhere in the *atmosphere*. These substances emit infrared radiation in all directions, but, everything else being equal, the net amount emitted to space is normally less than would have been emitted in the absence of these absorbers because of the decline of temperature with altitude in the *troposphere* and the consequent weakening of emission. An increase in the concentration of GHGs increases the magnitude of this effect; the difference is sometimes called the enhanced greenhouse effect. The change in a GHG concentration because of *anthropogenic emissions* contributes to an instantaneous *radiative forcing*. Surface temperature and *troposphere* warm in response to this forcing, gradually restoring the radiative balance at the top of the *atmosphere*.

Greenhouse gas (GHG): Greenhouse gases are those gaseous constituents of the *atmosphere*, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the earth's surface, the *atmosphere* itself, and by clouds. This property causes the *greenhouse effect*. Water vapour (H_2O), *carbon dioxide* (CO_2), *nitrous oxide* (N_2O), *methane* (CH_4) and *ozone* (O_3) are the primary GHGs in the earth's *atmosphere*. Moreover, there are a number of entirely human-made GHGs in the *atmosphere*, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the *Montreal Protocol*. Beside CO_2, N_2O and CH_4, the *Kyoto Protocol* deals with the GHGs *sulphur hexafluoride* (SF_6), *hydrofluorocarbons (HFCs)* and *perfluorocarbons (PFCs)*. For a list of well-mixed GHGs, see WGI AR5 Table 2.A.1.

Gross domestic product (GDP): The sum of gross value added, at purchasers' prices, by all resident and non-resident producers in the economy, plus any taxes and minus any subsidies not included in the value of the products in a country or a geographic region for a given period, normally one year. GDP is calculated without deducting for depreciation of fabricated assets or depletion and degradation of natural resources.

Gross national expenditure (GNE): The total amount of public and private consumption and capital expenditures of a nation. In general, national account is balanced such that *gross domestic product (GDP)* + import = GNE + export.

Gross national product: The value added from domestic and foreign sources claimed by residents. GNP comprises *gross domestic product (GDP)* plus net receipts of primary income from non-resident income.

Gross world product: An aggregation of the individual country's *gross domestic products (GDP)* to obtain the world or global *GDP*.

Heat island: The relative warmth of a city compared with surrounding rural areas, associated with changes in runoff, effects on heat retention, and changes in surface *albedo*.

Human Development Index (HDI): The Human Development Index allows the assessment of countries' progress regarding social and economic development as a composite index of three indicators: (1) health measured by life expectancy at birth; (2) knowledge as measured by a combination of the adult literacy rate and the combined primary, secondary and tertiary school enrolment ratio; and (3) standard of living as *gross domestic product (GDP)* per capita (in purchasing power parity). The HDI sets a minimum and a maximum for each dimension, called goalposts, and then shows where each country stands in relation to these goalposts, expressed as a value between 0 and 1. The HDI only acts as a broad proxy for some of the key issues of human development; for instance, it does not reflect issues such as political participation or gender inequalities.

Hybrid vehicle: Any vehicle that employs two sources of propulsion, particularly a vehicle that combines an internal combustion engine with an electric motor.

Hydrofluorocarbons (HFCs): One of the six types of *greenhouse gases (GHGs)* or groups of GHGs to be mitigated under the *Kyoto Protocol*. They are produced commercially as a substitute for *chlorofluorocarbons (CFCs)*. HFCs largely are used in refrigeration and semiconductor manufacturing. See also *Global Warming Potential (GWP)* and Annex II.9.1 for GWP values.

Hydropower: Power harnessed from the flow of water.

Incremental costs: See *Climate finance*.

Incremental investment: See *Climate finance*.

Indigenous peoples: Indigenous peoples and nations are those that, having a historical continuity with pre-invasion and pre-colonial societies that developed on their territories, consider themselves distinct from other sectors of the societies now prevailing on those territories, or parts of them. They form at present principally non-dominant sectors of society and are often determined to preserve, develop, and transmit to future generations their ancestral territories, and their ethnic identity, as the basis of their continued existence as peoples, in accordance with their own cultural patterns, social *institutions*, and common law system.[5]

Indirect emissions: See *Emissions*.

Indirect land use change (iLUC): See *Land use*.

Industrial Revolution: A period of rapid industrial growth with far-reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of *fossil fuels* and emission of, in particular, fossil *carbon dioxide*. In this report the terms pre-industrial and industrial refer, somewhat arbitrarily, to the periods before and after 1750, respectively.

Industrialized countries/developing countries: There are a diversity of approaches for categorizing countries on the basis of their level of development, and for defining terms such as industrialized, developed, or developing. Several categorizations are used in this report. (1) In the United Nations system, there is no established convention for designating of developed and developing countries or areas. (2) The United Nations Statistics Division specifies developed and developing regions based on common practice. In addition, specific countries are designated as *Least Developed Countries (LCD)*, landlocked developing countries, small island developing states, and transition economies. Many countries appear in more than one of these categories. (3) The World Bank uses income as the main criterion for classifying countries as low, lower middle, upper middle, and high income. (4) The UNDP aggregates indicators for life expectancy, educational attainment, and income into a single composite *Human Development Index (HDI)* to classify countries as low, medium, high, or very high human development. See WGII AR5 Box 1–2.

Input-output analysis: See *Environmental input-output analysis*.

Institution: Institutions are rules and norms held in common by social actors that guide, constrain and shape human interaction. Institutions can be formal, such as laws and policies, or informal, such as norms and conventions. Organizations—such as parliaments, regulatory agencies, private firms, and community bodies—develop and act in response to institutional frameworks and the incentives they frame. Institutions can guide, constrain and shape human interaction through direct control, through incentives, and through processes of socialization.

Institutional feasibility: Institutional feasibility has two key parts: (1) the extent of administrative workload, both for public authorities and for regulated entities, and (2) the extent to which the *policy* is viewed as legitimate, gains acceptance, is adopted, and is implemented.

Integrated assessment: A method of analysis that combines results and models from the physical, biological, economic, and social sciences, and the interactions among these components in a consistent framework to evaluate the status and the consequences of environmental change and the *policy* responses to it. See also *Integrated Models*.

Integrated models: See *Models*.

IPAT identity: IPAT is the lettering of a formula put forward to describe the impact of human activity on the environment. Impact (*I*) is viewed as the product of population size (*P*), affluence (*A*=GDP/person) and technology (*T*= impact per GDP unit). In this conceptualization, population growth by definition leads to greater environmental impact if *A* and *T* are constant, and likewise higher income leads to more impact (Ehrlich and Holdren, 1971).

Iron fertilization: Deliberate introduction of iron to the upper ocean intended to enhance biological productivity which can sequester additional atmospheric *carbon dioxide* (CO_2) into the oceans. See also *Geoengineering* and *Carbon Dioxide Removal (CDR)*.

Jevon's paradox: See *Rebound effect*.

[5] This glossary entry builds on the definitions used in Cobo (1987) and previous IPCC reports.

Joint Implementation (JI): A mechanism defined in Article 6 of the *Kyoto Protocol*, through which investors (governments or companies) from developed *(Annex B) countries* may implement projects jointly that limit or reduce emissions or enhance *sinks*, and to share the *Emissions Reduction Units (ERU)*. See also *Kyoto Mechanisms*.

Kaya identity: In this identity global emissions are equal to the population size, multiplied by per capita output (*gross world product*), multiplied by the *energy intensity* of production, multiplied by the *carbon intensity* of *energy*.

Kyoto Mechanisms (also referred to as Flexibility Mechanisms): Market-based mechanisms that Parties to the *Kyoto Protocol* can use in an attempt to lessen the potential economic impacts of their commitment to limit or reduce *greenhouse gas (GHG)* emissions. They include *Joint Implementation (JI)* (Article 6), *Clean Development Mechanism (CDM)* (Article 12), and *Emissions trading* (Article 17).

Kyoto Protocol: The Kyoto Protocol to the *United Nations Framework Convention on Climate Change (UNFCCC)* was adopted in 1997 in Kyoto, Japan, at the Third Session of the *Conference of the Parties (COP)* to the UNFCCC. It contains legally binding commitments, in addition to those included in the UNFCCC. Countries included in *Annex B* of the Protocol (most Organisation for Economic Cooperation and Development countries and countries with economies in transition) agreed to reduce their anthropogenic *greenhouse gas (GHG)* emissions (*carbon dioxide (CO_2)*, *methane (CH_4)*, *nitrous oxide (N_2O)*, *hydrofluorocarbons (HFCs)*, *perfluorocarbons (PFCs)*, and *sulphur hexafluoride (SF_6)*) by at least 5 % below 1990 levels in the commitment period 2008–2012. The Kyoto Protocol entered into force on 16 February 2005.

Land use (change, direct and indirect): Land use refers to the total of arrangements, activities and inputs undertaken in a certain land cover type (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction and conservation). In urban settlements it is related to land uses within cities and their hinterlands. Urban land use has implications on city management, structure, and form and thus on energy demand, *greenhouse gas (GHG)* emissions, and mobility, among other aspects.

Land use change (LUC): Land use change refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and LUC may have an impact on the surface *albedo*, evapotranspiration, *sources* and *sinks* of GHGs, or other properties of the *climate system* and may thus give rise to *radiative forcing* and/or other impacts on *climate*, locally or globally. See also the IPCC Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000).

Indirect land use change (iLUC): Indirect land use change refers to shifts in land use induced by a change in the production level of an agricultural product elsewhere, often mediated by markets or driven by *policies*. For example, if agricultural land is diverted to fuel production, *forest* clearance may occur elsewhere to replace the former agricultural production. See also *Afforestation*, *Deforestation* and *Reforestation*.

Land use, land use change and forestry (LULUCF): A *greenhouse gas (GHG)* inventory sector that covers *emissions* and removals of GHGs resulting from direct human-induced *land use*, *land use change* and forestry activities excluding *agricultural emissions*. See also *Agriculture, Forestry and Other Land Use (AFOLU)*.

Land value capture: A financing mechanism usually based around transit systems, or other infrastructure and services, that captures the increased value of land due to improved accessibility.

Leakage: Phenomena whereby the reduction in emissions (relative to a *baseline*) in a jurisdiction/sector associated with the implementation of *mitigation policy* is offset to some degree by an increase outside the jurisdiction/sector through induced changes in consumption, production, prices, land use and/or trade across the jurisdictions/sectors. Leakage can occur at a number of levels, be it a project, state, province, nation, or world region. See also *Rebound effect*.

In the context of *Carbon Dioxide Capture and Storage (CCS)*, 'CO_2 leakage' refers to the escape of injected *carbon dioxide (CO_2)* from the storage location and eventual release to the atmosphere. In the context of other substances, the term is used more generically, such as for '*methane (CH_4)* leakage' (e.g., from *fossil fuel* extraction activities), and '*hydrofluorocarbon (HFC)* leakage' (e.g., from refrigeration and air-conditioning systems).

Learning curve/rate: Decreasing cost-prices of technologies shown as a function of increasing (total or yearly) supplies. The learning rate is the percent decrease of the cost-price for every doubling of the cumulative supplies (also called progress ratio).

Least Developed Countries (LDCs): A list of countries designated by the Economic and Social Council of the United Nations (ECOSOC) as meeting three criteria: (1) a low income criterion below a certain threshold of gross national income per capita of between USD 750 and USD 900, (2) a human resource weakness based on indicators of health, education, adult literacy, and (3) an economic vulnerability weakness based on indicators on instability of agricultural production, instability of export of goods and services, economic importance of non-traditional activities, merchandise export concentration, and the handicap of economic smallness. Countries in this category are eligible for a number of programmes focused on assisting countries most in need. These privileges include certain benefits under the articles of the *United Nations Framework Convention on Climate Change (UNFCCC)*. See also *Industrialized/developing countries*.

Levelized cost of conserved carbon (LCCC): See Annex II.3.1.3 for concepts and definition.

Levelized cost of conserved energy (LCCE): See Annex II.3.1.2 for concepts and definition.

Levelized cost of energy (LCOE): See Annex II.3.1.1 for concepts and definition.

Lifecycle assessment (LCA): A widely used technique defined by ISO 14040 as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". The results of LCA studies are strongly dependent on the system boundaries within which they are conducted. The technique is intended for relative comparison of two similar means to complete a product. See also Annex II.6.3.

Likelihood: The chance of a specific outcome occurring, where this might be estimated probabilistically. This is expressed in this report using a standard terminology (Mastrandrea et al., 2010): virtually certain 99–100 % probability, very likely 90–100 %, likely 66–100 %, about as likely as not 33–66 %, unlikely 0–33 %, very unlikely 0–10 %, exceptionally unlikely 0–1 %. Additional terms (more likely than not > 50–100 %, and more unlikely than likely 0–< 50 %) may also be used when appropriate. Assessed likelihood is typeset in italics, e. g., *very likely*. See also *Agreement*, *Confidence*, *Evidence* and *Uncertainty*.

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Lock-in: Lock-in occurs when a market is stuck with a *standard* even though participants would be better off with an alternative.

Marginal abatement cost (MAC): The cost of one unit of additional *mitigation*.

Market barriers: In the context of climate change *mitigation*, market barriers are conditions that prevent or impede the diffusion of *cost-effective* technologies or practices that would mitigate *greenhouse gas (GHG)* emissions.

Market-based mechanisms, GHG emissions: Regulatory approaches using price mechanisms (e.g., taxes and auctioned *emission permits*), among other instruments, to reduce the *sources* or enhance the *sinks* of *greenhouse gases (GHGs)*.

Market exchange rate (MER): The rate at which foreign currencies are exchanged. Most economies post such rates daily and they vary little across all the exchanges. For some developing economies, official rates and black-market rates may differ significantly and the MER is difficult to pin down. See also *Purchasing power parity (PPP)* and Annex II.1.3 for the monetary conversion process applied throughout this report.

Market failure: When private decisions are based on market prices that do not reflect the real scarcity of goods and services but rather reflect market distortions, they do not generate an efficient allocation of resources but cause welfare losses. A market distortion is any event in which a market reaches a market clearing price that is substantially different from the price that a market would achieve while operating under conditions of perfect competition and state enforcement of legal contracts and the ownership of private property. Examples of factors causing market prices to deviate from real economic scarcity are environmental *externalities*, *public goods*, monopoly power, information asymmetry, *transaction costs*, and non-rational *behaviour*. See also *Economic efficiency*.

Material flow analysis (MFA): A systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner and Rechberger, 2004). See also Annex II.6.1.

Measures: In climate *policy*, measures are technologies, processes or practices that contribute to *mitigation*, for example *renewable energy (RE)* technologies, waste minimization processes, public transport commuting practices.

Meeting of the Parties (CMP): The *Conference of the Parties (COP)* to the *United Nations Framework Convention on Climate Change (UNFCCC)* serves as the CMP, the supreme body of the *Kyoto Protocol*, since the latter entered into force on 16 February 2005. Only Parties to the *Kyoto Protocol* may participate in deliberations and make decisions.

Methane (CH_4): One of the six *greenhouse gases (GHGs)* to be mitigated under the *Kyoto Protocol* and is the major component of natural gas and associated with all hydrocarbon fuels. Significant emissions occur as a result of animal husbandry and agriculture and their management represents a major *mitigation* option. See also *Global Warming Potential (GWP)* and Annex II.9.1 for GWP values.

Methane recovery: Any process by which *methane (CH_4)* emissions (e.g., from oil or gas wells, coal beds, peat bogs, gas transmission pipelines, landfills, or anaerobic digesters) are captured and used as a fuel or for some other economic purpose (e.g., chemical feedstock).

Millennium Development Goals (MDGs): A set of eight time-bound and measurable goals for combating poverty, hunger, disease, illiteracy, discrimination against women and environmental degradation. These goals were agreed to at the UN Millennium Summit in 2000 together with an action plan to reach the goals.

Mitigation (of climate change): A human intervention to reduce the *sources* or enhance the *sinks* of *greenhouse gases (GHGs)*. This report also assesses human interventions to reduce the *sources* of other substances which may contribute directly or indirectly to limiting *climate change*, including, for example, the reduction of *particulate matter (PM)* emissions that can directly alter the radiation balance (e.g., *black carbon*) or *measures* that control emissions of carbon monoxide, *nitrogen oxides (NO_x)*, *Volatile Organic Compounds (VOCs)* and other pollutants that can alter the concentration of tropospheric *ozone (O_3)* which has an indirect effect on the *climate*.

Mitigation capacity: A country's ability to reduce anthropogenic *greenhouse gas (GHG)* emissions or to enhance natural *sinks*, where ability refers to skills, competencies, fitness, and proficiencies that a country has attained and depends on technology, *institutions*, wealth, equity, infrastructure, and information. Mitigative capacity is rooted in a country's *sustainable development (SD)* path.

Mitigation scenario: A plausible description of the future that describes how the (studied) system responds to the implementation of *mitigation policies* and *measures*. See also *Baseline/reference*, *Climate scenario*, *Emission scenario*, *Representative Concentration Pathways (RCPs)*, *Scenario*, *Shared socio-economic pathways*, *Socio-economic scenarios*, *SRES scenarios*, *Stabilization*, and *Transformation pathways*.

Models: Structured imitations of a system's attributes and mechanisms to mimic appearance or functioning of systems, for example, the *climate*, the economy of a country, or a crop. Mathematical models assemble (many) variables and relations (often in a computer code) to simulate system functioning and performance for variations in parameters and inputs.

Computable General Equilibrium (CGE) Model: A class of economic models that use actual economic data (i.e., input/output data), simplify the characterization of economic *behaviour*, and solve the whole system numerically. CGE models specify all economic relationships in mathematical terms and predict the changes in variables such as prices, output and economic welfare resulting from a change in economic policies, given information about technologies and consumer preferences (Hertel, 1997). See also *General equilibrium analysis*.

Integrated Model: Integrated models explore the interactions between multiple sectors of the economy or components of particular systems, such as the *energy system*. In the context of *transformation pathways*, they refer to models that, at a minimum, include full and disaggregated representations of the *energy system* and its linkage to the overall economy that will allow for consideration of interactions among different elements of that system. Integrated models may also include representations of the full economy, *land use* and *land use change (LUC)*, and the *climate system*. See also *Integrated assessment*.

Sectoral Model: In the context of this report, sectoral models address only one of the core sectors that are discussed in this report, such as buildings, industry, transport, energy supply, and *Agriculture, Forestry and Other Land Use (AFOLU)*.

Montreal Protocol: The Montreal Protocol on Substances that Deplete the Ozone Layer was adopted in Montreal in 1987, and subsequently adjusted and amended in London (1990), Copenhagen (1992), Vienna (1995), Montreal (1997) and Beijing (1999). It controls the consumption and production of chlorine- and bromine- containing chemicals that destroy stratospheric *ozone (O_3)*, such as *chlorofluorocarbons (CFCs)*, methyl chloroform, carbon tetrachloride and many others.

Multi-criteria analysis (MCA): Integrates different decision parameters and values without assigning monetary values to all parameters. Multi-criteria analysis can combine quantitative and qualitative information. Also referred to as multi-attribute analysis.

Multi-attribute analysis: See *Multi-criteria analysis (MCA)*.

Multi-gas: Next to *carbon dioxide (CO_2)*, there are other forcing components taken into account in, e.g., achieving reduction for a basket of *greenhouse gas (GHG)* emissions (CO_2, *methane (CH_4)*, *nitrous oxide (N_2O)*, and fluorinated gases) or *stabilization* of *CO_2-equivalent concentrations* (multi-gas *stabilization*, including GHGs and *aerosols*).

Nationally Appropriate Mitigation Action (NAMA): Nationally Appropriate Mitigation Actions are a concept for recognizing and financing emission reductions by *developing countries* in a post-2012 climate regime achieved through action considered appropriate in a given national context. The concept was first introduced in the Bali Action Plan in 2007 and is contained in the *Cancún Agreements*.

Nitrogen oxides (NO_X): Any of several oxides of nitrogen.

Nitrous oxide (N_2O): One of the six *greenhouse gases (GHGs)* to be mitigated under the *Kyoto Protocol*. The main anthropogenic source of N_2O is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, *fossil fuel* combustion, and chemical industrial processes. N_2O is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests. See also *Global Warming Potential (GWP)* and Annex II.9.1 for GWP values.

Non-Annex I Parties/countries: Non-Annex I Parties are mostly *developing countries*. Certain groups of *developing countries* are recognized by the Convention as being especially vulnerable to the adverse impacts of *climate change*, including countries with low-lying coastal areas and those prone to *desertification* and drought. Others, such as countries that rely heavily on income from *fossil fuel* production and commerce, feel more vulnerable to the potential economic impacts of *climate change* response measures. The Convention emphasizes activities that promise to answer the special needs and concerns of these vulnerable countries, such as investment, insurance, and technology transfer. See also *Annex I Parties/countries*.

Normative analysis: Analysis in which judgments about the desirability of various *policies* are made. The conclusions rest on value judgments as well as on facts and theories. See also *Descriptive analysis*.

Ocean energy: *Energy* obtained from the ocean via waves, tidal ranges, tidal and ocean currents, and thermal and saline gradients.

Offset (in climate policy): A unit of *CO_2-equivalent emissions* that is reduced, avoided, or sequestered to compensate for emissions occurring elsewhere.

Oil sands and oil shale: Unconsolidated porous sands, sandstone rock, and shales containing bituminous material that can be mined and converted to a liquid fuel. See also *Unconventional fuels*.

Overshoot pathways: Emissions, concentration, or temperature pathways in which the metric of interest temporarily exceeds, or 'overshoots', the long-term goal.

Ozone (O_3): Ozone, the triatomic form of oxygen (O_3), is a gaseous atmospheric constituent. In the *troposphere*, it is created both naturally and by photochemical reactions involving gases resulting from human activities (smog). Tropospheric O_3 acts as a *greenhouse gas (GHG)*. In the *stratosphere*, it is created by the interaction between solar ultraviolet radiation and molecular oxygen (O_2). Stratospheric O_3 plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the O_3 layer.

Paratransit: Denotes flexible passenger transportation, often but not only in areas with low population density, that does not follow fixed routes or schedules. Options include minibuses (matatus, marshrutka), shared taxis and jitneys. Sometimes paratransit is also called community transit.

Pareto optimum: A state in which no one's welfare can be increased without reducing someone else's welfare. See also *Economic efficiency*.

Particulate matter (PM): Very small solid particles emitted during the combustion of *biomass* and *fossil fuels*. PM may consist of a wide variety of substances. Of greatest concern for health are particulates of diameter less than or equal to 10 nanometers, usually designated as PM_{10}. See also *Aerosol*.

Passive design: The word 'passive' in this context implies the ideal target that the only *energy* required to use the designed product or service comes from renewable sources.

Path dependence: The generic situation where decisions, events, or outcomes at one point in time constrain *adaptation*, *mitigation*, or other actions or options at a later point in time.

Payback period: Mostly used in investment appraisal as financial payback, which is the time needed to repay the initial investment by the returns of a project. A payback gap exists when, for example, private investors and micro-financing schemes require higher profitability rates from *renewable energy (RE)* projects than from fossil-fired projects. Energy payback is the time an *energy* project needs to deliver as much *energy* as had been used for setting the project online. Carbon payback is the time a *renewable energy (RE)* project needs to deliver as much net *greenhouse gas (GHG)* savings (with respect to the fossil reference *energy system*) as its realization has caused GHG emissions from a perspective of *lifecycle assessment (LCA)* (including *land use changes (LUC)* and loss of terrestrial carbon stocks).

Perfluorocarbons (PFCs): One of the six types of *greenhouse gases (GHGs)* or groups of GHGs to be mitigated under the *Kyoto Protocol*. PFCs are by-products of aluminium smelting and uranium enrichment. They also replace *chlorofluorocarbons (CFCs)* in manufacturing semiconductors. See also *Global Warming Potential (GWP)* and Annex II.9.1 for GWP values.

Photovoltaic cells (PV): Electronic devices that generate electricity from light *energy*. See also *Solar energy*.

Policies (for mitigation of or adaptation to climate change): Policies are a course of action taken and/or mandated by a government, e.g., to enhance *mitigation* and *adaptation*. Examples of *policies* aimed at *mitigation* are support mechanisms for *renewable energy (RE)* supplies, carbon or energy taxes, fuel efficiency *standards* for automobiles. See also *Measures*.

Polluter pays principle (PPP): The party causing the pollution is responsible for paying for remediation or for compensating the damage.

Positive analysis: See *Descriptive analysis*.

Potential: The possibility of something happening, or of someone doing something in the future. Different metrics are used throughout this report for the quantification of different types of potentials, including the following:

> ***Technical potential:*** Technical potential is the amount by which it is possible to pursue a specific objective through an increase in deployment of technologies or implementation of processes and practices that were not previously used or implemented. Quantification of technical potentials may take into account other than technical considerations, including social, economic and/or environmental considerations.

Precautionary principle: A provision under Article 3 of the *United Nations Framework Convention on Climate Change (UNFCCC)*, stipulating that the Parties should take precautionary *measures* to anticipate, prevent, or minimize the causes of *climate change* and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason to postpone such *measures*, taking into account that *policies* and *measures* to deal with *climate change* should be *cost-effective* in order to ensure global benefits at the lowest possible cost.

Precursors: Atmospheric compounds that are not *greenhouse gases (GHGs)* or *aerosols*, but that have an effect on GHG or *aerosol* concentrations by taking part in physical or chemical processes regulating their production or destruction rates.

Pre-industrial: See *Industrial Revolution*.

Present value: Amounts of money available at different dates in the future are discounted back to a present value, and summed to get the present value of a series of future cash flows. See also *Discounting*.

Primary production: All forms of production accomplished by plants, also called primary producers.

Primary energy: See *Energy*.

Private costs: Private costs are carried by individuals, companies or other private entities that undertake an action, whereas social costs include additionally the *external costs* on the environment and on society as a whole. Quantitative estimates of both private and social costs may be incomplete, because of difficulties in measuring all relevant effects.

Production-based accounting: Production-based accounting provides a measure of emissions released to the *atmosphere* for the production of goods and services by a certain entity (e.g., person, firm, country, or region). See also *Consumption-based accounting*.

Public good: Public goods are non-rivalrous (goods whose consumption by one consumer does not prevent simultaneous consumption by other consumers) and non-excludable (goods for which it is not possible to prevent people who have not paid for it from having access to it).

Purchasing power parity (PPP): The purchasing power of a currency is expressed using a basket of goods and services that can be bought with a given amount in the home country. International comparison of, for example, *gross domestic products (GDP)* of countries can be based on the purchasing power of currencies rather than on current exchange rates. PPP estimates tend to lower per capita *GDP* in *industrialized countries* and raise per capita *GDP* in *developing countries*. (PPP is also an acronym for *polluter pays principle*). See also *Market exchange rate (MER)* and Annex II.1.3 for the monetary conversion process applied throughout this report.

Radiation management: See *Solar Radiation Management*.

Radiative forcing: Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in W m^{-2}) at the tropopause or top of *atmosphere* due to a change in an external driver of *climate change*, such as, for example, a change in the concentration of *carbon dioxide* (CO_2) or the output of the sun. For the purposes of this report, radiative forcing is further defined as the change relative to the year 1750 and refers to a global and annual average value.

Rebound effect: Phenomena whereby the reduction in *energy* consumption or emissions (relative to a *baseline*) associated with the implementation of *mitigation measures* in a jurisdiction is offset to some degree through induced changes in consumption, production, and prices within the same jurisdiction. The rebound effect is most typically ascribed to technological *energy efficiency (EE)* improvements. See also *Leakage*.

Reducing Emissions from Deforestation and Forest Degradation (REDD): An effort to create financial value for the carbon stored in *forests*, offering incentives for *developing countries* to reduce emissions from forested lands and invest in low-carbon paths to *sustainable development (SD)*. It is therefore a mechanism for *mitigation* that results from avoiding *deforestation*. REDD+ goes beyond *reforestation* and *forest* degradation, and includes the role of conservation, sustainable management of forests and enhancement of forest carbon stocks. The concept was first introduced in 2005 in the 11th Session of the *Conference of the Parties (COP)* in Montreal and later given greater recognition in the 13th Session of the COP in 2007 at Bali and inclusion in the Bali Action Plan which called for "policy approaches and positive incentives on issues relating to reducing emissions to deforestation and forest degradation in developing countries (REDD) and the role of conservation, sustainable management of forests and enhancement of forest carbon stock in developing countries". Since then, support for REDD has increased and has slowly become a framework for action supported by a number of countries.

Reference scenario: See *Baseline/reference*.

Reforestation: Planting of *forests* on lands that have previously sustained *forests* but that have been converted to some other use. Under the *United Nations Framework Convention on Climate Change (UNFCCC)* and the *Kyoto Protocol*, reforestation is the direct human-induced conversion of non-forested land to forested land through planting, seeding, and/or human-induced promotion of natural seed sources, on land that was previously forested but converted to non-forested land. For the first commitment period of the *Kyoto Protocol*, reforestation activities will be limited to reforestation occurring on those lands that did not contain forest on 31 December 1989.

For a discussion of the term *forest* and related terms such as *afforestation*, reforestation and *deforestation*, see the IPCC Report on Land Use, Land-Use Change and Forestry (IPCC, 2000). See also the Report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).

Renewable energy (RE): See *Energy*.

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Representative Concentration Pathways (RCPs): *Scenarios* that include time series of emissions and concentrations of the full suite of *greenhouse gases (GHGs)* and *aerosols* and chemically active gases, as well as *land use*/land cover (Moss et al., 2008). The word *representative* signifies that each RCP provides only one of many possible *scenarios* that would lead to the specific *radiative forcing* characteristics. The term *pathway* emphasizes that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome (Moss et al., 2010).

RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which Integrated Assessment Models produced corresponding *emission scenarios*. Extended Concentration Pathways (ECPs) describe extensions of the RCPs from 2100 to 2500 that were calculated using simple rules generated by stakeholder consultations, and do not represent fully consistent *scenarios*.

Four RCPs produced from Integrated Assessment Models were selected from the published literature and are used in the present IPCC Assessment as a basis for the *climate predictions* and *projections* presented in WGI AR5 Chapters 11 to 14:

RCP2.6 One pathway where *radiative forcing* peaks at approximately 3 W m^{-2} before 2100 and then declines (the corresponding ECP assuming constant emissions after 2100);

RCP4.5 and RCP6.0 Two intermediate *stabilization* pathways in which *radiative forcing* is stabilized at approximately 4.5 W m^{-2} and 6.0 W m^{-2} after 2100 (the corresponding ECPs assuming constant concentrations after 2150);

RCP8.5 One high pathway for which *radiative forcing* reaches greater than 8.5 W m^{-2} by 2100 and continues to rise for some amount of time (the corresponding ECP assuming constant emissions after 2100 and constant concentrations after 2250).

For further description of future *scenarios*, see WGI AR5 Box 1.1. See also *Baseline/reference*, *Climate prediction*, *Climate projection*, *Climate scenario*, *Shared socio-economic pathways*, *Socio-economic scenario*, *SRES scenarios*, and *Transformation pathway*.

Reservoir: A component of the *climate system*, other than the *atmosphere*, which has the capacity to store, accumulate or release a substance of concern, for example, carbon, a *greenhouse gas (GHG)* or a *precursor*. Oceans, soils and *forests* are examples of reservoirs of carbon. Pool is an equivalent term (note that the definition of pool often includes the *atmosphere*). The absolute quantity of the substance of concern held within a reservoir at a specified time is called the stock. In the context of *Carbon Dioxide Capture and Storage (CCS)*, this term is sometimes used to refer to a geological *carbon dioxide (CO_2)* storage location. See also *Sequestration*.

Resilience: The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for *adaptation*, learning, and transformation (Arctic Council, 2013).

Revegetation: A direct human-induced activity to increase carbon stocks on sites through the establishment of vegetation that covers a minimum area of 0.05 hectares and does not meet the definitions of *afforestation* and *reforestation* contained here (UNFCCC, 2002).

Risk: In this report, the term risk is often used to refer to the potential, when the outcome is uncertain, for adverse consequences on lives, livelihoods, health, *ecosystems* and species, economic, social and cultural assets, services (including environmental services), and infrastructure.

Risk assessment: The qualitative and/or quantitative scientific estimation of *risks*.

Risk management: The plans, actions, or policies to reduce the likelihood and/or consequences of a given *risk*.

Risk perception: The subjective judgment that people make about the characteristics and severity of a *risk*.

Risk tradeoff: The change in the portfolio of *risks* that occurs when a countervailing *risk* is generated (knowingly or inadvertently) by an intervention to reduce the target *risk* (Wiener and Graham, 2009). See also *Adverse side-effect*, and *Co-benefit*.

Risk transfer: The practice of formally or informally shifting the *risk* of financial consequences for particular negative events from one party to another.

Scenario: A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of *technological change (TC)*, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are useful to provide a view of the implications of developments and actions. See also *Baseline/reference*, *Climate scenario*, *Emission scenario*, *Mitigation scenario*, *Representative Concentration Pathways (RCPs)*, *Shared socio-economic pathways*, *Socioeconomic scenarios*, *SRES scenarios*, *Stabilization*, and *Transformation pathway*.

Scope 1, Scope 2, and Scope 3 emissions: See *Emissions*.

Secondary energy: See *Primary energy*.

Sectoral Models: See *Models*.

Sensitivity analysis: Sensitivity analysis with respect to quantitative analysis assesses how changing assumptions alters the outcomes. For example, one chooses different values for specific parameters and re-runs a given *model* to assess the impact of these changes on model output.

Sequestration: The uptake (i.e., the addition of a substance of concern to a *reservoir*) of carbon containing substances, in particular *carbon dioxide (CO_2)*, in terrestrial or marine *reservoirs*. Biological sequestration includes direct removal of CO_2 from the *atmosphere* through *land-use change (LUC)*, *afforestation*, *reforestation*, *revegetation*, carbon storage in landfills, and practices that enhance soil carbon in agriculture (*cropland management*, *grazing land management*). In parts of the literature, but not in this report, (carbon) sequestration is used to refer to *Carbon Dioxide Capture and Storage (CCS)*.

Shadow pricing: Setting prices of goods and services that are not, or are incompletely, priced by market forces or by administrative regulation, at the height of their social marginal value. This technique is used in *cost-benefit analysis (CBA)*.

Shared socio-economic pathways (SSPs): Currently, the idea of SSPs is developed as a basis for new emissions and *socio-economic scenarios*. An SSP is one of a collection of pathways that describe alternative futures of socio-economic development in the absence of climate *policy* intervention. The combination of SSP-based *socio-economic scenarios* and *Representative Concentration Pathway (RCP)*-based *climate projections* should provide a useful integrative frame for climate impact and *policy* analysis. See also *Baseline/reference*, *Climate scenario*, *Emission scenario*, *Mitigation scenario*, *Scenario*, *SRES scenarios*, *Stabilization*, and *Transformation pathway*.

Short-lived climate pollutant (SLCP): Pollutant emissions that have a warming influence on *climate* and have a relatively short lifetime in the *atmosphere* (a few days to a few decades). The main SLCPs are *black carbon (BC)* ('soot'), *methane (CH_4)* and some *hydroflurorcarbons (HFCs)* some of which are regulated under the *Kyoto Protocol*. Some pollutants of this type, including CH_4, are also *precursors* to the formation of tropospheric *ozone (O_3)*, a strong warming agent. These pollutants are of interest for at least two reasons. First, because they are short-lived, efforts to control them will have prompt effects on *global warming*—unlike long-lived pollutants that build up in the *atmosphere* and respond to changes in emissions at a more sluggish pace. Second, many of these pollutants also have adverse local impacts such as on human health.

Sink: Any process, activity or mechanism that removes a *greenhouse gas (GHG)*, an *aerosol,* or a *precursor* of a GHG or *aerosol* from the *atmosphere*.

Smart grids: A smart grid uses information and communications technology to gather data on the *behaviours* of suppliers and consumers in the production, distribution, and use of electricity. Through automated responses or the provision of price signals, this information can then be used to improve the efficiency, reliability, economics, and *sustainability* of the electricity network.

Smart meter: A meter that communicates consumption of electricity or gas back to the utility provider.

Social cost of carbon (SCC): The net present value of climate damages (with harmful damages expressed as a positive number) from one more tonne of carbon in the form of *carbon dioxide (CO_2)*, conditional on a global emissions trajectory over time.

Social costs: See *Private costs*.

Socio-economic scenario: A *scenario* that describes a possible future in terms of population, *gross domestic product (GDP)*, and other socio-economic factors relevant to understanding the implications of *climate change*. See also *Baseline/reference*, *Climate scenario*, *Emission scenario*, *Mitigation scenario*, *Representative Concentration Pathways (RCPs)*, *Scenario*, *Shared socio-economic pathways*, *SRES scenarios*, *Stabilization*, and *Transformation pathway*.

Solar energy: *Energy* from the sun. Often the phrase is used to mean *energy* that is captured from solar radiation either as heat, as light that is converted into chemical energy by natural or artificial photosynthesis, or by photovoltaic panels and converted directly into electricity.

Solar Radiation Management (SRM): Solar Radiation Management refers to the intentional modification of the earth's shortwave radiative budget with the aim to reduce *climate change* according to a given metric (e.g., surface temperature, precipitation, regional impacts, etc.). Artificial injection of stratospheric *aerosols* and cloud brightening are two examples of SRM techniques. Methods to modify some fast-responding elements of the longwave radiative budget (such as cirrus clouds), although not strictly speaking SRM, can be related to SRM. SRM techniques do not fall within the usual definitions of *mitigation* and *adaptation* (IPCC, 2012, p. 2). See also *Carbon Dioxide Removal (CDR)* and *Geoengineering*.

Source: Any process, activity or mechanism that releases a *greenhouse gas (GHG)*, an *aerosol* or a *precursor* of a GHG or *aerosol* into the *atmosphere*. Source can also refer to, e.g., an *energy* source.

Spill-over effect: The effects of domestic or sector *mitigation measures* on other countries or sectors. Spill-over effects can be positive or negative and include effects on trade, (carbon) *leakage*, transfer of innovations, and diffusion of environmentally sound technology and other issues.

SRES scenarios: SRES scenarios are *emission scenarios* developed by Nakićenović and Swart (2000) and used, among others, as a basis for some of the *climate projections* shown in Chapters 9 to 11 of IPCC (2001) and Chapters 10 and 11 of IPCC (2007) as well as WGI AR5. The following terms are relevant for a better understanding of the structure and use of the set of SRES scenarios:

Scenario family: *Scenarios* that have a similar demographic, societal, economic and technical change storyline. Four scenario families comprise the SRES scenario set: A1, A2, B1, and B2.

Illustrative Scenario: A *scenario* that is illustrative for each of the six scenario groups reflected in the Summary for Policymakers of Nakićenović and Swart (2000). They include four revised marker scenarios for the scenario groups A1B, A2, B1, B2, and two additional *scenarios* for the A1FI and A1T groups. All scenario groups are equally sound.

Marker Scenario: A *scenario* that was originally posted in draft form on the SRES website to represent a given scenario family. The choice of markers was based on which of the initial quantifications best reflected the storyline, and the features of specific models. Markers are no more likely than other scenarios, but are considered by the SRES writing team as illustrative of a particular storyline. They are included in revised form in Nakićenović and Swart (2000). These scenarios received the closest scrutiny of the entire writing team and via the SRES open process. *Scenarios* were also selected to illustrate the other two scenario groups.

Storyline: A narrative description of a *scenario* (or family of *scenarios*), highlighting the main *scenario* characteristics, relationships between key driving forces and the dynamics of their evolution.

See also *Baseline/reference*, *Climate scenario*, *Emission scenario*, *Mitigation scenario*, *Representative Concentration Pathways (RCPs)*, *Shared socio-economic pathways*, *Socio-economic scenario*, *Stabilization*, and *Transformation pathway*.

Stabilization (of GHG or CO_2-equivalent concentration): A state in which the atmospheric concentrations of one *greenhouse gas (GHG)* (e.g., *carbon dioxide*) or of a *CO_2-equivalent* basket of GHGs (or a combination of GHGs and *aerosols*) remains constant over time.

Standards: Set of rules or codes mandating or defining product performance (e.g., grades, dimensions, characteristics, test methods, and rules for use). Product, technology or performance standards establish minimum requirements for affected products or technologies. Standards impose reductions in *greenhouse gas (GHG)* emissions associated with the manufacture or use of the products and/or application of the technology.

Stratosphere: The highly stratified region of the *atmosphere* above the *troposphere* extending from about 10 km (ranging from 9 km at high latitudes to 16 km in the tropics on average) to about 50 km altitude.

Structural change: Changes, for example, in the relative share of *gross domestic product (GDP)* produced by the industrial, agricultural, or services sectors of an economy, or more generally, systems transformations whereby some components are either replaced or potentially substituted by other components.

Subsidiarity: The principle that decisions of government (other things being equal) are best made and implemented, if possible, at the lowest most decentralized level, that is, closest to the citizen. Subsidiarity is designed to strengthen accountability and reduce the dangers of making decisions in places remote from their point of application. The principle does not necessarily limit or constrain the action of higher orders of government, but merely counsels against the unnecessary assumption of responsibilities at a higher level.

Sulphur hexafluoride (SF_6): One of the six types of *greenhouse gases (GHGs)* to be mitigated under the *Kyoto Protocol*. SF_6 is largely used in heavy industry to insulate high-voltage equipment and to assist in the manufacturing of cable-cooling systems and semi-conductors. See *Global Warming Potential (GWP)* and Annex II.9.1 for GWP values.

Sustainability: A dynamic process that guarantees the persistence of natural and human systems in an equitable manner.

Sustainable development (SD): Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987).

Technical potential: See *Potential*.

Technological change (TC): Economic models distinguish autonomous (exogenous), endogenous, and induced TC.

Autonomous (exogenous) technological change: Autonomous (exogenous) technological change is imposed from outside the model (i.e., as a parameter), usually in the form of a time trend affecting factor and/or energy productivity and therefore *energy* demand and/or economic growth.

Endogenous technological change: Endogenous technological change is the outcome of economic activity within the model (i.e., as a variable) so that factor productivity or the choice of technologies is included within the model and affects *energy* demand and/or economic growth.

Induced technological change: Induced technological change implies endogenous technological change but adds further changes induced by *policies* and *measures*, such as *carbon taxes* triggering research and development efforts.

Technological learning: See *Learning curve/rate*.

Technological/knowledge spillovers: Any positive *externality* that results from purposeful investment in technological innovation or development (Weyant and Olavson, 1999).

Territorial emissions: See *Emissions*.

Trace gas: A minor constituent of the *atmosphere*, next to nitrogen and oxygen that together make up 99 % of all volume. The most important trace gases contributing to the *greenhouse effect* are *carbon dioxide (CO_2)*, *ozone (O_3)*, *methane (CH_4)*, *nitrous oxide (N_2O)*, *perfluorocarbons (PFCs)*, *chlorofluorocarbons (CFCs)*, *hydrofluorocarbons (HFCs)*, *sulphur hexafluoride (SF_6)* and water vapour (H_2O).

Tradable (green) certificates scheme: A *market-based mechanism* to achieve an environmentally desirable outcome (*renewable energy (RE)* generation, *energy efficiency (EE)* requirements) in a *cost-effective* way by allowing purchase and sale of certificates representing under and over-compliance respectively with a quota.

Tradable (emission) permit: See *Emission permit*.

Tradable quota system: See *Emissions trading*.

Transaction costs: The costs that arise from initiating and completing transactions, such as finding partners, holding negotiations, consulting with lawyers or other experts, monitoring agreements, or opportunity costs, such as lost time or resources (Michaelowa et al., 2003).

Transformation pathway: The trajectory taken over time to meet different goals for *greenhouse gas (GHG)* emissions, atmospheric concentrations, or *global mean surface temperature* change that implies a set of economic, *technological*, and *behavioural changes*. This can encompass changes in the way *energy* and infrastructure is used and produced, natural resources are managed, *institutions* are set up, and in the pace and direction of *technological change (TC)*. See also *Baseline/reference*, *Climate scenario*, *Emission scenario*, *Mitigation scenario*, *Representative Concentration Pathways (RCPs)*, *Scenario*, *Shared socio-economic pathways*, *Socio-economic scenarios*, *SRES scenarios*, and *Stabilization*.

Transient climate response: See *Climate sensitivity*.

Transit oriented development (TOD): Urban development within walking distance of a transit station, usually dense and mixed with the character of a walkable environment.

Troposphere: The lowest part of the *atmosphere*, from the surface to about 10 km in altitude at mid-latitudes (ranging from 9 km at high latitudes to 16 km in the tropics on average), where clouds and weather phenomena occur. In the troposphere, temperatures generally decrease with height. See also *Stratosphere*.

Uncertainty: A cognitive state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human *behaviour*. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts) (see Moss and Schneider, 2000; Manning et al., 2004; Mastrandrea et al., 2010). See also *Agreement*, *Evidence*, *Confidence* and *Likelihood*.

Unconventional resources: A loose term to describe *fossil fuel* reserves that cannot be extracted by the well-established drilling and mining processes that dominated extraction of coal, gas, and oil throughout the 20th century. The boundary between conventional and unconventional resources is not clearly defined. Unconventional oils include *oil shales*, tar sands/bitumen, heavy and extra heavy crude oils, and deep-sea oil occurrences. Unconventional natural gas includes gas in Devonian shales, tight sandstone formations, geopressured aquifers, coal-bed gas, and *methane (CH_4)* in clathrate structures (gas hydrates) (Rogner, 1997).

United Nations Framework Convention on Climate Change (UNFCCC): The Convention was adopted on 9 May 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. It contains commitments for all Parties under the principle of 'common but differentiated responsibilities'. Under the Convention, Parties included in *Annex I* aimed to return *greenhouse gas (GHG)* emissions not controlled by the *Montreal Protocol* to 1990 levels by the year 2000. The convention entered in force in March 1994. In 1997, the UNFCCC adopted the *Kyoto Protocol*.

Urban heat island: See *Heat island*.

Verified Emissions Reductions: Emission reductions that are verified by an independent third party outside the framework of the *United Nations Framework Convention on Climate Change (UNFCCC)* and its *Kyoto Protocol*. Also called 'Voluntary Emission Reductions'.

Volatile Organic Compounds (VOCs): Important class of organic chemical air pollutants that are volatile at ambient air conditions. Other terms used to represent VOCs are *hydrocarbons* (HCs), *reactive organic gases* (ROGs) and *non-methane volatile organic compounds* (NMVOCs). NMVOCs are major contributors—together with *nitrogen oxides (NO_x)*, and carbon monoxide (CO)—to the formation of photochemical oxidants such as *ozone (O_3)*.

Voluntary action: Informal programmes, self-commitments, and declarations, where the parties (individual companies or groups of companies) entering into the action set their own targets and often do their own monitoring and reporting.

Voluntary agreement (VA): An agreement between a government authority and one or more private parties to achieve environmental objectives or to improve environmental performance beyond compliance with regulated obligations. Not all voluntary agreements are truly voluntary; some include rewards and/or penalties associated with joining or achieving commitments.

Voluntary Emission Reductions: See *Verified Emissions Reductions*.

Watts per square meter ($W\ m^{-2}$): See *Radiative forcing*.

Wind energy: Kinetic *energy* from air currents arising from uneven heating of the earth's surface. A wind turbine is a rotating machine for converting the kinetic energy of the wind to mechanical shaft energy to generate electricity. A windmill has oblique vanes or sails and the mechanical power obtained is mostly used directly, for example, for water pumping. A wind farm, wind project, or wind power plant is a group of wind turbines interconnected to a common utility system through a system of transformers, distribution lines, and (usually) one substation.

Acronyms and chemical symbols

AAU	Assigned Amount Unit
ADB	Asian Development Bank
AfDB	African Development Bank
AFOLU	Agriculture, Forestry and Other Land Use
AME	Asian Modeling Exercise
AMPERE	Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates
AOSIS	Alliance of Small Island States
APEC	Asia-Pacific Economic Cooperation
AR4	IPCC Fourth Assessment Report
ASEAN	Association of Southeast Asian Nations
ASIA	Non-OECD Asia
BAMs	Border adjustment measures
BAT	Best available technology
BAU	Business-as-usual
BC	Black carbon
BECCS	Bioenergy with carbon dioxide capture and storage
BEVs	Battery electric vehicles
BNDES	Brazilian Development Bank
BOD	Biochemical Oxygen Demand
BRT	Bus rapid transit
C	Carbon
C40	C40 Cities Climate Leadership Group
CBA	Cost-benefit analysis
CBD	Convention on Biological Diversity
CBD	Central business district
CCA	Climate Change Agreement
CCE	Cost of conserved energy
CCL	Climate Change Levy
CCS	Carbon dioxide capture and storage
CDM	Clean Development Mechanism
CDR	Carbon dioxide removal
CEA	Cost-effectiveness analysis
CERs	Certified Emissions Reductions
CFCs	Chlorofluorocarbons
CGE	Computable general equilibrium
CH_4	Methane
CHP	Combined heat and power
CIFs	Climate Investment Funds
CMIP	Coupled Model Intercomparison Project
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide-equivalent, CO_2-equivalent
COD	Chemical oxygen demand
COP	Conference of the Parties
CRF	Capital recovery factor
CSP	Concentrated solar power
CTCN	Climate Technology Centre and Network
DAC	Direct air capture
DAC	Development Assistance Committee
DALYs	Disability-adjusted life years
DANN	Designated National Authority
DCs	Developing countries
DRI	Direct reduced iron
DSM	Demand-side management
EAF	Electric arc furnace
EAS	East Asia
ECA	Economic Commission for Africa
ECN	Energy Research Center of the Netherlands
ECOWAS	Economic Community of West African States
EDGAR	Emissions Database for Global Atmospheric Research
EE	Energy efficiency
EIA	U.S. Energy Information Administration
EITs	Economies in Transition
EMF	Energy Modeling Forum
EPA	U.S. Environmental Protection Agency
EPC	Energy performance contracting
ERU	Emissions reduction unit
ESCOs	Energy service companies
ETS	Emissions Trading System
EU	European Union
EU ETS	European Union Emissions Trading Scheme
EVs	Electric vehicles
F-gases	Fluorinated gases
FAO	Food and Agriculture Organization of the United Nations
FAQ	Frequently asked questions
FAR	IPCC First Assessment Report
FCVs	Fuel cell vehicles
FDI	Foreign Direct Investment
FE	Final energy
FEEM	Fondazione Eni Enrico Mattei
FF&I	Fossil fuel and industrial
FIT	Feed-in tariff
FOLU	Forestry and Other Land Use
FSF	Fast-start Finance
G20	Group of Twenty Finance Ministers
G8	Group of Eight Finance Ministers
GATT	General Agreement on Tariffs and Trade
GCAM	Global Change Assessment Model
GCF	Green Climate Fund
GCM	General Circulation Model
GDP	Gross domestic product
GEA	Global Energy Assessment
GEF	Global Environment Facility
GHG	Greenhouse gas
GNE	Gross national expenditure
GSEP	Global Superior Energy Performance Partnership
GTM	Global Timber Model
GTP	Global Temperature Change Potential
GWP	Global Warming Potential

H_2	Hydrogen
HCFCs	Hydrochlorofluorocarbons
HDI	Human Development Index
HDVs	Heavy-duty vehicles
HFCs	Hydrofluorocarbon
HFC-23	Trifluoromethane
Hg	Mercury
HHV	Higher heating value
HIC	High-income countries
HVAC	Heating, ventilation and air conditioning
IAEA	International Atomic Energy Agency
IAMC	Integrated Assessment Modelling Consortium
ICAO	International Civil Aviation Organization
ICE	Internal combustion engine
ICLEI	International Council for Local Environmental Initiatives
ICT	Information and communication technology
IDB	Inter-American Development Bank
IDP	Integrated Design Process
IEA	International Energy Agency
IET	International Emissions Trading
IGCC	Integrated gasification combined cycle
IIASA	International Institute for Applied Systems Analysis
iLUC	Indirect land-use change
IMF	International Monetary Fund
IMO	International Maritime Organization
INT TRA	International transport
IO	International organization
IP	Intellectual property
IPAT	Income-Population-Affluence-Technology
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRR	Internal rate of return
ISO	International Organization for Standardization
JI	Joint Implementation
JICA	Japan International Cooperation Agency
KfW	Kreditanstalt für Wiederaufbau
LAM	Latin America
LCA	Lifecycle Assessment
LCCC	Levelized costs of conserved carbon
LCD	Liquid crystal display
LCCE	Levelized cost of conserved energy
LCOE	Levelized costs of energy
LDCs	Least Developed Countries
LDCF	Least Developed Countries Fund
LDVs	Light-duty vehicles
LED	Light-emitting diode
LHV	Lower heating value
LIC	Low-income countries
LIMITS	Low Climate Impact Scenarios and Implications of Required Tight Emission Control Strategies
LMC	Lower-middle income countries
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LUC	Land-use change
LULUCF	Land Use, Land-Use Change and Forestry
MAC	Marginal abatement cost
MAF	Middle East and Africa
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change
MCA	Multi-criteria analysis
MDB	Multilateral Development Bank
MDGs	Millennium Development Goals
MEF	Major Economies Forum on Energy and Climate
MER	Market exchange rate
MFA	Material flow analysis
MNA	Middle East and North Africa
MRIO	Multi-Regional Input-Output Analysis
MRV	Measurement, reporting, and verification
MSW	Municipal solid waste
N	Nitrogen
N_2O	Nitrous oxide
NAM	North America
NAMA	Nationally Appropriate Mitigation Action
NAPA	National Adaptation Programmes of Action
NAS	U.S. National Academy of Science
NF_3	Nitrogen trifluoride
NGCC	Natural gas combined cycle
NGO	Non-governmental organization
NH_3	Ammonia
NO_x	Nitrogen oxides
NPV	Net present value
NRC	U.S. National Research Council
NREL	U.S. National Renewable Energy Laboratory
NZEB	Net zero energy buildings
O_3	Ozone
O&M	Operation and maintenance
OC	Organic carbon
ODA	Official development assistance
ODS	Ozone-depleting substances
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of Petroleum Exporting Countries
PACE	Property Assessed Clean Energy
PAS	South-East Asia and Pacific
PBL	Netherlands Environmental Assessment Agency
PC	Pulverized Coal
PDF	Probability density function
PEVs	Plug-in electric vehicles
PFC	Perfluorocarbons
PHEVs	Plug-in hybrid electric vehicles
PIK	Potsdam Institute for Climate Impact Research
PM	Particulate Matter
PNNL	Pacific Northwest National Laboratories
POEDC	Pacific OECD 1990 members (Japan, Aus, NZ)
PPP	Polluter pays principle

PPP	Purchasing power parity
PV	Photovoltaic
R&D	Research and development
RCPs	Representative Concentration Pathways
RD&D	Research, Development and Demonstration
RE	Renewable energy
RECIPE	Report on Energy and Climate Policy in Europe
REDD	Reducing Emissions From Deforestation and Forest Degradation
REEEP	Renewable Energy and Energy Efficiency Partnership
RES	Renewable energy sources
RGGI	Regional Greenhouse Gas Initiative
RoSE	Roadmaps towards Sustainable Energy futures
ROW	Rest of the World
RPS	Renewable portfolio standards
SAR	IPCC Second Assessment Report
SAS	South Asia
SCC	Social cost of carbon
SCCF	Special Climate Change Fund
SCP	Sustainable consumption and production
SD	Sustainable development
SF_6	Sulphur hexafluoride
SLCP	Short-lived climate pollutant
SMEs	Small and Medium Enterprises
SO_2	Sulphur dioxide
SPM	Summary for Policymakers
SRES	IPCC Special Report on Emission Scenarios
SREX	IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SRM	Solar radiation management
SRREN	IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation
SRCSS	IPCC Special Report on Carbon dioxide Capture and Storage
SSA	Sub-Saharan Africa
SUVs	Sport Utility Vehicles
SWF	Social welfare function
TAR	IPCC Third Assessment Report
TC	Technological change
TCR	Transient climate response
Th	Thorium
TNAs	Technology Needs Assessments
TOD	Transit-oriented development
TPES	Total primary energy supply
TRIPs	Trade Related Intellectual Property Rights
TT	Technology transfer
U	Uranium
UHI	Urban heat island
UMC	Upper-middle income countries
UN	United Nations
UN DESA	United Nations Department for Economic and Social Affairs
UNCCD	United Nations Convention to Combat Desertification
UNCSD	United Nations Conference on Sustainable Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
USD	U.S. Dollars
VAs	Voluntary agreements
VOCs	Volatile Organic Compounds
VKT	Vehicle kilometers travelled
WACC	Weighted costs of capital
WBCSD	World Business Council on Sustainable Development
WCED	World Commission on Environment and Development
WCI	Western Climate Initiative
WEU	Western Europe
WGI	IPCC Working Group I
WGII	IPCC Working Group II
WGIII	IPCC Working Group III
WHO	World Health Organization
WTP	Willingness to pay
WWTP	Wastewater plant
WTO	World Trade Organization

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ANNEX

II

Metrics & Methodology

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AII

This annex on methods and metrics provides background information on material used in the Working Group III Contribution to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (WGIII AR5). The material presented in this annex documents metrics, methods, and common data sets that are typically used across multiple chapters of the report. The annex is composed of three parts: Part I introduces standards metrics and common definitions adopted in the report; Part II presents methods to derive or calculate certain quantities used in the report; and Part III provides more detailed background information about common data sources that go beyond what can be included in the chapters. While this structure may help readers to navigate through the annex, it is not possible in all cases to unambiguously assign a certain topic to one of these parts, naturally leading to some overlap between the parts.

Part I: Units and definitions

A.II.1 Standard units and unit conversion

The following section, A.II.1.1, introduces standard units of measurement that are used throughout this report. This includes Système International (SI) units, SI-derived units, and other non-SI units as well the standard prefixes for basic physical units. It builds upon similar material from previous IPCC reports (IPCC, 2001; Moomaw et al., 2011).

In addition to establishing a consistent set of units for reporting throughout the report, harmonized conventions for converting units as reported in the scientific literature have been established and are summarized in Section A.II.1.2 (physical unit conversion) and Section A.II.1.3 (monetary unit conversion).

A.II.1.1 Standard units

Table A.II.1 | Système International (SI) units.

Physical Quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Thermodynamic temperature	kelvin	K
Amount of Substance	mole	mol

Table A.II.2 | Special names and symbols for certain SI-derived units.

Physical Quantity	Unit	Symbol	Definition
Force	Newton	N	kg m s^2
Pressure	Pascal	Pa	kg m^–1 s^–2 (= N m^–2)
Energy	Joule	J	kg m^2 s^–2
Power	Watt	W	kg m^2 s^–3 (= J s^–1)
Frequency	Hertz	Hz	s^–1 (cycles per second)
Ionizing Radiation Dose	sievert	Sv	J kg^-1

Table A.II.3 | Non-SI standard units.

Monetary units	Unit	Symbol
Currency (Market Exchange Rate, MER)	constant US Dollar 2010	USD_{2010}
Currency (Purchasing Power Parity, PPP)	constant International Dollar 2005	$Int\$_{2005}$
Emission- and Climate-related units	**Unit**	**Symbol**
Emissions	Metric tonnes	t
CO_2 Emissions	Metric tonnes CO_2	tCO_2
CO_2-equivalent Emissions	Metric tonnes CO_2-equivalent*	tCO_2eq
Abatement Costs and Emissions Prices/Taxes	constant US Dollar 2010 per metric tonne	USD_{2010}/t
CO_2 concentration or Mixing Ratio (μmol mol–1)	Parts per million (10^6)	ppm
CH_4 concentration or Mixing Ratio (μmol mol–1)	Parts per billion (10^9)	ppb
N_2O concentration or Mixing Ratio (μmol mol–1)	Parts per billion (10^9)	ppb
Radiative forcing	Watts per square meter	W/m^2
Energy-related units	**Unit**	**Symbol**
Energy	Joule	J
Electricity and Heat generation	Watt Hours	Wh
Power (Peak Capacity)	Watt (Watt thermal, Watt electric)	W (W_{th}, W_e)
Capacity Factor	Percent	%
Technical and Economic Lifetime	Years	yr
Specific Energy Investment Costs	US Dollar 2010 per kW (peak capacity)	USD_{2010}/kW
Energy Costs (e.g., LCOE) and Prices	constant US Dollar 2010 per GJ or US Cents 2010 per kWh	USD_{2010}/GJ and $USct_{2010}/kWh$
Passenger-Distance	passenger-kilometer	p-km
Payload-Distance	tonne-kilometer	t-km
Land-related units	**Unit**	**Symbol**
Area	Hectare	ha

Note:
* CO_2-equivalent emissions in this report are—if not stated otherwise—aggregated using global warming potentials (GWPs) over a 100-year time horizon, often derived from the IPCC Second Assessment Report (IPCC, 1995a). A discussion about different GHG metrics can be found in Sections 1.2.5 and 3.9.6 (see Annex II.9.1 for the GWP values of the different GHGs).

Table A.II.4 | Prefixes for basic physical units.

Multiple	Prefix	Symbol	Fraction	Prefix	Symbol
1E+21	zeta	Z	1E-01	deci	d
1E+18	exa	E	1E-02	centi	c
1E+15	peta	P	1E-03	milli	m
1E+12	tera	T	1E-06	micro	µ
1E+09	giga	G	1E-09	nano	n
1E+06	mega	M	1E-12	pico	p
1E+03	kilo	k	1E-15	femto	f
1E+02	hecto	h	1E-18	atto	a
1E+01	deca	da	1E-21	zepto	z

A.II.1.2 Physical unit conversion

Table A.II.5 | Conversion table for common mass units (IPCC, 2001).

To:		kg	t	lt	St	lb
From:	multiply by:					
kilogram	kg	1	1.00E-03	9.84E-04	1.10E-03	2.20E+00
tonne	t	1.00E+03	1	9.84E-01	1.10E+00	2.20E+03
long ton	lt	1.02E+03	1.02E+00	1	1.12E+00	2.24E+03
short ton	st	9.07E+02	9.07E-01	8.93E-01	1	2.00E+03
Pound	lb	4.54E-01	4.54E-04	4.46E-04	5.00E-04	1

A.II.1.3 Monetary unit conversion

To achieve comparability across cost und price information from different regions, where possible all monetary quantities reported in the WGIII AR5 have been converted to constant US Dollars 2010 (USD_{2010}). This only applies to monetary quantities reported in market exchange rates (MER), and not to those reported in purchasing power parity (PPP, unit: Int$).

To facilitate a consistent monetary unit conversion process, a simple and transparent procedure to convert different monetary units from the literature to USD_{2010} was established which is described below.

It is important to note that there is no single agreed upon method of dealing with monetary unit conversion, and thus data availability, transparency, and—for practical reasons—simplicity, were the most important criteria for choosing a method to be used throughout this report.

To convert from year X local currency unit (LCU_X) to 2010 US Dollars (USD_{2010}) two steps are necessary:

1. in-/deflating from year X to 2010, and
2. converting from LCU to USD.

Table A.II.6 | Conversion table for common volumetric units (IPCC, 2001).

To:		gal US	gal UK	bbl	ft³	l	m³
From:	multiply by:						
US Gallon	gal US	1	8.33E-01	2.38E-02	1.34E-01	3.79E+00	3.80E-03
UK/Imperial Gallon	gal UK	1.20E+00	1	2.86E-02	1.61E-01	4.55E+00	4.50E-03
Barrel	bbl	4.20E+01	3.50E+01	1	5.62E+00	1.59E+02	1.59E-01
Cubic foot	ft³	7.48E+00	6.23E+00	1.78E-01	1	2.83E+01	2.83E-02
Liter	l	2.64E-01	2.20E-01	6.30E-03	3.53E-02	1	1.00E-03
Cubic meter	m³	2.64E+02	2.20E+02	6.29E+00	3.53E+01	1.00E+03	1

Table A.II.7 | Conversion table for common energy units (NAS, 2007; IEA, 2012a).

To:		TJ	Gcal	Mtoe	Mtce	MBtu	GWh
From:	multiply by:						
Tera Joule	TJ	1	2.39E+02	2.39E-05	3.41E-05	9.48E+02	2.78E-01
Giga Calorie	Gcal	4.19E-03	1	1.00E-07	1.43E-07	3.97E+00	1.16E-03
Mega Tonne Oil Equivalent	Mtoe	4.19E+04	1.00E+07	1	1.43E+00	3.97E+07	1.16E+04
Mega Tonne Coal Equivalent	Mtce	2.93E+04	7.00E+06	7.00E-01	1	2.78E+07	8.14E+03
Million British Thermal Units	MBtu	1.06E-03	2.52E-01	2.52E-08	3.60E-08	1	2.93E-04
Giga Watt Hours	GWh	3.60E+00	8.60E+02	8.60E-05	0.000123	3.41E+03	1

In practice, the order of applying these two steps will lead to different results. In this report, the conversion route LCU_{X} -> LCU_{2010} -> USD_{2010} is adopted, i.e., national/regional deflators are used to measure country- or region-specific inflation between year X and 2010 in local currency and current (2010) exchange rates are then used to convert to USD_{2010}.

To reflect the change in prices of all goods and services that an economy produces, and to keep the procedure simple, the economy's GDP deflator is chosen to convert to a common base year. Finally, when converting from LCU_{2010} to USD_{2010}, official 2010 exchange rates, which are readily available, but on the downside often fluctuate significantly in the short term, are adopted for currency conversion in the report.

Consistent with the choice of the World Bank databases as the primary source for gross domestic product (GDP) (see Section A.II.9) and other financial data throughout the report, deflators and exchange rates from the World Bank's World Development Indicators (WDI) database (World Bank, 2013) is used.

To summarize, the following procedure has been adopted to convert monetary quantities reported in LCU_{X} to USD_{2010}:

1. Use the country-/region-specific deflator and multiply with the deflator value to convert from LCU_{X} to LCU_{2010}. In case national/regional data are reported in non-LCU units (e.g., USD_{X} or Euro_{X}), which is often the case in multi-national or global studies, apply the corresponding currency deflator to convert to 2010 currency (i.e., the US deflator and the Eurozone deflator in the examples above).
2. Use the appropriate 2010 exchange rate to convert from LCU_{2010} to USD_{2010}.

A.II.2 Region definitions

In this report a number of different sets of regions are used to present results of analysis. These region sets are referred to as RC5, RC10 (Region Categorization 5 and 10, respectively), see Table A.II.8, and ECON4 (income-based economic categorization), see Table A.II.9. RC10 is a breakdown of RC5 and can be aggregated to RC5 as shown in Table A.II.8. Note that for some exceptional cases in this report there are minor deviations from the RC5 and RC10 definitions given here. In addition to these three standard aggregations some chapters feature an 11 region aggregation (GEA R11) used in the Global Energy Assessment (GEA, 2012) and other studies.

A.II.2.1 RC10

NAM (North America): Canada, Guam, Saint Pierre and Miquelon, United States

WEU (Western Europe): Aland Islands, Andorra, Austria, Belgium, Channel Islands, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Guernsey, Holy See (Vatican City State), Iceland, Ireland, Isle of Man, Italy, Jersey, Liechtenstein, Luxembourg, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Svalbard and Jan Mayen, Sweden, Switzerland, United Kingdom, Turkey

POECD (Pacific OECD): Australia, Japan, New Zealand

EIT (Economies in Transition): Croatia, Cyprus, Czech Republic, Estonia, Latvia, Lithuania, Malta, Poland, Russian Federation, Slovakia,

Table A.II.8 | Description of regions in the RC5 and RC10 region sets.

RC5		RC10	
OECD-1990	OECD Countries in 1990	**NAM**	North America
		WEU	Western Europe
		POECD	Pacific OECD (Japan, Australia, New Zealand)
EIT	Economies in Transition (sometimes referred to as Reforming Economies)	**EIT**	Economies in Transition (Eastern Europe and part of former Soviet Union)
LAM	Latin America and Caribbean	**LAM**	Latin America and Caribbean
MAF	Middle East and Africa	**SSA**	Sub-Saharan Africa
		MNA	Middle East and North Africa
ASIA	Non-OECD Asia	**EAS**	East Asia
		SAS	South Asia
		PAS	South-East Asia and Pacific
INT TRA	International transport	**INT TRA**	International transport

Slovenia, Kyrgyzstan, Tajikistan, Armenia, Georgia, Moldova (Republic of), Ukraine, Uzbekistan, Albania, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Hungary, Kazakhstan, Macedonia, Montenegro, Romania, Serbia, Serbia and Montenegro, Turkmenistan

Table A.II.9 | ECON4 income-based economic country aggregations.

HIC	High-income countries
UMC	Upper-middle income countries
LMC	Lower-middle income countries
LIC	Low income countries
INT-TRA	International transport

LAM (Latin America and Caribbean): Anguilla, Antarctica, Antigua and Barbuda, Aruba, Bahamas, Barbados, Bermuda, Bouvet Island, British Virgin Islands, Cayman Islands, Chile, Curacao, Falkland Islands (Malvinas), French Guiana, French Southern Territories, Guadeloupe, Martinique, Montserrat, Netherlands Antilles, Puerto Rico, Saint Kitts and Nevis, Sint Maarten, South Georgia and the South Sandwich Islands, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, US Virgin Islands, Haiti, Bolivia, El Salvador, Guatemala, Guyana, Honduras, Nicaragua, Paraguay, Argentina, Belize, Brazil, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, Grenada, Jamaica, Mexico, Panama, Peru, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Venezuela

SSA (Sub Saharan Africa): Equatorial Guinea, Mayotte, Reunion, Saint Helena, Benin, Burkina Faso, Burundi, Central African Republic, Chad, Comoros, Congo (The Democratic Republic of the), Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Kenya, Liberia, Madagascar, Malawi, Mali, Mozambique, Niger, Rwanda, Sierra Leone, Somalia, Tanzania, Togo, Uganda, Zimbabwe, Cameroon, Cape Verde, Congo, Cote d'Ivoire, Djibouti, Ghana, Lesotho, Mauritania, Nigeria, Sao Tome and Principe, Senegal, Swaziland, Zambia, Angola, Botswana, Gabon, Mauritius, Namibia, Seychelles, South Africa

MNA (Middle East and North Africa): Bahrain, Israel, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates, Egypt, Morocco, Palestine, South Sudan, Sudan, Syrian Arab Republic, Western Sahara, Yemen, Algeria, Iran, Iraq, Jordan, Lebanon, Libya, Tunisia

EAS (East Asia): South Korea, Korea (Democratic People's Republic of), Mongolia, China

SAS (South Asia): British Indian Ocean Territory, Afghanistan, Bangladesh, Nepal, Bhutan, India, Pakistan, Sri Lanka, Maldives

PAS (South-East Asia and Pacific): Brunei Darussalam, Christmas Island, Cocos (Keeling) Islands, French Polynesia, Heard Island and McDonald Islands, New Caledonia, Norfolk Island, Northern Mariana Islands, Pitcairn, Singapore, Tokelau, US Minor Outlying Islands, Wallis and Futuna, Cambodia, Myanmar, Indonesia, Kiribati, Laos (People's Democratic Republic), Micronesia (Federated States of), Nauru, Papua New Guinea, Philippines, Samoa, Solomon Islands, Timor-Leste, Vanuatu, Viet Nam, Niue, American Samoa, Cook Islands, Fiji, Malaysia, Marshall Islands, Palau, Thailand, Tonga, Tuvalu

INT TRA (International transport): International Aviation, International Shipping

A.II.2.2 RC5

For country mapping to each of the RC5 regions see RC10 mappings (Section A.II.2.1) and their aggregation to RC5 regions in Table A.II.8. It should be noted that this region set was also used in the so-called Representative Concentration Pathways (RCPs, see Section 6.3.2) and therefore has been adopted as a standard in integrated modelling scenarios (Section A.II.10).

A.II.2.3 ECON4

High Income (HIC): Aland Islands, Andorra, Anguilla, Antarctica, Antigua and Barbuda, Aruba, Australia, Austria, Bahamas, Bahrain, Barbados, Belgium, Bermuda, Bouvet Island, British Indian Ocean Territory, British Virgin Islands, Brunei Darussalam, Canada, Cayman Islands, Channel Islands, Chile, Christmas Island, Cocos (Keeling) Islands, Croatia, Curacao, Cyprus, Czech Republic, Denmark, Equatorial Guinea, Estonia, Falkland Islands (Malvinas), Faroe Islands, Finland, France, French Guiana, French Polynesia, French Southern Territories, Germany, Gibraltar, Greece, Greenland, Guadeloupe, Guam, Guernsey, Heard Island and McDonald Islands, Holy See (Vatican City State), Iceland, Ireland, Isle of Man, Israel, Italy, Japan, Jersey, Kuwait, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Martinique, Mayotte, Monaco, Montserrat, Netherlands, Netherlands Antilles, New Caledonia, New Zealand, Norfolk Island, Northern Mariana Islands, Norway, Oman, Pitcairn, Poland, Portugal, Puerto Rico, Qatar, Reunion, Russian Federation, Saint Helena, Saint Kitts and Nevis, Saint Pierre and Miquelon, San Marino, Saudi Arabia, Singapore, Sint Maarten, Slovakia, Slovenia, South Georgia and the South Sandwich Islands, South Korea, Spain, Svalbard and Jan Mayen, Sweden, Switzerland, Tokelau, Trinidad and Tobago, Turks and Caicos Islands, United Arab Emirates, United Kingdom, United States, Uruguay, US Minor Outlying Islands, US Virgin Islands, Wallis and Futuna

Upper Middle Income (UMC): Albania, Algeria, American Samoa, Angola, Argentina, Azerbaijan, Belarus, Belize, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria, China, Colombia, Cook Islands, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, Fiji, Gabon, Grenada, Hungary, Iran, Iraq, Jamaica, Jordan, Kazakhstan, Lebanon, Libya, Macedonia, Malaysia, Maldives, Marshall Islands, Mauritius, Mexico, Montenegro, Namibia, Niue, Palau, Panama, Peru, Romania, Saint Lucia, Saint Vincent and the Grenadines, Serbia, Serbia and Montenegro, Seychelles, South Africa, Suriname, Thailand, Tonga, Tunisia, Turkey, Turkmenistan, Tuvalu, Venezuela

Lower Middle Income (LMC): Armenia, Bhutan, Bolivia, Cameroon, Cape Verde, Congo, Cote d'Ivoire, Djibouti, Egypt, El Salvador, Georgia, Ghana, Guatemala, Guyana, Honduras, India, Indonesia, Kiribati, Laos (People's Democratic Republic), Lesotho, Mauritania, Micronesia (Federated States of), Moldova (Republic of), Mongolia, Morocco, Nauru, Nicaragua, Nigeria, Pakistan, Palestine, Papua New Guinea, Paraguay, Philippines, Samoa, Sao Tome and Principe, Senegal, Solomon Islands, South Sudan, Sri Lanka, Sudan, Swaziland, Syrian Arab Republic, Timor-Leste, Ukraine, Uzbekistan, Vanuatu, Viet Nam, Western Sahara, Yemen, Zambia

Low Income (LIC): Afghanistan, Bangladesh, Benin, Burkina Faso, Burundi, Cambodia, Central African Republic, Chad, Comoros, Congo (The Democratic Republic of the), Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Haiti, Kenya, Korea (Democratic People's Republic of), Kyrgyzstan, Liberia, Madagascar, Malawi, Mali, Mozambique, Myanmar, Nepal, Niger, Rwanda, Sierra Leone, Somalia, Tajikistan, Tanzania, Togo, Uganda, Zimbabwe

INT TRA (International transport): International Aviation, International Shipping

A.II.2.4 GEA R11

The 11 regions of GEA R11 are similar to the above RC10 and consist of North America (NAM), Western Europe (WEU), Pacific OECD (POECD [PAO]), Central and Eastern Europe (EEU), Former Soviet Union (FSU), Centrally Planned Asia and China (CPA), South Asia (SAS), Other Pacific Asia (PAS), Middle East and North Africa (MNA [MEA]), Latin America and the Caribbean (LAM [LAC]) and Sub-Saharan Africa (SSA [AFR]). The differences to RC10 are the following:

- RC10 EIT is split in GEA R11 FSU and EEU. To FSU belong Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine and Uzbekistan and to EEU belong Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Macedonia, Hungary, Latvia, Lithuania, Montenegro, Poland, Romania, Serbia, Slovak Republic and Slovenia.
- GEA R11 NAM matches RC10 NAM plus Puerto Rico and the British Virgin Islands.
- GEA R11 LAM matches RC10 LAM without Puerto Rico and the British Virgin Islands.
- GEA R11 CPA matches RC10 EAS plus Cambodia, Laos (People's Democratic Republic), Viet Nam, without South Korea.
- GEA R11 PAS matches RC10 PAS plus South Korea and Taiwan, Province of China, without Cambodia, Laos (People's Democratic Republic), Viet Nam.

Part II: Methods

A.II.3 Costs metrics

Across this report, a number of different metrics to characterize cost of climate change mitigation are employed. These cost metrics reflect the different levels of detail and system boundaries at which mitigation analysis is conducted. For example, in response to mitigation policies, different technologies are deployed across different sectors. To facilitate a meaningful comparison of economics across diverse options at the technology level, the metric of 'levelized costs' is used throughout several chapters (7, 8, 9, 10, and 11) of this report in various forms (Section A.II.3.1). In holistic approaches to mitigation, such as the ones used in Chapter 6 on transformation pathways, different mitigation cost metrics are used, the differences among which are discussed in Section A.II.3.2.

A.II.3.1 Levelized costs

Levelizing costs means to express all lifetime expenditures of a stream of relatively homogeneous outputs that occur over time as cost per unit of output. Most commonly, the concept is applied to electricity as an output. It is also being applied to express costs of other streams of outputs such as energy savings and greenhouse gas (GHG) emission savings. Each of these metrics provides a benchmark for comparing different technologies or practices of providing the respective output. Each also comes with a set of context-specific caveats that need to be taken into account for correct interpretation. Various literature sources caution against drawing too strong conclusions from these metrics. The levelized cost of energy (LCOE), the levelized cost of conserved energy (LCCE), and the levelized cost of conserved carbon (LCCC) are used throughout the WGIII AR5 to provide output-specific benchmarks for comparison. They are explained and discussed below in the mentioned order.[1]

A.II.3.1.1 Levelized cost of energy

Background

In order to compare energy supply technologies from an economic point of view, the concept of 'levelized cost of energy' (LCOE, also called levelized unit cost or levelized generation cost) frequently is applied (IEA and NEA, 2005; IEA, 2010a; Fischedick et al., 2011; Lar-

[1] This section, however, does not take into account the implications for additional objectives beyond energy supply (LCOE), energy savings (LCCE) or mitigation (LCCC)—often referred to as co-benefits and adverse side-effects (see Glossary in Annex I). In particular, external costs are not taken into account if they are not internalized (e.g., via carbon pricing).

son et al., 2012; Turkenburg et al., 2012; UNEP, 2012; IRENA, 2013). Simply put, 'levelized' cost of energy is a measure that can be loosely defined as the long-run 'average' cost of a unit of energy provided by the considered technology (albeit, calculated correctly in an economic sense by taking into account the time value of money). Strictly speaking, the levelized cost of energy is "the cost per unit of energy that, if held constant through the analysis period, would provide the same net present revenue value as the net present value cost of the system." (Short et al., 1995, p. 93). The calculation of the respective 'average' cost (expressed, for instance in US cent/kWh or USD/GJ) palpably facilitates the comparison of projects, which differ in terms of plant size and/or plant lifetime.

General formula and simplifications

According to the definition given above, "the levelized cost is the unique break-even cost price where discounted revenues (price x quantities) are equal to the discounted net expenses" (Moomaw et al., 2011):

$$\sum_{t=0}^{n} \frac{E_t \cdot LCOE}{(1+i)^t} := \sum_{t=0}^{n} \frac{Expenses_t}{(1+i)^t} \qquad \text{(Equation A.II.1)}$$

where $LCOE$ are the levelized cost of energy, E_t is the energy delivered in year t (which might vary from year to year), $Expenses_t$ cover all (net) expenses in the year t, i is the discount rate and n the lifetime of the project.

After solving for LCOE this gives:

$$LCOE := \frac{\sum_{t=0}^{n} \frac{Expenses_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+i)^t}} \qquad \text{(Equation A.II.2)}$$

Note that while it appears as if energy amounts were discounted in Equation A.II.2, this is just an arithmetic result of rearranging Equation A.II.1 (Branker et al., 2011). In fact, originally, revenues are discounted and not energy amounts per se (see Equation A.II.1).

Considering energy conversion technologies, the lifetime expenses comprise investment costs I, operation and maintenance cost $O\&M$ (including waste management costs), fuel costs F, carbon costs C, and decommissioning costs D. In this case, levelized cost can be determined by (IEA, 2010a):

$$LCOE := \frac{\sum_{t=0}^{n} \frac{I_t + O\&M_t + F_t + C_t + D_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+i)^t}} \qquad \text{(Equation A.II.3)}$$

In simple cases, where the energy E provided annually is constant during the lifetime of the project, this translates to:

$$LCOE := \frac{CRF \cdot NPV\ (Lifetime\ Expenses)}{E} = \frac{Annuity\ (Lifetime\ Expenses)}{E} \qquad \text{(Equation A.II.4)}$$

where $CRF := \frac{i}{1-(1+i)^{-n}}$ is the capital recovery factor and NPV the net present value of all lifetime expenditures (Suerkemper et al., 2011). For the simplified case, where the annual costs are also assumed constant over time, this can be further simplified to ($O\&M$ costs and fuel costs F constants):

$$LCOE = \frac{CRF \cdot I + O\&M + F}{E} \qquad \text{(Equation A.II.5)}$$

Where I is the upfront investment, $O\&M$ are the annual operation and maintenance costs, F are the annual fuel costs, and E is the annual energy provision. The investment I should be interpreted (here and also in Equations A.II.7 and A.II.9) as the sum of all capital expenditures needed to make the investment fully operational discounted to t = 0. These might include discounted payments for retrofit payments during the lifetime and discounted decommissioning costs at the end of the lifetime. Where applicable, annual O&M costs have to take into account revenues for by-products and existing carbon costs must be added or treated as part of the annual fuel costs.

Discussion of LCOE

The LCOE of a technology is only one indicator for its economic competitiveness, but there are more dimensions to it. Integration costs, time dependent revenue opportunities (especially in the case of intermittent renewables), and relative environmental impacts (e.g., external costs) play an important role as well (Heptonstall, 2007; Fischedick et al., 2011; Joskow, 2011a; Borenstein, 2012; Mills and Wiser, 2012; Edenhofer et al., 2013a; Hirth, 2013). Joskow (2011b) for instance, pointed out that LCOE comparisons of intermittent generating technologies (such as solar energy converters and wind turbines) with dispatchable power plants (e.g., coal or gas power plants) may be misleading as these comparisons fail to take into account the different production schedule and the associated differences in the market value of the electricity that is provided. An extended criticism of the concept of LCOE as applied to renewable energies is provided by (Edenhofer et al., 2013b).

Taking these shortcomings into account, there seems to be a clear understanding that LCOE are not intended to be a definitive guide to actual electricity generation investment decisions (IEA and NEA, 2005; DTI, 2006). Some studies suggest that the role of levelized costs is to give a 'first order assessment' (EERE, 2004) of project viability.

In order to capture the existing uncertainty, sensitivity analyses, which are sometimes based on Monte Carlo methods, are frequently carried out in numerical studies. Darling et al. (2011), for instance, suggest that transparency could be improved by calculating LCOE as a distribution, constructed using input parameter distributions, rather than a single number. Studies based on empirical data, in contrast, may suffer from using samples that do not cover all cases. Summarizing country studies in an effort to provide a global assessment, for instance, might have a bias as data for developing countries often are not available (IEA, 2010a).

As Section 7.8.2 shows, typical LCOE ranges are broad as values vary across the globe depending on the site-specific renewable energy resource base, on local fuel and feedstock prices as well as on country specific projected costs of investment, and operation and maintenance. While noting that system and installation costs vary widely, Branker et al. (2011) document significant variations in the underlying assumptions that go into calculating LCOE for photovoltaic (PV), with many analysts not taking into account recent cost reductions or the associated technological advancements. In summary, a comparison between different technologies should not be based on LCOE data solely; instead, site-, project- and investor specific conditions should be considered (Fischedick et al., 2011).

A.II.3.1.2 Levelized cost of conserved energy

Background

The concept of 'levelized cost of conserved energy' (LCCE), or more frequently referred to as 'cost of conserved energy (CCE)', is very similar to the LCOE concept, primarily intended to be used for comparing the cost of a unit of energy saved to the purchasing cost per unit of energy. In essence the concept, similarly to LCOE, also annualizes the investment and operation and maintenance cost differences between a baseline technology and the energy-efficiency alternative, and divides this quantity by the annual energy savings (Brown et al., 2008). Similarly to LCOE, it also bridges the time lag between the initial additional investment and the future energy savings through the application of the capital recovery factor (Meier, 1983).

General formula and simplifications

The conceptual formula for LCCE is essentially the same as Equation A.II.4 above, with ΔE meaning in this context the amount of energy saved annually (Suerkemper et al., 2011):

$$LCCE := \frac{CRF \cdot NPV(\Delta \text{Lifetime Expenses})}{\Delta E} = \frac{\text{Annuity } (\Delta \text{Lifetime Expenses})}{\Delta E} \qquad \text{(Equation A.II.6)}$$

In the case of assumed annually constant O&M costs over the lifetime, this simplifies to (equivalent to Equation A.II.5) (Hansen, 2012):

$$LCCE = \frac{CRF \cdot \Delta I + \Delta O\&M}{\Delta E} \qquad \text{(Equation A.II.7)}$$

Where ΔI is the difference in investment costs of an energy saving measure (e.g., in USD) as compared to a baseline investment; $\Delta O\&M$ is the difference in annual operation and maintenance costs of an energy saving measure (e.g., in USD) as compared to the baseline in which the energy saving measure is not implemented; ΔE is the annual energy conserved by the measure (e.g., in kWh) as compared to the usage of the baseline technology; and *CRF* is the capital recovery factor depending on the discount rate i and the lifetime of the measure *n* in years as defined above. It should be stressed once more that this equation is only valid if $\Delta O\&M$ and ΔE are constant over the lifetime. As LCCE are designed to be compared with complementary levelized cost of energy supply, they do not include the annual fuel cost difference. Any additional monetary benefits that are associated with the energy saving measure must be taken into account as part of the O&M difference.

Discussion of LCCE

The main strength of the LCCE concept is that it provides a metric of energy saving investments that are independent of the energy price, and can thus be compared to different energy purchasing cost values for determining the profitability of the investment (Suerkemper et al., 2011).

The key difference in the concept with LCOE is the usage of a reference/baseline technology. LCCE can only be interpreted in context of a reference, and is thus very sensitive to how this reference is chosen (see Section 9.3 and 9.6). For instance, the replacement of a very inefficient refrigerator can be very cost-effective, but if we consider an already relatively efficient product as the reference technology, the LCCE value can be many times higher. This is one of the main challenges in interpreting LCCE.

Another challenge in the calculation of LCCE should be pinpointed. The lifetimes of the efficient and the reference technology may be different. In this case the investment cost difference needs to be used that incurs throughout the lifetime of the longer-living technology. For instance, a compact fluorescent lamp (CFL) lasts as much as 10 times as long as an incandescent lamp. Thus, in the calculation of the LCCE for a CFL replacing an incandescent lamp the saved investments in multiple incandescent lamps should be taken into account (Ürge-Vorsatz, 1996). In such a case, as in some other cases, too, the difference in annualized investment cost can be negative resulting in negative LCCE values. Negative LCCE values mean that the investment is already profitable at the investment level, without the need for the energy savings to recover the extra investment costs.

Taking into account incremental operation and maintenance cost can be important for applications where those are significant, for instance, the lamp replacement on streetlamps, bridges. In such cases a longer-lifetime product, as it typically applies to efficient lighting technologies, is already associated with negative costs at the investment level (less frequent needs for labour to replace the lamps), and thus can result in significantly negative LCCEs or cost savings (Ürge-Vorsatz, 1996). In case of such negative incremental investment cost, some peculiarities may occur. For instance, as can be seen from Equation A.II.7, LCCE decrease (become more negative) with increasing *CRF*, e.g., as a result of an increase in discount rates.

A.II.3.1.3 Levelized cost of conserved carbon

Background

Many find it useful to have a simple metric for identifying the costs of GHG emission mitigation. The metric can be used for comparing mitigation costs per unit of avoided emissions, and comparing these specific emission reduction costs for different options, within a company, within a sector, or even between sectors. This metric is often referred to as levelized cost of conserved carbon (LCCC) or specific GHG mitigation costs. There are several caveats, which will be discussed below, after the general approach is introduced.

General formula and simplification

For calculation of specific mitigation costs, the following, equation holds, where ΔC is the annual reduction in GHG emissions achieved through the implementation of an option. The equation is equivalent to Equations A.II.4 and A.II.6.

$$LCCC := \frac{CRF \cdot NPV(\Delta LifetimeExpenses)}{\Delta C} = \frac{Annuity(\Delta LifetimeExpenses)}{\Delta C}$$

(Equation A.II.8)

Also this equation can be simplified under the assumption of annual GHG emission reduction, annual O&M costs and annual benefits ΔB being constant over the lifetime of the option.

$$LCCC = \frac{CRF \cdot \Delta I + \Delta O\&M - \Delta B}{\Delta C}$$ (Equation A.II.9)

Where ΔI is the difference in investment costs of a mitigation measure (e.g., in USD) as compared to a baseline investment; $\Delta O\&M$ is the difference in annual operation and maintenance costs (e.g., in USD) and ΔB denotes the annual benefits, all compared to a baseline for which the option is not implemented. Note that annual benefits include reduced expenditures for fuels, if the investment project reduces GHG emissions via a reduction in fuel use. As such LCCC depend on energy prices.

An important characteristic of this equation is that LCCC can become negative if ΔB is bigger than the sum of the other two terms in the numerator.

Discussion of LCCC

Several issues need to be taken into account when using LCCC. First of all, the calculation of LCCC for one specific option does not take into account the fact that each option is implemented in a system, and the value of the LCCC of one option will depend on whether other options will be implemented or not (e.g., because the latter might influence the specific emissions of the background system). To solve this issue, analysts use integrated models, in which ideally these interactions are taken into account (see Chapter 6). Second, energy prices and other benefits are highly variable from region to region, rarely constant over time, and often difficult to predict. This issue is relevant for any analysis on mitigation, but it is always important to be aware of the fact that even if one single LCCC number is reported, there will be substantial uncertainty in that number. Uncertainty tends to increase from LCOE to LCCE, for example, due to additional uncertainty with regard to the choice of the baseline, and even further for LCCC, since not only a baseline needs to be defined, but furthermore the monetary benefit from energy savings needs to be taken into account (if the mitigation measure affects energy consumption). Moving from LCOE to LCCC in the field of energy supply technologies, for instance, results in comparing LCOE differences to the differences of the specific emissions of the mitigation technology compared to the reference plant (Rubin, 2012). As Sections 7.8.1 and 7.8.2 have shown, LCOE and specific emissions exhibit large uncertainties in their own, which result in an even exaggerated uncertainty once combined to yield the LCCC. Third, options with negative costs can occur, for example, in cases where incremental investment cost are taken to be negative. Finally, there is also a debate whether options with negative costs can occur at all, as it apparently suggests a situation of non-optimized behaviour. For further discussion of negative costs, see Box 3.10 in Chapter 3 of this report.

Levelized costs of conserved carbon are used to determine abatement cost curves, which are frequently applied in climate change decision making. The merits and shortcoming of abatement cost curves are discussed in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (Fischedick et al., 2011) and in Chapter 3 (Section 3.9.3) of the AR5. In order to avoid some of the shortcomings of abatement cost curves, the AR5 opted to use integrated modelling scenarios in order to evaluate the economic potential of specific mitigation options in a consistent way. Integrated models are able to determine the economic potential of single mitigation options within the context of (other) competing supply-side and demand-side options by taking their interaction and potential endogenous learning effects into account. The results obtained in this way are discussed in Chapter 6.

A.II.3.2 Mitigation cost metrics

There is no single metric for reporting the costs of mitigation, and the metrics that are available are not directly comparable (see Section 3.9.3 for a more general discussion; see Section 6.3.6 for an overview of costs used in model analysis). In economic theory the most direct cost measure is a change in welfare due to changes in the amount and composition of consumption of goods and services by individuals. Important measures of welfare change include 'equivalent variation' and 'compensating variation', which attempt to discern how much individual income would need to change to keep consumers just as well off after the imposition of a policy as before. However, these are quite difficult to calculate, so a more common welfare measurement is change in consumption, which captures the total amount of money consumers are able to spend on goods and services. Another common metric is the change in gross domestic product (GDP). However, GDP is a less satisfactory measure of overall mitigation cost than those focused on individual income and consumption, because it is an output-related measure that in addition to consumption also includes investment, imports and exports, and government spending. Aggregate consumption and GDP losses are only available from an analysis of the policy impact on the full economy. Common cost measures used in studies of the policy impact on specific economic sectors, such as the energy sector, are the reduction in consumer and producer surplus and the 'area under the marginal abatement cost function'.

From a practical perspective, different modelling frameworks applied in mitigation analysis are capable of producing different cost estimates (Section 6.2). Therefore, when comparing cost estimates across mitigation scenarios from different models, some degree of incomparability must necessarily result. In representing costs across transformation pathways in this report and more specifically Chapter 6, consumption losses are used preferentially when available from general equilibrium models, and costs represented by the area under the marginal abatement cost function or the reduction of consumer and producer surplus are used for partial equilibrium models. Costs are generally measured relative to a baseline scenario without mitigation policy. Consumption losses can be expressed in terms of, inter alia, the reduction of baseline consumption in a given year or the annual average reduction of consumption growth in the baseline over a given time period.

One popular measure used in different studies to evaluate the economic implications of mitigation actions is the emissions price, often presented in per tonne of CO_2 or per tonne of CO_2-equivalent (CO_2eq). However, it is important to emphasize that emissions prices are not cost measures. There are two important reasons why emissions prices are not a meaningful representation of costs. First, emissions prices measure marginal cost, i.e., the cost of an incremental reduction of emissions by one unit. In contrast, total costs represent the costs of all mitigation that took place at lower cost than the emissions price. Without explicitly accounting for these 'inframarginal' costs, it is impossible to know how the carbon price relates to total mitigation costs. Second, emissions prices can interact with other existing or new policies and measures, such as regulatory policies that aim at reducing GHG emissions (e.g., feed-in tariffs, subsidies to low-carbon technologies, renewable portfolio standards) or other taxes on energy, labour, or capital. If mitigation is achieved partly by these other measures, the emissions price will not take into account the full costs of an additional unit of emissions reductions, and will indicate a lower marginal cost than is actually warranted.

It is important to calculate the total cost of mitigation over the entire lifetime of a policy. The application of discounting is common practice in economics when comparing costs over time. In Chapter 3, Section 3.6.2 provides some theoretical background on the choice of discount rates in the context of cost-benefit analysis (CBA), where discounting is crucial, because potential climate damages, and thus benefits from their avoidance, will occur far in the future, are highly uncertain, and are often in the form of non-market goods. In Chapter 6, mitigation costs are assessed primarily in the context of cost-effectiveness analysis, in which a target for the long-term climate outcome is specified and models are used to estimate the cost of reaching it, under a variety of constraints and assumptions (Section 6.3.2). These scenarios do not involve the valuation of damages and the difficulties arising from their aggregation. Nonetheless, the models surveyed in Chapter 6 consider transformation pathways over long time horizons, so they must specify how decision makers view intertemporal tradeoffs.

The standard approach is to use a discount rate that approximates the interest rate, that is, the marginal productivity of capital. Empirical estimates of the long-run average return to a diversified portfolio are typically in the 4%–6% range. In scenarios where the long-term target is set, the discounting approach will have an effect only on the speed and shape of the mitigation schedule, not on the overall level of stringency (note that this is in sharp contrast to cost-benefit analysis, where the discounting approach is a strong determinant of the level of stringency). Although a systematic comparison of alternative discounting approaches in a cost-effectiveness setting does not exist in the literature, we can make the qualitative inference that when a policy-maker places more (less) weight on the future, mitigation effort will be shifted sooner (later) in time. Because of long-lived capital dynamics in the energy system, and also because of expected technical change, mitigation effort in a cost-effectiveness analysis typically begins gradually and increases over time, leading to a rising cost profile. Thus, an analogous inference can be made that when a policy-maker places more (less) weight on the future, mitigation costs will be higher (lower) earlier and lower (higher) later.

Estimates of the macroeconomic cost of mitigation usually represent direct mitigation costs and do not take into account co-benefits or adverse side-effects of mitigation actions (see red arrows in Figure A.II.1). Further, these costs are only those of mitigation; they do not capture the benefits of reducing CO_2eq concentrations and limiting climate change.

Two further concepts are introduced in Chapter 6 to classify cost estimates (Section 6.3.6). The first is an idealized implementation approach in which a ubiquitous price on carbon and other GHGs is applied across the globe in every sector of every country and which rises over time at a rate that reflects the increase in the cost of the next available unit of emissions reduction. The second is an idealized implementation environment of efficient global markets in which there are no pre-existing distortions or interactions with other, non-climate market failures. An idealized implementation approach minimizes mitigation costs in an idealized implementation environment. This is not necessarily the case in non-idealized environments in which climate policies interact with existing distortions in labour, energy, capital, and land markets. If those market distortions persist or are aggravated by climate policy, mitigation costs tend to be higher. In turn, if climate policy is brought to bear on reducing such distortions, mitigation costs can be lowered by what has been frequently called a double dividend of climate policy (see blue arrows in Figure A.II.1). Whether or not such a double dividend is available will depend on assumptions about the policy environment and available climate policies.

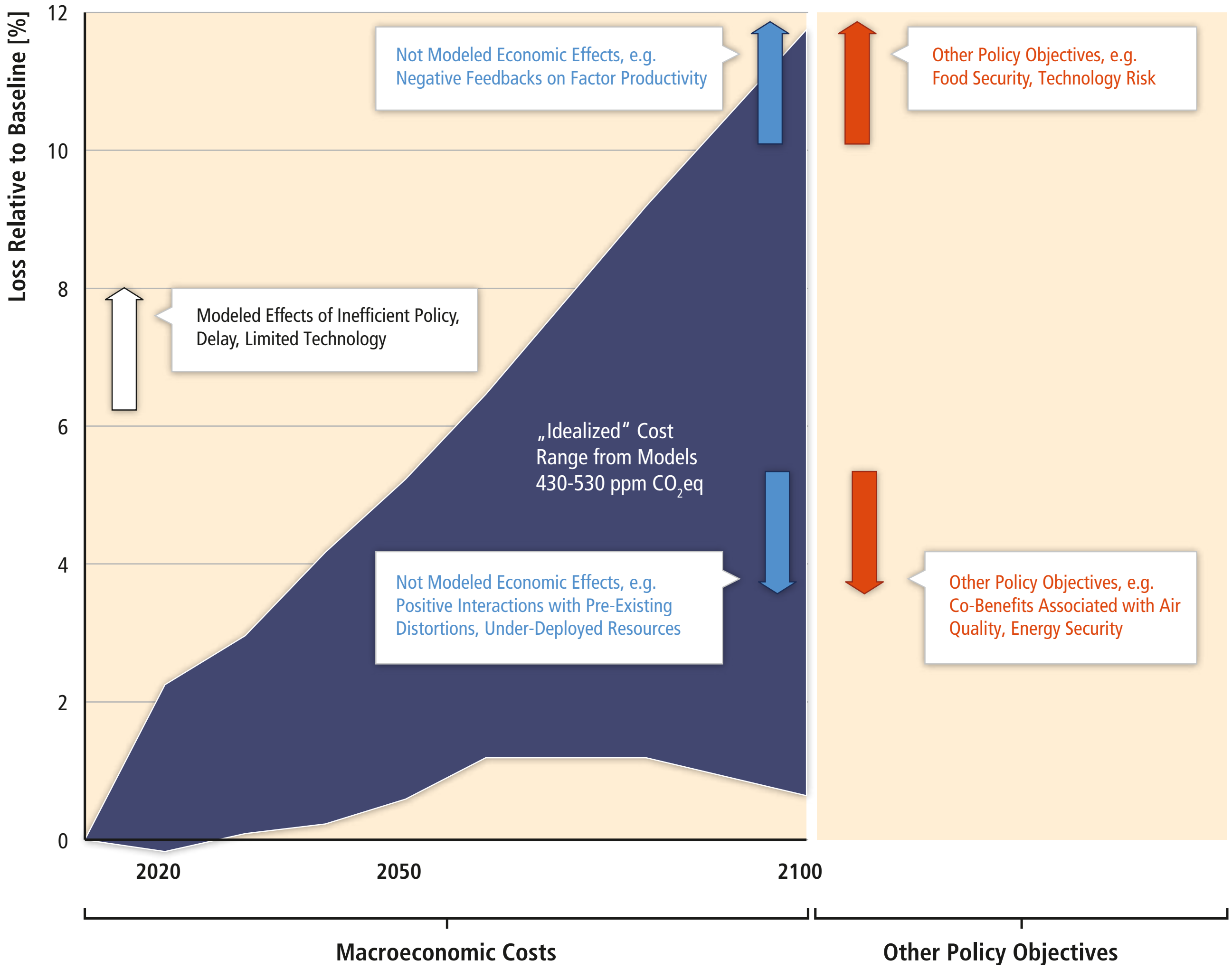

Figure A.II.1 | Modelled policy costs in a broader context. The plotted range summarizes costs expressed as percentage loss relative to baseline across models for cost-effective scenarios reaching 430–530 ppm CO_2eq. Scenarios were sorted by total NPV costs for each available metric (loss in GDP, loss in consumption, area under marginal abatement cost curve as a fraction of GDP). The lower boundary of the plotted range reflects the minimum across metrics of the 25th percentile, while the upper boundary reflects the maximum across metrics of the 75th percentile. A comprehensive treatment of costs and cost metrics, including the effects of non-idealized scenario assumptions, is provided in Section 6.3.6. Other arrows and annotations indicate the potential effects of considerations outside of those included in models. Source: WGIII AR5 Scenario Database.

A.II.4 Primary energy accounting

Following the standard set by the SRREN, this report adopts the direct-equivalent accounting method for the reporting of primary energy from non-combustible energy sources. The following section largely reproduces Annex A.II.4 of the SRREN (Moomaw et al., 2011) with some updates and further clarifications added.

Different energy analyses use a variety of accounting methods that lead to different quantitative outcomes for both reporting of current primary energy use and primary energy use in scenarios that explore future energy transitions. Multiple definitions, methodologies, and metrics are applied. Energy accounting systems are utilized in the literature often without a clear statement as to which system is being used (Lightfoot, 2007; Martinot et al., 2007). An overview of differences in primary energy accounting from different statistics has been described by Macknick (2011) and the implications of applying different accounting systems in long-term scenario analysis were illustrated by Nakicenovic et al., (1998), Moomaw et al. (2011) and Grubler et al. (2012).

Three alternative methods are predominantly used to report primary energy. While the accounting of combustible sources, including all fossil energy forms and biomass, is identical across the different methods, they feature different conventions on how to calculate primary energy supplied by non-combustible energy sources, i.e., nuclear energy and all renewable energy sources except biomass. These methods are:

- *the physical energy content method* adopted, for example, by the OECD, the International Energy Agency (IEA) and Eurostat (IEA/OECD/Eurostat, 2005);
- *the substitution method*, which is used in slightly different variants by BP (2012) and the U.S. Energy Information Administration (EIA, 2012a, b, Table A6), both of which publish international energy statistics; and

Table A.II.10 | Comparison of global total primary energy supply in 2010 using different primary energy accounting methods (data from IEA 2012b).

	Physical content method		Direct equivalent method		Substitution method*	
	EJ	%	EJ	%	EJ	%
Fossil fuels	432.99	81.32	432.99	84.88	432.99	78.83
Nuclear	30.10	5.65	9.95	1.95	26.14	4.76
Renewables	69.28	13.01	67.12	13.16	90.08	16.40
Bioenergy	52.21	9.81	52.21	10.24	52.21	9.51
Solar	0.75	0.14	0.73	0.14	1.03	0.19
Geothermal	2.71	0.51	0.57	0.11	1.02	0.19
Hydro	12.38	2.32	12.38	2.43	32.57	5.93
Ocean	0.002	0.0004	0.002	0.0004	0.005	0.001
Wind	1.23	0.23	1.23	0.24	3.24	0.59
Other	0.07	0.01	0.07	0.01	0.07	0.01
Total	532.44	100.00	510.13	100.00	549.29	100.00

* For the substitution method, conversion efficiencies of 38 % for electricity and 85 % for heat from non-combustible sources were used. The value of 38 % is used by BP for electricity generated from hydro and nuclear. BP does not report solar, wind, and geothermal in its statistics for which, here, also 38 % is used for electricity and 85 % for heat.

- *the direct equivalent method* that is used by UN Statistics (2010) and in multiple IPCC reports that deal with long-term energy and emission scenarios (Nakicenovic and Swart, 2000; Morita et al., 2001; Fisher et al., 2007; Fischedick et al., 2011).

For non-combustible energy sources, the *physical energy content method* adopts the principle that the primary energy form should be the first energy form used down-stream in the production process for which multiple energy uses are practical (IEA/OECD/Eurostat, 2005). This leads to the choice of the following *primary* energy forms:

- heat for nuclear, geothermal, and solar thermal, and
- electricity for hydro, wind, tide/wave/ocean, and solar PV.

Using this method, the primary energy equivalent of hydro energy and solar PV, for example, assumes a 100 % conversion efficiency to 'primary electricity', so that the gross energy input for the source is 3.6 MJ of primary energy = 1 kWh of electricity. Nuclear energy is calculated from the gross generation by assuming a 33 % thermal conversion efficiency[2], i.e., 1 kWh = (3.6 ÷ 0.33) = 10.9 MJ. For geothermal, if no country-specific information is available, the primary energy equivalent is calculated using 10 % conversion efficiency for geothermal electricity (so 1 kWh = (3.6 ÷ 0.1) = 36 MJ), and 50 % for geothermal heat.

The *substitution method* reports primary energy from non-combustible sources in such a way as if they had been substituted for combustible energy. Note, however, that different variants of the substitution method use somewhat different conversion factors. For example, BP applies 38 % conversion efficiency to electricity generated from nuclear and hydro whereas the World Energy Council used 38.6 % for nuclear and non-combustible renewables (WEC, 1993; Grübler et al., 1996; Nakicenovic et al., 1998), and the U.S. Energy Information Administration (EIA) uses still different values. For useful heat generated from non-combustible energy sources, other conversion efficiencies are used. Macknick (2011) provides a more complete overview.

The *direct equivalent method* counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy, i.e., 1 kWh of electricity or heat is accounted for as 1 kWh = 3.6 MJ of primary energy. This method is mostly used in the long-term scenarios literature, including multiple IPCC reports (IPCC, 1995b; Nakicenovic and Swart, 2000; Morita et al., 2001; Fisher et al., 2007; Fischedick et al., 2011), because it deals with fundamental transitions of energy systems that rely to a large extent on low-carbon, non-combustible energy sources.

The accounting of combustible sources, including all fossil energy forms and biomass, includes some ambiguities related to the definition of the heating value of combustible fuels. The higher heating value (HHV), also known as gross calorific value (GCV) or higher calorific value (HCV), includes the latent heat of vaporization of the water produced during combustion of the fuel. In contrast, the lower heating value (LHV) (also: net calorific value (NCV) or lower calorific value (LCV)) excludes this latent heat of vaporization. For coal and oil, the LHV is about 5 % smaller than the HHV, for natural gas and derived gases the difference is roughly 9–10 %, while the concept does not apply to non-combustible energy carriers such as electricity and heat for which LHV and HHV are therefore identical (IEA, 2012a).

In the WGIII AR5, IEA data are utilized, but energy supply is reported using the *direct equivalent method*. In addition, the reporting of com-

[2] As the amount of heat produced in nuclear reactors is not always known, the IEA estimates the primary energy equivalent from the electricity generation by assuming an efficiency of 33 %, which is the average of nuclear power plants in Europe (IEA, 2012b).

bustible energy quantities, including primary energy, should use the LHV which is consistent with the IEA energy balances (IEA, 2012a; b). Table A.II.10 compares the amounts of global primary energy by source and percentages using the *physical energy content, the direct equivalent* and a variant of the *substitution method* for the year 2010 based on IEA data (IEA, 2012b). In current statistical energy data, the main differences in absolute terms appear when comparing nuclear and hydro power. As they both produced comparable amounts of electricity in 2010, under both *direct equivalent* and *substitution methods*, their share of meeting total final consumption is similar, whereas under the *physical energy content method,* nuclear is reported at about three times the primary energy of hydro.

The alternative methods outlined above emphasize different aspects of primary energy supply. Therefore, depending on the application, one method may be more appropriate than another. However, none of them is superior to the others in all facets. In addition, it is important to realize that total primary energy supply does not fully describe an energy system, but is merely one indicator amongst many. Energy balances as published by IEA (2012a; b) offer a much wider set of indicators which allows tracing the flow of energy from the resource to final energy use. For instance, complementing total primary energy consumption by other indicators, such as total final energy consumption and secondary energy production (e.g., of electricity, heat), using different sources helps link the conversion processes with the final use of energy.

A.II.5 Indirect primary energy use and CO_2 emissions

Energy statistics in most countries of the world and at the International Energy Agency (IEA) display energy use and carbon dioxide (CO_2) emissions from fuel combustion directly in the energy sectors. As a result, the energy sector is the major source of reported energy use and CO_2 emissions, with the electricity and heat industries representing the largest shares.

However, the main driver for these energy sector emissions is the consumption of electricity and heat in the end use sectors (industry, buildings, transport, and agriculture). Electricity and heat mitigation opportunities in these end use sectors reduce the need for producing these energy carriers upstream and therefore reduce energy and emissions in the energy sector.

In order to account for the impact of mitigation activities in the end use sectors, a methodology has been developed to reallocate the energy consumption and related CO_2 emissions from electricity and heat produced and delivered to the end use sectors (de la Rue du Can and Price, 2008).

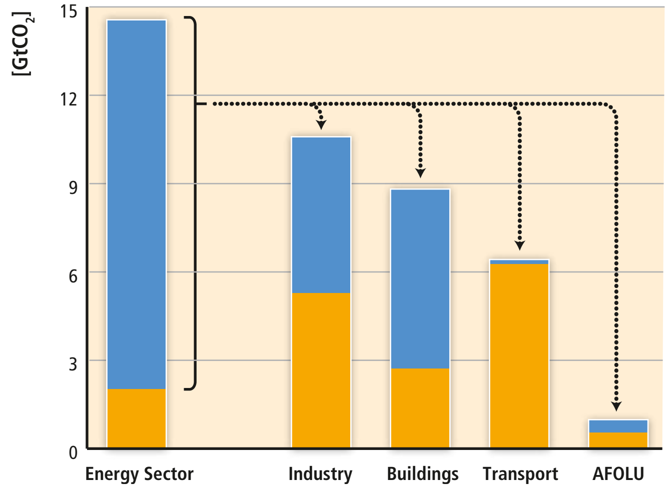

Figure A.II.2 | Energy sector electricity and heat CO_2 emissions calculated for the end-use sectors in 2010. Note that industry sector CO_2 emissions do not include process emissions. Data source: (IEA, 2012b; c).

Using IEA data, the methodology calculates a series of primary energy factors and CO_2 emissions factors for electricity and heat production at the country level. These factors are then used to re-estimate energy and emissions from electricity and heat produced and delivered to the end use sectors proportionally to their use in each end-use sectors. The calculated results are referred to as primary energy[3] and indirect CO_2 emissions.

The purpose of allocating primary energy consumption and indirect CO_2 emissions to the sectoral level is to relate the energy used and the emissions produced along the entire supply chain to provide energy services in each sector (consumption-based approach). For example, the consumption of one kWh of electricity is not equivalent to the consumption of one kWh of coal or natural gas, because of the energy required and the emissions produced in the generation of one kWh of electricity.

Figure A.II.2 shows the resulting reallocation of CO_2 emissions from electricity and heat production from the energy sector to the industrial, buildings, transport, and agriculture sectors at the global level based on the methodology outlined in de la Rue du Can and Price (2008) and described further below.

A.II.5.1 Primary electricity and heat factors

Primary electricity and heat factors have been derived as the ratio of fuel inputs of power plants relative to the electricity and heat delivered. These factors reflect the efficiency of these transformations.

[3] Note that final energy and primary energy consumption are different concepts (Section A.II.3.4). Final energy consumption (sometimes called site energy consumption) represents the amount of energy consumed in end use applications whereas primary energy consumption (sometimes called source energy consumption) in addition includes the energy required to generate, transmit and distribute electricity and heat.

Primary Electricity Factor:

$$PEF = \frac{\sum_{e,p} EI}{\sum_{p} EO - E\,OU - E\,DL}$$

Where

- *EI* is the total energy (e) inputs for producing Electricity in TJ
- *EO* is the total Electricity Output produced in TJ
- *E OU* is the energy use for own use for Electricity production
- *E DL* is the distribution losses needed to deliver electricity to the end use sectors

Primary Heat Factor:

$$PHF = \frac{\sum_{e,p} HI}{\sum_{p} HO - H\,OU - H\,DL}$$

Where

- *HI* is the total energy (e) inputs for producing Heat in TJ
- *HO* is the total Heat Output produced in TJ
- *H OU* is the energy use for own use for Heat production
- *H DL* is the distribution losses needed to deliver heat to the end use sectors

p represents the 6 plant types in the IEA statistics (Main Activity Electricity Plant, Autoproducer Electricity Plant, Main Activity CHP plant, Autoproducer CHP plant, Main Activity Heat Plant and Autoproducer Heat Plant)

e represents the energy products

It is important to note that two accounting conventions were used to calculate these factors. The first involves estimating the portion of fuel input that produces electricity in combined heat and power plants (CHP) and the second involves accounting for the primary energy value of non-combustible fuel energy used as inputs for the production of electricity and heat. The source of historical data for these calculations is the International Energy Agency (IEA, 2012c; d).

For the CHP calculation, fuel inputs for electricity production were separated from inputs for heat production according to the fixed-heat-efficiency approach used by the IEA (IEA, 2012c). This approach fixes the efficiency for heat production equal to 90 %, which is the typical efficiency of a heat boiler (except when the total CHP efficiency was greater than 90 %, in which case the observed efficiency is used). The estimated input for heat production based on this efficiency was then subtracted from the total CHP fuel inputs, and the remaining fuel inputs to CHP were attributed to the production of electricity. As noted by the IEA, this approach may overstate the actual heat efficiency in certain circumstances (IEA, 2012c; d).

As described in Section A.II.4 in more detail, different accounting methods to report primary energy use of electricity and heat production from non-combustible energy sources, including non-biomass renewable energy and nuclear energy, exist. The direct equivalent accounting method is used here for this calculation.

Global average primary and electricity factors and their historical trends are presented in Figure A.II.3. Average factors for fossil power and heat plants are in the range of 2.5 and 3 and factors for non-biomass renewable energy and nuclear energy are by convention a little above one, depending on heat and electricity own use consumption and distribution losses.

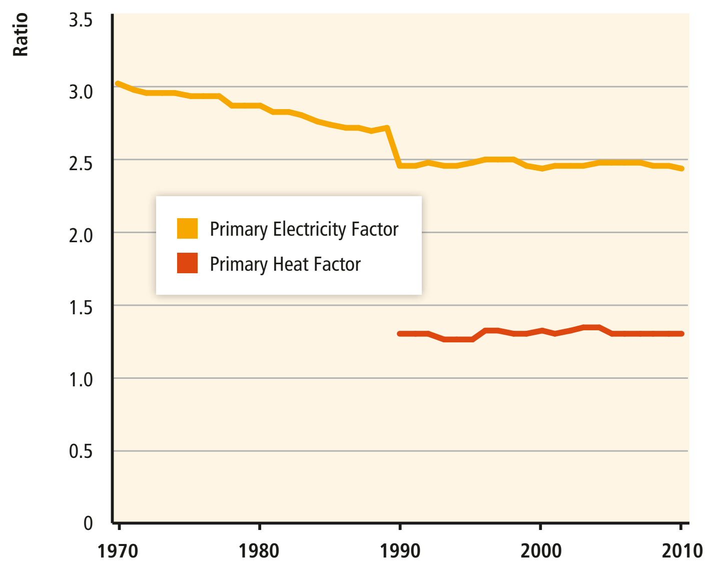

Figure A.II.3 | Historical primary electricity and heat factors. Data source: (IEA, 2012b).

A.II.5.2 Carbon dioxide emission factors

Carbon dioxide emission factors for electricity and heat have been derived as the ratio of CO_2 emissions from fuel inputs of power plants relative to the electricity and heat delivered. The method is equivalent to the one described above for primary factors. The fuel inputs have in addition been multiplied by their CO_2 emission factors of each fuel type as defined in IPCC (2006). The calculation of electricity and heat related CO_2 emission factors are conducted at the country level. Indirect carbon emissions related to electricity and heat consumption are then derived by simply multiplying the amount of electricity and heat consumed with the derived electricity and heat CO_2 emission factors at the sectoral level.

When the results of the methodology described above to estimate end-use CO_2 emissions from electricity and heat production are compared with the reported IEA direct emissions from the heat and electricity sectors there is an average difference of + 1.36 % over the years 1970 to 2010, indicating a slight overestimation of global CO_2 emissions. This difference varies by year, with the largest negative dif-

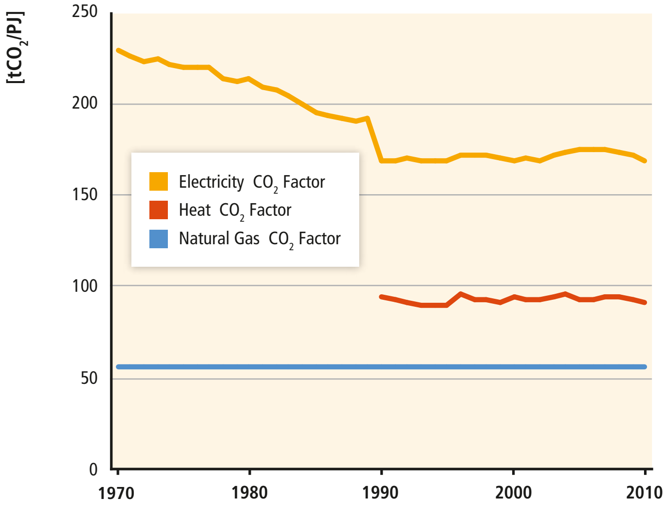

Figure A.II.4 | Historical electricity and heat CO_2 emissions factors. Data source: (IEA, 2012b; c).

ference in 1976 (-2.99 %) and the largest positive difference in 1990 (3.23 %).

The cross-sectoral annual total indirect carbon emissions were then normalized to the direct emission from electricity and heat production on the global level.

Figure A.II.4 shows the historical electricity CO_2 emission factors. The factors reflect both the fuel mix and conversion efficiencies in electricity generation and the distribution losses. Regions with high shares of non-fossil electricity generation have low emissions coefficients. For example, Latin America has a high share of hydro power and therefore a low CO_2 emission factor in electricity generation.

Primary heat and heat carbon factors were also calculated however, due to irregularity in data availability over the years at the global level, only data from 1990 are shown in the figures.

The emission factor for natural gas, 56.1 tCO_2 per PJ combusted, is shown in the graph for comparison.

A.II.6 Material flow analysis, input-output analysis, and lifecycle assessment

In the WGIII AR5, findings from material flow analysis, input-output analysis, and lifecycle assessment are used in Chapters 1, 4, 5, 7, 8, 9, 11, and 12. The following section briefly sketches the intellectual background of these methods and discusses their usefulness for mitigation research, and discusses some relevant assumptions, limitations, and methodological issues.

The anthropogenic contributions to climate change, caused by fossil fuel combustion, land conversion for agriculture, commercial forestry and infrastructure, and numerous agricultural and industrial processes, result from the use of natural resources, i. e., the manipulation of material and energy flows by humans for human purposes. Mitigation research has a long tradition of addressing the energy flows and associated emissions, however, the sectors involved in energy supply and use are coupled with each other through material stocks and flows, which leads to feedbacks and delays. These linkages between energy and material stocks and flows have, despite their considerable relevance for GHG emissions, so far gained little attention in climate change mitigation (and adaptation). The research agendas of industrial ecology and ecological economics with their focus on the socioeconomic metabolism (Wolman, 1965; Baccini and Brunner, 1991; Ayres and Simonis, 1994; Fischer-Kowalski and Haberl, 1997) also known as the biophysical economy (Cleveland et al., 1984), can complement energy assessments in important manners and support the development of a broader framing of mitigation research as part of sustainability science. The socioeconomic metabolism consists of the physical stocks and flows with which a society maintains and reproduces itself (Fischer-Kowalski and Haberl, 2007). These research traditions are relevant for sustainability because they comprehensively account for resource flows and hence can be used to address the dynamics, efficiency, and emissions of production systems that convert or utilize resources to provide goods and services to final consumers. Central to the socio-metabolic research methods are material and energy balance principles applied at various scales ranging from individual production processes to companies, regions, value chains, economic sectors, and nations.

An important application of these methods is carbon footprinting, i. e., the determination of lifecycle GHG emissions of products, organizations, households, municipalities, or nations. The carbon footprint of products usually determined using lifecycle assessment, while the carbon footprint of households, regional entities, or nations is commonly modeled using input-output analysis.

A.II.6.1 Material flow analysis

Material flow analysis (MFA)—including substance flow analysis (SFA)—is a method for describing, modelling (using socio-economic and technological drivers), simulating (scenario development), and visualizing the socioeconomic stocks and flows of matter and energy in systems defined in space and time to inform policies on resource and waste management and pollution control. Mass- and energy balance consistency is enforced at the level of goods and/or individual substances. As a result of the application of consistency criteria they are useful to analyze feedbacks within complex systems, e.g., the interrelations between diets, food production in cropland and livestock

AII

systems, and availability of area for bioenergy production (e.g., Erb et al. (2012), see Section 11.4).

The concept of socioeconomic metabolism (Ayres and Kneese, 1969; Boulding, 1972; Martinez-Alier, 1987; Baccini and Brunner, 1991; Ayres and Simonis, 1994; Fischer-Kowalski and Haberl, 1997) has been developed as an approach to study the extraction of materials or energy from the environment, their conversion in production and consumption processes, and the resulting outputs to the environment. Accordingly, the unit of analysis is the socioeconomic system (or some of its components), treated as a systemic entity, in analogy to an organism or a sophisticated machine that requires material and energy inputs from the natural environment in order to carry out certain defined functions and that results in outputs such as wastes and emissions.

Some MFAs trace the stocks and flows of aggregated groups of materials (fossil fuels, biomass, ores and industrial minerals, construction materials) through societies and can be performed on the global scale (Krausmann et al., 2009), for national economies and groups of countries (Weisz et al., 2006), urban systems (Wolman, 1965; Kennedy et al., 2007) or other socioeconomic subsystems. Similarly comprehensive methods that apply the same system boundaries have been developed to account for energy flows (Haberl, 2001a; b; Haberl et al., 2006), carbon flows (Erb et al., 2008) and biomass flows (Krausmann et al., 2008) and are often subsumed in the Material and Energy Flow Accounting (MEFA) framework (Haberl et al., 2004). Other MFAs have been conducted for analyzing the cycles of individual substances (e.g., carbon, nitrogen, or phosphorus cycles; Erb et al., 2008) or metals (e.g., copper, iron, or cadmium cycles; Graedel and Cao, 2010) within socioeconomic systems. A third group of MFAs have a focus on individual processes with an aim to balance a wide variety of goods and substances (e.g., waste incineration, a shredder plant, or a city).

The MFA approach has also been extended towards the analysis of socio-ecological systems, i.e., coupled human-environment systems. One example for this research strand is the 'human appropriation of net primary production' or HANPP which assesses human-induced changes in biomass flows in terrestrial ecosystems (Vitousek et al., 1986; Wright, 1990; Imhoff et al., 2004; Haberl et al., 2007). The socioecological metabolism approach is particularly useful for assessing feedbacks in the global land system, e.g., interrelations between production and consumption of food, agricultural intensity, livestock feeding efficiency, and bioenergy potentials, both residue potentials and area availability for energy crops (Haberl et al., 2011; Erb et al., 2012).

Anthropogenic stocks (built environment) play a crucial role in sociometabolic systems: (1) they provide services to the inhabitants, (2) their operation often requires energy and releases emissions, (3) any increase or renewal/maintenance of these stocks requires materials, and (4) the stocks embody materials (often accumulated over the past decades or centuries) that may be recovered at the end of the stocks' service lives ('urban mining') and, when recycled or reused, substitute primary resources and save energy and emissions in materials production (Müller et al., 2006). In contrast to flow variables, which tend to fluctuate much more, stock variables usually behave more robustly and are therefore often suitable as drivers for developing long-term scenarios (Müller, 2006). The exploration of built environment stocks (secondary resources), including their composition, performance, and dynamics, is therefore a crucial pre-requisite for examining long-term transformation pathways (Liu et al., 2012). Anthropogenic stocks have therefore been described as the engines of socio-metabolic systems. Moreover, socioeconomic stocks sequester carbon (Lauk et al., 2012); hence policies to increase the carbon content of long-lived infrastructures may contribute to climate-change mitigation (Gustavsson et al., 2006).

So far, MFAs have been used mainly to inform policies for resource and waste management. Studies with an explicit focus on climate change mitigation are less frequent, but rapidly growing. Examples involve the exploration of long-term mitigation pathways for the iron/steel industry (Milford et al., 2013; Pauliuk et al., 2013a), the aluminium industry (Liu et al., 2011, 2012), the vehicle stock (Pauliuk et al., 2011; Melaina and Webster, 2011), or the building stock (Pauliuk et al., 2013b).

A.II.6.2 Input-output analysis

Input-output (IO) analysis is an approach to trace the production process of products by economic sectors, and their use as intermediate demand by producing sectors (industries) and final demand including that by households and the public sector (Miller and Blair, 1985). Input-output tables describe the structure of the economy, i.e., the interdependence of different producing sectors and their role in final demand. Input-output tables are produced as part of national economic accounts (Leontief, 1936). Through the assumption of fixed input coefficients, input-output models can be formed, determining, e.g., the economic activity in all sectors required to produce a unit of final demand. The mathematics of input-output analysis can be used with flows denoted in physical or monetary units and has been applied also outside economics, e.g., to describe energy and nutrient flows in ecosystems (Hannon et al., 1986).

Environmental applications of input-output analysis include analyzing the economic role of abatement sectors (Leontief, 1971), quantifying embodied energy (Bullard and Herendeen, 1975) and the employment benefits of energy efficiency measures (Hannon et al., 1978), describing the benefits of pre-consumer scrap recycling (Nakamura and Kondo, 2001), tracing the material composition of vehicles (Nakamura et al., 2007), and identifying an environmentally desirable global division of labour (Stromman et al., 2009). Important for mitigation research, input-output analysis has been used to estimate the GHG emissions associated with the production and delivery of goods for final consumption, the 'carbon footprint' (Wiedmann and Minx, 2008). This type of analysis basically redistributes the emissions occurring in producing sectors to final consumption. It can be used to quantify GHG emissions associated with import and export (Wyckoff and Roop, 1994), with national consumption (Hertwich and Peters, 2009), or the consumption by specific groups of society (Lenzen and Schaeffer, 2004), regions (Turner et al., 2007), or institutions (Larsen and Hertwich, 2009; Minx et al., 2009; Peters, 2010; Berners-Lee et al., 2011).[4]

Global, multiregional input-output models are currently seen as the state-of-the-art tool to quantify 'consumer responsibility' (Chapter 5) (Hertwich, 2011; Wiedmann et al., 2011). Multiregional tables are necessary to adequately represent national production patterns and technologies in the increasing number of globally sourced products. Important insights provided to mitigation research are the quantification of the total CO_2 emissions embodied in global trade (Peters and Hertwich, 2008), the growth of net emissions embodied in trade from non-Annex B to Annex B countries (Peters et al., 2011b), to show that the UK (Druckman et al., 2008; Wiedmann et al., 2010) and other Annex B countries have increasing carbon footprints while their territorial emissions are decreasing, to identify the contribution of different commodity exports to the rapid growth in China's GHG emissions (Xu et al., 2009), and to quantify the income elasticity of the carbon footprint of different consumption categories like food, mobility, and clothing (Hertwich and Peters, 2009).

Input-output models have an increasingly important instrumental role in mitigation. They are used as a backbone for consumer carbon calculators, to provide sometimes spatially explicit regional analysis (Lenzen et al., 2004), to help companies and public institutions target climate mitigation efforts , and to provide initial estimates of emissions associated with different alternatives (Minx et al., 2009).

Input-output calculations are usually based on industry-average production patterns and emissions intensities and do not provide an insight into marginal emissions caused by additional purchases. However, efforts to estimate future and marginal production patterns and emissions intensities exist (Lan et al., 2012). At the same time, economic sector classifications in many countries are not very fine, so that IO tables provide carbon footprint averages of broad product groups rather than specific products, but efforts to disaggregate tables to provide more detail in environmentally relevant sectors exist (Tukker et al., 2013). Many models are not good at addressing waste management and recycling opportunities, although hybrid models with a physical representation of end-of-life processes do exist (Nakamura and Kondo, 2001). At the time of publication, national input-output tables describe the economy several years ago. Multiregional input-output tables are produced as part of research efforts and need to reconcile different national conventions for the construction of the tables and conflicting international trade data (Tukker et al., 2013). Efforts to provide a higher level of detail of environmentally relevant sectors and to nowcast tables are currently under development (Lenzen et al., 2012).

[4] GHG emissions related to land-use change have not yet been addressed in MRIO-based carbon footprint analysis due to data limitations.

A.II.6.3 Lifecycle assessment

Product lifecycle assessment (LCA) was developed as a method to determine the embodied energy use (Boustead and Hancock, 1979) and environmental pressures associated with specific product systems (Finnveden et al., 2009). A product system describes the production, distribution, operation, maintenance, and disposal of the product. From the beginning, the assessment of energy technologies has been important, addressing questions such as how many years of use would be required to recover the energy expended in producing a photovoltaic cell (Kato et al., 1998). Applications in the consumer products industry addressing questions of whether cloth or paper nappies (diapers) are more environmentally friendly (Vizcarra et al., 1994), or what type of washing powder, prompted the development of a wider range of impact assessment methods addressing issues such as aquatic toxicity (Gandhi et al., 2010), eutrophication, and acidification (Huijbregts et al., 2000). By now, a wide range of methods has been developed addressing either the contribution to specific environmental problems (midpoint methods) or the damage caused to ecosystem or human health (endpoint methods). At the same time, commonly used databases have collected lifecycle inventory information for materials, energy products, transportation services, chemicals, and other widely used products. Together, these methods form the backbone for the wide application of LCA in industry and for environmental product declarations, as well as in policy.

Lifecycle assessment plays an increasingly important role in climate mitigation research (SRREN Annex II, Moomaw et al., 2011). In WGIII AR5, lifecycle assessment has been used to quantify the GHG emissions associated with mitigation technologies, e.g., wind power, heat recovery ventilation systems, or carbon dioxide capture and storage. Lifecycle assessment is thus used to compare different ways to deliver the same functional unit, such as one kWh of electricity.

Lifecycle assessment has also been used to quantify co-benefits and detrimental side-effects of mitigation technologies and measures, including other environmental problems and the use of resources such as water, land, and metals. Impact assessment methods have been developed to model a wide range of impact pathways.

A range of approaches is used in LCA to address the climate impact of environmental interventions, starting from GHG through other pollutants (such as aerosols) to the inclusion of geophysical effects such as albedo changes or indirect climate effects (Bright et al., 2012), also exploring radiation-based climate metrics (Peters et al., 2011a). The timing of emissions and removals has traditionally not been considered, but issues associated with biomass production and use have given rise to a approaches to quantify the effects of carbon sequestration and temporary carbon storage in long-lived products (Brandão et al., 2013; Guest et al., 2013; Levasseur et al., 2013) and of temporarily increased atmospheric CO_2 concentrations from 'carbon-neutral' bioenergy systems (Cherubini et al., 2011).

Life-cycle inventories are normally derived from empirical information on actual processes or modelled based on engineering calculations. A key aspect of lifecycle inventories for energy technologies is that they contribute to understanding the thermodynamics of the wider product system; combined with appropriate engineering insight, they can provide some upper bound for possible technological improvements. These process LCAs provide detail and specificity, but do usually not cover all input requirements, as this would be too demanding. The cut-off error is the part of the inventory that is not covered by conventional process analysis; it is commonly between 20–50 % of the total impact (Lenzen, 2001). Hybrid lifecycle assessment utilizes input-output models to cover inputs of services or items that are used in small quantities (Treloar, 1996; Suh et al., 2004; Williams et al., 2009). Through their better coverage of the entire product system, hybrid LCAs tend to more accurately represent all inputs to production (Majeau-Bettez et al., 2011). They have also been used to estimate the cut-off error of process LCAs (Norris, 2002; Deng et al., 2011).

It must be emphasized that LCA is a research method that answers specific research questions. To understand how to interpret and use the results of an LCA case study, it is important to understand what the research question is. The research questions "what are the environmental impacts of product x" or "… of technology y" needs to be specified with respect to timing, regional context, operational mode, background system, etc. Modelling choices and assumption thus become part of an LCA. This implies that LCA studies are not always comparable because they do not address the same research question. Further, most LCAs are interpreted strictly on a functional unit basis, expressing the impact of a unit of the product system in a described production system, without either up-scaling the impacts to total impacts in the entire economy or saying something about the scale-dependency of the activity. For example, an LCA may identify the use of recycled material as beneficial, but the supply of recycled material is limited by the availability of suitable waste, so that an up-scaling of recycling is not feasible. Hence, an LCA that shows that recycling is beneficial is not sufficient to document the availability of further opportunities to reduce emissions. Lifecycle assessment, however, coupled with an appropriate system models (using material flow data) is suitable to model the emission gains from the expansion of further recycling activities.

Lifecycle assessment was developed with the intention to quantify resource use and emissions associated with existing or prospective product systems, where the association reflects physical causality within economic systems. Depending on the research question, it can be sensible to investigate average or marginal inputs to production. Departing from this descriptive approach, it has been proposed to model a wider socioeconomic causality describing the consequences of actions (Ekvall and Weidema, 2004). While established methods and a common practice exist for descriptive or 'attributional' LCA, such methods and standard practice are not yet established in 'consequential' LCA (Zamagni et al., 2012). Consequential LCAs are dependent on the decision context. It is increasingly acknowledged in LCA that for investigating larger sustainability questions, the product focus is not sufficient and larger system changes need to be modelled as such (Guinée et al., 2010).

For climate change mitigation analysis, it is useful to put LCA in a wider scenario context (Arvesen and Hertwich, 2011; Viebahn et al., 2011). The purpose is to better understand the contribution a technology can make to climate change mitigation and to quantify the magnitude of its resource requirements, co-benefits and side-effects. For mitigation technologies on both the demand and supply side, important contributors to the total impact are usually energy, materials, and transport. Understanding these contributions is already valuable for mitigation analysis. As all of these sectors will change as part of the scenario, LCA-based scenarios show how much impacts per unit are likely to change as part of the scenario.

Some LCAs take into account behavioural responses to different technologies (Takase et al., 2005; Girod et al., 2011). Here, two issues must be distinguished. One is the use of the technology. For example, it has been found that better insulated houses consistently are heated or cooled to higher/lower average temperature (Haas and Schipper, 1998; Greening et al., 2001). Not all of the theoretically possible technical gain in energy efficiency results in reduced energy use (Sorrell and Dimitropoulos, 2008). Such direct rebound effects can be taken into account through an appropriate definition of the energy services compared, which do not necessarily need to be identical in terms of the temperature or comfort levels. Another issue are larger market-related effects and spillover effects. A better-insulated house leads to energy savings. Both questions of (1) whether the saved energy would then be used elsewhere in the economy rather than not produced, and (2) what the consumer does with the money saved, are not part of the product system and hence of product lifecycle assessment. They are sometimes taken up in LCA studies, quantified, and compared. However, for climate mitigation analysis, these mechanisms need to be addressed by scenario models on a macro level. (See also Section 11.4 for a discussion of such systemic effects).

A.II.7 Fat tailed distributions

If we have observed *N* independent loss events from a given loss distribution, the probability that the next loss event will be worse than all the others is *1/(N+1)*. How much worse it will be depends on the tail of the loss distribution. Many loss distributions including losses due to hurricanes are very fat tailed. The notion of a 'fat tailed distribution' may be given a precise mathematical meaning in several ways, each capturing different intuitions. Older definitions refer to 'fat tails' as 'leptokurtic' meaning that the tails are fatter than the normal distribution. Nowadays, mathematical definitions are most commonly framed in terms of regular variation or subexponentiality (Embrechts et al., 1997).

A positive random variable X has regular variation with tail index $\alpha > 0$ if the probability $P(X > x)$ of exceeding a value x decreases at a polynomial rate x^{-a} as x gets large. For any $r > \alpha$, the *r-th* moment of X is infinite, the α-th moment may be finite or infinite depending on the distribution. If the first moment is infinite, then running averages of independent realizations of X increase to infinity. If the second moment is infinite, then running averages have an infinite variance and do not converge to a finite value. In either case, historical averages have little predictive value. The gamma, exponential, and Weibull distributions all have finite *r-th* moment for all positive r.

A positive random variable X is subexponential if for any n independent copies $X1,\ldots Xn$, the probability that the sum $X1+\ldots+Xn$ exceeds a value x becomes identical to the probability that the maximum of $X1,\ldots Xn$ exceeds x, as x gets large. In other words, 'the sum of $X1,\ldots Xn$ is driven by the largest of the $X1,\ldots Xn$'. Every regularly varying distribution is subexponential, but the converse does not hold. The Weibull distribution with shape parameter less than one is subexponential but not regularly varying. All its moments are finite, but the sum of n independent realizations tends to be dominated by the single largest value.

For X with finite first moment, the mean excess curve is a useful diagnostic. The mean excess curve of X at point x is the expected value of $X - x$ given that X exceeds x. If X is regularly varying with tail index $\alpha > 1$, the mean excess curve of X is asymptotically linear with slope $1/(\alpha-1)$. If X is subexponential its mean excess curve increases to infinity, but is not necessarily asymptotically linear. Thus, the mean excess curve for a subexponential distribution may be 'worse' than a regularly varying distribution, even though the former has finite moments. The mean excess curve for the exponential distribution is constant, that for the normal distribution is decreasing. The following figures show mean excess curves for flood insurance claims in the United States, per county per year per dollar income (hereby correcting for growth in exposure, Figure A.II.5) and insurance indemnities for crop loss per county per year in the United States (Figure A.II.6). Note that flood claims' mean excess curve lies well above the line with unit slope, whereas that for crop losses lie below (Kousky and Cooke, 2009).

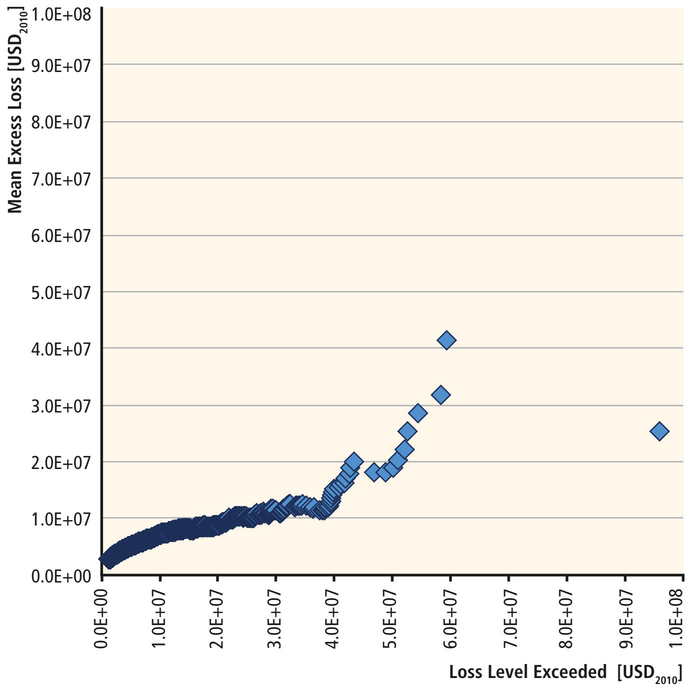

Figure A.II.6 | Mean excess curve of US crop insurance indemnities paid from the US Department of Agriculture's Risk Management Agency, aggregated by county and year for the years 1980 to 2008 in USD_{2010}. Note: The vertical axis gives mean excess loss, given loss at least as large as the horizontal axis. Source: adapted from (Kousky and Cooke, 2009).

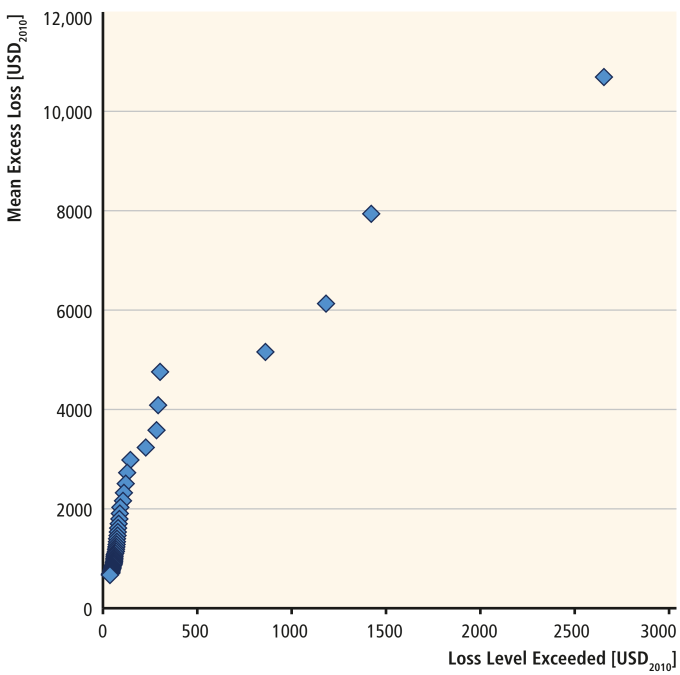

Figure A.II.5 | Mean excess curve for US flood insurance claims from the National Flood Insurance Program per dollar income per county per year for the years 1980 to 2008 in USD_{2010}. Considering dollar claims per dollar income in each county corrects for increasing exposure. Note: The vertical axis gives mean excess loss, given loss at least as large as the horizontal axis. Source: adapted from (Kousky and Cooke, 2009).

A.II.8 Growth rates

For the calculation of annual growth rates as frequently shown in this report, a number of different methods exist, all of which lead to slightly different numerical results. If not stated otherwise, the annual growth rates shown, have been derived using the *Log Difference Regression* technique or *Geometric Average,* techniques which can be shown to be equivalent.

The Log Difference Regression growth rate r_{LD} is calculated the following way:

$$r_{LD} = e^{\beta} - 1 \quad with \quad \beta = \frac{1}{T-1}\sum_{t=2}^{T} \Delta lnX_t \qquad \text{(Equation A.II.10)}$$

The *Geometric Average* growth rate r_{GEO} is calculated as shown below:

$$r_{GEO} = \left(\frac{X_T}{X_1}\right)^{\frac{1}{T-1}} - 1 \qquad \text{(Equation A.II.11)}$$

Other methods that are used to calculate annual growth rates include the *Ordinary Least Square* technique and the *Average Annual Growth Rate* technique.

Part III: Data sets

A.II.9 Historical data

AII

To aid coherency and consistency, core historic data presented throughout the report uses the same sources and applied the same methodologies and standards—these are detailed here:

- The standard country aggregations to regions are detailed in Section A.II.2.
- The central historic GHG emission data set was based on IEA (2012c) and Emissions Database for Global Atmospheric Research (EDGAR) (JRC/PBL, 2013) data. This data set provides annual emissions on a country level for the time span 1970 to 2010. The two sources are mapped as described in Section A.II.9.1.
- As default dataset for GDP in Purchasing Power Parity (PPP) World Bank data was supplemented according to the methodology described in Section A.II.9.2.
- The data sources and methodology for historic indirect emissions from electricity and heat production are defined in Section A.II.5.
- Lifecycle GHG emission data sets of energy supply technologies, predominantly used in Chapter 7, are introduced in Section A.II.9.3. The underlying methodology is explained in Section A.II.6 of this Annex.

A.II.9.1 Mapping of emission sources to sectors

The list below shows how emission sources are mapped to sectors throughout the WGIII AR5. This defines unambiguous system boundaries for the sectors as represented in Chapters 7–11 in the report and enables a discussion and representation of emission sources without double-counting.

Emission sources refer to the definitions by the IPCC Task Force on National Greenhouse Gas Inventories (TFI) (IPCC, 2006). Where further disaggregated data was required, additional source categories were introduced consistent with the underlying datasets (IEA, 2012c; JRC/PBL, 2013). This information appears in the following systematic sequence throughout this section:

Emission source category (chapter emission source category numbering)

Emission Source (Sub-)Category (IPCC Task force definition) [gases emitted by emission source (CO_2 data set used)]

A common dataset ('IEA/EDGAR') is used across WGIII AR5 chapters to ensure consistent representation of emission trends across the report. Uncertainties of this data are discussed in the respective chapters (Chapter 1; Chapter 5; and Chapter 11). CO_2 emissions from fossil fuel combustion are taken from IEA (2012c), the remaining CO_2 and non-CO_2 GHG emissions are taken from EDGAR (JRC/PBL, 2013), see the following sections for categories and sources used. For the FOLU subsector EDGAR (JRC/PBL, 2013) represents land-based CO_2 emissions from forest and peat fires and decay to approximate the CO_2 flux from anthropogenic emission sources.

Following general scientific practice, 100-year GWPs from the IPCC Second Assessment Report (SAR) (Schimel et al., 1996) are used as the index for converting GHG emissions to common units of CO_2-equivalent emissions in EDGAR (JRC/PBL, 2013). The following gases and associated GWPs based on the SAR are covered in EDGAR: CO_2 (1), CH_4 (21), N_2O (310), HFC-125 (2800), HFC-134a (1300), HFC-143a (3800), HFC-152a (140), HFC-227ea (2900), HFC-23 (11700), HFC-236fa (6300), HFC-245fa (560), HFC-32 (650), HFC-365mfc (1000), HFC-43–10-mee (1300), C_2F_6 (9200), C_3F_8 (7000), C_4F_{10} (7000), C_5F_{12} (7500), C_6F_{14} (7400), C_7F_{16} (7400), c-C_4F_8 (8700), CF_4 (6500), SF_6 (23900).

A.II.9.1.1 Energy (Chapter 7)

Electricity & heat (7.1)

Power and Heat Generation (1A1a) [CO_2 (IEA), CH_4, N_2O]
  Public Electricity Plants (1A1a1) [CO_2 (IEA)]
  Public Combined Heat and Power Generation (1A1a2) [CO_2 (IEA)]
  Public Heat Plants (1A1a3) [CO_2 (IEA)]
  Public Electricity Generation (own use) (1A1a4) [CO_2 (IEA)]
  Electricity Generation (autoproducers) (1A1a5) [CO_2 (IEA)]
  Combined Heat and Power Generation (autoproducers) (1A1a6) [CO_2 (IEA)]
  Heat Plants (autoproducers) (1A1a7) [CO_2 (IEA)]
Public Electricity and Heat Production (biomass) (1A1ax) [CH_4, N_2O]

Petroleum refining (7.2)
Other Energy Industries (1A1bc) [CO_2 (IEA)]

Manufacture of solid fuels (7.3)
Other transformation sector (BKB, etc.) (1A1r) [CH_4, N_2O]
Manufacture of Solid Fuels and Other Energy Industries (biomass) (1A1cx) [CH_4, N_2O]

Fuel production and transport (7.4)
Fugitive emissions from solids fuels except coke ovens (1B1r) [CO_2 (EDGAR), CH_4, N_2O]
Flaring and fugitive emissions from oil and Natural Gas (1B2) [CO_2 (EDGAR), CH_4, N_2O]

Others (7.5)
Electrical Equipment Manufacture (2F8a) [SF_6]
Electrical Equipment Use (includes site installation) (2F8b) [SF_6]
Fossil fuel fires (7A) [CO_2 (EDGAR), CH_4, N_2O]

Indirect N2O emissions from energy (7.6)
Indirect N_2O from NO_x emitted in cat. 1A1 (7B1) [N_2O]
Indirect N_2O from NH_3 emitted in cat. 1A1 (7C1) [N_2O]

A.II.9.1.2 Transport (Chapter 8)

Aviation (8.1)
Domestic air transport (1A3a) [CO_2 (IEA), CH_4, N_2O]

Road transportation (8.2)
Road transport (includes evaporation) (fossil) (1A3b) [CO_2 (IEA), CH_4, N_2O]
Road transport (includes evaporation) (biomass) (1A3bx) [CH_4, N_2O]
Adiabatic prop: tyres (2F9b) [SF_6]

Rail transportation (8.3)
Rail transport (1A3c) [CO_2 (IEA), CH_4, N_2O]
Non-road transport (rail, etc.) (fossil) (biomass) (1A3cx) [CH_4, N_2O]

Navigation (8.4)
Inland shipping (fossil) (1A3d) [CO_2 (IEA), CH_4, N_2O]
Inland shipping (fossil) (biomass) (1A3dx) [CH_4, N_2O]

Others incl. indirect N_2O emissions from transport (8.5)
Non-road transport (fossil) (1A3e) [CO_2 (IEA), CH_4, N_2O]
  Pipeline transport (1A3e1) [CO_2 (IEA)]
  Non-specified transport (1A3er) [CO_2 (IEA)]
Non-road transport (fossil) (biomass) (1A3ex) [CH_4, N_2O]
Refrigeration and Air Conditioning Equipment (HFC) (Transport) (2F1a1) [HFC]
Indirect N_2O from NO_x emitted in cat. 1A3 (7B3) [N_2O]
Indirect N_2O from NH_3 emitted in cat. 1A3 (7C3) [N_2O]

International Aviation (8.6)
Memo: International aviation (1C1) [CO_2 (IEA), CH_4, N_2O]

International Shipping (8.7)
Memo: International navigation (1C2) [CO_2 (IEA), CH_4, N_2O]

A.II.9.1.3 Buildings (Chapter 9)

Commercial (9.1)
Commercial and public services (fossil) (1A4a) [CO_2 (IEA), CH_4, N_2O]
Commercial and public services (biomass) (1A4ax) [CH_4, N_2O]

Residential (9.2)
Residential (fossil) (1A4b) [CO_2 (IEA), CH_4, N_2O]
Residential (biomass) (1A4bx) [CH_4, N_2O]

Others (9.3)
Refrigeration and Air Conditioning Equipment (HFC) (Building) (2F1a2) [HFC]
Fire Extinguishers (2F3) [PFC]
Aerosols/ Metered Dose Inhalers (2F4) [HFC]
Adiabatic prop: shoes and others (2F9a) [SF_6]
Soundproof windows (2F9c) [SF_6]

Indirect N_2O emissions from buildings (9.4)
Indirect N_2O from NO_x emitted in cat. 1A4 (7B4) [N_2O]
Indirect N_2O from NH_3 emitted in cat. 1A4 (7C4) [N_2O]

A.II.9.1.4 Industry (Chapter 10)

Ferrous and non-ferrous metals (10.1)
Fuel combustion coke ovens (1A1c1) [CH_4, N_2O]
Blast furnaces (pig iron prod.) (1A1c2) [CH_4, N_2O]
Iron and steel (1A2a) [CO_2 (IEA), CH_4, N_2O]
Non-ferrous metals (1A2b) [CO_2 (IEA), CH_4, N_2O]
Iron and steel (biomass) (1A2ax) [CH_4, N_2O]
Non-ferrous metals (biomass) (1A2bx) [CH_4, N_2O]
Fuel transformation coke ovens (1B1b1) [CO_2 (EDGAR), CH_4]
Metal Production (2C) [CO_2 (EDGAR), CH_4, PFC, SF_6]
  Iron and Steel Production (2C1) [CO_2 (EDGAR)]
    Crude steel production total (2C1a) [CO_2 (EDGAR)]
  Ferroy Alloy Production (2C2) [CO_2 (EDGAR)]
  Aluminum production (primary) (2C3) [PFC]
  SF6 Used in Aluminium and Magnesium Foundries (2C4) [SF_6]
    Magnesium foundries: SF_6 use (2C4a) [SF_6]
    Aluminium foundries: SF_6 use (2C4b) [SF_6]
  Non-ferrous metals production (2Cr) [CO_2 (EDGAR)]

Chemicals (10.2)
Chemicals (1A2c) [CO_2 (IEA), CH_4, N_2O]
Chemicals (biomass) (1A2cx) [CH_4, N_2O]

Production of chemicals (2B) [CO_2 (EDGAR), CH_4, N_2O]
Production of Halocarbons and SF6 (2E) [HFC, SF6]
Non-energy use of lubricants/waxes (2G) [CO_2 (EDGAR)]
Solvent and other product use: paint (3A) [CO_2 (EDGAR)]
Solvent and other product use: degrease (3B) [CO_2 (EDGAR)]
Solvent and other product use: chemicals (3C) [CO_2 (EDGAR)]
Other product use (3D) [CO_2 (EDGAR), N_2O]

Cement production (10.3)
Cement production (2A1) [CO_2 (EDGAR)]

Landfill & waste incineration (10.4)
Solid waste disposal on land (6A) [CH_4]
Waste incineration (6C) [CO_2 (EDGAR), CH_4, N_2O]
Other waste handling (6D) [CH_4, N_2O]

Wastewater treatment (10.5)
Wastewater handling (6B) [CH_4, N_2O]

Other industries (10.6)
Pulp and paper (1A2d) [CO_2 (IEA), CH_4, N_2O]
Food and tobacco (1A2e) [CO_2 (IEA), CH_4, N_2O]
Other industries (stationary) (fossil) (1A2f) [CO_2 (IEA), CH_4, N_2O]
- Non-metallic minerals (1A2f1) [CO_2 (IEA)]
- Transport equipment (1A2f2) [CO_2 (IEA)]
- Machinery (1A2f3) [CO_2 (IEA)]
- Mining and quarrying (1A2f4) [CO_2 (IEA)]
- Wood and wood products (1A2f5) [CO_2 (IEA)]
- Construction (1A2f6) [CO_2 (IEA)]
- Textile and leather (1A2f7) [CO_2 (IEA)]
- Non-specified industry (1A2f8) [CO_2 (IEA)]

Pulp and paper (biomass) (1A2dx) [CH_4, N_2O]
Food and tobacco (biomass) (1A2ex) [CH_4, N_2O]
Off-road machinery: mining (diesel) (1A5b1) [CH_4, N_2O]
Lime production (2A2) [CO_2 (EDGAR)]
Limestone and Dolomite Use (2A3) [CO_2 (EDGAR)]
Production of other minerals (2A7) [CO_2 (EDGAR)]
Refrigeration and Air Conditioning Equipment (PFC) (2F1b) [PFC]
Foam Blowing (2F2) [HFC]
F-gas as Solvent (2F5) [PFC]
Semiconductor Manufacture (2F7a) [HFC, PFC, SF_6]
Flat Panel Display (FPD) Manufacture (2F7b) [PFC, SF_6]
Photo Voltaic (PV) Cell Manufacture (2F7c) [PFC]
Other use of PFC and HFC (2F9) [HFC, PFC]
Accelerators/HEP (2F9d) [SF_6]
Misc. HFCs/SF_6 consumption (AWACS, other military, misc.) (2F9e) [SF6]
Unknown SF_6 use (2F9f) [SF_6]

Indirect N_2O emissions from industry (10.7)
Indirect N_2O from NO_x emitted in cat. 1A2 (7B2) [N_2O]
Indirect N_2O from NH_3 emitted in cat. 1A2 (7C2) [N_2O]

A.II.9.1.5 AFOLU (Chapter 11)

Fuel combustion (11.1)
Agriculture and forestry (fossil) (1A4c1) [CO_2 (IEA), CH_4, N_2O]
Off-road machinery: agric./for. (diesel) (1A4c2) [CH_4, N_2O]
Fishing (fossil) (1A4c3) [CO_2 (IEA), CH_4, N_2O]
Non-specified Other Sectors (1A4d) [CO_2 (IEA), CH_4, N_2O]
Agriculture and forestry (biomass) (1A4c1x) [CH_4, N_2O]
Fishing (biomass) (1A4c3x) [N_2O]
Non-specified other (biomass) (1A4dx) [CH_4, N_2O]

Livestock (11.2)
Enteric Fermentation (4A) [CH_4]
Manure management (4B) [CH_4, N_2O]

Rice cultivation (11.3)
Rice cultivation (4C) [CH_4]

Direct soil emissions (11.4)
Other direct soil emissions (4D4) [CO_2 (EDGAR)]
Agricultural soils (direct) (4Dr) [N_2O]

Forrest fires and decay (11.5)
Savannah burning (4E) [CH_4, N_2O]
Forest fires (5A) [CO_2 (EDGAR), CH_4, N_2O]
Grassland fires (5C) [CH_4, N_2O]
Forest Fires-Post burn decay (5F2) [CO_2 (EDGAR), N_2O]

Peat fires and decay (11.6)
Agricultural waste burning (4F) [CH_4, N_2O]
Peat fires and decay of drained peatland (5D) [CO_2 (EDGAR), CH_4, N_2O]

Indirect N_2O emissions from AFOLU (11.7)
Indirect Emissions (4D3) [N_2O]
Indirect N_2O from NO_x emitted in cat. 5 (7B5) [N_2O]
Indirect N_2O from NH_3 emitted in cat. 5 (7C5) [N_2O]

A.II.9.1.6 Comparison of IEA and EDGAR CO_2 emission datasets

As described above the merged IEA/EDGAR historic emission dataset uses emission data from IEA (2012c) and EDGAR (JRC/PBL, 2013). Here we compare IEA/EDGAR to the pure EDGAR dataset (JRC/PBL, 2013). The comparison details the differences between the two datasets as the remaining CO_2 and non-CO_2 GHG emissions are identical between the two datasets. Table A.II.11 maps EDGAR categories to the IEA categories used in IEA/EDGAR forming 21 groups. Figure A.II.7 shows the quantitative differences for aggregated global emissions of these 21 groups between the two sources.

Table A.II.11 | Mapping of IEA (2012c) and EDGAR (JRC/PBL, 2013) CO_2 emission categories. Figure A.II.7 shows the quantitative difference for each Comparison Group (using Comparison Group number as reference).

Comparison Groups		EDGAR		IEA	IEA/EDGAR category
number	group name	IPCC category	category name	category name	
1	Power Generation	1A1a	Public electricity and heat production	Main activity electricity plants	1A1a1
				Main activity CHP plants	1A1a2
				Main activity heat plants	1A1a3
				Own use in electricity, CHP and heat plants	1A1a4
				Autoproducer electricity plants	1A1a5
				Autoproducer CHP plants	1A1a6
				Autoproducer heat plants	1A1a7
2	Other Energy Industries	1A1c1	Fuel combustion coke ovens	Other energy industry own use	1A1bc
		1A1c2	Blast furnaces (pig iron prod.)		
		1A1r	Other transformation sector (BKB, etc.)		
3	Iron and steel	1A2a	Iron and steel	Iron and steel	1A2a
4	Non-ferrous metals	1A2b	Non-ferrous metals	Non-ferrous metals	1A2b
5	Chemicals	1A2c	Chemicals	Chemical and petrochemical	1A2c
6	Pulp and paper	1A2d	Pulp and paper	Paper, pulp and printing	1A2d
7	Food and tobacco	1A2e	Food and tobacco	Food and tobacco	1A2e
8	Other Industries w/o NMM	1A2f	Other industries (incl. offroad) (fos.)	Transport equipment	1A2f2
				Machinery	1A2f3
				Mining and quarrying	1A2f4
				Wood and wood products	1A2f5
				Construction	1A2f6
				Textile and leather	1A2f7
				Non-specified industry	1A2f8
9	Non-metallic minerals	1A2f-NMM	Non-metallic minerals (cement proxy)	Non-metallic minerals	1A2f1
10	Domestic air transport	1A3a	Domestic air transport	Domestic aviation	1A3a
11	Road transport (incl. evap.) (foss.)	1A3b	Road transport (incl. evap.) (foss.)	Road	1A3b
12	Rail transport	1A3c	Non-road transport (rail, etc.) (fos.)	Rail	1A3c
13	Inland shipping (fos.)	1A3d	Inland shipping (fos.)	Domestic navigation	1A3d
14	Other transport	1A3e	Non-road transport (fos.)	Pipeline transport	1A3e1
				Non-specified transport	1A3er
				Non-energy use in transport	1A3er
15	Commercial and public services (fos.)	1A4a	Commercial and public services (fos.)	Commercial and public services	1A4a
16	Residential (fos.)	1A4b	Residential (fos.)	Residential	1A4b
17	Agriculture and forestry (fos.)	1A4c1	Agriculture and forestry (fos.)	Agriculture/forestry	1A4c1
		1A4c2	Off-road machinery: agric./for. (diesel)		
		1A5b1	Off-road machinery: mining (diesel)		
18	Fishing (fos.)	1A4c3	Fishing (fos.)	Fishing	1A4c3
19	Non-specified Other Sectors	1A4d	Non-specified other (fos.)	Non-specified other	1A4d
20	Memo: International aviation	1C1	International air transport	Memo: International aviation bunkers	1C1
21	Memo: International navigation	1C2	International marine transport (bunkers)	Memo: International marine bunkers	1C2

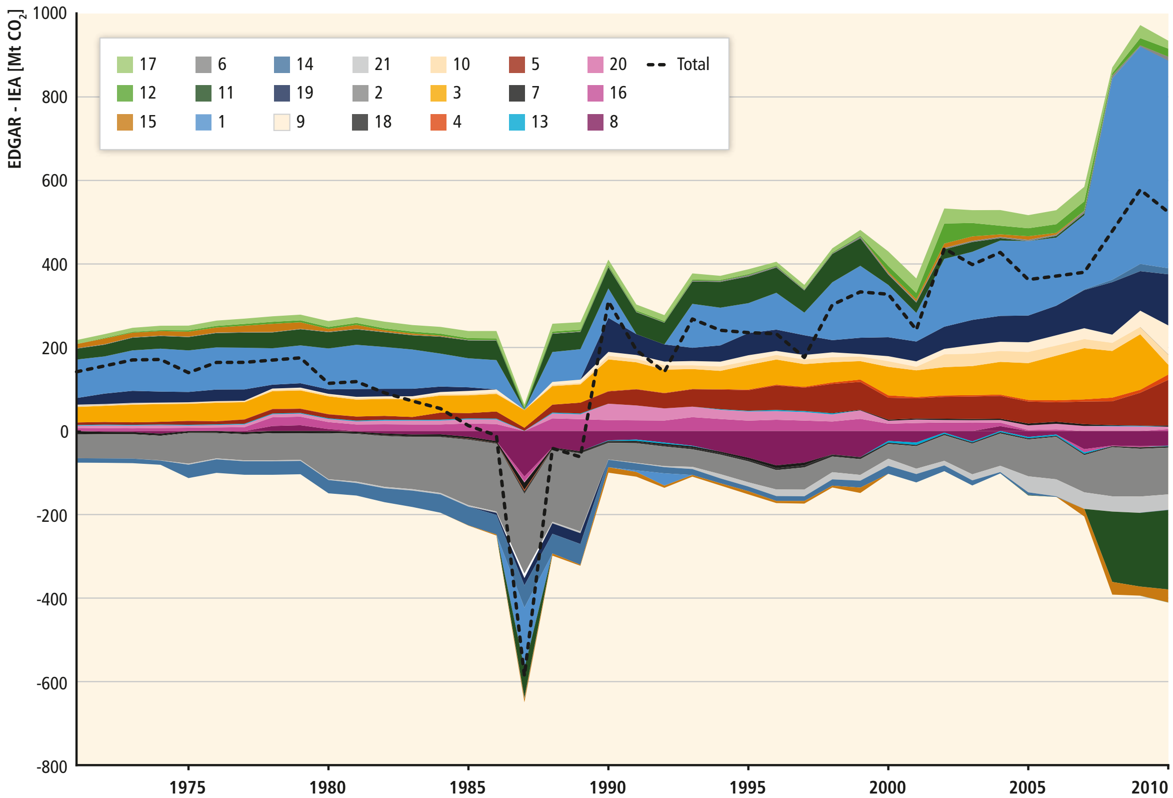

Figure A.II.7 | Difference of CO_2 emissions between analogous IEA (2012c) and EDGAR (JRC/PBL, 2013) categories as detailed in Table A.II.11. (Numbers in key refer to Table A.II.11 Comparison Groups).

A.II.9.2 Historic GDP PPP data

As default dataset for GDP in Purchasing Power Parity (PPP) World Bank data was used (World Bank, 2013). In line with the methodology described in Section A.II.1.3 and by Nordhaus (2007) the initial dataset (1980–2012 PPP in constant Int$_{2011}$[5]) was extended backwards using World Bank GDP growth rates in constant local currency unit[6]. Further data gaps were closed extending World Bank data by applying growth rates as supplied by the IMF (2012) for 1980 and later. For gaps prior to 1980 Penn World Tables (PWT)(Heston et al., 2011) was used. In addition, missing countries were added using PWT (Heston et al., 2011)(Cuba, Puerto Rico, Marshall Islands, Somalia, Bermuda), IMF (2012) (Kosovo, Myanmar, Tuvala, Zimbabwe) and IEA (Dem Rep. Korea, Gibraltar, Netherlands Antilles) GDP data.

A.II.9.3 Lifecycle greenhouse gas emissions

In Chapter 7, Figure 7.6 and 7.7, the lifecycle GHG emissions of different technologies are compared. This section describes how these numbers are derived. The air pollutant emission numbers in Figure 7.8 are from (Hertwich et al., 2013). The assessment of GHG emissions and other climate effects associated with electricity production technologies presented here is based on two distinct research enterprises.

The first effort started with the review of lifecycle GHG emission started for SRREN (Sathaye et al., 2011). This work was extended to a harmonization of LCA studies following the approach by Farrell et al. (2006) and resulted in a set of papers published a special issue of the *Journal of Industrial Ecology* (Brandão et al., 2012; Heath and Mann, 2012). The collected data points of LCA results of GHG emissions of different technologies from this comprehensive review are available online in tabular and chart form at http://en.openei.org/apps/LCA/ and have been obtained from there, but the underlying scientific papers from the peer reviewed literature are referred to here.

The second effort is a broader study of lifecycle environmental impacts and resource requirements under way for the International Resource Panel (Hertwich et al., 2013). The study aims at a consistent technology comparison where lifecycle data collected under uniform instructions in a common format are evaluated in a single assessment model based on a common set of background processes. The model is capable of evaluating environmental impacts in nine different regions and reflecting the background technology at three different points in time (2010/30/50). It addresses more complete inventories than common process-based analysis through the use of hybrid LCA.

[5] http://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD
[6] http://data.worldbank.org/indicator/NY.GDP.MKTP.KN

Table A.II.12 | Methane emission (gCH4/MJ_{LHV}) from coal and gas production (Burnham et al., 2012). Based on the minimum, mean, and maximum values provided by Burnham, the parameters μ and σ of a lognormal distribution were estimated. Coal is the weighted average of 60 % from underground mines and 40 % from surface mines.

	Min	Mean	Max	μ	σ
Underground coal mining	0.25	0.34	0.45	−1.09	0.147
Surface coal mining	0.025	0.05	0.068	−3.09	0.291
Natural gas production	0.18	0.52	1.03	−0.75	0.432

Table A.II.13 | Efficiency ranges assumed in power generation assumed in the calculation of fugitive emissions. The best estimate plant efficiency are based on NETL (NETL, 2010a; b; c; d; e) with ranges based (Singh et al., 2011a; Corsten et al., 2013). Note that the min and max efficiencies are not derived from the literature and were not used to calculate direct emissions; rather, they are used only to establish the possible range of fugitive emissions.

	Direct emissions (tCO_2eq/MWh)			Efficiency (% based on LHV)			Infrastructure & Supplies (tCO_2eq/MWh)		
Technology	Min	Average	Max	Max	Average	Min	Min	Average	Max
Gas—Single Cycle	0.621	0.667	0.706	33.1	30.8	29.1	0.001	0.002	0.002
Coal—average	0.913	0.961	1.009	33.3	35.0	36.8	0.010	0.011	0.013
Gas—average	0.458	0.483	0.507	39.9	42.0	44.1	0.001	0.002	0.003
Gas—Combined Cycle	0.349	0.370	0.493	59.0	55.6	41.7	0.001	0.002	0.002
Coal—PC	0.673	0.744	0.868	47.6	43.0	36.9	0.008	0.010	0.012
Coal—IGCC	0.713	0.734	0.762	44.9	43.6	42.0	0.003	0.004	0.006
CCS—Coal—Oxyfuel	0.014	0.096	0.110	35	30.2	27	0.014	0.017	0.023
CCS—Coal—PC	0.095	0.121	0.138	32	29.4	27	0.022	0.028	0.036
CCS—Coal—IGCC	0.102	0.124	0.148	34	32.3	27	0.008	0.010	0.013
CCS—Gas—Combined Cycle	0.030	0.047	0.098	49	47.4	35	0.007	0.009	0.012

The GHG emissions for coal carbon dioxide capture and storage (CCS), PV, concentrating solar power (CSP), and wind power associated with the two different efforts have been compared and have been found to be in agreement. The data has been supplemented by selected literature data where required. The specific numbers displayed come from following data sources.

A.II.9.3.1 Fossil fuel based power

For fossil fuel based power, three different sources of emissions were distinguished: (1) direct emissions from the power plant, (2) emissions of methane from the fuel production and delivery system, and (3) the remaining lifecycle emissions, mostly connected to the infrastructure of the entire energy system including the power plant itself, and supplies such as solvents. Each of these emissions categories was assessed separately, because emerging findings on methane emissions required a reassessment of the lifecycle emissions of established studies, which often use only a generic emissions factor. In our work, probability distributions for emissions from the three different systems were assessed and combined through a Monte Carlo analysis.

Fugitive emissions: The most important source of indirect emissions of fossil fuel based power is the supply of fuel, where fugitive emissions of methane are a major source of GHG gases. We have revisited the issue of fugitive methane emissions given new assessments of these emissions. As described in Section 7.5.1, fugitive emissions were modelled as the product of a log-normal distributions based on the parameters specified in Table A.II.12 and the efficiencies given by a triangular distribution with the parameters specified in Table A.II.13.

The data for the infrastructure component is from Singh et al. (2011a). A uniform distribution was used in the Monte Carlo Analysis. The data is provided in Table A.II.13. Direct emissions and associated efficiency data for Natural Gas Combined Cycle (NGCC) with and without CCS is from Singh et al. (2011b). Minimum and maximum numbers are from Corsten et al. (2013, Table 4), with an assumed direct/indirect share of 40 % and 60 %. For pulverized coal, Corsten et al. (2013, Table 5) reports characterized impacts, with direct and indirect emission shares for pulverized coal with and without CCS. For Integrated Gasification Combined Cycle (IGCC), calculations were performed by Hertwich et al. (2013) based on data obtained from NETL (2010a; d). For oxyfuel, the best estimate is based on a 90 % separation efficiency from Singh et al. (2011a) with the range assuming higher separation efficiency as indicated by Corsten et al. (2013). Ranges are based on Corsten et al. (2013) also considering the ranges reported by NETL (2010a; b; c; d; e). Triangular distributions were used in the Monte Carlo simulation. The contribution analysis shown in Figure 7.6 is based on Singh et al. (2011a) with adjustments to the higher fugitive emissions based on Burnham (2012) and lower average efficiencies and hence direct emissions for gas fired power as obtained from the distributions above.

A log-normal distribution does not have well-defined maximum and minimum values. The range in Figures 7.6 and 7.7 hence shows the 1st to 99th percentile.

A.II.9.3.2 Nuclear power

The data on nuclear power was taken from Lenzen (2008) and Warner and Heath (2012). There is no basis in the literature as far as we know to distinguish between 2nd and 3rd generation power plants.

A.II.9.3.3 Renewable energy

Concentrated solar power: The data range is based on both the assessments conducted for the International Resource Panel (Hertwich et al., 2013) work based on the analysis of Viebahn et al. (2011), Burkhardt et al. (2011), Whitaker et al. (2013), and the review of Burkhardt et al. (2012).

Photovoltaic power: Ranges are based largely on the reviews of Hsu et al. (2012) and Kim et al. (2012). The analysis of newer thin-film technologies analyzed in Hertwich et al. (2013) indicates that recent technical progress has lowered emissions.

Wind power: The data is based on the review of Arvesen and Hertwich (2012) and has been cross-checked with Dolan and Heath (2012) and Hertwich et al. (2013).

Ocean Energy: There have been very few LCAs of ocean energy devices. The numbers are based on the Pelamis (Parker et al., 2007) and Oyster wave energy device (Walker and Howell, 2011), the SeaGen tidal turbine (Douglas et al., 2008; Walker and Howell, 2011), and tidal barrages (Woollcombe-Adams et al., 2009; Kelly et al., 2012). Based on these available assessments, tidal turbines have the lowest GHG emissions and tidal barrages the highest.

Hydropower: The indirect emissions of hydropower are largely associated with fossil fuel combustion in the construction of the plant. The data presented here is based on SRREN (Kumar et al., 2011). The data was cross-checked with a recent review (Raadal et al., 2011) and analysis (Moreau et al., 2012).

The issue of biogenic emissions resulting from the degradation of biomass in reservoirs had been reviewed in SRREN, however, without providing estimates of the size of biogenic GHG emissions per kWh. Please note that only CH_4 emissions are included in the analysis. N_2O emissions have not been broadly investigated, but are assumed to be small (Demarty and Bastien, 2011). Carbon dioxide emissions can be substantial, but these emissions represent carbon that would probably have oxidized elsewhere; it is not clear what fraction of the resulting CO_2 would have entered the atmosphere (Hertwich, 2013). We have hence excluded biogenic CO_2 emissions from reservoirs from the assessment. The distribution of biogenic methane emissions comes from an analysis of methane emissions per kWh of power generated by Hertwich (2013) based on literature data collected and reviewed by Barros et al. (2011). Independent estimates based on recent empirical studies (Maeck et al., 2013) come to similar results. For the maximum number (2 kg CO_2eq/kWh), a specific power station analyzed by Kemenes et al. (2007) was chosen; as it is not clear that the much higher value from the 99th percentile of the distribution determined by Hertwich (2013) is really realistic.

Biomass: Life-cycle direct global climate impacts of bioenergy come from the peer-reviewed literature from 2010 to 2012 and are based on a range of electric conversion efficiencies of 27–50 %. The category "Biomass—dedicated and crop residues" includes perennial grasses, like switchgrass and miscanthus, short rotation species, like willow and eucalyptus, and agricultural byproducts, like wheat straw and corn stover. "Biomass—forest wood" refers to forest biomass from long rotation species in various climate regions. Ranges include global climate impacts of CO_2 emissions from combustion of regenerative biomass (i.e., biogenic CO_2) and the associated changes in surface albedo following ecosystem disturbances, quantified according to the IPCC framework for emission metrics (Forster et al., 2007) and using 100-year GWPs as characterization factors (Cherubini et al., 2012).

These impacts are site-specific and generally more significant for long rotation species. The range in "Biomass—forest wood" is representative of various forests and climates, e.g., aspen forest in Wisconsin (US), mixed forest in Pacific Northwest (US), pine forest in Saskatchewan (Canada), and spruce forest in Southeast Norway. In areas affected by seasonal snow cover, the cooling contribution from the temporary change in surface albedo can be larger than the warming associated with biogenic CO_2 fluxes and the bioenergy system can have a net negative impact (i.e., cooling). Change in soil organic carbon can have a substantial influence on the overall GHG balance of bioenergy systems, especially for the case "Biomass—dedicated and crop residues", but are not covered here due to their high dependence on local soil conditions and previous land use (Don et al., 2012; Gelfand et al., 2013).

Additional information on the LCA of bioenergy alternatives is provided in Section 11.A.4.

A.II.10 Scenario data

A.II.10.1 Process

The AR5 Scenario Database comprises 31 models and 1,184 scenarios, summarized in Table A.II.14. In an attempt to be as inclusive as possible, an open call for scenarios was made through the Integrated Assessment Modeling Consortium (IAMC) with approval from the IPCC

Table A.II.14 | Contributing models to the WGIII AR5 Scenario Database.

Model (versions)	Economic coverage and feedback	Myopic/ Foresight	Regional and emissions* detail	Representation of climate and land use	Cost measures	Scenario Publications	Number of Scenarios included in AR5 database
AIM-Enduse (12.1; backcast 1.0)	Partial equilibrium	Myopic	32 regions; 5 substances (v. 12.1)/8 substances (v. backcast 1.0)	None	Energy system cost mark-up (v 12.1; backcast 1.0)/area under marginal abatement cost curve (backcast 1.0)	(Akashi et al., 2014; Kriegler et al., 2014b; Tavoni et al., 2014)	41
BET (1.5)	General equilibrium	Foresight	32 regions; CO_2 only	Climate damages; no land use	Consumption loss, GDP loss, energy system cost mark-up	(Yamamoto et al., 2014)	23
DNE21+ (v.11, v.12)	Partial equilibrium	Foresight	54 regions; 6 substances (v.11)/13 substances (v.12)	Temperature change; no land use	Energy system cost mark-up	(Akimoto et al., 2012; Wada et al., 2012; Kriegler et al., 2014a; Riahi et al., 2014; Sano et al., 2014)	43
EC-IAM 2012	General equilibrium	Foresight	11 regions; 6 substances	Climate damages; no land use	Consumption loss, GDP loss, energy system cost mark-up, welfare loss	(Kriegler et al., 2014c)	21
Ecofys Energy Model	Partial equilibrium	Myopic	1 region; 3 substances	No climate; land use for bioenergy	Energy system cost mark-up	(Deng et al., 2012)	1
ENV-Linkages (WEO2012)	General equilibrium	Myopic	15 regions; 6 substances	No climate; land use for food consumption	Consumption loss, GDP loss, equivalent variation, welfare loss	(Kriegler et al., 2014c)	17
FARM (3.0)	General equilibrium	Myopic	15 regions; CO_2 only	No climate; land use by land type for bioenergy and food consumption	Consumption loss, GDP loss, equivalent variation, welfare loss	(Sands et al., 2014)	12
GCAM (2.0, 3.0, 3.1, MiniCAM)	Partial equilibrium	Myopic	14 regions; 13 substances	Temperature change; Land use by land type for bioenergy and food consumption	Area under marginal abatement cost curve	(Calvin et al., 2009a, 2012, 2013, 2014; Iyer et al., 2014; Kriegler et al., 2014b; Tavoni et al., 2014)	139
GEM-E3-ICCS	General equilibrium	Myopic	37 regions; 11 substances	No climate; land use for food consumption	Consumption loss, GDP loss, equivalent variation	(Kriegler et al., 2014a)	11
GRAPE (ver1998, ver2011)	General equilibrium	Foresight	15 regions; 5 substances	Temperature change; land use by land type for food consumption	Consumption loss, GDP loss	(Calvin et al., 2012; Kriegler et al., 2014c)	14
GTEM REF32	General equilibrium	Myopic	13 regions; 5 substances	No climate; land use for food consumption and crop prices	Consumption loss, GDP loss, welfare loss	(Mi et al., 2012)	4
IEEJ (ver.2011)	Econometric	Foresight	43 regions; CO_2 only	Temperature change; no land use	Energy system cost mark-up	(Matsuo et al.)	2
IGSM	General equilibrium	Myopic	16 regions; 12 substances	Climate damages; land use by land type for bioenergy, food consumption and crop prices	Consumption loss, GDP loss, equivalent variation, welfare loss; area under marginal abatement cost curve; energy system cost mark-up	(Prinn et al., 2011)	5
IMACLIM (v1.1)	General equilibrium	Myopic	12 regions; CO_2 only	Temperature change; no land use	Welfare loss, GDP loss, consumption loss, equivalent variation	(Bibas and Méjean, 2014; Kriegler et al., 2014a; Riahi et al., 2014)	53
IMAGE (2.4)	Partial equilibrium	Myopic	26 regions; 13 substances	Temperature change; land use by land type for bioenergy and food consumption	Area under marginal abatement cost curve	(van Vliet et al., 2009, 2014; van Ruijven et al., 2012; Lucas et al., 2013; Kriegler et al., 2014a; b; Riahi et al., 2014; Tavoni et al., 2014)	79
iPETS (1.2.0)	General equilibrium	Foresight	9 regions; CO_2 only	Land use for food consumption	Consumption loss, GDP loss, welfare loss	(O'Neill et al., 2012)	4
KEI-Linkages	General equilibrium	Myopic	13 regions; CO_2 only	No climate; land use for food consumption and crop prices	Consumption loss, equivalent variation	(Lim and Kim, 2012)	4

Model (versions)	Economic coverage and feedback	Myopic/ Foresight	Regional and emissions* detail	Representation of climate and land use	Cost measures	Scenario Publications	Number of Scenarios included in AR5 database
MARIA23_org	General equilibrium	Foresight	23 regions; 6 substances	Temperature change and climate damage; land use by land type for bioenergy and food consumption	Welfare loss, GDP loss, consumption loss, GDP loss, energy system cost mark-up	(Mori, 2012)	5
MERGE (AME, EMF22, EMF27)	General equilibrium	Foresight	9 (AME)/8 (EMF22) regions; 7 (AME,EMF22) /12 (EMF27) substances	Climate damages; no land use	Consumption loss, GDP loss, welfare loss	(Blanford et al., 2009, 2014b; Calvin et al., 2012)	44
MERGE-ETL (2011)	General equilibrium	Foresight	9 regions; 5 substances	Temperature change; no land use	Consumption loss, GDP loss, welfare loss	(Marcucci and Turton, 2014; Kriegler et al., 2014a; Riahi et al., 2014)	48
MESSAGE (V.1, V.2, V.3, V.4)	General equilibrium	Foresight	11 regions; 10 (V.1)/13 (V.2, V.3, V.4) substances	Temperature change; land use by land type for bioenergy (all versions)	GDP loss, energy system cost mark-up (all versions); area under marginal abatement cost curve (V.1, V.3, V.4); consumption loss (V.3, V.4)	(Krey and Riahi, 2009; Riahi et al., 2011, 2012, 2014; van Vliet et al., 2012; Kriegler et al., 2014a; b; McCollum et al., 2014; Tavoni et al., 2014)	140
Phoenix (2012.4)	General equilibrium	Myopic	24 regions; CO_2 only	Radiative forcing; land as factor of production in agriculture and forestry (including feedstocks for biofuels)	Welfare loss, GDP loss, consumption loss, equivalent variation	(Fisher-Vanden et al., 2012; Kriegler et al., 2014c)	31
POLES (AMPERE, EMF27, AME)	Partial equilibrium/ econometric	Myopic	57 regions (AMPERE, EMF27)/47 regions (AME); 6 substances	No climate; land use by land type for bioenergy (AMPERE, AME)	Area under marginal abatement cost curve	(Dowling and Russ, 2012; Griffin et al., 2014; Kriegler et al., 2014a; Riahi et al., 2014)	79
REMIND (1.1, 1.2, 1.3, 1.4, 1.5)	General equilibrium	Foresight	11 regions; CO_2 only (1.1, 1.2)/4 substances (1.3)/ 6 substances (1.4)/6–9 substances (1.5)	Temperature change; land use emissions via MAC (1.2, 1.3, 1.4) and from a land use model (MAgPIE; 1.5)	Consumption loss, GDP loss, welfare loss	(Leimbach et al., 2010; Luderer et al., 2012a; b; Arroyo-Currás et al., 2013; Bauer et al., 2013; Aboumahboub et al., 2014; Tavoni et al., 2014; Klein et al., 2014; Kriegler et al., 2014a; b; Riahi et al., 2014)	158
SGM	General equilibrium	Myopic	8 regions; CO_2 only	None	Consumption loss, GDP loss, equivalent variation, area under marginal abatement cost curve	(Calvin et al., 2009b)	7
TIAM-ECN	Partial equilibrium	Foresight	15 regions; 3 Substances	Radiative forcing; no land use	Energy cost increase; energy system cost mark-up	(Kober et al., 2014; Kriegler et al., 2014b; Tavoni et al., 2014)	12
TIAM-World (2007, 2012.02, Mar2012)	Partial equilibrium	Foresight	16 regions; 3 Substances	Temperature change; land use for bioenergy	Area under marginal abatement cost curve (all versions); welfare loss (2012.02); energy system cost mark-ups (2007, Mar2012)	(Loulou et al., 2009; Labriet et al., 2012; Kanudia et al., 2014)	41
TIMES-VTT	Partial equilibrium	Foresight	17 regions; 6 Substances	Temperature change; no land use	Consumption loss, energy system cost mark-ups	(Koljonen and Lehtilä, 2012)	6
WITCH (AME, AMPERE, EMF22, EMF27, LIMITS, RECIPE, ROSE)	General equilibrium	Foresight	13 regions/ 12 regions (RECIPE); 6 Substances	Temperature change (AME, AMPERE); climate damages (EMF22, EMF27; no land use	Consumption loss, GDP loss, welfare loss, energy system cost mark-ups	(Bosetti et al., 2009; de Cian et al., 2012; Massetti and Tavoni, 2012; De Cian et al., 2014; Kriegler et al., 2014a; b; Marangoni and Tavoni, 2014; Riahi et al., 2014; Tavoni et al., 2014)	132
WorldScan2	General equilibrium	Myopic	5 regions; 8 Substances	No climate; land use for food consumption	Welfare loss, GDP loss, equivalent variation	(Kriegler et al., 2014a)	8

* The substances reported under emissions detail include GHGs, radiatively and chemically active substances where the reference list includes the following set of 13 substances: CO_2, CH_4, N_2O, CFCs, HFCs, SF_6, CO, NO_x, VOC, SO_2, BC, OC, and NH_3.

Table A.II.15 | Model inter-comparison exercises generating transformation pathway scenarios included in AR5 Scenario Database.

Model Intercomparison Exercise	Year Completed	Number of Models in WGIII AR5 scenario database	Number of Scenarios in WGIII AR5 scenario database	Areas of Harmonization	Lead Institution	Overview Publication
ADAM (Adaptation and Mitigation Strategies—Supporting European Climate Policy)	2009	1	15	Technology availability, Mitigation policy	Potsdam Institute for Climate Impact Research (PIK)	(Edenhofer et al., 2010)
AME (Asian Modeling Exercise)	2012	16	83	Mitigation policy	Pacific Northwest National Laboratories (PNNL)	(Calvin et al., 2012)
AMPERE (Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates)	2013	11	378	Technology availability; mitigation policy; GDP; population	Potsdam Institute for Climate Impact Research (PIK)	AMPERE2: (Riahi et al., 2014) AMPERE3: (Kriegler et al., 2014a)
EMF 22 (Energy Modeling Forum 22)	2009	7	70	Technology availability, mitigation policy	Stanford University	(Clarke et al., 2009)
EMF 27 (Energy Modeling Forum 27)	2013	16	362	Technology availability, mitigation policy	Stanford University	(Blanford et al., 2014a; Krey et al., 2014; Kriegler et al., 2014c)
LIMITS (Low Climate Impact Scenarios and the Implications of required tight emissions control strategies)	2014	7	84	Mitigation policies	Fondazione Eni Enrico Mattei (FEEM)	(Kriegler et al., 2014b; Tavoni et al., 2014)
POeM (Policy Options to engage Emerging Asian economies in a post-Kyoto regime)	2012	1	4	Mitigation policies	Chalmers University of Technology	(Lucas et al., 2013)
RECIPE (Report on Energy and Climate Policy in Europe)	2009	2	18	Mitigation policies	Potsdam Institute for Climate Impact Research (PIK)	(Luderer et al., 2012a)
RoSE (Roadmaps towards Sustainable Energy futures)	2013	3	105	Mitigation policy; GDP growth; population growth, fossil fuel availability	Potsdam Institute for Climate Impact Research (PIK)	(Bauer et al., 2013; De Cian et al., 2013; Calvin et al., 2014; Chen et al., 2014; Luderer et al., 2014)

WGIII Technical Support Unit. To be included in the database, four criteria had to be met. First, only scenarios published in the peer-reviewed literature could be considered, per IPCC protocol. Second, the scenario had to contain a minimum set of required variables and some basic model and scenario documentation (meta data) had to be provided. Third, only models with at least full energy system representation were considered given that specific sectoral studies were assessed in Chapters 8–11. Lastly, the scenario had to provide data out to at least 2030. Scenarios were submitted by entering the data into a standardized data template that was subsequently uploaded to a database system[7] administered by the International Institute of Applied System Analysis (IIASA).

[7] https://secure.iiasa.ac.at/web-apps/ene/AR5DB

A.II.10.2 Model inter-comparison exercises

The majority of scenarios (about 95 %) included in the database were generated as part of nine model inter-comparison exercises, summarized in Table A.II.15. The Energy Modeling Forum (EMF), established at Stanford University in 1976, is considered one of the first major efforts to bring together modelling teams for the purpose of model inter-comparison. Since its inception, EMF and other institutions have worked on a large number of model inter-comparison projects with topics ranging from energy and the economy, to natural gas markets, to climate change mitigation strategies. Recent model inter-comparison studies have focused on, for example, delayed and fragmented mitigation, effort sharing, the role of technology availability and energy resources for mitigation and have looked into the role of specific regions (e.g., Asia) in a global mitigation regime.

Table A.II.16 | Scenario classifications.

Name	Climate Category	Carbon Budget 2050 and 2100 Category		Negative Emissions Category	Overshoot Category	Technology Category	Policy Category
Binning criterion	Radiative forcing (total or Kyoto), CO_2 budget	Cumulative CO_2 emissions budget to 2100	Cumulative CO_2 emissions budget to 2050	Maximum annual net negative emissions	Overshoot of 2100 forcing levels	Availability of negative emissions and other technology	Scenario definitions in Model Intercomparison Projects (MIPs)
# of classes	7 classes (1–7)	7 classes (1–7)	7 classes (1–7)	2 classes (N1, N2)	2 classes (O1, O2)	4 classes (T0–T3)	11 classes (P0–P7, P1+, P3+, P4+)
Notes	Extended to models that do not report forcing based on CO_2 budgets. Extrapolated to a subset of 2050 scenarios.		Classes for 2050 budgets cannot be unambiguously mapped to climate outcomes and thus overlap	Only for scenarios that run out to 2100	Only for models that run out to 2100 and report full or Kyoto forcing		

A.II.10.3 Classification of scenarios

The analysis of transformation pathway or scenario data presented in Chapters 1, 6, 7, 8, 9, 10 and 11 uses a common classification scheme to distinguish the scenarios along several dimensions. The key dimensions of this classification are:

- Climate Target (determined by 2100 CO_2eq concentrations and radiative forcing or carbon budgets)
- Overshoot of 2100 CO_2eq concentration or radiative forcing levels
- Scale of deployment of carbon dioxide removal or net negative emissions
- Availability of mitigation technologies, in particular carbon dioxide removal (CDR) or negative emissions technologies
- Policy configuration, such as immediate mitigation, delayed mitigation, or fragmented participation

Table A.II.16 summarizes the classification scheme for each of these dimensions, which are discussed in more detail in the following sections.

A.II.10.3.1 Climate category

Climate target outcomes are classified in terms of radiative forcing as expressed in CO_2-equivalent concentrations (CO_2eq). Note that in addition to CO_2eq concentrations, also CO_2eq emissions are used in the WGIII AR5 to express the contribution of different radiative forcing agents in one metric. The CO_2-equivalent concentration metric refers to the hypothetical concentration of CO_2 that would result in the same instantaneous radiative forcing as the total from all sources, including aerosols[8]. By contrast, the CO_2eq emissions metric refers to a sum of Kyoto GHG emissions weighted by their global warming potentials (GWPs, see Chapter 3, Section 3.9.6) as calculated in the SAR (IPCC, 1995a), for consistency with other data sources. It is important to note that these are fundamentally different notions of 'CO_2-equivalence'.

There are several reasons to use radiative forcing as an indicator for anthropogenic interference with the climate system and—in the case of climate policy scenarios—mitigation stringency: 1) it connects well to the Representative Concentration Pathways (RCPs) used in CMIP5 (see WGI AR5), 2) it is used as a definition of mitigation target in many modelling exercises, 3) it avoids problems introduced by the uncertainty in climate sensitivity, and 4) it integrates across different radiative forcing agents. These advantages outweigh some difficulties of the radiative forcing approach, namely that not all model scenarios in the WGIII AR5 Scenario Database fully represent radiative forcing, and that there is still substantial natural science uncertainty involved in converting emissions (a direct output of all models investigated in Chapter 6) into global radiative forcing levels.

To rectify these difficulties, the following steps were taken:

1. The emissions of all scenarios in the WGIII AR5 Scenario Database (see following bullets for details) were run through a single climate model MAGICC6.3 (where applicable) to establish comparability between the concentration, forcing, and climate outcome between scenarios. This removes natural science uncertainty due to different climate model assumptions in integrated models. The MAGICC output comes with an estimate of parametric uncer-

[8] More technically speaking, CO_2-equivalent concentrations can be converted to forcing numbers using the formula log(CO_2eq / CO_2_preindustrial) / log(2) · RF(2 x CO_2) with *RF(2 x CO_2) = 3.7 W/m*^{2} the forcing from a doubling of pre-industrial CO_2 concentration.

tainty within the MAGICC framework (Meinshausen et al., 2009, 2011a; b). Calculated MAGICC radiative forcing values are mean values given these uncertainties. MAGICC closely reflects the climate response of General Circulation Model (GCM) ensembles such as studied in CMIP5, and therefore can be considered a useful yardstick for measuring and comparing forcing outcomes between scenarios (Schaeffer et al., 2013). Emissions scenarios were harmonized to global inventories in 2010 to avoid a perturbation of climate projections from differences in reported and historical emissions that were assumed for the calibration of MAGICC (Schaeffer et al., 2013). The scaling factors were chosen to decline linearly to unity in 2050 to preserve as much as possible the character of the emissions scenarios. In general, the difference between harmonized and reported emissions is very small. The MAGICC runs were performed independently of whether or not a model scenario reports endogenous climate information, and both sets of information can deviate. As a result, MAGICC output may no longer fully conform to 'nameplate' targets specified in the given scenarios and as originally assessed by the original authors. Nevertheless, given the benefit of comparability both between AR5 scenarios and with WGI climate projections, scenarios were classified based on radiative forcing derived from MAGICC.

2. As a minimum requirement to apply MAGICC to a given emissions scenario, CO_2 from the fossil fuel and industrial (FF&I) sector, CH_4 from FF&I and land use sectors, and N_2O from FF&I and land use sectors needed to be reported. In case of missing land-use related CO_2 emissions the average of the RCPs was used. If fluorinated gas (F-gas), carbonaceous aerosols and/or nitrate emissions were missing, those were added by interpolating data from RCP2.6 and RCP8.5 on the basis of the energy-related CO_2 emissions of the relevant scenario vis-à-vis these RCPs. If scenarios were part of a model intercomparison project and gases, or forcers were missing, data was used from what was diagnosed as a "central" model for the same scenario (Schaeffer et al., 2013). As a minimum requirement to derive not only Kyoto forcing, but also full anthropogenic forcing, sulfur emissions in addition to CO_2, CH_4, and N_2O needed to be reported. Forcing from mineral dust and land use albedo was fixed at year-2000 values.

3. For the remaining scenarios, which only run to 2050 or that do not fulfill the minimum requirements to derive Kyoto forcing with MAGICC, an auxiliary binning based on cumulative CO_2 emissions budgets was implemented. Those scenarios came from models that only represent fossil fuel and industry emissions or only CO_2 emissions. The categorization of those scenarios is discussed below and includes a considerable amount of uncertainty from the mapping of CO_2 emissions budgets to forcing outcomes. The uncertainty increases significantly for scenarios that only run to 2050. In many cases, 2050 scenarios could only be mapped to the union of two neighbouring forcing categories given the large uncertainty.

The CO_2-equivalent concentrations were converted to full anthropogenic forcing ranges by using the formula in footnote 8, assuming CO_2_preindustrial = 278 ppm and rounding to the first decimal. All scenarios from which full forcing could be re-constructed from MAGICC were binned on this basis (Table A.II.17). Those scenarios that only allowed the re-construction of Kyoto forcing were binned on the basis of the adjusted Kyoto forcing scale that was derived from a regression of Kyoto vs. full forcing on the subset of those scenarios that reported both quantities. Thus, the binning in terms of Kyoto forcing already entails an uncertainty associated with this mapping.

AII

We note the following:

- CO_2 equivalent and forcing numbers refer to the year 2100. Temporary overshoot of the forcing prior to 2100 can occur. The overshoot categories (see Section A.II.10.3.3) can be used to further control for overshoot.
- No scenario included in the WGIII AR5 Scenario Database showed lower forcing than 430 ppm CO_2eq and 2.3 W/m², respectively, so no lower climate category was needed.
- When labeling the climate categories in figures and text, the CO_2-equivalent range should be specified, e.g., 430–480 ppm CO_2eq for Category 1. If neighbouring categories are lumped into one bin, then the lower and upper end of the union of categories should be named, e.g., 430–530 ppm CO_2eq for Categories 1 & 2 or > 720 ppm CO_2eq for Categories 6 and 7.

Table A.II.17 | Climate forcing classes (expressed in ppm CO_2eq concentration levels).

Category	Forcing categories (in ppm CO_2eq)	Full anthropogenic forcing equivalent [W/m²]	Kyoto forcing equivalent [W/m²]	Centre	RCP (W/m²)
1	430–480	2.3–2.9	2.5–3.1	455	2.6
2	480–530	2.9–3.45	3.1–3.65	505	-
3	530–580	3.45–3.9	3.65–4.1	555	(3.7)
4	580–650	3.9–4.5	4.1– 4.7	650	4.5
5	650–720	4.5–5.1	4.7–5.3		
6	720–1000	5.1–6.8	5.3–7.0	860	6
7	> 1000	> 6.8	> 7.0	-	8.5

Table A.II.18 | 2011–2100 emissions budget binning (rounded to 25 $GtCO_2$).

2100 Emissions Category	Cumulated 2011–2100 CO_2 emissions [$GtCO_2$]	Associated Climate forcing category	Forcing (in ppm CO_2eq)
1	350–950	1	430–480
2	950–1500	2	480–530
3	1500–1950	3	530–580
4	1950–2600	4	580–650
5	2600–3250	5	650–720
6	3250–5250	6	720–1000
7	> 5250	7	> 1000

Table A.II.19 | 2011–2050 emissions budget binning (rounded to 25 $GtCO_2$).

2050 Emissions Category	Cumulated 2011–2050 CO_2 emissions [$GtCO_2$]	Associated Climate forcing category if negative emissions are available (Classes T0 or T2 below)	Associated Climate forcing category if negative emissions are not available (Classes T1 or T3 below)
1	< 825	1	1
2	825–1125	1–2	2
3	1125–1325	2–4	3–4
4	1325–1475	3–5	4–5
5	1475–1625	4–6	5–6
6	1625–1950	6	6
7	> 1950	7	7

A.II.10.3.2 Carbon budget categories

The classification of scenarios in terms of cumulative CO_2 emissions budgets is mainly used as an auxiliary binning to map scenarios that do not allow the direct calculation of radiative forcing (see above) to forcing categories (Tables A.II.18 and A.II.19). However, it is also entertained as a separate binning across scenarios for diagnostic purposes. The mapping between full anthropogenic forcing and CO_2 emissions budgets has been derived from a regression over model scenarios that report both quantities (from the models GCAM, MESSAGE, IMAGE, MERGE, REMIND) and is affected by significant uncertainty (Figure A.II.8). This uncertainty is the larger the shorter the time span of cumulating CO_2 emissions is. Due to the availability of negative emissions, and the inclusion of delayed action scenarios in some studies, the relationship of 2011–2050 CO_2 emissions budgets and year 2100 radiative forcing was weak to the point that a meaningful mapping was hard to identify (Figure A.II.9). As a remedy, a mapping was only attempted for 2050 scenarios that do not include a strong element of delayed action (i.e., scenario policy classes P0, P1, P2 and P6; see Section A.II.10.3.6), and the mapping was differentiated according to whether or not negative emissions would be available (scenario technology classes T0–T3, see Section A.II.10.3.5). As a result of the weak relationship between budgets and radiative forcing, 2050 CO_2 emissions budget categories could only be mapped to the union of neighbouring forcing categories in some cases (Table A.II.19).

CO_2 emissions numbers refer to total CO_2 emissions including emissions from the AFOLU sector. However, those models that only reported CO_2 fossil fuel and industrial emissions were also binned according to this scheme. This can be based on the simplifying assumption that net land use change emissions over the cumulation period are zero.

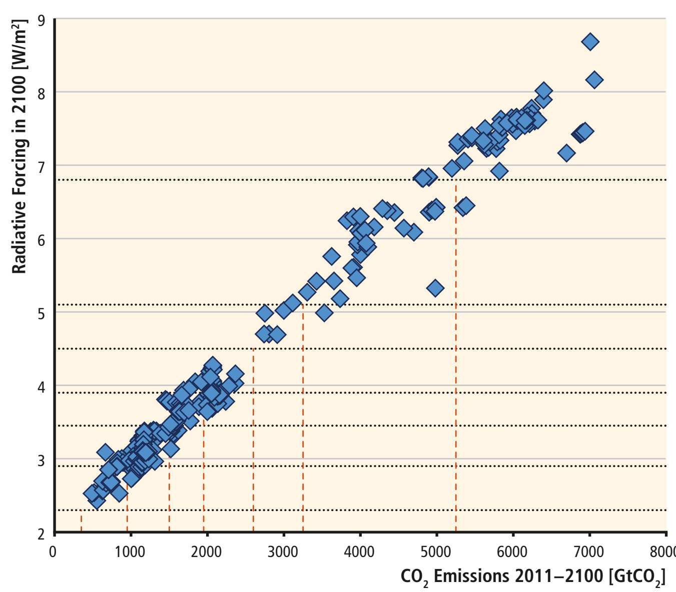

Figure A.II.8 | Regression of radiative forcing against 2011–2100 cumulative CO_2 emissions. Scenarios of full forcing models GCAM, MERGE, MESSAGE, REMIND and IMAGE were used for this analysis. Regression was done separately for each model, and resulting budget ranges averaged across models.

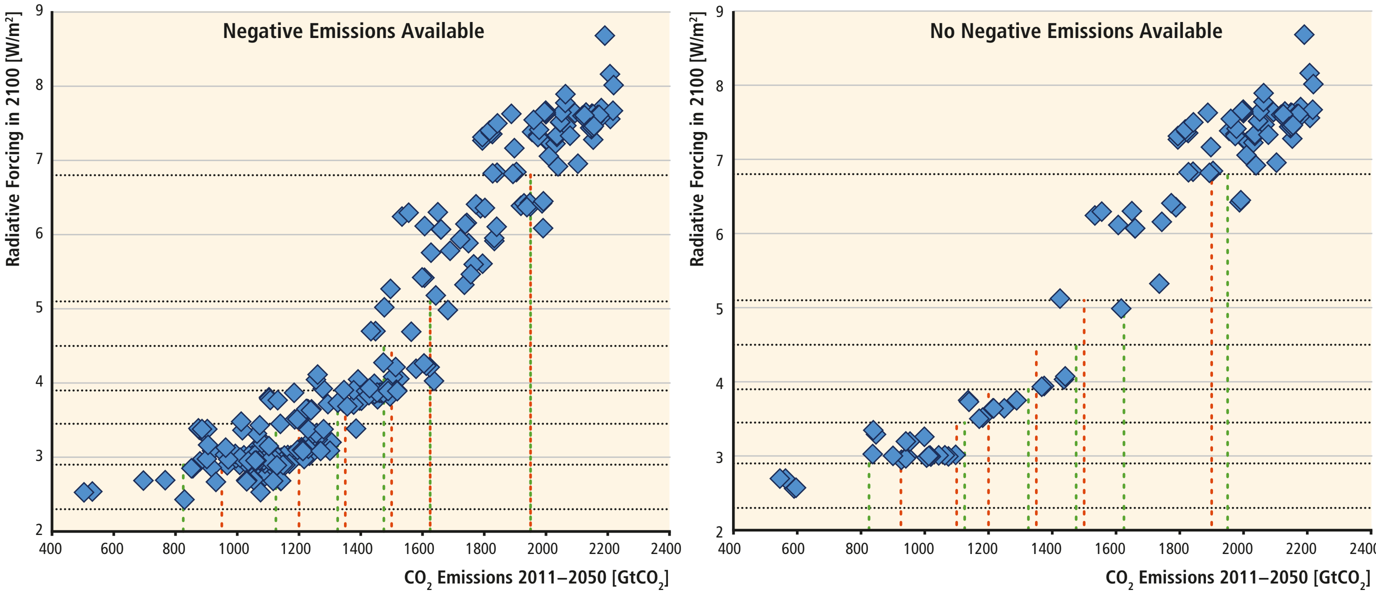

Figure A.II.9 | Regression of radiative forcing against 2011–2050 CO_2 emissions. Red lines show mean results of fit and depend on whether (left panel) or not (right panel) negative emissions are available. Green lines show harmonized bins between both categories for the mapping in Table A.II.19.

A.II.10.3.3 Overshoot category

The overshoot categorization shown in Table A.II.20 applies to the maximum overshoot of the 2100 radiative forcing level before 2100. The binning is only applied to models running until 2100. If full radiative forcing was not available, Kyoto forcing was used. If radiative forcing information was not available, no assignment was made.

A.II.10.3.4 Negative emissions category

The negative emissions categories apply to the maximum amount of net negative CO_2 emissions (incl. land use) in any given year over the 21st century. Scenarios with very large annual fluxes of negative emissions are also able to overshoot strongly, because the overshoot can be compensated with large net negative emissions within a relatively short period of time. Only a small number of scenarios show net negative emissions larger than 20 $GtCO_2$/yr, which was used to separate scenarios with large negative emissions from those with bounded negative emissions (Table A.II.21).

A.II.10.3.5 Technology category

The technology dimension of the categorization scheme indicates the technology availability in a given scenario. We identify two key factors:

1. the availability of negative emissions or CDR technologies that can be either confined by restrictions stipulated in the scenario definition or by the fact that the model does not represent negative emissions technologies, and
2. the restricted use of the portfolio of mitigation technologies that would be available in the model with default technology assumptions.

Combining these two factors lead to four distinct technology categories as shown in Table A.II.22.

Table A.II.20 | Overshoot categories.

Small Overshoot	*Large Overshoot*
< 0.4 W/m²	*> 0.4 W/m²*
O1	O2

Table A.II.21 | Negative emissions categories.

Bounded net negative emissions	*Large net negative emissions*
< 20 $GtCO_2$/yr	*> 20 $GtCO_2$/yr*
N1	N2*

* The GCAM 3.0 scenario EMF27–450-FullTech came in at –19.96 GtCO2/yr and was also included in class N2.

Table A.II.22 | Technology categories.

No restriction Neg. Emissions	No negative emissions model	Restriction, but with negative emissions	No negative emissions and (other) restrictions
T0	T1	T2	T3

Note that some scenarios improve technology performance over the default version (e.g., larger biomass availability, higher final energy intensity improvements, or advanced / expanded technology assumptions). These cases were not further distinguished and assigned to T0 and T1, if no additional technology restrictions existed.

A.II.10.3.6 Policy category

Policy categories are assigned based on scenario definitions in the study protocols of model intercomparison projects (MIPs). The policy categories summarize the type of different policy designs that were investigated in recent studies (Table A.II.23). We stress that the long-term target level (where applicable) is not part of the policy design categorization. This dimension is characterized in terms of climate categories (see above). Individual model studies not linked to one of the larger MIPs were assigned to baseline (P0) and immediate action (P1) categories where obvious, and otherwise left unclassified. The residual class (P7) contains the G8 scenario from the EMF27 study (Table A.II.15), with ambitious emissions caps by Annex I countries (starting immediately) and Non-Annex I countries (starting after 2020), but with a group of countries (fossil resource owners) never taking a mitigation commitment over the 21st century. The RECIPE model intercomparison project's delay scenarios start acting on a global target already in 2020, and thus are in between categories P1 and P2. P0 does not include climate policy after 2010 (it may or may not include Kyoto Protocol commitments until 2012), while P1 typically assumes full 'when', 'where' and 'what' flexibility of emissions reductions in addition to immediate action on a target (so called idealized implementation scenarios). The scenario class P6 characterizes the case of moderate fragmented action throughout the 21st century, without aiming at a long term global target, usually formulated as extrapolations of the current level of ambition. Policy categories P2 to P4 describe variants of adopting a global target or a global carbon price at some later point in the future. With the important exception of the AMPERE2 study, all scenarios in the P2-P4 class assume a period of regionally fragmented action prior to the adoption of a global policy regime. For further details of the scenario policy categories P2-P6, see the individual studies listed in Table A.II.15.

For the policy categories P1 (Idealized), P3 (Delay 2030), and P4 (Accession to Price Regime) subcategories P1+, P3+ and P4+ respectively exist for which in addition to climate policy supplementary policies (Supp.)(e.g., infrastructure polices) that are not part of the underlying baseline scenario have been included. These categories have been assigned to the climate policy scenarios of the IMACLIM v1.1 model from the AMPERE project to distinguish them from similar scenarios (e.g., EMF27) where these supplementary policies were not included and therefore policy costs are generally higher.

A.II.10.3.7 Classification of baseline scenarios

Baseline scenarios used in the literature are often identical or at least very close for one model across different studies. However, in some exercises, characteristics of baseline scenarios, such as population and economic growth assumptions, are varied systematically to study their influence on future emissions, energy demand, etc. Table A.II.24 below provides an overview of unique Kaya-factor decompositions of baseline scenarios in the AR5 scenario database. The results are shown in Figures 6.1 and 6.2 in Chapter 6.

Table A.II.23 | Policy categories.

Category		Target adoption	Staged accession	Long-term frag / Free rider	MIPs
P0	Baseline	None	No	N/A	All
P1	Idealized	Immediate	No	No / No	All
P1+	Idealized + Supp. Policies	Immediate	No	No / No	AMPERE2, AMPERE3
P2	Delay 2020	Model year after 2020	No	No / No	RoSE, LIMITS
P3	Delay 2030	Model year after 2030	No	No / No	RoSE, LIMITS, AMPERE2
P3+	Delay 2030 + Supp. Policies	Model year after 2030	No	No / No	AMPERE2
P4	Accession to Price Regime	None	Yes (2030–2050)	No / No	AMPERE3
P4+	Accession to Price Regime + Supp. Policies	None	Yes (2030–2050)	No / No	AMPERE3
P5	Accession to Target	Yes (starting 2010)	Yes (2030–2070)	No / No	EMF22
P6	Fragmented Ref Pol	No	N/A	Yes / Yes (EMF27)—No (Other)	EMF27, RoSE, LIMITS, AMPERE3
P7	Other cases	N/A	N/A	N/A	EMF27, RECIPE

Table A.II.24 | Classification of unique Kaya factor projections in the baseline scenario literature.

Study	Models Contributing Global Results	Population			Per Capita Income				Energy Intensity		Carbon Intensity
		Harmonized		Unharmonized	Harmonized			Unharmonized	Unharmonized		Unharmonized
		High	Default		High	Default	Low		Default	Fast	
ADAM	1			1				1	1		3
AME	16			16				16	15		15
AMPERE	11		11			10		10	10	9	65
EMF22	7			7			1	7	8		8
EMF27	16			16				31	16	15	119
GEA	1			1				0	0		1
LIMITS	7			7				7	7		7
POeM	1			1				1	1		1
RECIPE	1			1				1	1		1
RCP 8.5	1	1					2		1		1
RoSE	3	3	3		5	3	7		15		31
Other	2			2				2	1		1
	67	4	14	52	5	13	10	76	76	24	253
				= 70				= 104		= 100	

Notes:
All AMPERE scenarios harmonized population along a default trajectory
RoSE specified two harmonized population trajectories: default and high
RCP 8.5 was based on an intentionally high population trajectory
In all other cases, no guidance was given regarding population harmonization
AMPERE scenarios specified a default harmonization of GDP
One model in AMPERE (IMAGE) did not follow GDP harmonization, thus it was classified as unharmonized
AMPERE WP2 (9 of 11 participated) specified an alternative low energy intensity baseline with unharmonized implications for per capita income
One model in EMF22 (MERGE) included an alternative baseline with intentionally low per capita income
EMF27 specified an alternative low energy intensity baseline (15 of 16 ran it) with unharmonized implications for per capita income
ROSE specified several alternative GDP baselines, some run by all three models, others by only one or two
In all other cases, no guidance was given regarding per capita income or GDP harmonization
One study included a model not reporting data for GDP: GEA (MESSAGE)
Three studies included a model not reporting data for total primary energy: AME (Phoenix); AMPERE (GEM-E3); and Other (IEEJ)
No study successfully harmonized energy demand, thus scenarios are classified as default if a low energy intensity baseline was not specifically indicated
Alternative supply technology scenarios generally do not affect energy intensity, thus only default supply technology scenarios are classified

A.II.10.4 Comparison of integrated and sectorally detailed studies

In Section 6.8 of this report, but also in a number of other sections, integrated studies included in the AR5 Scenario Database that is described in Sections A.II.10.1 to A.II.10.3 above are compared to sectorally detailed studies assessed in Chapters 8, 9, and 10 that deal with the end-use sectors transport, buildings and industry respectively. Table A.II.25 provides an overview of the sectorally detailed studies that are included in this comparison. It should be noted that not all studies provide the data necessary to derive final energy demand reduction compared to baseline and low-carbon fuel shares as, for example, shown in Figure 6.37 and 6.38. In addition, some of the sectorally detailed studies do not cover the entire sector, but restrict themselves to the most important services within a sector (e.g., space heating and cooling and hot water provision in the buildings sector).

Table A.II.25 | Sectorally detailed energy end-use studies compared to transformation pathways.

Sector	Study (Literature Reference)	Scenario Name	Scenario Type
Transport (Ch. 8)	World Energy Outlook 2012 (IEA, 2012e)	New Policies	Base
		450 Scenario	Policy
	Energy Technology Perspectives 2008 (IEA, 2008)	Baseline	Base
		ACT Map	Policy
		BLUE Map	Policy
		BLUE conservative	Policy
		BLUE EV	Policy
		BLUE FCV	Policy
	Energy Technology Perspectives 2010 (IEA, 2010b)	Baseline	Base
		BlueMap	Policy
	Energy Technology Perspectives 2012 (IEA, 2012f)	4DS	Policy
		2DS	Policy
	Global Energy Assessment (Kahn Ribeiro et al., 2012)	REF	Base
		GEA-Act	Policy
		GEA-Supply	Policy
		GEA-Mix	Policy
		GEA-Efficiency	Policy
	World Energy Technology Outlook 2050 (EC, 2006)	Hydrogen Scenario	Policy
	World Energy Council 2011 (WEC, 2011)	Freeway	Base
		Tollway	Policy
	Asia/World Energy Outlook 2011 (IEEJ, 2011)	Enhanced Development Scenario	Policy
Buildings (Ch. 9)	World Energy Outlook 2010 (IEA, 2010c)	Current Policies	Base
		450 Scenario	Policy
	Energy Technology Perspectives 2010 (IEA, 2010b)	Baseline	Base
		BlueMap	Policy
	3CSEP HEB (Ürge-Vorsatz et al., 2012)	Frozen efficiency	Base
		Deep efficiency	Policy
	Harvey (Harvey, 2010)	High Slow efficiency no heat pump	Base
		High Fast efficiency with heat pump	Policy
	The Energy Report (WWF/Ecofys/OMA, 2011; Deng et al., 2012)	Baseline	Base
		The Energy Report	Policy
Industry (Ch. 10)	Energy Technology Perspectives 2012 (IEA, 2012f)	6DS Low-demand	Base
		6DS High-demand	Base
		4DS Low-demand	Policy
		4DS High-demand	Policy
		2DS Low-demand	Policy
		2DS High-demand	Policy
	Energy Technology Transitions for Industry (IEA, 2009)	BLUE low	Policy
		BLUE high	Policy
	Global Energy Assessment (Banerjee et al., 2012)	Energy Efficient Scenario	Policy
	Energy [R]evolution 2012 (GWEC et al., 2012)	Reference Scenario	Base
		Energy [R]evolution	Policy
	The Energy Report (WWF/Ecofys/OMA, 2011; Deng et al., 2012)	The Energy Report	Policy

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ANNEX

III

Technology-specific Cost and Performance Parameters

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A.III.1 Introduction

Annex III contains data on technologies and practices that have been collected to produce a summary assessment of the potentials and costs of selected mitigation options in various sectors as displayed in Figure 7.7, Table 8.3, Figures 10.7, 10.8, 10.9, 10.10, 10.19, 10.21, Figure 11.16 as well as in corresponding figures in the Technical Summary.

The nature and quantity of mitigation options, as well as data availability and quality of the available data, vary significantly across sectors. Even for largely similar mitigation options, a large variety of context-specific metrics is used to express their cost and potentials that involve conversions of input data into particular output formats. For the purpose of the Working Group III (WGIII) contribution to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), a limited but still diverse set of sector-specific metrics is used to strike a balance between harmonization of approaches across sectors and adequate consideration of the complexities involved.

Mitigation potentials are approached via product-specific or service-specific emission intensities, i.e., emissions per unit of useful outputs, which are as diverse as electricity, steel, and cattle meat. Mitigation potentials on a product/service level can be understood as the potential reduction in specific emissions that can result from actions such as switching to production processes that cause lower emissions for otherwise comparable products[1] and reducing production/consumption of emission-intensive products.

Mitigation costs are approached via different levelized cost metrics, which share a common methodological basis but need to be interpreted in very different ways. A detailed introduction to the metrics used can be found in the Metrics and Methodology (M&M) Annex (Section A.II.3.1). All of these cost metrics are derived under specific conditions that vary in practice and, hence, need to be set by assumption. These assumptions are not always clear from the literature, where such metrics are presented. Hence, comparison of the same metric taken from different studies is not always possible. For this reason, in the AR5 these metrics are generally re-calculated under specified conditions, e.g., with respect to weighted average cost of capital, based on underlying input parameters that are less sensitive to assumptions. Sensitivities to assumptions made in the AR5 are made explicit. In several cases, however, the availability of data on the parameters needed to re-calculate the relevant cost metric is very limited. In such cases, expert judgment was used to assess information on costs taken directly from the literature.

More detail on sector-specific metrics, the respective input data and assumptions used as well as the conversions required is presented in the sector-specific sections below.

References for data, justifications for assumptions, and additional context is provided in footnotes to the data tables. Footnotes are inserted at the most general level possible, i.e., footnotes are inserted at table headings where they apply to the majority of data, at column/row headings where they apply to the majority of data in the respective column/row, and at individual cells where they apply only to data points or ranges given in individual cells. Input data are included in normal font type, output data resulting from data conversions shown in figures and tables mentioned above are bolded, and intermediate outputs are italicized.

A.III.2 Energy supply

A.III.2.1 Approach

The emission intensity of electricity production (measured in kg CO_2-equivalents (CO_2eq)/MWh) can be used as a measure to compare the specific greenhouse gas (GHG) emissions of suggested emission mitigation options and those of conventional power supply technologies. With respect to costs, the levelized cost of energy (LCOE), measured in USD_{2010}/MWh, serves the same purpose.[2]

The calculation of LCOE of a technology requires data on all cash flows that occur during its lifetime (see formula in Annex II.3.1.1) as well as on the amount of energy that is provided by the respective technology. Cash flows are usually reported in some aggregate form based on widely deployed monetary accounting principles combining cash flows into different categories of expenditures and revenues that occur at varying points during the lifetime of the investment.

The applied method presents LCOE that include all relevant costs associated with the construction and operation of the investigated power plant in line with the approach in IEA (2010). Taxes and subsidies are excluded, and it is assumed that grids are available to transport the electricity. Additional costs associated with the integration of variable sources are neglected as well (see Section 7.8.2 for an assessment of these costs).

[1] Note that comparability of products is not always given even for seemingly similar ones. For instance, in the case of electricity, the timing of production is crucial for the value of the product and reduces the insights that can be derived from simple comparisons of the metrics used here.

[2] The merits and shortcomings of this method are discussed in detail in the Metrics and Methodology Annex of the WGIII AR5 (Annex II).

The input data used to calculate LCOE are summarized in Table 1 below. The conversion of input data into LCOE requires the steps outlined in the following:

Levelized cost (LCOE) in USD_{2010}/MWh_e

$$LCOE = \frac{\alpha \cdot I + OM + F}{E} \quad \text{(Equation A.III.1)}$$

$$\alpha = \frac{r}{1 - (1 + r)^{-L_T}} \quad \text{(Equation A.III.2)}$$

$$I = \frac{C}{L_B} \cdot \sum_{t=1}^{L_B} (1 + i)^t \cdot \left(1 + \frac{d}{(1 + r)^{L_T}}\right) \quad \text{(Equation A.III.3)}$$

$$OM = FOM + (VOM - REV + d_v) \cdot E \quad \text{(Equation A.III.4)}$$

$$E = P \cdot FLH \quad \text{(Equation A.III.5)}$$

$$F = FC \cdot \frac{E}{\eta} \quad \text{(Equation A.III.6)}$$

Where:

- *LCOE* is the levelized cost of electricity.
- α is the capital recovery factor (CRF).
- *r* is the weighted average cost of capital (WACC—taken as either 5 % or 10 %).
- *I* is the investment costs, including finance cost for construction at interest *i*.
- *C* is the capital costs, excluding finance cost for construction ('overnight cost'). In order to calculate the cost for construction, the overnight costs are equally distributed over the construction period.
- *d* represent the decommissioning cost. Depending on the data in the literature, this is incorporated as an extra capital cost at the end of the project duration which is discounted to t = 0 (using a decommissioning factor *d*, as in (Equation A.III.3)), or as a corresponding variable cost (d_v in (Equation A.III.4)). d = 0.15 for nuclear energy, and zero for all other technologies (given the low impact on *LCOE*).
- *OM* are the net annual operation and maintenance costs; summarizing fixed OM (*FOM*), variable OM (*VOM*), and variable by-product revenues (*REV*). As a default and if not stated explicitly otherwise, carbon costs (e.g., due to carbon taxes or emission trading schemes) are not taken into account in calculating the *LCOE* values.
- *E* is the energy (electricity) produced annually, which is calculated by multiplying the capacity (*P*) with the number of (equivalent) full load hours (*FLH*).
- *F* are the annual fuel costs,
  - *FC* are the fuel costs per unit of energy input, and
  - η is the conversion efficiency (in lower heating value—LHV).
- *i* is the interest rate over the construction loan (taken as 5 %).
- L_T is the project duration (in operation), as defined in IEA (2010).
- L_B is the construction period.

Emission Intensities:

For data, see Table AIII.2 below. For methodological issues and literature sources, see Annex II, Section A.II.9.3.

A.III.2.2 Data

Table A.III.1 | Cost and performance parameters of selected electricity supply technologies[i, ii]

Options	*C*	L_B	*FOM*	*VOM*	*REV*	*F*
	Overnight capital expenditure (excl. construction interest) (USD_{2010}/kW)	Construction time (yr)	Fixed annual operation and maintenance cost (USD_{2010}/kW)[iii]	Variable operation and maintenance cost (USD_{2010}/MWh)[iii]	Variable by-product revenue (USD_{2010}/MWh)	Average fuel price (USD_{2010}/GJ)
	Min/Median/Max	Avg	Min/Median/Max	Min/Median/Max	Min/Median/Max	Min/Max
Currently Commercially Available Technologies						
Coal—PC[iv]	380/2200/3900	5	0/23/75	0/3.4/9.0		2.9/5.3
Gas—Combined Cycle[v]	550/1100/2100	4	0/7/39	0/3.2/4.9		3.8/14
Biomass—CHP[vi]	2000/5600/11000	4.5	0/101/400	0/0/56	4/26/93[vii]	3.3/9.3
Biomass—cofiring[vi, viii]	350/900/1800	1	13/20/20	0/0/2		3.3/9.3
Biomass—dedicated[vi]	1900/3600/6500	4.5	42/99/500	0/3.8/34		3.3/9.3
Geothermal[ix, x]	1000/5000/10000	3	0/0/150	0/11/31		
Hydropower[xi, xii]	500/1900/8500	5	5/35/250	0/0/15		
Nuclear[xiii, xiv]	1600/4300/6400	9	0/0/110	1.7/13/30		0.74/0.87

Options	*C* Overnight capital expenditure (excl. construction interest) (USD_{2010}/kW)	L_B Construction time (yr)	*FOM* Fixed annual operation and maintenance cost (USD_{2010}/kW)[iii]	*VOM* Variable operation and maintenance cost (USD_{2010}/MWh)[iii]	*REV* Variable by-product revenue (USD_{2010}/MWh)	*F* Average fuel price (USD_{2010}/GJ)
	Min/Median/Max	Avg	Min/Median/Max	Min/Median/Max	Min/Median/Max	Min/Max
Concentrated Solar Power[xv, xvi]	3700/5100/11000	2	0/50/66	0/0/35		
Solar PV—rooftop[xvii, xviii]	2200/4400/5300	0	17/37/44	0/0/0		
Solar PV—utility[xvii, xviii]	1700/3200/4300	0	12/20/30	0/0/0		
Wind onshore[xix, xx]	1200/2100/3700	1.5	0/0/60	0/14/26		
Wind offshore[xix, xxi]	2900/4400/6500	3.5	0/40/130	0/16/63		
Pre-commercial Technologies						
CCS—Coal—Oxyfuel[xxii]	2800/4000/5600	5	0/58/140	9.1/10/12[xxiii]		2.9/5.3
CCS—Coal—PC[xxii]	1700/3300/6600	5	0/45/290	11/15/28[xxiii]		2.9/5.3
CCS—Coal—IGCC,[xxii]	1700/3700/6600	5	0/23/110	12/13/23[xxiii]		2.9/5.3
CCS—Gas—Combined Cycle[xxii]	1100/2000/3800	4	5/13/73	4.8/8.3/15[xxiii]		3.8/14
Ocean[xxiv, xxv]	2900/5400/12000	2	0/78/360	0/0.16/20		

Table A.III.1 (continued) | Cost and performance parameters of selected electricity supply technologies[i, ii]

Options	η Plant efficiency (%)	*FLH* Capacity utilization /FLH (hr)	*LT* Plant lifetime (yr)	Decommissioning cost[xxvi]	*LCOE* Levelized cost of electricity[i] (USD_{2010}/MWh): 10 % WACC, high FLH, 0 $USD_{2010}/tCO_2eq_{direct}$	5 % WACC, high FLH, 0 $USD_{2010}/tCO_2eq_{direct}$	10 % WACC, low FLH, 0 $USD_{2010}/tCO_2eq_{direct}$	10 % WACC, high FLH, 100 $USD_{2010}/tCO_2eq_{direct}$
	Min/Median/Max	Min/Max	Avg		Min/Median/Max	Min/Median/Max	Min/Median/Max	Min/Median/Max
Currently Commercially Available Technologies								
Coal—PC[iv]	33/39/48	3700/7400	40	See endnote xxvi	**30/78/120**	**27/61/95**	**36/120/190**	**97/150/210**
Gas—Combined Cycle[v]	41/55/60	3700/7400	30		**34/79/150**	**31/71/140**	**43/100/170**	**69/120/200**
Biomass—CHP[vi]	14/29/36	3500/7000	30		**85/180/400**	**71/150/330**	**130/310/610**	**-**[xxvii]
Biomass—cofiring[vi]	38/41/48	3700/7400	40		**65/89/110**	**49/67/88**	**100/140/170**	**160/200/260**[xxviii]
Biomass—dedicated[vi]	20/31/48	3500/7000	40		**77/150/320**	**63/130/270**	**120/230/440**	**–**[xxvii]
Geothermal[ix, x]		5300/7900	30		**18/89/190**	**12/60/130**	**25/130/260**	**18/89/190**
Hydropower[xi, xii]		1800/7900	50		**9/35/150**	**6/22/95**	**40/160/630**	**9/35/150**
Nuclear[xiii, xiv]	33/33/34	3700/7400	60		**45/99/150**	**32/65/94**	**72/180/260**	**45/99/150**
Concentrated Solar Power[xv, xvi]		2200/3500	20		**150/200/310**	**110/150/220**	**220/320/480**	**150/200/310**
Solar PV—rooftop[xvii, xviii]		1100/2400	25		**110/220/270**	**74/150/180**	**250/490/600**	**110/220/270**
Solar PV—utility[xvii, xviii]		1200/2400	25		**84/160/210**	**56/110/130**	**170/310/400**	**84/160/210**
Wind onshore[xx, xx]		1800/3500	25		**51/84/160**	**35/59/120**	**92/160/300**	**51/84/160**
Wind offshore[xxi, xx]		2600/3900	25		**110/170/250**	**80/120/180**	**160/240/350**	**110/170/250**
Pre-commercial Technologies								
CCS—Coal—Oxyfuel[xxii]	32/35/41	3700/7400	40		**90/120/170**	**71/100/130**	**140/180/270**	**92/130/180**
CCS—Coal—PC[xxii]	28/30/43	3700/7400	40		**69/130/200**	**57/110/150**	**97/210/310**	**78/150/210**
CCS—Coal—IGCC[xxii]	30/32/35	3700/7400	40		**75/120/200**	**63/100/150**	**100/180/310**	**85/140/210**
CCS—Gas—Combined Cycle[xxii]	37/47/54	3700/7400	30		**52/100/210**	**45/86/190**	**70/140/270**	**55/110/220**
Ocean[xxiv, xxv]		2000/5300	20		**82/150/300**	**60/110/210**	**200/390/780**	**82/150/300**

Notes:

[i] General: Input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized. Note that many input parameters (C, FOM, VOM, and η) are not independent from each other; they come in parameter sets. Parameters that are systematically varied to obtain output values include fuel prices, WACC, and full load hours (FLH). Lifetimes and construction times are set to standard values. The range in levelized cost of electricity (LCOE) results from calculating two LCOE values per individual parameter set, one at a low and one at a high fuel price, for the number of individual parameter sets available per technology. Variation with WACC and with FLHs is shown in separate output columns. This approach is different from the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (IPCC, 2011), where input parameters were considered as independent from each other and the lowest (highest) LCOE value resulted from taking all best-case (worst-case) parameter values.

[ii] General: Comparison of data on capital expenditures with values presented in SRREN (IPCC, 2011) are only possible to limited degrees, since the datasets used in the AR5 reflect a larger sample of projects (including those with more extreme costs) than in the SRREN.

[iii] General: Some literature references only report on fixed OM costs (FOM), some only on variable OM costs (VOM), some on both, and some none. The data in the FOM and VOM columns show the range found in literature. Hence, note that these FOM and VOM values cannot be combined to derive total OM costs. The range of levelized costs of electricity shown in the table is the result of calculations for the individual combinations of parameters found in the literature.

[iv] Coal PC (Pulverized Coal): Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2013a), IEA-RETD (2013), Schmidt et al. (2012), US EIA (2013).

[v] Gas Combined Cycle: Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2011),IEA (2013a), IEA-RETD (2013), Schmidt et al. (2012), US EIA (2013).

[vi] Biomass: Black and Veatch (2012), DEA (2012), IPCC-SRREN (2011), IRENA (2012), Augustine et al. (2012), US EIA (2013).

[vii] Biomass CHP (Combined Heat and Power): Revenues from heat from CHP are assumed to be the natural gas price divided by 90% (this is the assumed reference boiler efficiency). It is assumed that one-third of the heat production is marketable, caused by losses and seasonal demand changes. This income is subtracted from the variable operation and maintenance costs (proportional to the amount of heat produced per unit of power), where applicable. Only heat production from biomass-CHP is treated in this manner.

[viii] Biomass Co-firing: Capital costs for co-firing as reported in literature (and the summary table) represent an investment to upgrade a dedicated coal power plant to a co-firing installation. The LCOEs shown in the summary table are those of the total upgraded plant. For the calculation of the LCOEs, the capital costs of the co-firing upgrade are added to the median coal PC capital costs. Fuel costs are obtained by weighting coal and biomass costs with their share in the fuel mix (with biomass shares ranging between 5% and 20%). To calculate specific emissions, the dedicated biomass emissions and (pulverized) coal emissions were added, taking into account biomass shares ranging between 5% and 20%. In the direct emissions coal-related emissions are shown, while the biomass related emissions are shown in column n (Biogenic, geogenic CO_2 and albedo), indicating indirect emissions. We applied an efficiency of 35% to the coal part of the combustion.

[ix] Geothermal: This category includes both flash steam and binary cycle power plants. Data on costs show wide ranges, depending on specific conditions. Geothermal (binary plant) LCOE averages have increased by 39% since the SRREN (BNEF, and Frankfurt and School-UNEP Centre, 2013). Low-end estimate is from Augustine et al. (2012) for a flash plant at higher temperatures; the high-end estimate is from Black and Veatch and based on enhanced geothermal systems, which are not fully commercialized. IRENA (2013) reports values down to 1400 USD_{2011}/kW.

[x] Geothermal: Black and Veatch (2012), IEA (2013a), Augustine et al. (2012), Schmidt et al. (2012), UK CCC (2011), US EIA (2013).

[xi] Hydropower: This includes both run-of-the-river and reservoir hydropower, over a wide range of capacities. Project data from recent IRENA inventories are incorporated, showing a wider range than reported in SRREN. High-end of capital expenditures refers to Japan, but other sources also report these higher values.

[xii] Hydropower: Black and Veatch (2012), IEA (2013a), IEA-RETD (2013), IRENA (2012), Schmidt et al. (2012), UK CCC (2011), US EIA (2013).

[xiii] Nuclear: Limited recent data and/or original data are available in the published literature. More recent, (grey literature) sources provide investment cost and LCOE estimates that are considerably higher than the ones shown here (Brandão et al., 2012). Nuclear fuel prices (per GJ input) are based on fuel cycle costs (usually expressed per MWh generated), assuming a conversion efficiency of 33%. They include the front-end (Uranium mining and milling, conversion, enrichment, and fuel fabrication) and back-end (spent fuel transport, storage, reprocessing, and disposal) costs of the nuclear fuel cycle (see IEA and NEA, 2010).

[xiv] Nuclear: IAEA (2012), EPRI (2011), IEA/NEA (2010), Rangel and Lévêque (2012), UK CCC (2011), US EIA (2013).

[xv] Concentrated Solar Power: This includes both CSP with storage as well as CSP without storage. To prevent an overestimation of the LCOE for CSP with storage, full load hours were used that are directly linked to the design of the system (in- or excluding storage). Project data from recent IRENA inventories are incorporated, showing a wider range than reported in SRREN. High-end value comes from IRENA (solar tower, 6-15 hours of storage). Low-end comes from IEA and is supported by IRENA data.

[xvi] Concentrated Solar Power: Black and Veatch (2012), IEA (2013a), IRENA (2012), US EIA (2013).

[xvii] Solar Photovoltaic: IEA (2013a), IRENA (2013), JRC (2012), LBNL (2013), UK CCC (2011), US EIA (2013).

[xviii] Solar Photovoltaic: Solar PV module prices have declined substantially since the SRREN (IPCC, 2011), accounting for much of the decline in capital costs shown here relative to those used in SRREN. The LCOE of (crystalline silicon) photovoltaic systems fell by 57% since 2009 (BNEF, and Frankfurt and School-UNEP Centre, 2013).

[xix] Wind: Black and Veatch (2012), DEA (2012), IEA (2013a), IEA-RETD (2013), IRENA (2012), JRC (2012), UK CCC (2011), US DoE (2013), US EIA (2013).

[xx] Wind onshore: High-end of capital expenditures is taken from IEA-RETD study (Mostajo Veiga et al., 2013) for Japan. The capital costs presented here show a higher upper end than in the SRREN, and reflect generally smaller wind projects or projects located in remote or otherwise-costly locations. Data from IRENA for Other Asia and Latin America show cost ranges well beyond SRREN. In some regions of the world, wind projects have been increasingly located in lower-quality wind resource sites since the publication of the SRREN (due in part to scarcity of developable higher-quality sites). The FLHs on wind projects, however, have not necessarily decreased -- and in many cases have increased -- due to a simultaneous trend towards longer rotors and higher hub heights. Wind onshore average LCOE have decreased by 15% (BNEF, and Frankfurt and School-UNEP Centre, 2013).

[xxi] Wind offshore: Offshore wind costs have generally increased since the SRREN, partially explaining the higher upper-end of the cost range shown here. Average LCOE of offshore wind have increased by 44% (BNEF, and Frankfurt and School-UNEP Centre, 2013). Higher capital expenditures reported here are in line with market experiences, i.e., a tendency to more remote areas, deeper seas, higher construction costs and higher steel prices.

[xxii] Carbon Dioxide Capture and Storage (CCS): Black and Veatch (2012), DEA (2012), Herzog (2011), IPCC-SRCCS (2005), Klara and Plunkett (2010), US EIA (2013), Versteeg and Rubin (2011), IEA (2011).

[xxiii] Carbon Dioxide Capture and Storage: Includes transport and storage costs of USD_{2010}10/tCO_2.

[xxiv] Ocean: Ocean includes both tidal and wave energy conversion technologies. The high-end of capital expenditures is for wave energy DEA (2012). Since the SRREN, marine wave and tidal average LCOE have increased by 36 and 49% respectively (BNEF, and Frankfurt and School-UNEP Centre, 2013).

[xxv] Ocean: Black and Veatch (2012), DEA (2012), UK CCC (2011).

[xxvi] General: Some literature references report decommissioning costs under VOM. If decommissioning costs are not given, default assumptions are made (see 'Definition of additional parameters').

[xxvii] Biomass: Due to the complexities involved in estimating GHG emissions from biomass, no estimates for LCOE at a positive carbon price are given here.

[xxviii] Biomass co-firing: Only direct emissions of coal share in fuel consumption are considered to calculate LCOE at a carbon price of 100 USD_{2010}/tCO_2eq.

Table A.III.2 | Emissions of selected electricity supply technologies (gCO_2eq/kWh)[i]

Options	Direct emissions	Infrastructure & supply chain emissions	Biogenic CO_2 emissions and albedo effect	Methane emissions	Lifecycle emissions (incl. albedo effect)
	Min/Median/Max	**Typical values**			**Min/Median/Max**
Currently Commercially Available Technologies					
Coal—PC	670/760/870	*9.6*	*0*	*47*	**740/820/910**
Gas—Combined Cycle	350/370/490	*1.6*	*0*	*91*	**410/490/650**
Biomass—cofiring	n. a. [ii]	–	–	–	**620/740/890**[iii]
Biomass—dedicated	n. a. [ii]	*210*	*27*	*0*	**130/230/420**[iv]
Geothermal	0	*45*	*0*	*0*	**6.0/38/79**
Hydropower	0	*19*	*0*	*88*	**1.0/24/2200**
Nuclear	0	*18*	*0*	*0*	**3.7/12/110**
Concentrated Solar Power	0	*29*	*0*	*0*	**8.8/27/63**
Solar PV—rooftop	0	*42*	*0*	*0*	**26/41/60**
Solar PV—utility	0	*66*	*0*	*0*	**18/48/180**
Wind onshore	0	*15*	*0*	*0*	**7.0/11/56**
Wind offshore	0	*17*	*0*	*0*	**8.0/12/35**
Pre-commercial Technologies					
CCS—Coal—Oxyfuel	14/76/110	*17*	*0*	*67*	**100/160/200**
CCS—Coal—PC	95/120/140	*28*	*0*	*68*	**190/220/250**
CCS—Coal—IGCC	100/120/150	*9.9*	*0*	*62*	**170/200/230**
CCS—Gas—Combined Cycle	30/57/98	*8.9*	*0*	*110*	**94/170/340**
Ocean	0	*17*	*0*	*0*	**5.6/17/28**

Notes:

[i] For a comprehensive discussion of methodological issues and underlying literature sources see Annex II, Section A.II.9.3. Note that input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized.

[ii] Direct emissions from biomass combustion at the power plant are positive and significant, but should be seen in connection with the CO_2 absorbed by growing plants. They can be derived from the chemical carbon content of biomass and the power plant efficiency. For a comprehensive discussion see Chapter 11, Section 11.13. For co-firing, carbon content of coal and relative fuel shares need to be considered.

[iii] Indirect emissions for co-firing are based on relative fuel shares of biomass from dedicated energy crops and residues (5-20%) and coal (80-95%).

[iv] Lifecycle emissions from biomass are for dedicated energy crops and crop residues. Lifecycle emissions of electricity based on other types of biomass are given in Chapter 7, Figure 7.6. For a comprehensive discussion see Chapter 11, Section 11.13.4. For a description of methodological issues see Annex II of this report.

A.III.3 Transport

A.III.3.1 Approach

The following tables provide a limited number of examples of transport modes and technologies in terms of their typical potential CO_2eq emissions per passenger kilometre (p-km) and freight tonne kilometre (t-km), now and in the 2030 timeframe. Estimates of mitigation cost ranges (USD_{2010}/tCO_2eq avoided) are also provided for the limited set of comparisons where data were available. Mitigation cost ranges for HDVs, shipping and air travel were taken directly from the literature. For sport utility vehicles (SUVs) and light duty vehicles (LDVs), specific mitigation costs were re-calculated for well-defined conditions based on basic input parameter sets (see equations and data provided below). The methodology to calculate specific mitigation costs, also called levelized cost of conserved carbon (LCCC), is discussed in Annex II. Future estimates of both emission intensities and specific mitigation costs are highly uncertain and depend on a range of assumptions.

The variation in emission intensities reflects variation in vehicle efficiencies together with narrow ranges for vehicle occupancy rates, or reflects estimates extracted directly from the literature. No cost uncertainty analysis was conducted. As mentioned above, mitigation cost ranges for HDVs, shipping, and air travel were taken directly from the literature. A standardized uncertainty range of +/- 100 USD_{2010}/tCO_2eq was used for SUVs and LDVs. Some parameters such as CO_2eq emitted from electricity generation systems and well-to-wheel CO_2eq emission levels from advanced biofuels should be considered as specific examples only.

This approach was necessary due to a lack of comprehensive studies that provide estimates across the full range of vehicle and technology types. Therefore, possible inconsistencies in assumptions and results mean that the output ranges provided here should be treated with caution. The output ranges shown are more indicative than absolute, as suggested by the fairly wide bands for most emission intensity and mitigation cost results.

The meta-analysis of mitigation cost for alternative road transport options was conducted using a 5 % discount rate and an approximate vehicle equipment life of 15 years. No fuel or vehicle taxes were included. Assumptions were based on the literature review provided throughout Chapter 8 and the estimates shown in Tables 8.1 and 8.2. Changes in assumptions could result in quite different results.

Some of the key assumptions are included in footnotes below the tables. Further information is available upon request from authors of Chapter 8.

Where emission intensities and LCCC were re-calculated based on specific input data, those inputs are summarized in Table 1 below. The conversion of input data into emission intensities and LCCC requires the steps outlined in the following:

Emissions per useful distance travelled (tCO_2eq/p-km and tCO_2eq/t-km)

$$EI = \frac{VEff_i \cdot FCI_i}{OC_i} \cdot \beta \qquad \text{(Equation A.III.7)}$$

Where:

- EI is the emission intensity
- $VEff$ is the typical vehicle efficiency
- FCI is the fuel carbon intensity
- OC is the vehicle occupancy
- ß is a unit conversion factor

Levelized Cost of Conserved Carbon (USD_{2010}/tCO_2eq)

$$LCCC_r = \frac{\Delta E}{\Delta C} \qquad \text{(Equation A.III.8)}$$

$$\Delta E = \alpha \Delta I + \Delta F \qquad \text{(Equation A.III.9)}$$

$$\alpha = \frac{r}{1-(1+r)^{-L}} \qquad \text{(Equation A.III.10)}$$

$$\Delta F = (VEff_i \cdot AD_i \cdot FC_i - VEff_j \cdot AD_j \cdot FC_j) \cdot \gamma \qquad \text{(Equation A.III.11)}$$

$$\Delta C = (VEff_j \cdot FCI_j \cdot AD_j - VEff_i \cdot FCI_i \cdot AD_i) \cdot \eta \qquad \text{(Equation A.III.12)}$$

Where:

- ΔE is the annualized travel cost increment
- ΔC is the difference in annual CO_2eq emissions of alternative i and baseline vehicle j, i.e., the amount of CO_2eq saved
- α is the capital recovery factor (CRF).
- ΔI is the difference in purchase cost of baseline and the alternative vehicle
- ΔF is the difference in annualized fuel expenditures of alternative i and baseline vehicle j
- r is the weighted average cost of capital (WACC)
- L is the vehicle lifetime
- $VEff$ is the typical vehicle efficiency as above, but in calculations for ΔFC and ΔC average typical vehicle efficiency is used.
- AD is the average annual distance travelled
- FC_i is average unit fuel purchase cost (taxes or subsidies excluded) of fuel used in vehicle i
- γ and η are unit conversion factors

Remarks:

Variation in output EI derives from variation of vehicle fuel consumption $VEff$ and vehicle occupancy OC.

A.III.3.2 Data

Table A.III.3 | Passenger transport—currently commercially available technologies[i]

Option	VEff Vehicle fuel consumption (l/100km for fossil fuel; kWh/km for electricity)[ii]	FCI CO_2eq intensity of fuel[iii]	OC Vehicle occupancy (capita)[iv]	ΔI Vehicle price markup on baseline (Incremental capital expenditure) (USD_{2010})[v]	L Vehicle lifetime (yrs)[vi]	AD Annual distance travelled (km/yr)[vii]
Aviation (commercial, medium to long haul)						
2010 Stock Average	–	73 g/MJ	–	–	–	–
Narrow and Wide Body	–	73 g/MJ	–	baseline	–	–
Rail (Light Rail Car)						
Electric, 600 g CO_2eq/kWh_{el}	1.3–2.0	600 g/kWh	60–80	–	–	–
Electric, 200 g CO_2eq/kWh_{el}	1.3–2.0	200 g/kWh	60–80	–	–	–
Road						
New Buses, Large Size						
Diesel	36–42	3.2 kg/l	40–50	–	–	–
Hybrid Diesel	25–29	3.2 kg/l	40–50	–	–	–
New Sport Utility Vehicles (SUV), Mid-Size						
2010 Stock average SUV	10–14	2.8 kg/l	1.5–1.7	–	15	15,000
Gasoline	9.6–12	2.8 kg/l	1.5–1.7	baseline	15	15,000
Hybrid Gasoline (25 % better)	7.2–9	2.8 kg/l	1.5–1.7	5000	15	15,000
New Light Duty Vehicles (LDV), Mid-Size						
2010 Stock average LDV	8–11	2.8 kg/l	1.5–1.7	–	15	15,000
Gasoline	7.8–9	2.8 kg/l	1.5–1.7	baseline	15	15,000
Hybrid Gasoline (28 % better)	5.6–6.5	2.8 kg/l	1.5–1.7	3000	15	15,000
Diesel	5.9–6.7	3.2 kg/l	1.5–1.7	2500	15	15,000
CNG	7.8–9	2.1 kg/l	1.5–1.7	2000	15	15,000
Electric, 600 g CO_2eq/kWh_{el}	0.24–0.3	600 g/kWh	1.5–1.7	16000	15	15,000
Electric, 200 g CO_2eq/kWh_{el}	0.24–0.3	200 g/kWh	1.5–1.7	16000	15	15,000
New 2-Wheelers (Scooter up to 200 cm^3 cylinder capacity)						
2010 Stock Average	1.5–2.5	2.8 kg/l	1.1–1.3	–	–	–
Gasoline	1.1–1.9	2.8 kg/l	1.1–1.3	–	–	–

Table A.III.3 (continued) | Passenger transport—currently commercially available technologies

Option	FC	EI	ΔE	ΔC	$LCCC_{5\,\%}$
	Average annual fuel purchase cost (USD_{2010}/l for fossil fuel; $UScents_{2010}$/kWh)[viii]	Emissions per useful distance travelled (gCO_2eq/p-km)	Annualized travel cost increment (USD_{2010}/yr)	Annual CO_2eq savings from vehicle switch (tCO_2eq/yr)	Levelized cost of conserved carbon at 5 % WACC (USD_{2010}/tCO_2eq)
Aviation (commercial, medium to long haul)					
2010 Stock Average	–	**80–218**[ix]	–	–	–
Narrow and Wide Body	–	**66–95**[x]	–	–	**–200**[xi]
Rail (Light Rail Car)					
Electric, 600 g CO_2eq/kWh_{el}	–	**10–20**	–	–	–
Electric, 200 g CO_2eq/kWh_{el}	–	**3.3–6.7**	–	–	–
Road					
New Buses, Large Size					
Diesel	–	**23–34**	–	–	–
Hybrid Diesel	–	**16–24**	–	–	–
New Sport Utility Vehicles (SUV), Mid-Size					
2010 Stock average SUV	0.81	**160–260**	–	–	–
Gasoline	0.81	**160–220**	*baseline*	*baseline*	**baseline**
Hybrid Gasoline (25 % better)	0.81	**120–170**	*150*	*1.1*	**140**
New Light Duty Vehicles (LDV), Mid-Size					
2010 Stock average LDV	0.81	**130–200**	–	–	–
Gasoline	0.81	**130–170**	*baseline*	*baseline*	**baseline**
Hybrid Gasoline (28 % better)	0.81	**92–120**	*2.5*	*1.0*	**2.6**
Diesel	0.81	**110–150**	*–15*	*0.43*	**–35**
CNG	0.35	**97–130**	*–390*	*0.83*	**–470**
Electric, 600 g CO_2eq/kWh_{el}	0.12	**85–120**	*1000*	*1.1*	**950**
Electric, 200 g CO_2eq/kWh_{el}	0.12	**28–40**	*1000*	*2.7*	**370**
New 2-Wheelers (Scooter up to 200 cm^3 cylinder capacity)					
2010 Stock Average	–	**32–63**	–	–	–
Gasoline	–	**24–47**	–	–	–

Notes:

i Note that input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized.

ii Vehicle fuel economy estimates for road vehicles based on IEA (2012a) and IEA Mobility Model (MoMo) data values, using averages for stock and new vehicles around the world to establish ranges. For rail, water, and air these estimates are based on a range of studies, see Chapter 8 Section 8.3. Rail estimates were based on expert judgment.

iii CO_2eq fuel intensities are based on IPCC (2006). CO_2eq intensities of electricity based on generic low and high carbon power systems. Well-to-wheel estimates from a range of sources, and specific examples as indicated in tables.

iv Occupancy rates for trains, buses, SUVs, LDVs, and 2-wheelers based on IEA Mobility Model averages from around the world. Bus and rail represent relatively high intensity usage; average loadings in some countries and regions will be lower.

v Vehicle purchase price increments for LDVs based primarily on NRC (2013) and IEA (2012a).

vi For LDVs, vehicle lifetime-kilometres set to 156,000 kms based on discounting 15 years and 15,000 km per year. Other vehicle type assumptions depend on literature. No normalization was attempted.

vi Annual distance travelled as described above.

vii Fuel prices are point estimates based on current and projected future prices in IEA (2012b). Variation in relative fuel prices can have significant impacts on transport costs and LCCC. Though no cost uncertainty analysis was performed, cost ranges were used where available and a standardized $USD_{2010}100/tCO_2eq$ uncertainty range was added around all final point estimates.

ix Current energy consumption per passenger kilometre is 1.1–3 MJ/p-km (IEA, 2009a).

x Based on TOSCA (2011, Table S-1). Slightly wider range for new/very new to account for range of load factors and distances.

xi Based on IEA and TOSCA analysis. IEA based on 30 years, 10% discount rate.

Table A.III.4 | Passenger transport—future (2030) expected technologies[i]

Option	VEff Vehicle fuel consumption (l/100km)	FCI CO_2eq intensity of fuel[ii]	OC Vehicle occupancy (capita) [iii]	ΔI Vehicle price mark-up on baseline (Incremental capital expenditure) (USD_{2010})[iv]	L Vehicle lifetime (yrs) [v]	AD Annual distance travelled (km/yr) [vi]
Aviation						
Narrow Body (20 % better)	–	–	–[vii]	–	15	–
Narrow Body, Open Rotor Engine (33 % better)	–	–	– [vii]	–	15	–
Road						
Optimized Sport Utility Vehicles (SUV), Mid-Size						
Gasoline (40 % better)	5.8–7.2	2.8 kg/l	1.5–1.7	3500[viii], future baseline	15	15,000
Hybrid Gasoline (50 % better)	4.8–6[ix]	2.8 kg/l	1.5–1.7	1200	15	15,000
Optimized Light Duty Vehicles (LDV), Mid-Size						
Gasoline (40 % better)	4.7–5.4[x]	2.8 kg/l	1.5–1.7	2500[viii], future baseline	15	15,000
Hybrid Gasoline (50 % better)	3.9–4.5[xi]	2.8 kg/l	1.5–1.7	1000	15	15,000
Hybrid Gasoline/Biofuel (50/50 share) (Assuming 70 % less CO_2eq/MJ biofuel than/MJ gasoline)	3.9–4.5[xi]	2.8 kg/l	1.5–1.7	1000	15	15,000
Diesel Hybrid	3.3–3.8[xii]	3.2 kg/l	1.5–1.7	1700	15	15,000
CNG Hybrid	3.9–4.5 [xi]	2.1 kg/l	1.5–1.7	1200	15	15,000
Electric, 200 g CO_2eq/kWh_{el}	0.19–0.26[xiii]	200 g/kWh	1.5–1.7	3600	15	15,000

AIII

Table A.III.4 (continued) | Passenger transport—future (2030) expected technologies[i]

Option	FC	EI	ΔE	ΔC	$LCCC_{5\%}$
	Average annual fuel purchase cost (USD_{2010}/l for fossil fuel; $UScents_{2010}$/kWh)[xiv]	Emissions per useful distance travelled (gCO_2eq/p-km)	Annualized travel cost increment (USD_{2010}/yr)	Annual CO_2eq savings from vehicle switch (tCO_2eq/yr)	Levelized cost of conserved carbon at 5 % WACC (USD_{2010}/tCO_2eq)
Aviation					
Narrow Body (20 % better)	–	**–**	–	–	**0–150**
Narrow Body, Open Rotor Engine (33 % better)	–	**44–63**[xv]	–	–	**0–350**
Road					
Optimized Sport Utility Vehicles (SUV), Mid-Size					
Gasoline (40 % better)	0.93	**94–130**	*–190*[xvi]	*1.8*[xvi]	**–110**[xvi]
Hybrid Gasoline (50 % better)	0.93	**78–110**	*–440*	*2.2*	**–200**
Optimized Light Duty Vehicles (LDV), Mid-Size					
Gasoline (40 % better)	0.93	**76–100**	*–230*[xvii]	*1.4*[xvii]	**–160**[xvii]
Hybrid Gasoline (50 % better)	0.93	**64–83**	*–21*	*0.35*	**– 61**
Hybrid Gasoline/Biofuel (50/50 share) (Assuming 70 % less CO_2eq/MJ biofuel than/MJ gasoline)	0.93	**41–54**	*38*	*1.0*	**39**
Diesel Hybrid	0.93	**63–83**	*–15*	*0.36*	**–43**
CNG Hybrid	0.44	**48–63**	*–310*	*0.77*	**–410**
Electric, 200 g CO_2eq/kWh_{el}	0.13	**23–35**	*86*	*1.4*	**61**

Notes:

i Only those options, where data were available and where significant advances are expected are listed. Other transport options, such as trains, buses and 2-wheelers will remain relevant means of transport in the future but are not covered due to data limitations. Note that input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized.

ii CO_2eq fuel intensities are based on IPCC (2006). CO_2eq intensities of electricity are based on generic low and high carbon power systems. Well-to-wheel estimates from a range of sources, and specific examples as indicated in tables.

iii Occupancy rates for trains, buses, SUVs, LDVs, 2-wheelers based on IEA Mobility Model averages from around the world. Bus and rail represent relatively high intensity usage; average loadings in some countries and regions will be lower.

iv Future vehicle purchase price mark ups based primarily on NRC (2013) and NRC (2010), also IEA (2009a), TIAX (2011), TOSCA (2011), Horton G. (2010) and other sources.

v For LDVs, vehicle lifetime-kilometres set to 156,000 km based on discounting 15 years and 15,000 km per year. Other vehicle type assumptions depend on literature. No normalization was attempted.

vi Annual distance travelled as described above.

vii Horton G. (2010) gives ranges from 100 to 150 for Boeing 737-800 and 350 to 500 for Airbus A380.

viii Relative to 2010 baseline.

ix Based on NRC (2013) and other studies, see Section 8.3.

x Based on NRC (2013) and other studies, see Section 8.3.

xi Fuel consumption of future hybrid gasoline, hybrid gasoline/biofuel, and hybrid CNG based on NRC (2013) and other studies, see Section 8.3.

xii Fuel consumption of future diesel based on NRC (2013) and other studies, see Section 8.3.

xiii Fuel consumption of future electric based on NRC (2013) and other studies, see Section 8.3.

xiv Future fuel prices based on IEA (2012b). These are point estimates—variation in relative fuel prices can have significant impacts on transport costs and LCCC.

xv Value results from assumption of 33% improvement relative to current new narrow and medium body aircrafts based on TOSCA (2011) and Horton G. (2010).

xvi Relative to 2010 gasoline SUV at 2010 fuel price of 0.81 USD_{2010}/l.

xvii Relative to 2010 gasoline LDV at 2010 fuel price of 0.81 USD_{2010}/l.

Table A.III.5 | Freight transport—currently commercially available technologies[i]

Option	VEff	FCI	OC	ΔI	L	AD
	Vehicle fuel consumption (l/100km)	CO_2eq intensity of fuel[ii]	Vehicle load (t)	Vehicle price markup on baseline (Incremental capital expenditure) (USD_{2010})	Vehicle lifetime	Annual distance travelled (km/yr)
Aviation (commercial, long haul)[iii]						
2010 Stock Average	–	–	–	–	–	–
Dedicated Aircraft	–	–	–	–	–	–
Belly-hold	–	–	–	–	–	–
Rail (freight train)[iv]						
Diesel, light goods	–	–	–	–	–	–
Diesel, heavy goods	–	–	–	–	–	–
Electric, 200g CO_2eq/kWh_{el}	–	–	–	–	–	–
Maritime[v]						
Current Average International Shipping	–	–	–	–	–	–
New Large International Container Vessel[vi]	–	–	–	–	–	–
Large Bulk Carrier/Tanker[vii]	–	–	–	–	–	–
LNG Bulk Carrier[viii]	–	–	–	–	–	–
Road[ix]						
New Medium Duty Trucks						
2010 Stock Average	16–24	3.2 kg/l	1.6–1.9	–	–	–
Diesel	14–18	3.2 kg/l	1.6–1.9	–	–	–
Diesel Hybrid	11–14	3.2 kg/l	1.6–1.9	–	–	–
CNG	18–23	2.1 kg/l	1.6–1.9	–	–	–
New Heavy Duty, Long-Haul Trucks						
2010 Stock Average	28–44	3.2 kg/l	8–12	–	–	–
Diesel	25–32	3.2 kg/l	8–12	–	–	–
CNG	31–40	2.1 kg/l	8–12	–	–	–

Table A.III.5 (continued) | Freight transport—currently commercially available technologies [i]

Option	FC	EI	ΔE	ΔC	$LCCC_{5\%}$
	Average annual fuel purchase cost (USD_{2010}/l for fossil fuel; $UScents_{2010}$/kWh)	Emissions per useful distance travelled (gCO_2eq/t-km)	Annualized travel cost increment (USD_{2010}/yr)	Annual CO_2eq savings from vehicle switch (tCO_2eq/yr)	Levelized cost of conserved carbon at 5 % WACC (USD_{2010}/tCO_2eq)
Aviation (commercial, long haul) [iii]					
2010 Stock Average	–	550–740	–	–	–
Dedicated Aircraft	–	500–820	–	–	**–200**[x]
Belly-hold	–	520–700[xi]	–	–	–
Rail (freight train) [iv]					
Diesel, light goods	–	26–33	–	–	–
Diesel, heavy goods	–	18–25	–	–	–
Electric, 200g CO_2eq/kWh_{el}	–	6–12	–	–	–
Maritime[v]					
Current Average International Shipping	–	10–40	–	–	–
New Large International Container Vessel[vi]	–	10–20	–	–	–
Large Bulk Carrier/Tanker[vii]	–	3–6	–	–	–
LNG Bulk Carrier[viii]	–	9–13	–	–	–
Road[ix]					
New Medium Duty Trucks					
2010 Stock Average	–	**270–490**	–	–	–
Diesel	–	**240–370**	–	–	–
Diesel Hybrid	–	**180–270**	–	–	–
CNG	–	**200–300**	–	–	–
New Heavy Duty, Long-Haul Trucks					
2010 Stock Average	–	**76–180**	–	–	–
Diesel	–	**70–130**	–	–	–
CNG	–	**60–110**	–	–	–

Notes:

i Note that input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized.

ii CO_2eq fuel intensities are based on IPCC (2006). CO_2eq intensities of electricity based on generic low and high carbon power systems. Well-to-wheel estimates from a range of sources, and specific examples as indicated in tables.

iii These baseline carbon intensity values for long haul air freight are based on mean estimates from DEFRA (2013). They relate to Boeing 747 and 757 air freight with an average carrying capacity of 84 tonnes and load factor of 69%. High and low estimates set at 15% above and below the means to reflect differences in the energy efficiency of different aircraft types operating with differing load factors.

iv The carbon intensity values for rail freight are based mainly on analyses by DEFRA (2013) and EcoTransit (2011). Expert judgment has been exercised to allow for international differences in the age, capacity, and efficiency of railway rolling stock and railway operating practices.

v Estimates are derived mainly from DEFRA (2012). This source presents mean carbon intensity values for particular types and size ranges of vessels. The ranges around these means allow for differences in actual vessel size, loading, and energy efficiency on the basis of expert judgment.

vi Carrying more than 8000 twenty-foot equivalent units (TEU).

vii 100-200,000 dead weight tonnes.

viii 100-200,000 cubic metres.

ix Truck CO_2eq/t-km ranges estimated from NRC (2010) and IEA Mobility Model data for averages for truck load factors around the world; vehicle efficiency estimates primarily from NRC (2010), IEA (2009a) and TIAX (2011). Baseline estimates derived from DEFRA (2013), EcoTransit (2011) and IEA (2009a). High and low estimates allow for variations in vehicle size, weight, age, operation and loading in different parts of the world.

x Aviation freight cost estimates assumptions similar to passenger. Based on IEA and TOSCA analysis, IEA based on 30 years, 10% discount rate.

xi The allocation of emissions between passenger and freight traffic on belly-hold services conforms to a standard 'freight weighting' method.

Table A.III.6 | Freight transport—future (2030) expected technologies [i]

Options[ii]	VEff	FCI	OC	ΔI	L	AD	FC	EI	ΔE	ΔC	$LCCC_{5\%}$
	Vehicle fuel consumption (l/100km)	CO_2eq intensity of fuel[iii]	Vehicle load (t)	Vehicle price markup on baseline (Incremental capital expenditure) (USD_{2010})	Vehicle lifetime	Annual distance travelled (km/yr)	Average annual fuel purchase cost (USD_{2010}/l for fossil fuel; $UScents_{2010}$/kWh)	Emissions per useful distance travelled (gCO_2eq/t-km)	Annualized travel cost increment (USD_{2010}/yr)	Annual CO_2eq savings from vehicle switch (tCO_2eq/yr)	Levelized cost of conserved carbon at 5 % WACC (USD_{2010}/tCO_2eq)
Aviation (commercial, long haul)											
Improved Aircraft (25 % better)	–	–	–	–	–	–	–	300–450[v]	–	–	**150**[vi]
Improved, Open Rotor Engine (33 % better)	–	–	–	–	–	–	–	270–400[v]	–	–	**350**[vi]
Maritime											
Optimized Container Vessel	–	–	–	–	–	–	–	7–13[vii]	–	–	**–100**[viii]
Optimized Bulk Carrier	–	–	–	–	–	–	–	2–4[vii]	–	–	**–100**[viii]
Road[iv]											
Optimized Medium Duty Trucks											
Diesel	8–13	3.2 kg/l	1.6–1.9	–	–	–	–	**140–260**	–	–	**–100**
Optimized Heavy Duty, Long-Haul Trucks											
Diesel	15–22	3.2 kg/l	8–12	–	–	–	–	**41–91**	–	–	**–250**
Diesel/Biofuel (50/50 share) (Assuming 70 % less CO_2eq/MJ biofuel than/MJ diesel)	15–22	2.1 kg/l	8–12	–	–	–	–	**26–59**	–	–	**–**

Notes:

i Note that input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized.

ii No future rail CO_2eq or cost estimates were included due to lack of information.

iii CO_2eq fuel intensities are based on IPCC (2006). CO_2eq intensities of electricity based on generic low and high carbon power systems. Well-to-wheel estimates from a range of sources, and specific examples as indicated in tables.

iv Future truck efficiencies and costs primarily from NRC (2010), Zhao et al (2013).

v These baseline carbon intensity values for long haul airfreight are based on mean estimates from DEFRA (2013). They relate to Boeing 747 and 757 airfreight with an average carrying capacity of 84 tonnes and load factor of 69%. High and low estimates set at 15% above and below the means to reflect differences in the energy efficiency of different aircraft types operating with differing load factors.

vi Projections of the carbon mitigation costs of future aircraft development are based mainly on Tosca. Mitigation costs for future technologies assumed similar to passenger aircraft since the specific large commercial type aircraft are mostly the same configuration.

vii Estimates are derived mainly from DEFRA (2012). This source presents mean carbon intensity values for particular types and size ranges of vessels. The ranges around these means allow for differences in actual vessel size, loading and energy efficiency on the basis of expert judgment.

viii Shipping cost estimates based primarily on Buhaug (2009), Lloyds Register/DNV (2011), and IEA (2009a) (review of literature).

A.III.4 Industry

A.III.4.1 Introduction

The data presented below has been used to assess typical product-specific CO_2eq emissions (i.e., emission per unit of product)[3] for different production practices, which are commercially available today or may become so in the future, and for selected industrial sectors. Both direct and indirect specific emissions are assessed. Specific emissions could be reduced by switching to production processes that cause lower emissions for otherwise comparable products[4] and by reducing production/consumption of emission-intensive products. Some production practices are mutually exclusive; others can be combined to yield deeper reductions in specific emissions. The impact of decarbonizing electricity supplied for industrial processes has been assessed, too, for well-defined exemplary conditions.

For all input parameters and specific CO_2eq emissions global average values are given as a benchmark. Parameters of individual production practices are generally estimates of typical values based on limited studies and expert judgment. Comparisons of input parameters across different individual production practices and with global averages (see Tables A.III.8–A.III.12 below) yields insights into the intermediate effect via which changes in final specific CO_2eq emissions occur for certain production practices.

Estimates of future global averages in specific CO_2eq emissions are derived for long-term scenarios that stabilized GHG concentrations at about 450 ppm CO_2eq and provide data at the necessary level of detail. These can be considered as another rough benchmark for emission intensities that can be achieved with currently available and potential future production practices. Generally, scenarios that provide sufficient detail at the level of industrial subsectors/products are very scarce (2–3 models) and are in many cases derived from the same data source as data for individual production practices (mostly International Energy Agency)[5]. Comparisons of emission intensities in future 450 ppm stabilization scenarios with available production practices can yield rough insights into future trends for production practices with different specific emissions, but need to be considered with caution.

Specific mitigation costs have been assessed for all production practices except for the decarbonization of electricity supply, the costs of which are dealt with in Chapter 7 (Section 7.8). Specific mitigation costs are expressed in USD_{2010}/tCO_2 or USD_{2010}/tCO_2eq and take into account total incremental operational and capital costs. Generally, costs of the abatement options shown vary widely between individual regions and from plant to plant. Factors influencing the costs include typical capital stock turnover rates (some measures can only be applied when plants are replaced), relative energy costs, etc. No meta-analysis of such individual cost components has been attempted, however, due to limited data availability. Estimates are based on expert judgment of the limited data that is available. Hence, the estimates of specific mitigation costs should be considered with care and as indicative only.

Information on specific emissions of different production practices and associated specific mitigation cost is presented in Figures 10.7–10.10 and in Figures 10.19 and 10.20.

A.III.4.2 Approaches and data by industry sector

A.III.4.2.1 Cement

Direct specific emissions of cement (tCO_2/t cement) are derived from technical parameters via the following equation:

$$EI_{direct} = (1 - \lambda) \cdot clc \cdot (e_{n-el} \cdot FCI_{n-el} + CI_{calc}) \qquad \text{(Equation A.III.13)}$$

Where

- λ is the percentage of emissions captured and stored via CCS
- clc is the clinker to cement ratio
- $e_{n\text{-}el}$ is the specific non-electric energy use, i.e., the non-electric energy use per unit of clinker
- $FCI_{n\text{-}el}$ is the carbon intensity of the non-electric fuel used
- CI_{calc} is the carbon intensity of the calcination process

Indirect specific emissions of cement (tCO_2/t cement) are derived from specific electricity use and the carbon intensity of electricity:

$$EI_{indirect} = e_{el} \cdot FCI_{el} \qquad \text{(Equation A.III.14)}$$

Where

- e_{el} is the specific electric energy use, i.e., the electricity use per unit of cement
- FCI_{el} is the carbon intensity of the electricity used

[3] Emissions cannot always be expressed in product-specific terms. In the case of chemicals, products are too heterogeneous to express emissions per unit of product. Hence, global emissions of different production practices/technologies have been assessed for total global chemicals production.

[4] Note that the extent to which certain production processes can be replaced by others is often constrained by various conditions that need to be considered on a case by case basis. The replacement of blast oxygen steel furnaces by electric arc furnaces, for instance, is limited by availability of scrap.

[5] Further literature sources are assessed in Chapter 10 (Section 10.7). The data sources assessed in 10.7 could, however, often not be used in the summary assessment mainly due to non-comparability of methodological approaches. Chapter 6 presents more comprehensive scenario assessments including all sectors of the economy, which often comes, however, at the expense of sectoral detail. Chapter 10 (Section 10.10) discusses these scenarios from an industry perspective.

Total specific emissions of cement (tCO_2/t cement) are the sum of both direct and indirect specific emissions:

$$EI_{total} = EI_{direct} + EI_{indirect} \quad \text{(Equation A.III.15)}$$

Remarks:

Variation in emission intensity derives from variation in selected input parameters. Individual input parameters are varied systematically, i.e., in accordance with the definition of each production practice, while all other input parameters are kept at global average values.

Data on technical input parameters is also very limited. Sources are specified in footnotes to data entries.

Specific mitigation costs (cost of conserved carbon) are estimated based on expert assessment of limited selected studies. See footnote ii for details.

Table A.III.7 | Technical parameters and estimates for cost of conserved carbon of cement production processes[i]

Options	*clc*	$e_{n\text{-}el}$	$FCI_{n\text{-}el}$	CI_{calc}	e_{el}	FCI_{el}	λ	EI_{direct}	$EI_{indirect}$	EI_{total}	*LCCC*
	Clinker to cement ratio (%)	Non-electric fuel intensity (GJ/t clinker)	CO_2 intensity of non-electric fuel (tCO_2/GJ)	CO_2 intensity of calcination process (t CO_2/t clinker)	Electricity intensity (kWh/t cement)	CO_2 intensity of electricity ($kgCO_2$/kWh)	CO_2 capture rate (%)	Direct emission intensity w/CCS (tCO_2/t cement)	Indirect emission intensity (tCO_2/t cement)	Total emission intensity (tCO_2/t cement)	Levelized cost of conserved carbon (USD_{2010}/tCO_2)[ii]
Historical Global Average Data and Future Data for 450 ppm Scenarios from Integrated Models											
Global average (2030) [iii]	–	–	–	–	–	–	–	–	–	**0.38–0.59**	
Global average (2050) [iii]	–	–	–	–	–	–	–	–	–	**0.24–0.39**	
Global average (2010)	0.8	3.9	0.1	0.51	109	0.46[iv]	0	*0.72*	*0.05*	**0.77**	
Currently Commercially Available Technologies											
Best practice energy intensity	0.8	2.9–3.1[v]	0.1	0.51	80–90[vi]	0.46[iv]	0	*0.64–0.66*	*0.037–0.041*	**0.68–0.70**	< 0–150
Best practice clinker to cement ratio	0.6–0.7[vii]	3.9	0.1	0.51	109	0.46[iv]	0	*0.54–0.63*	*0.05*	**0.59–0.68**	< 0–50[viii]
Best practice energy intensity and clinker to cement ratio combined	0.6–0.7[vii]	2.9–3.1[v]	0.1	0.51	80–90[vi]	0.46[iv]	0	*0.48–0.57*	*0.037–0.041*	**0.52–0.62**	< 0–150[viii]
Improvements in non-electric fuel mix[ix]	0.8	3.9	0.056[x]	0.51	109	0.46[iv]	0	*0.58*	*0.05*	**0.63**	< 0–150[viii]
Decarbonization of electricity supply	0.8	3.9	0.1	0.51	109	0–0.39[xi]	0	*0.72*	*0–0.043*	**0,72–0.76**	
Pre-commercial Technologies											
CCS[xii]	0.8	3.9	0.1	0.51	109	0.46[iv]	75–90	*0.072–0.18*	*0.05*	**0.12–0.23**	50–150[xiii]
CCS and fully decarbonized electricity[xiv]	0.8	3.9	0.1	0.51	109	0	75–90	*0.072–0.18*	*0*	**0.072–0.18**	

Notes:

i Note that input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized.

ii Expert judgment based on McKinsey (2009), 2012, IEA (2009b, 2012a), BEE (2012), and others. The costs of the abatement options shown vary widely between individual regions and from plant to plant. Factors influencing the costs include typical capital stock turnover rates (some measures can only be applied when plants are replaced), relative energy costs, etc.

iii Data range is taken from the following models: AIM Enduse model (Akashi et al., 2013), IEA 2DS low demand (IEA, 2012a).

iv Based on global industry-wide average CO_2eq intensity of primary energy used in electricity and heat supply in 2010 (see Chapter 10. Table 10.2)

v This range is based on best practice operation of 4 to 6 stage pre-heater and pre-calciner kiln technology based on IEA (2009b). Actual operation performance does depend on issues such as moisture content and raw material quality and can be above this range.

vi Best practice electricity consumption is based on IEA (2007).

vii Minimum clinker to cement ratio is for Portland cement according to IEA (2007), which is a globally achievable value taking availability of substitutes into account IEA (2009b). Further reductions in the clinker to cement ratio are possible for other types of cement (e.g., fly ash or blast furnace slag cement).

viii For clinker substitution and fuel mix changes, costs depend on the regional availability and price of clinker substitutes and alternative fuels.

ix This is assuming that only natural gas is used as non-electric fuel. Further reductions in non-electric fuel emission intensity are technically possible, e.g., by increased use of biomass.

x Natural gas fuel emission factor (IPCC, 2006).

xi The upper end of the range is based on natural gas combined cycle (NGCC) with an efficiency of 55 % and fuel emission factors from IPCC (2006).

xii CCS: Carbon dioxide capture and storage. This option assumes no improvements in fuel mix. Feasibility of CCS depends on global CCS developments. CCS is currently not yet applied in the cement sector.

xiii IEA GHG (2008) estimates CCS abatement cost at 63 to 170 USD/tCO_2 avoided.

xiv This option assumes no improvements in non-electric fuel mix.

A.III.4.2.2 Iron and steel

Direct specific CO_2 emissions of crude steel (tCO_2/t steel) are derived from technical parameters via the following equation:

$$EI_{direct} = (1 - \lambda) \cdot EI_{direct,noCCS} \qquad \text{(Equation A.III.16)}$$

Where

- λ is the percentage of emissions captured and stored via CCS
- $EI_{direct,noCCS}$ is the direct emission intensity without CCS

Indirect specific CO_2 emissions of crude steel (tCO_2/t steel) are derived from specific electricity use and the carbon intensity of electricity:

$$EI_{indirect} = e_{el} \cdot FCI_{el} \qquad \text{(Equation A.III.17)}$$

Where

- e_{el} is the specific electric energy use, i.e., the electricity use per unit of crude steel
- FCI_{el} is the carbon intensity of the electricity used

Total specific CO_2 emissions of crude steel (tCO_2/t steel) are the sum of both direct and indirect specific emissions:

$$EI_{total} = EI_{direct} + EI_{indirect} \qquad \text{(Equation A.III.18)}$$

Remarks:

Data on technical input parameters is limited and almost exclusively based on IEA (2007). Emission intensities of the advanced blast furnace route, the natural gas DRI route, and the scrap-based electric arc furnace route are point estimates of global best practice based on IEA (2007). Since no variation in input parameters could be derived from the literature, output ranges have been constructed as an interval around the mean value based on +/-10% of the respective savings. Where input parameters are set by assumption, they are varied within typical ranges and become the sole source of variation in output values, while all other input parameters are kept at global average values.

Specific mitigation costs (cost of conserved carbon) are estimated based on expert assessment of limited selected studies. See footnote vi for details.

A.III.4.2.3 Chemicals

Global direct CO_2 emissions ($GtCO_2$) of global chemicals production in 2010 are derived from technical parameters via the following equation:

$$CO2_{direct} = (1 - \lambda) \cdot CO2_{direct,noCCS} \qquad \text{(Equation A.III.19)}$$

Where

- λ is the percentage of emissions captured and stored via CCS
- $CO2_{direct,noCCS}$ are global direct CO_2 emissions in chemicals production in 2010 without CCS

Global indirect CO_2 emissions ($GtCO_2$) of global chemicals production in 2010 are derived from global electricity use in chemicals production and the carbon intensity of electricity:

$$CO2_{indirect} = Elec \cdot FCI_{el} \cdot \gamma \qquad \text{(Equation A.III.20)}$$

Where

- $Elec$ is the global electric energy use in the chemicals sector in 2010
- FCI_{el} is the carbon intensity of the electricity used
- γ is a unit conversion factor of 1/1000

Total global CO_2eq emissions ($GtCO_2eq$) of chemicals production in 2010 are the sum of direct and indirect CO_2 emissions and CO_2-equivalents of non-CO_2 emissions:

$$CO2e_{total} = CO2_{direct} + CO2_{indirect} + CO2e_{acid} + CO2e_{HFC-22} \qquad \text{(Equation A.III.21)}$$

Where

- $CO2e_{acid}$ are global direct N_2O emissions from global nitric and adipic acid production expressed in CO_2 equivalents
- $CO2e_{HFC\text{-}22}$ are global direct HFC-23 emissions from HFC-22 production expressed in CO_2 equivalents

Remarks:

For most production practices, only central estimates for technical input parameters could be derived from the available literature. Where input parameters are set by assumption, they are varied within typical ranges and become a source of variation in output values. Where no variation in input parameters could be derived from the literature, output ranges have been constructed as an interval around the mean value based on +/-10% of the respective savings.

Specific mitigation costs (cost of conserved carbon) are estimated based on expert assessment of limited selected studies. See footnote iv for details.

Table A.III.8 | Technical parameters and estimat+es for cost of conserved carbon of iron and steel production processes[i]

Options[ii]	$EI_{direct,noCCS}$ Specific direct CO_2 emissions w/o CCS[iii] (tCO_2/t steel)	e_{el} Specific electricity consumption (kWh/t steel)	FCI_{el} CO_2 intensity of electricity ($kgCO_2$/kWh)	λ CO_2 capture rate[iv] (%)	EI_{direct} Specific direct CO_2 emissions w/CCS[v] (tCO_2/t steel)	$EI_{indirect}$ Indirect emission intensity (tCO_2/t steel)	EI_{total} Total emission intensity (tCO_2/t steel)	$LCCC$ Levelized cost of conserved carbon (USD_{2010}/tCO_2)[vi]
Historical Global Average Data and Future Data for 450 ppm Scenarios from Integrated Models								
Global average (2030)[vii]	–	–	–	–	–	–	0.92–1.36	
Global average (2050)[vii]	–	–	–	–	–	–	0.47–0.84	
Global average (2010)	1.8[viii]	820[ix]	0.46[x]	0	*1.8*	*0.38*	**2.2**	
Currently Commercially Available Technologies								
Advanced blast furnace route[xi]	1.3[xii]	350[xiii]	0.46[x]	0	*1.3*	*0.16*	**1.5**	< 0–150
Natural gas DRI route[xiv, xi]	0.7[xii]	590[xiii]	0.46[x]	0	*0.7*	*0.27*	**0.97**	50–150
Scrap based EAF[xv, xi]	0.25[xii]	350[xiii]	0.46[x]	0	*0.25*	*0.16*	**0.41**	< 0–50[xvi]
Decarbonization of electricity supply	1.8[viii]	820[ix]	0–0.39[xvii]	0	*1.8*	*0–0.32*	**1.8–2.1**	
Pre-commercial Technologies								
CCS[xviii]	1.8[viii]	820[ix]	0.46[x]	75–90	*0.18–0.45*	*0.38*	**0.56–0.82**	50–150
CCS and fully decarbonized electricity[xix]	1.8[viii]	–	0	75–90	*0.18–0.45*	*0*	**0.18–0.45**	

Note:

i Note that input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized.

ii Non-electric fuel mix improvements are not listed as an abatement option because a large share of the coal use in the iron and steel industry, via the intermediate production of coke, is an inherent feature of the blast furnace technology. The coke is used to reduce iron ore to iron and for structural reasons in the furnace. The limited data availability did not allow assessing the limited potential related to the part of the fuel use that can be substituted.

iii Direct CO_2 emissions contain all emissions from steel production that are unrelated to electricity consumption.

iv As percentage of specific direct CO_2 emissions in steel production.

v Direct CO_2 emissions contain all emissions from steel production that are unrelated to electricity consumption.

vi Expert judgment based on McKinsey (2009; 2010), IEA (2009b, 2012a), BEE (2012) and others. The costs of the abatement options shown vary widely between individual regions and from plant to plant. Factors influencing the costs include typical capital stock turnover rates (some measures can only be applied when plants are replaced), relative energy costs, etc.

vii Data range is provided by AIM Enduse model (Akashi et al., 2013) DNE21+ (Sano et al., 2013a; b) and IEA 2DS low demand (IEA, 2012a).

viii IEA (2012a).

ix Derived from IEA (2012a, 2013b).

x Based on global industry-wide average CO_2eq intensity of primary energy used in electricity and heat supply in 2010 (see Chapter 10, Table 10.2). This is a simplified calculation in line with the method used for other sectors ignoring the practice in many iron and steel plants to use process derived gases (blast furnace gas and basic oxygen furnace gas) for electricity production. The emissions from these derived gases are already included in the direct emissions.

xii Excluding rolling and finishing.

xii Value equals lower bound of total emission intensity in IEA (2007, p. 108, table 5.4) as that is for zero-carbon electricity.

xiii Derived from spread in total emission intensity in IEA (2007, p. 108, table 5.4) and using a typical coal emission factor of 0.85.

xiv DRI: Direct reduced iron.

xv EAF: Electric arc furnace.

xvi Costs depend heavily on the regional availability and price of scrap.

xvii The upper end of the range is based on natural gas combined cycle (NGCC) with an efficiency of 55 % and fuel emission factors from IPCC (2006). The approach taken here is a simplified calculation, consistent with the approach for other sectors and does not explicitly take into account the share of the electricity consumed that is produced with process derived gases (see also footnote ix).

xviii CCS: Carbon dioxide capture and storage. This option assumes no improvements in fuel mix.

xix This option assumes no improvements in non-electric fuel mix.

Table A.III.9 | Technical parameters and estimates for cost of conserved carbon of chemicals production processes [i]

Options	$CO2_{direct,noCCS}$ Global direct CO_2 emissions w/o CCS ($GtCO_2$)	$CO2e_{acid}$ Global non-CO_2 emissions from HFC-22 production ($GtCO_2eq$)[ii]	$CO2e_{HFC-22}$ Global non-CO_2 emissions from adipic and nitric acid production ($GtCO_2eq$)[ii]	$Elec$ Global electricity use (TWh)	FCI_{el} CO_2 intensity of electricity ($kgCO_2/kWh$)	λ CO_2 capture rate[iii] (%)	$CO2_{direct}$ Global direct CO_2 emissions w/ CCS ($GtCO_2$)	$CO2_{indirect}$ Global indirect CO_2 emissions ($GtCO_2$)	$CO2_{total}$ Global total emissions ($GtCO_2eq$)	$LCCC$ Cost of conserved carbon (USD_{2010}/tCO_2eq)[iv]
Historical Data and Future Data from IEA ETP 2DS Scenario										
Global total (2030)[v]	–	–	–	1400	–	–	1.5–1.6	–	–	
Global total (2050)[v]	–	–	–	1400	–	–	1.3	–	–	
Global total (2010)	1.6[vi]	0.13	0.12	1100[vii]	0.46[viii]	0	**1.6**	**0.51**	**2.4**	
Currently Commercially Available Technologies										
Best practice energy intensity	*1.0*[ix]	0.13	0.12	860[x]	0.46[viii]	0	**1.0**	**0.39**	**1.7**	< 0–150
Enhanced recycling, cogeneration and process intensification	*1.3*[xi]	0.13	0.12	1100[vii]	0.46[viii]	0	**1.3**	**0.51**	**2.1**	20–150
Abatement of N_2O from nitric and adipic acid	1.6[vi]	0.13	*0.01*[xii]	1100[vii]	0.46[viii]	0	**1.6**	**0.51**	**2.3**	0–50
Abatement of HFC-23 emissions from HFC-22 production	1.6[vi]	*0*[xiii]	0.12	1100[vii]	0.46[viii]	0	**1.6**	**0.51**	**2.2**	0–20
Improvements in non-electric fuel mix[xiv]	*1.2*[xv]	0.13	0.12	1100[vii]	0.46[viii]	0	**1.2**	**0.51**	**2.0**	< 0–150
Decarbonization of electricity supply	1.6[vi]	0.13	0.12	1100[vii]	0–0.39[xvi]	0	**1.6**	**0–0.44**	**1.8–2.3**	
Pre-commercial Technologies										
CCS for ammonia production[xvii]	1.6[vi]	0.13	0.12	1100[vii]	0.46[viii]	3.5[xviii]	**1.5**	**0.51**	**2,3**	50–150
CCS[xix]	1.6[vi]	0.13	0.12	1100[vii]	0.46[viii]	75–90	**0.16–0.4**	**0.51**	**0.92–1.16**	50–150
CCS and fully decarbonized electricity[xx]	1.6[vi]	0.13	0.12	1100[vii]	0	75–90	**0.16–0.4**	**0**	**0.41–0.65**	

Notes:

i Note that input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized.

ii Based on EPA (2013) unless specified otherwise.

iii As percentage of global direct CO_2 emissions in chemicals production.

iv Expert judgment based on McKinsey (2009; 2010), IEA (2009c, 2012a), BEE (2012), and others. The costs of the abatement options shown vary widely between individual regions and from plant to plant. Factors influencing the costs include typical capital stock turnover rates (some measures can only be applied when plants are replaced), relative energy costs, etc.

v Based on IEA ETP 2DS scenarios with high and low global energy demand (IEA, 2012a).

vi Based on IEA (2012a).

vii Based on IEA (IEA, 2013b). IEA (2012a) provided higher values of 1340 TWh.

viii Based on global industry-wide average CO_2eq intensity of primary energy used in electricity and heat supply in 2010 (see Chapter 10. Table 10.2).

ix Based on global potential for savings of 35 % in direct emissions in chemicals production as estimated for 2006 (IEA, 2009c) applied to direct emissions in 2010.

x Based on potential for electricity savings of 0.91 EJ (IEA, 2012a).

xi Based on global technical potential for saving in primary energy consumption of 4.74 EJ (IEA, 2012a) and assuming that conserved primary energy supply is based on natural gas with an emission factor of 56.2 kg CO_2eq/GJ (2006). This translates into savings in global direct CO_2 emissions of 0.27 $GtCO_2eq$.

xii Based on a global technical potential to save 85 % of non-CO_2 emissions from HFC-22 production (EPA, 2013).

xiii Based on a global technical potential to save 100 % of non-CO_2 emissions from production of adipic and nitric acid (Miller and Kuijpers, 2011)

xiv This is assuming that only natural gas is used as non-electric fuel. Further reductions in non-electric fuel emission intensity are technically possible, e. g., by increased use of biomass.

xv Based on the assumption that 23 % of direct CO_2 emissions can be saved from a switch to natural gas (IEA, 2009c).

xvi The upper end of the range is based on natural gas combined cycle (NGCC) with an efficiency of 55 % and fuel emission factors from IPCC (2006).

xvii Ammonia production was 159 Mt in 2010 (IEA, 2012a). According to Neelis et al. (2005), a best practice gas-based ammonia facility produces 1.6 tCO_2/t ammonia, of which 70 % are pure CO_2 emissions (1.1 t CO_2/t ammonia). 50 % of that pure CO_2 stream is assumed to be used in urea production (0.55 t CO_2/t ammonia). 90 % of the remaining 0.55 tCO_2/t ammonia is assumed to be captured. This results in an effective CO_2 capture rate of 3.5 % of total emissions in chemicals by application of CCS in ammonia production.

xviii This is the effective rate of CO_2 emissions captured in ammonia production relative to global direct CO_2 emissions in chemicals. See also endnote xvii.

xix This option assumes no improvements in fuel mix.

xx This option assumes no improvements in non-electric fuel mix.

A.III.4.2.4 Pulp and paper

Specific direct CO_2 emissions of paper (tCO_2/t paper) are derived from technical parameters via the following equation:

$$EI_{direct} = (1 - \lambda) \cdot EI_{direct,noCCS} \qquad \text{(Equation A.III.22)}$$

Where

- λ is the percentage of emissions captured and stored via CCS
- $EI_{direct,noCCS}$ is the direct emission intensity without CCS

Indirect specific CO_2 emissions of paper (tCO_2/t paper) are derived from specific electricity use and the carbon intensity of electricity:

$$EI_{indirect} = e_{el} \cdot FCI_{el} \qquad \text{(Equation A.III.23)}$$

Where

- e_{el} is the specific electric energy use, i.e., the electricity use per tonne of paper
- FCI_{el} is the carbon intensity of the electricity used

Total specific CO_2 emissions of paper (tCO_2/t paper) are the sum of both direct and indirect specific emissions:

$$EI_{total} = EI_{direct} + EI_{indirect} \qquad \text{(Equation A.III.24)}$$

<u>Remarks:</u>

For most production practices, only central estimates for technical input parameters could be derived from the available literature. Where input parameters are set by assumption, they are varied within typical ranges and become a source of variation in output values. Where no variation in input parameters could be derived from the literature, output ranges have been constructed as an interval around the mean value based on +/-10 % of the respective savings.

Specific mitigation costs (cost of conserved carbon) are estimated based on expert assessment of limited selected studies. See footnote v for details.

A.III.4.2.5 Municipal Solid Waste (MSW)

For waste treatment practices that reduce landfill, specific methane emission (gCH_4/kg MSW) and specific nitrous oxide emissions (gN_2O/kg MSW) are taken directly from the literature. Methane emission intensities (gCH_4/kg MSW) of conventional and improved landfill options are derived from technical parameters given below. CO_2eq emission intensities (tCO_2eq/t MSW) are calculated using global warming potentials (GWP) of methane and nitrous oxide of 21 and 310, respectively.

$$EI_{CH4} = MCF \cdot DOC \cdot DOCf \cdot F \cdot (1 - OX) \cdot (1 - R) \cdot \gamma \cdot \eta \qquad \text{(Equation A.III.25)}$$

Where

- *MCF* is the methane correction factor, *Min(MCF) = 0.6, Max(MCF) = 1*
- *DOC* is degradable organic carbon (gC/kg MSW)
- *DOCf* is the fraction of *DOC* dissimilated, *DOCf = 0.5*
- *F* is the fraction of methane in landfill gas, *F = 0.5*
- *OX* is oxidation factor (fraction)
- *R* is the fraction of recovered methane
- γ is the unit conversion factor of C into CH_4, $\gamma = 16/12$
- η is a unit conversion factor of 1/1000

Values given above are based on Frøiland Jensen and Pipatti (2001) and Pipatti et al. (2006) default values.

Variation in specific emissions is from maximum to minimum assuming all input parameters are independently distributed.

Cost are taken from EPA (2013) and based on a 10 % WACC.

Table A.III.10 | Technical parameters and estimates for cost of conserved carbon of pulp and paper production processes[i]

Options	$EI_{direct,noCCS}$	e_{el}	FCI_{el}	λ	EI_{direct}	$EI_{indirect}$	EI_{total}	$LCCC$
	Specific direct CO_2 emissions w/o CCS[ii] (tCO_2/t paper)	Specific electricity consumption (kWh/t paper)	CO_2 intensity of electricity ($kgCO_2$/kWh)	CO_2 capture rate[iii] (%)	Specific direct CO_2 emissions w/CCS[iv] (tCO_2/t paper)	Indirect emission intensity (tCO_2/t paper)	Total emission intensity (tCO_2/t paper)	Cost of conserved carbon (USD_{2010}/tCO_2)[v]
Historical Data and Future Data from IEA ETP 2DS Scenario								
Global average (2030) [vi]	–	*990–1100*[vii]	–	–	**0.26–0.30**[vii]	–	–	
Global average (2050) [vi]	–	*920–950*[vii]	–	–	**0.16–0.20**[vii]	–	–	
Global average (2010)	*0.56*[viii]	*1,200*[ix]	0.46[x]	0	**0.56**	**0.55**	**1,1**	
Currently Commercially Available Technologies								
Best practice energy intensity	*0.48*[xi]	*1,000*[xii]	0.46[x]	0	**0.48**	**0.46**	**0.94**	< 0–150
Co-generation	*0.53*[xiii]	*1,200*[ix]	0.46[x]	0	**0.53**	**0.55**	**1.1**	20–50
Decarbonization of electricity supply	*0.56*[viii]	*1,200*[ix]	0–0.39[xiv]	0	**0.56**	**0–0.47**	**0.56–1,0**	
Pre-commercial Technologies								
CCS[xv]	*0.56*[viii]	*1,200*[ix]	0.46[x]	75–90	**0.056–0.14**	**0.55**	**0.61–0.69**	50–150
CCS and fully decarbonized electricity[xvi]	*0.56*[viii]	*1,200*[ix]	0–0.39	75–90	**0.056–0.14**	**0–0.47**	**0.056–0.14**	

Notes:

i Note that input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized.

ii Direct CO_2 emissions w/o CCS contain all emissions from paper production that are unrelated to electricity consumption, including those that could be captured and stored.

iii As percentage of specific direct CO_2 emissions in steel production.

iv Direct CO_2 emissions w/CCS contain all non-captured emissions from paper production that are unrelated to electricity consumption.

v Expert judgment based on McKinsey (2009; 2010), IEA (2009b, 2012a), BEE (2012), and others. The costs of the abatement options shown vary widely between individual regions and from plant to plant. Factors influencing the costs include typical capital stock turnover rates (some measures can only be applied when plants are replaced), relative energy costs, etc.

vi Based on IEA ETP 2DS scenarios with high and low global energy demand (IEA, 2012a).

vii Derived from IEA (2012a).

viii Based on global direct emissions of 0.22 $GtCO_2$ and global paper production of 395 Mt (IEA, 2012a).

ix Based on global electricity consumption in pulp and paper production of 1.7 EJ (IEA, 2013b) and global paper production of 395 Mt (IEA, 2012a).

x Based on global industry-wide average CO_2eq intensity of primary energy used in electricity and heat supply in 2010 (see Chapter 10. Table 10.2).

xi Based on technical potential for savings in non-electric fuel input of 1.5 GJ/t paper (IEA, 2012a) and assuming no change in the non-electric fuel emission factor of 51 kg CO_2/GJ (derived from IEA, 2012a). This translates into savings in specific direct CO_2 emissions of 77 kg CO_2/t paper.

xii Based on technical potential for saving electricity of 200 kWh/t paper (IEA, 2012a).

xiii Based on technical potential for savings in non-electric fuel input of 0.6 GJ/t paper (derived from IEA, 2012a) and assuming that conserved fuel is natural gas with an emission factor of 56.2 kg CO_2eq/GJ (IPCC, 2006). This translates into savings in specific direct CO_2 emissions of 34 kg CO_2/t paper.

xiv The upper end of the range is based on natural gas combined cycle (NGCC) with an efficiency of 55 % and fuel emission factors from IPCC (2006).

xv This option assumes no improvements in fuel mix.

xvi This option assumes no improvements in non-electric fuel mix.

Table A.III.11 | Technical parameters and estimates for cost of conserved carbon of waste treatment practices[i]

Options	*DOC*	*OX*	*R*	*EI_{CH4}*	*EI_{N2O}*	*EI_{CO2eq}*	*LCCC*
	Degradable organic carbon (g C/kg MSW) [ii, iii]	**Oxidation factor (fraction)**	**Fraction of recovered CH_4**	**CH_4 emission intensity of MSW (gCH_4/kg MSW)** [ii, iv]	**N_2O emission intensity of MSW (g N_2O/kg MSW)** [ii, iv]	**CO_2eq emission intensity of MSW (tCO_2eq/t MSW)** [ii]	**Levelized cost of conserved carbon at 10 % WACC (USD_{2010}/tCO_2eq)** [v]
	min/max			**min/max**	**min/max**	**min/max**	**min/max**
Reference: Landfill at MSW disposal site	*140/210*	0	0	*42/110*	~0	**0.58/1.5**	
Reducing MSW landfill							
Composting	–	–	–	0.0/8	0.06/0.6	**0.019/0.35**	– 140/470
Anaerobic digestion	–	–	–	0/1/8	~0	**0/0.17**	150/590
Improving MSW landfill practices							
Biocover	*140/210*	0.8[vi]	0	*8.5/21*	~0	**0.12/0.19**	99/100
In-situ aeration	*140/210*	0.9	0	*4.2/11*	~0	**0.058/0.10**	99/130
Flaring	*140/210*	0	0.6/0.85	*6.4/43*	~0	**0.087/0.35**	5.0/58
CH_4 capture for power generation	*140/210*	0	0.6/0.9	*4.2/43*	~0	**0.058/0.35**	–37/66
CH_4 capture for heat generation	*140/210*	0	0.6/0.9	*4.2/43*	~0	**0.058/0.35**	–70/89

Notes:

i Note that input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized.

ii On wet weight basis.

iii Total DOC derived from estimates for regional composition of wastes and fraction of DOC in each type of waste (Pipatti et al., 2006, Tables 2.3 and 2.4).

iv Methane emissions intensity of reference and improved landfill practices is based on Frøiland Jensen and Pipatti (2001, Table 3) and approach above, which is based on equation 1 of aforementioned source. Methane emission intensity and nitrous oxide emissions intensity of reduced landfill options is based on IPCC (2006).

v Based on EPA (2013).

vi Based on EPA (2006).

A.III.4.2.6 Domestic wastewater

Specific CO_2eq emissions of wastewater (tCO_2/t BOD_5) are based on IPCC (2006) using the following equation to convert methane emissions.

$$EI_{CO2e} = MAX_{CH4} \cdot MCF \cdot GWP_{CH4} \qquad \text{(Equation A.III.26)}$$

Where

- MAX_{CH4} is the maximum CH_4 production
- MCF is the methane correction factor
- GWP_{CH4} is the global warming potential of methane, $GWP_{CH4} = 21$

The levelized cost of conserved carbon is taken directly from EPA (2013). The discount rate used by EPA (2013) to derive these values was 10 %.

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A.III.5 AFOLU

A.III.5.1 Introduction

Figure 11.16 shows ranges for baseline emission intensities of selected agricultural and forestry commodities, emission intensities after application of mitigation options, and specific mitigation costs.

A.III.5.2 Approach

Commodity definitions are taken from the FAOSTAT (2013) database, where 'cereals' is the aggregation of 16 cereal crops, 'rice' is paddy rice, 'milk' is whole, fresh milk from dairy cows, 'meat' is meat from cattle only, and wood is 'roundwood'.

A.III.5.2.1 Baseline Emission Intensities

Baseline emission intensities represent the minimum and maximum of regional averages for five world regions. For agricultural commodities (rice, cereals, milk, and meat), they are calculated based on 11-year averages (2000–2010) of total annual CO_2eq emissions and total annual production volumes per region taken from (FAOSTAT, 2013). The following emission categories are considered for the calculation of baseline emission intensities: 'synthetic fertilizer' for cereals, 'rice cultivation' for paddy rice, and 'enteric fermentation' and 'manure management' for milk and meat.

For production of roundwood only afforestation and reforestation of idle land is considered. Hence, baseline emission intensities are set to zero.

A.III.5.2.2 Improved emission intensities

Improved emission intensities are derived by deducing product-specific mitigation potentials from baseline emission intensities.

Table A.III.12 | Technical parameters and estimates for cost of conserved carbon of wastewater treatment practices.[i]

Options	MAX_{CH4} **Maximum CH_4 production ($kg\ CH_4/kg\ BOD_5$[ii])[iii]**	MCF **Methane Correction Factor (fraction)[iii]**	EI_{CO2e} **CO_2eq emission intensity (tCO_2/t BOD_5)**	$LCCC$ **Levelized cost of conserved carbon (USD_{2010}/tCO_2eq)[iv]**
Untreated system: Stagnant sewer (open and warm)[v]	0.6	0.4–0.8	**5–10**	–
Aerobic wastewater plant (WWTP)[vi]	0.6	0.2–0.4	**2.5–5**	0–530
Centralized wastewater collection and WWTP[vii]	0.6	0–0.1	**0–1.3**	0–530
Aerobic biomass digester with CH_4 collection[viii]	0.6	0–0.1	**0–1.3**	0–530

Notes:

i Note that input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized.

ii BOD: Biochemical Oxygen Demand. The amount of dissolved oxygen that biological organisms need in order to break down organic material into CH4. For domestic wastewater this value is in the range of 110–400 mg/l.

iii Based on IPCC (2006). N2O emission are neglected, since they do not play a significant role in emissions from domestic wastewater.

iv These values are directly taken from EPA (2013). They are relative to regional baselines.

v Untreated wastewater that is stored in a stagnant sewer under open and warm conditions.

vi Aerobic wastewater treatment refers to the removal of organic pollutants in wastewater by bacteria that require oxygen to work. Water and carbon dioxide are the end products of the aerobic wastewater treatment process.

vii Centralized wastewater collection improves the reduction efficiency. Processes are the same as for the aerobic treatment plant. Centralized collection of wastewater assumes that in general an infrastructure was established that ensures local wastewater storage in closed tanks and secures (emission impermeable) transport from production site to treatment plant.

viii Anaerobic wastewater treatment is a process whereby bacteria digest bio-solids in the absence of oxygen.

Mitigation options considered in the derivation of product-specific mitigation potentials include 'improved agronomic practices', 'nutrient management', 'tillage and residue management' and 'agroforestry' for cereals; 'rice land management' for rice; 'feeding' and 'dietary additives' for milk and meat production; and 'afforestation and reforestation' for roundwood production.

For cereals and paddy rice, data on mitigation potentials is provided by Smith et al. (2008) as average amount of CO_2eq sequestered per land area for four climate zones. These values are converted into amounts of CO_2eq sequestered per product by multiplication with global average product yields per land area based on FAOSTAT (2013).

For meat and milk, mitigation potentials are provided by Smith et al. (2008) as percentage reductions in emissions per mitigation option (see above) and region for five geographical regions. Minimum, average, and maximum of five regional values per mitigation option are taken and converted into amounts of CO_2eq sequestered per product by multiplication with an unweighted average of regional averages of emissions from enteric fermentation per product derived from FAOSTAT (2013). The derivation of the latter is done by dividing the 11-year (2000–2010) regional averages of emissions from enteric fermentation per commodity by the corresponding 11-year regional averages of the total number of producing animals for five geographical regions and by subsequently taking the unweighted average of those five regional averages. For roundwood, the carbon sequestration potential is calculated for representative tree species (based on FAO (2006) and IPCC (2006)) which match the rotation periods for short-term rotations given by Sathaye et al. (2006) for ten geographical regions. Regional and country averages are calculated based on the highest and lowest values for the ten geographical regions.

A.III.5.2.3 Levelized cost of conserved/sequestered carbon

Mitigation costs for agricultural mitigation options are taken from Smith et al. (2008) for cereals and paddy rice, and from US-EPA (2013) for milk and meat. For the livestock mitigation options, only the low end of the given cost range is considered. Costs for afforestation and reforestation are based on Sathaye et al. (2006).

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ANNEX

IV

Annex IV: Contributors to the IPCC WGIII Fifth Assessment Report

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ANNEX

V

Annex V: Expert Reviewers, Government Reviewers and Other Scientific Advisors of the IPCC WGIII Fifth Assessment Report

This annex should be cited as:

IPCC, 2014: Annex V: Expert Reviewers, Government Reviewers and Other Scientific Advisors of the IPCC WGIII Fifth Assessment Report. In: ***Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*** [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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ANNEX

VI

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*Note: * indicates the term also appears in the Glossary (Annex I). Bold page numbers indicate page spans for entire chapters. Italicized page numbers denote tables, figures and boxed material.*

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