Renewable Energy in the Context of Sustainable Development

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Chapter 9: Renewable Energy in the Context of Sustainable Development

CONTENTS

EXECUTIVE SUMMARY

Historically, economic development has been strongly correlated with increasing energy use and growth of greenhouse gas (GHG) emissions. Renewable energy (RE) can help decouple that correlation, contributing to sustainable development (SD). In addition, RE offers the opportunity to improve access to modern energy services for the poorest members of society, which is crucial for the achievement of any single of the eight Millennium Development Goals.

Theoretical concepts of SD can provide useful frameworks to assess the interactions between SD and RE. SD addresses concerns about relationships between human society and nature. Traditionally, SD has been framed in the three-pillar model—Economy, Ecology, and Society—allowing a schematic categorization of development goals, with the three pillars being interdependent and mutually reinforcing. Within another conceptual framework, SD can be oriented along a continuum between the two paradigms of weak sustainability and strong sustainability. The two paradigms differ in assumptions about the substitutability of natural and human-made capital. RE can contribute to the development goals of the three-pillar model and can be assessed in terms of both weak and strong SD, since RE utilization is defined as sustaining natural capital as long as its resource use does not reduce the potential for future harvest.

The relationship between RE and SD can be viewed as a hierarchy of goals and constraints that involve both global and regional or local considerations. Though the exact contribution of RE to SD has to be evaluated in a country specific context, RE offers the opportunity to contribute to a number of important SD goals: (1) social and economic development; (2) energy access; (3) energy security; (4) climate change mitigation and the reduction of environmental and health impacts. The mitigation of dangerous anthropogenic climate change is seen as one strong driving force behind the increased use of RE worldwide. The chapter provides an overview of the scientific literature on the relationship between these four SD goals and RE and, at times, fossil and nuclear energy technologies. The assessments are based on different methodological tools, including bottom-up indicators derived from attributional lifecycle assessments (LCA) or energy statistics, dynamic integrated modelling approaches, and qualitative analyses.

Countries at different levels of development have different incentives and socioeconomic SD goals to advance RE. The creation of employment opportunities and actively promoting structural change in the economy are seen, especially in industrialized countries, as goals that support the promotion of RE. However, the associated costs are a major factor determining the desirability of RE to meet increasing energy demand and concerns have been voiced that increased energy prices might endanger industrializing countries' development prospects; this underlines the need for a concomitant discussion about the details of an international burden-sharing regime. Still, decentralized grids based on RE have expanded and already improved energy access in developing countries. Under favorable conditions, cost savings in comparison to non-RE use exist, in particular in remote areas and in poor rural areas lacking centralized energy access. In addition, non-electrical RE technologies offer opportunities for modernization of energy services, for example, using solar energy for water heating and crop drying, biofuels for transportation, biogas and modern biomass for heating, cooling, cooking and lighting, and wind for water pumping. RE deployment can contribute to energy security by diversifying energy sources and diminishing dependence on a limited number of suppliers, therefore reducing the economy's vulnerability to price volatility. Many developing countries specifically link energy access and security issues to include stability and reliability of local supply in their definition of energy security.

Supporting the SD goal to mitigate environmental impacts from energy systems, RE technologies can provide important benefits compared to fossil fuels, in particular regarding GHG emissions. Maximizing these benefits often depends on the specific technology, management, and site characteristics associated with each RE project, especially with respect to land use change (LUC) impacts. Lifecycle assessments for electricity generation indicate that GHG emissions from RE technologies are, in general, considerably lower than those associated with fossil fuel options, and in a range of conditions, less than fossil fuels employing carbon capture and storage (CCS). The maximum estimate for concentrating solar power (CSP), geothermal, hydropower, ocean and wind energy is less than or equal to 100 g CO_2eq/kWh, and median values for all RE range from 4 to 46 g CO_2eq/kWh. The GHG balances of bioenergy production, however, have considerable uncertainties, mostly related to land management and LUC. Excluding LUC, most bioenergy systems reduce GHG emissions compared to fossil-fuelled systems and can lead to avoided GHG emissions from residues and wastes in landfill disposals and co-products; the combination of bioenergy with CCS may provide for further reductions. For transport fuels, some first-generation biofuels result in relatively modest GHG mitigation potential, while most next-generation biofuels could provide greater climate benefits. To optimize benefits from bioenergy production, it is critical to reduce uncertainties and to consider ways to mitigate the risk of bioenergy-induced LUC.

RE technologies can also offer benefits with respect to air pollution and health. Non-combustion-based RE power generation technologies have the potential to significantly reduce local and regional air pollution and lower associated health impacts compared to fossil-based power generation. Impacts on water and biodiversity, however, depend on local conditions. In areas where water scarcity is already a concern, non-thermal RE technologies or thermal RE technologies using dry cooling can provide energy services without additional stress on water resources. Conventional water-cooled thermal power plants may be especially vulnerable to conditions of water scarcity and climate change. Hydropower and some bioenergy systems are dependent on water availability, and can either increase competition or mitigate water scarcity. RE specific impacts on biodiversity may be positive or negative; the degree of these impacts will be determined by site-specific conditions. Accident risks of RE technologies are not negligible, but the technologies' often decentralized structure strongly limits the potential for disastrous consequences in terms of fatalities. However, dams associated with some hydropower projects may create a specific risk depending on site-specific factors.

The scenario literature that describes global mitigation pathways for RE deployment can provide some insights into associated SD implications. Putting an upper limit on future GHG emissions results in welfare losses (usually measured as gross domestic product or consumption foregone), disregarding the costs of climate change impacts. These welfare losses are based on assumptions about the availability and costs of mitigation technologies and increase when the availability of technological alternatives for constraining GHGs, for example, RE technologies, is limited. Scenario analyses show that developing countries are likely to see most of the expansion of RE production. Increasing energy access is not necessarily beneficial for all aspects of SD, as a shift to modern energy away from, for example, traditional biomass could simply be a shift to fossil fuels. In general, available scenario analyses highlight the role of policies and finance for increased energy access, even though forced shifts to RE that would provide access to modern energy services could negatively affect household budgets. To the extent that RE deployment in mitigation scenarios contributes to diversifying the energy portfolio, it has the potential to enhance energy security by making the energy system less susceptible to (sudden) energy supply disruption. In scenarios, this role of RE will vary with the energy form. With appropriate carbon mitigation policies in place, electricity generation can be relatively easily decarbonized through RE sources that have the potential to replace concentrated and increasingly scarce fossil fuels in the building and industry sectors. By contrast, the demand for liquid fuels in the transport sector remains inelastic if no technological breakthrough can be achieved. Therefore oil and related energy security concerns are likely to continue to play a role in the future global energy system; as compared to today these will be seen more prominently in developing countries. In order to take account of environmental and health impacts from energy systems, several models have included explicit representation of these, such as sulphate pollution. Some scenario results show that climate policy can help drive improvements in local air pollution (i.e., particulate matter), but air pollution reduction policies alone do not necessarily drive reductions in GHG emissions. Another implication of some potential energy trajectories is the possible diversion of land to support biofuel production. Scenario results have pointed at the possibility that climate policy could drive widespread deforestation if not accompanied by other policy measures, with land use being shifted to bioenergy crops with possibly adverse SD implications, including GHG emissions.

The integration of RE policies and measures in SD strategies at various levels can help overcome existing barriers and create opportunities for RE deployment in line with meeting SD goals. In the context of SD, barriers continue to impede RE deployment. Besides market-related and economic barriers, those barriers intrinsically linked to societal and personal values and norms will fundamentally affect the perception and acceptance of RE technologies and related deployment impacts by individuals, groups and societies. Dedicated communication efforts are therefore a crucial component of any transformation strategy and local SD initiatives can play an important role in this context. At international and national levels, strategies should include: the removal of mechanisms that are perceived to work against SD; mechanisms for SD that internalize environmental and social externalities; and RE strategies that support low-carbon, green and sustainable development including leapfrogging.

The assessment has shown that RE can contribute to SD to varying degrees; more interdisciplinary research is needed to close existing knowledge gaps. While benefits with respect to reduced environmental and health impacts may appear more clear-cut, the exact contribution to, for example, social and economic development is more ambiguous. In order to improve the knowledge regarding the interrelations between SD and RE and to find answers to the question of an effective, economically efficient and socially acceptable transformation of the energy system, a much closer integration of insights from social, natural and economic sciences (e.g., through risk analysis approaches), reflecting the different (especially intertemporal, spatial and intra-generational) dimensions of sustainability, is required. So far, the knowledge base is often limited to very narrow views from specific branches of research, which do not fully account for the complexity of the issue.

9.1 Introduction

Sustainable development (SD) emerged in the political, public and academic arena in 1972 with the Founex report and again in 1987 with the publication of the World Commission on Environment and Development (WCED) report *Our Common Future*—also known as the 'Brundtland Report'. This *Special Report on Renewable Energy Sources and Climate Change Mitigation* follows the Brundtland definition that SD meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987; Bojö et al., 1992). Due to the difficulty of putting such a concept into operation, many competing frameworks for SD have been put forward since then (Pezzey, 1992; Hopwood et al., 2005). In this chapter, some SD concepts will be introduced, links between SD and RE will be elucidated, and implications for decision making will be clarified.

SD was tightly coupled with climate change (and thence the IPCC) at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil in 1992 that sought to stabilize atmospheric concentrations of greenhouse gases at levels considered to be safe. As a consequence, and building on the IPCC's First Assessment Report that focused on the technology and cost-effectiveness of mitigation activities, the Second Assessment Report included equity concerns in addition to social considerations (IPCC, 1996a). The Third Assessment Report addressed global sustainability comprehensively (IPCC, 2007b) and the Fourth Assessment (AR4) included chapters on SD in both Working Group (WG) II and III reports with a focus on a review of both climate-first and development-first literature (IPCC, 2007a,b).

9.1.1 The concept of sustainable development

Traditionally, sustainability has been framed in the three-pillar model: Economy, Ecology and Society are all considered to be interconnected and relevant for sustainability (BMU, 1998). The three-pillar model explicitly acknowledges the encompassing nature of the sustainability concept and allows a schematic categorization of sustainability issues. The United Nations General Assembly aims for action to promote the integration of the three components of SD—economic development, social development and environmental protection—as interdependent and mutually reinforcing pillars (UN, 2005a). This view subscribes to an understanding where a certain set of actions (e.g., substitution of fossil fuels with RE sources) can fulfil all three development goals simultaneously. The three-pillar model has been criticized for diluting a strong normative concept with vague categorization and replacing the need to protect natural capital with a methodological notion of trans-sectoral integration (Brand and Jochum, 2000).

Within another conceptual framework, SD can be oriented along a continuum between the two paradigms of weak sustainability and strong sustainability. The two paradigms differ in assumptions about the substitutability of natural and human-made capital (Hartwick, 1977; Pearce et al., 1996; Neumayer, 2003). Weak sustainability has been labelled the substitutability paradigm (Neumayer, 2003) and is based on the idea that only the aggregate stock of capital needs to be conserved—natural capital can be substituted with man-made capital without compromising future well-being. As such, it can be interpreted as an extension of neoclassical welfare economics (Solow, 1974; Hartwick, 1977). For example, one can argue that non-renewable resources, such as fossil fuels, can be substituted, for example, by renewable resources and technological progress as induced by market prices (Neumayer, 2003). Weak sustainability also implies that environmental degradation can be compensated for with man-made capital such as more machinery, transport infrastructure, education and information technology.

Whereas weak sustainability assumes that the economic system flexibly adapts to varying availability of forms of capital, strong sustainability starts from an ecological perspective with the intent of proposing guardrails for socioeconomic pathways. Strong sustainability can be viewed as the non-substitutability paradigm (Pearce et al., 1996; Neumayer, 2003), based on the belief that natural capital cannot be substituted, either for production purposes or for environmental provision of regulating, supporting and cultural services (Norgaard, 1994). As an example, limited sinks such as the atmosphere's capacity to absorb GHG emissions may be better captured by applying the constraints of the strong sustainability concept (Neumayer, 2003; IPCC, 2007b). In one important interpretation, the physical stock of specific non-substitutable resources (so-called 'critical natural capital') must be preserved (not allowing for substitution between different types of natural capital) (Ekins et al., 2003). Guardrails for remaining within the bounds of sustainability are often justified or motivated by nonlinearities, discontinuities, non-smoothness and non-convexities (Pearce et al., 1996). As a typical correlate, natural scientists warn of and describe specific tipping points, critical thresholds at which a tiny perturbation can qualitatively alter the state or development of Earth systems (Lenton et al., 2008). The precautionary principle argues for keeping a safe distance from guardrails, putting the burden of proof for the non-harmful character of natural capital reduction on those taking action (Ott, 2003).

RE can contribute to the development goals of the three-pillar model and can be assessed in terms of both weak and strong sustainability. Consumption of non-RE sources, such as fossil fuels and uranium, reduces natural capital directly. RE, in contrast, sustains natural capital as long as its resource use does not reduce the potential for future harvest.

9.2 Interactions between sustainable development and renewable energies

The relationship between RE and sustainability can be viewed as a hierarchy of goals and constraints that involve both global and regional or local considerations. In this chapter, and consistent with the conclusion of the AR4, a starting point is that mitigation of dangerous anthropogenic climate change will be one strong driving force behind increased use of RE technologies worldwide. To the extent that climate change stabilization levels (e.g., a maximum of 550 ppm CO_2eq atmospheric GHG concentration or a maximum of 2°C temperature increase with respect to the pre-industrial global average) are accepted, there is an implicit acknowledgement of a strong sustainability principle, as discussed in Section 9.1.

RE is projected to play a central role in most GHG mitigation strategies (Chapter 10), which must be technically feasible and economically efficient so that any cost burdens are minimized. Knowledge about technological capabilities and models for optimal mitigation pathways are therefore important. However, energy technologies, economic costs and benefits, and energy policies, as described in other chapters of this report, depend on the societies and natural environment within which they are embedded. Spatial and cultural variations are therefore another important factor in coherently addressing SD. Sustainability challenges and solutions crucially depend on geographic setting (e.g., solar radiation), socioeconomic conditions (e.g., inducing energy demand), inequalities within and across societies, fragmented institutions, and existing infrastructure (e.g., electric grids) (Holling, 1997; NRC, 2000), but also on a varying normative understanding of the connotation of sustainability (Lele and Norgaard, 1996). Analysts therefore call for a differentiation of analysis and solution strategies according to geographic locations and specific places (e.g., Wilbanks, 2002; Creutzig and Kammen, 2009) and a pluralism of epistemological and normative perspectives of sustainability (e.g., Sneddon et al., 2006).

These aspects underline the need to assess both the social and environmental impacts of RE technologies to ensure that RE deployment remains aligned with overall SD goals. Some of these important caveats are addressed in this chapter, like the extent to which RE technologies may have their own environmental impact and reduce natural capital, for example, by upstream GHG emissions, destroying forests, binding land that cannot be used otherwise and consuming water. Evaluating these impacts from the perspectives of the weak and strong sustainability paradigms elucidates potential tradeoffs between decarbonization and other sustainability goals.

Hence, efforts to ensure SD can impose additional constraints or selection criteria on some mitigation pathways, and may in fact compel policymakers and citizens to accept trade-offs. For each additional boundary condition placed on the energy system, some development pathways are eliminated as being unsustainable, and some technically feasible scenarios for climate mitigation may not be viable if SD matters. However, as also discussed in this chapter, the business-as-usual trajectories to which climate mitigation scenarios are compared are probably also insufficient to achieve SD.

9.2.1 Framework of Chapter 9 and linkages to other chapters of this report

This chapter provides an overview of the role that RE can play in advancing the overarching goal of SD. Chapter 1 in this report introduces RE and makes the link to climate change mitigation, and Chapters 2 through 7 assess the potential and impacts of specific RE technologies in isolation. Chapter 8 focuses on the integration of renewable sources into the current energy system, and Chapters 10 and 11 discuss the economic costs and benefits of RE and climate mitigation, and of RE policies, respectively. As an integrative chapter, this chapter assesses the role of RE from a SD perspective by comparing and reporting the SD impacts of different energy technologies, by drawing on still limited insights from the scenario literature with respect to SD goals, and by discussing barriers to and opportunities of RE deployment in relation to SD. Figure 9.1 illustrates the links of Chapter 9 to other chapters in this report.

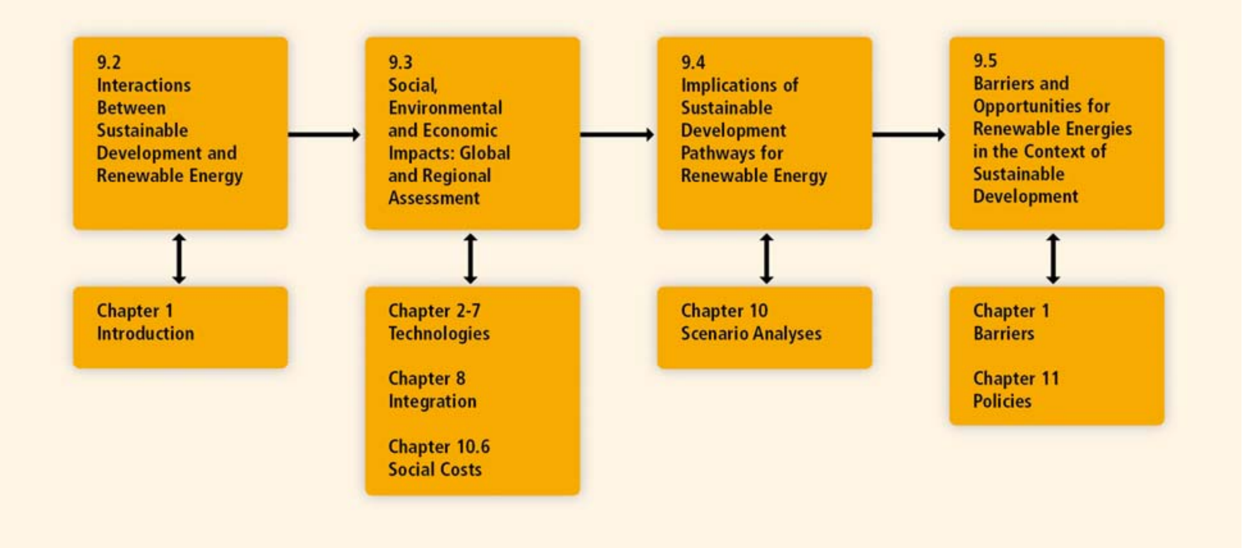

Figure 9.1 | Framework of Chapter 9 and linkages to other chapters.

For a conclusive and comprehensive assessment of sustainable RE deployment pathways, this chapter would need to integrate information on each specific energy technology, including associated economic costs and benefits and existing energy policies, as provided in the other chapters of this report. As a result, SD opportunities associated with RE deployment could be clearly outlined, informing policymakers about pathways and how to realize them while avoiding unintended side effects. However, given the diverse range of possible opportunities and the limitations of current modelling capacities, such comprehensive integrated assessments are not yet practicable. This chapter will focus its assessment on the clearly defined set of opportunities outlined in Section 1.4.1:

- social and economic development,
- energy access,
- energy security, and
- climate change mitigation and reduction of environmental and health impacts.

This set of opportunities can be viewed as goals that should be achieved for RE to contribute to SD. As will be discussed in the following section, the potential of RE to increase access to modern energy technologies can facilitate social and economic development. Energy access and social and economic development measures relate to current well-being and to some extent to intra-generational equity and sustainability, for example, through an emphasis on energy-related equity questions, including gender equity and empowerment. The potential contribution of RE to energy security, climate change mitigation and the reduction of environmental impacts addresses more explicitly the intertemporal and intergenerational well-being aspect inherent in sustainability. Energy access, social and economic development and energy security concerns are very often considered under the weak sustainability paradigm, because trade-offs are taken into account allowing for a balance between these goals. Environmental impacts, on the other hand, are usually evaluated under the strong sustainability paradigm because they are very often understood as constraints for transformation pathways. To enable responsible decision making, it is crucial to understand the implications and possible trade-offs of SD goals that result from alternative energy system choices.

This chapter provides an overview of the scientific literature on the relationship between these four SD goals and RE and, at times, fossil and nuclear energy technologies. SD aspects that need to be included in future and more comprehensive assessments of potential development pathways are outlined in a quantitative as well as in a qualitative and more narrative manner. Section 9.3 focuses on static bottom-up indicators based on currently available data (e.g., LCA) to assess the socioeconomic and environmental impacts of individual RE and other energy technologies. Section 9.4, on the other hand, aims to assess the interactions of future RE deployment and SD pathways in a more dynamic, top-down and integrated manner. Pathways are primarily understood as scenario results that attempt to address the complex interrelations among the different energy technologies at a global scale. Therefore the chapter mainly refers to global scenarios derived from large integrated models, which are also at the core of the analysis in Chapter 10. The analysis concludes with Section 9.5, which aims to analyze barriers and opportunities for RE in the context of SD.

To conclude, when evaluating RE with respect to the multi-dimensional challenge of SD, no single global answer is possible. Many solutions will depend strongly on local, regional and cultural conditions, and the approaches and emphases of developing and developed countries may also be different. Therefore, it is not possible for this chapter to provide a clear set of recommendations for a pathway towards SD using RE.

9.2.2 Sustainable development goals for renewable energy and sustainable development indicators

Energy indicators can assist countries in monitoring progress made in energy subsystems consistent with sustainability principles. Measurement and reporting of indicators not only gauges but also spurs the implementation of SD and can have a pervasive effect on decision making (Meadows, 1998; Bossel, 1999). However, measuring energy sustainability is surrounded by a wide range of conceptual and technical issues (Sathaye et al., 2007) and may require updated methodologies (Creutzig and Kammen, 2009).

Over the past two decades, progress has been made towards developing a uniform set of energy indicators for sustainable development which relate to the broad themes of economy, society and environment (Vera and Langlois, 2007). For RE technologies, quantitative indicators include price of generated electricity, GHG emissions during the full lifecycle of the technology, availability of renewable sources, efficiency of energy conversion, land requirements and water consumption (Evans et al., 2009). Other approaches develop a figure of merit to compare the different RE systems based upon their performance, net energy requirements, GHG emissions and other indicators (Varun et al., 2010).

Due to the need to expand the notion of economic development beyond the ubiquitously used gross domestic product (GDP), a variety of SD indicators have been suggested. Aggregate indicators of weak sustainability include green net national product, genuine savings (Hamilton, 1994; Hamilton and Clemens, 1999; Dasgupta, 2001), the index of sustainable economic welfare (ISEW) and the genuine progress indicator (GPI) (e.g., Daly, 2007), with the ISEW and GPI proposed as intermediate steps by proponents of strong sustainability. Notably, indicators that extend GDP, such as the latter two, tend to deviate qualitatively from the GDP since the 1970s or 1980s, stagnating (or in case of the UK decreasing) in many Organisation for Economic Co-operation and Development (OECD) countries (Lawn, 2003). Indicators more consistent with strong sustainability include carrying capacity, ecological footprint and resilience (Pearce et al., 1996), sustainable national income and sustainability gaps (Hueting, 1980; Ekins and Simon, 1999).

The use of aggregated indicators for economic development (e.g., the Human Development Index (HDI) or ISEW (Fleurbaey, 2009)), however, poses significant challenges. Resulting values are indexed with high uncertainty and are often challenged on methodological and epistemological grounds (Neumayer, 2003). Rigorous justification for specific choices for weighting the components of aggregate indicators is difficult to make and as many indicators are proxies, they may also convey a message of false quantitative accuracy. Also, it is often difficult to obtain reliable and internationally consistent data series across components of the composite indicator. Aggregate indicators of sustainability integrate many aspects of social and economic development, and hence, are ignorant of the specific sustainability impact of RE deployment. Sustainability assessment may instead require a well-identified dashboard of indicators (Stiglitz et al., 2009).

Section 9.3 evaluates RE in terms of static bottom-up measures while being cognizant of their limitations. The four SD goals, as defined in section 9.2.1, are used as guidelines to assess the contribution of RE to SD. Since sustainability is an open-boundary concept, and is confronted with tipping elements of unknown probability, doubts can be raised regarding the possibility of an ultimate coherent quantitative evaluation. Quantitative indicators, which might be adjusted as new challenges emerge and new data become available, reflect a suitable framework to assess the existing literature, but cannot close the considerable gaps in achieving a comprehensive and consistent measure of SD.

Social and economic development

The energy sector has generally been perceived as key to economic development with a strong correlation between economic growth and expansion of energy consumption. Indicators such as GDP or per capita GDP have been used as proxies for economic development for several decades (such as in integrated models, see Section 9.4.1) and the HDI has been shown to correlate well with per capita energy use (see Section 9.3.1). The HDI is used to assess comparative levels of development in countries and includes purchasing power parity-adjusted income, literacy and life expectancy as its three main matrices. The HDI is only one of many possible measures of the well-being of a society, but it can serve as a proxy indicator of development.

Due to the availability of data time series for these parameters (GDP, HDI), they will be used as indicators in this chapter (Sections 9.3.1.1 and 9.3.1.2). However, a key point is that aggregate macroeconomic parameters (GDP), or even extended versions of these economic indicators (HDI), are insufficient for obtaining a complete picture of the sustainability of social and economic development. A further indicator of technological development is decreasing energy intensity, that is, a decrease in the amount of energy needed to produce one dollar of GDP.

Beyond indicators that describe the efficiency characteristics of an economy, additional macroeconomic benefits are potentially associated with RE, for example, increased employment opportunities (see Section 9.3.1.3). Furthermore, under agreements such as that reached in Copenhagen in 2009, financial pledges have been made by wealthier nations to aid developing countries with climate change mitigation measures (see Section 9.3.1.4). Each of these latter points may have either positive or negative effects, depending on regional context and on the particular policies that are implemented.

Energy access

Access to modern energy services, whether from renewable or non-renewable sources, is closely correlated with measures of development, particularly for those countries at earlier development stages. Indeed, the link between adequate energy services and achievement of the Millennium Development Goals (MDGs) was defined explicitly in the Johannesburg Plan of Implementation that emerged from the World Summit on Sustainable Development in 2002 (IEA, 2010b). As emphasized by a number of studies, providing access to modern energy (such as electricity or natural gas) for the poorest members of society is crucial for the achievement of any single of the eight MDGs (Modi et al., 2006; GNESD, 2007a; Bazilian et al., 2010; IEA, 2010b).

Over the past few centuries, industrialized societies have transformed their quality of life by exploiting non-renewable fossil energy sources, nuclear energy and large-scale hydroelectric power. However, in 2010 almost 20% of the world population, mostly in rural areas, still lack access to electricity. Twice that percentage cook mainly with traditional biomass, mostly gathered in an unsustainable manner (IEA, 2010b). In the absence of a concerted effort to increase energy access, the absolute number of those without electricity and modern cooking possibilities is not expected to change substantially in the next few decades.

Concrete indicators to be discussed in more detail in Section 9.3.2 are per capita final energy consumption related to income, as well as breakdowns of electricity access (divided into rural and urban areas), and data for the number of those using coal or traditional biomass for cooking. Implicit in discussions of energy access is a need for models that can assess the sustainability of future energy system pathways with respect to decreasing the wide disparity between rural and urban areas (e.g., in terms of energy forms and quantities used or infrastructure reliability) within countries or regions (see Section 9.4.2).

Energy security

There is no commonly accepted definition of the term ‘energy security’ and its meaning is highly context-dependent (Kruyt et al., 2009). At a general level it can best be understood as robustness against (sudden) disruptions of energy supply (Grubb et al., 2006). Thinking broadly across energy systems, one can distinguish between different aspects of security that operate at varying temporal and geographical scales (Bazilian and Roques, 2008). Two broad themes can be identified that are relevant to energy security, whether for current systems or for the planning of future RE systems: availability and distribution of resources, and variability and reliability of energy supply. Given the interdependence of economic growth and energy consumption, access to a stable energy supply is a major political concern and a technical and economic challenge facing both developed and developing economies, since prolonged disruptions would create serious economic and basic functionality problems for most societies (Larsen and Sønderberg Petersen, 2009).

In the long term, the potential for fossil fuel scarcity and decreasing quality of fossil reserves represents an important reason for a transition to a sustainable worldwide RE system. The issue of recoverable fossil fuel resource amounts is contentious, with optimists (Greene et al., 2006) countered by more pessimistic views (Campbell and Laherrère, 1998) and cautious projections of lacking investments falling between the two poles (IEA, 2009). However, increased use of RE permits countries to substitute away from the use of fossil fuels, such that existing reserves of fossil fuels are depleted less rapidly and the point at which these reserves will eventually be exhausted is shifted farther into the future (Kruyt et al., 2009).

Concerns about limited availability and distribution of resources are also a critical component of energy security in the short term. All else being equal, the more reliant an energy system is on a single energy source, the more susceptible the energy system is to serious disruptions. Examples include disruptions to oil supply, unexpectedly large and widespread periods of low wind or solar insolation (e.g., due to weather), or the emergence of unintended consequences of any supply source.

Dependence on energy imports, whether of fossil fuels or the technology needed for implementation of RE, represents a potential source of energy insecurity for both developing and industrialized countries. For example, the response of member states of the International Energy Agency (IEA; itself created in response to the first oil shock of the 1970s) to vulnerability to oil supply disruption has been to mandate that countries hold stocks of oil as reserves in the amount of 90 days of net imports. Compared to fossil fuels, RE resources are far more evenly distributed around the globe (WEC, 2007) and in general less traded on the world market; increasing their share in a country’s energy portfolio can thus diminish the dependence on actual energy imports (Grubb et al., 2006). Hence, the extent to which RE sources contribute to the diversification of the portfolio of supply options and reduce an economy’s vulnerability to price volatility (Awerbuch and Sauter, 2006) represent opportunities to enhance energy security at the global, the national as well as the local level (Awerbuch, 2006; Bazilian and Roques, 2008).

The introduction of renewable technologies that vary on different time scales, ranging from minutes to seasonal, adds a new concern to energy security. Not only will there be concerns about disruption of supplies by unfriendly agents, but also the vulnerability of energy supply to the vagaries of chance and nature (such as extreme events like drought). However, RE can also make a contribution to increasing the reliability of energy services, in particular in remote and rural areas that often suffer from insufficient grid access. Irrespective, a diverse portfolio of energy sources, together with good management and system design (for example, including geographical diversity of sources where appropriate) can help to enhance security.

Specific indicators for security are difficult to identify. Based on the two broad themes described above, the indicators used to provide information about the energy security criterion of SD are the magnitude of reserves, the reserves-to-production ratio, the share of imports in total primary energy consumption, the share of energy imports in total imports, as well as the share of variable and unpredictable RE sources.

Climate change mitigation and reduction of environmental and health impacts

As discussed in Chapter 1, reducing GHG emissions with the aim of mitigating climate change is one of the key driving forces behind a growing demand for RE technologies. However, to evaluate the overall burden from the energy system on the environment, and to identify potential trade-offs, other impacts and categories have to be taken into account as well. Mass emissions to water and air, and usage of water, energy and land per unit of energy generated must be evaluated across technologies. Whereas some parameters can be rigorously quantified, for others comprehensive data or useful indicators may be lacking. In addition, deriving generic impacts on human health or biodiversity is a challenging task, as they are mostly specific to given sites, exposure pathways and circumstances, and often difficult to attribute to single sources.

There are multiple methods to evaluate environmental impacts of projects, such as environmental impact statements/assessments and risk assessments. Most are site-specific, and often limited to direct environmental impacts associated with operation of the facility. To provide a clear framework for comparison, lifecycle assessment (LCA) has been chosen as a bottom-up measure in Section 9.3.4, complemented by a comparative assessment of accident risks to account for burdens resulting from outside normal operation. Most published LCAs of energy supply technologies only assemble lifecycle inventories; quantifying emissions to the environment (or use of resources) rather than reporting effects (or impacts) on environmental quality. A similar approach is followed in Section 9.3.4, as literature reporting lifecycle impacts or aggregate sustainability indicators is scarce. Partly, this is due to the incommensurability of different impact categories. Attempts to combine various types of indicators into one overall score (for example by joining their impact pathways into a common endpoint, or by monetization) have been made; however uncertainties associated with such scoring approaches are often so high that they preclude decision making (Hertwich et al., 1999; Rabl and Spadaro, 1999; Schleisner, 2000; Krewitt, 2002; Heijungs et al., 2003; Sundqvist, 2004; Lenzen et al., 2006). Nevertheless, social costs are discussed in Chapter 10.6, and part of the analysis in Section 9.4.4 is based on monetization of impacts. The latter section analyzes the extent to which environmental impacts are represented in scenario analyses for RE deployment with a macro-perspective, with a focus on land use change and related GHG emissions, as well as local air pollution.

9.3 Social, environmental and economic impacts: global and regional assessment

Countries at different levels of development have different incentives to advance (RE). For developing countries, the most likely reasons to adopt RE technologies are providing access to energy (see Section 9.3.2.), creating employment opportunities in the formal (i.e., legally regulated and taxable) economy, and reducing the costs of energy imports (or, in the case of fossil energy exporters, prolong the lifetime of their natural resource base). For industrialized countries, the primary reasons to encourage RE include reducing carbon emissions to mitigate climate change (see Chapter 1), enhancing energy security (see Section 9.3.3.), and actively promoting structural change in the economy, such that job losses in declining manufacturing sectors are softened by new employment opportunities related to RE. For a conceptual description of the four SD goals assessed in this chapter, see Section 9.2.2.

9.3.1 Social and economic development

This section assesses the potential contributions of RE to sustainable social and economic development. Due to the multi-dimensional nature of SD neither a comprehensive assessment of all mitigation options nor a full accounting of all relevant costs can be performed. Rather, the following section identifies key issues and provides a framework to discuss the relative benefits and disadvantages of RE and fossil fuels with respect to development.

9.3.1.1 Energy and economic growth

With the ability to control energy flows being a crucial factor for industrial production and socioeconomic development (Cleveland et al., 1984; Krausmann et al., 2008), industrial societies are frequently characterized as ‘high-energy civilizations’ (Smil, 2000). Globally, per capita incomes are positively correlated with per capita energy use and economic growth can be identified as the most relevant factor behind increasing energy consumption in the last decades. Nevertheless, there is no agreement on the direction of the causal relationship between energy use and increased macroeconomic output, as the results crucially depend on the empirical methodology employed as well as the region and time period under study (D. Stern, 1993; Asafu-Adjaye, 2000; S. Paul and Bhattacharya, 2004; Ang, 2007, 2008; Lee and Chang, 2008).

Industrialization brings about structural change in the economy and therefore affects energy demand. As economic activity expands and diversifies, demands for more sophisticated and flexible energy sources arise: while societies that highly depend on agriculture derive a large part of primary energy consumption from traditional biomass (Leach, 1992; Barnes and Floor, 1996), coal and liquid fuels—such as kerosene and liquid petroleum gas—gain in importance with rising income, and electricity, gas and oil dominate at high per capita incomes (Grübler, 2004; Marcotullio and Schulz, 2007; Burke, 2010; see Section 9.3.2 and Figure 9.5). From a sectoral perspective, countries at an early stage of development consume the largest part of total primary energy in the residential (and to a lesser extent agricultural) sector. In emerging economies the manufacturing sector dominates, while in fully industrialized countries services and transport account for steadily increasing shares (Schafer, 2005; see Figure 9.2). Furthermore, several authors (Jorgenson, 1984; Schurr, 1984) have pointed out that electricity—which offers higher quality and greater flexibility compared to other forms of energy—has been a driving force for the mechanization and automation of production in industrialized countries and a significant contributor to continued increases in productivity.

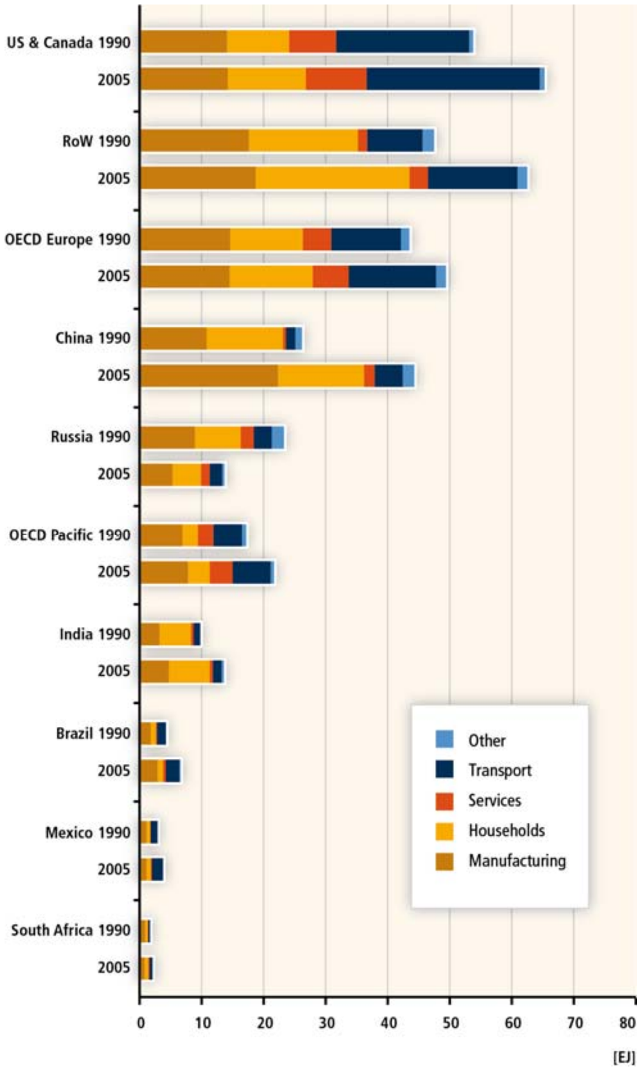

Figure 9.2 | Energy use (EJ) by economic sector. Note that the underlying data are calculated using the IEA physical content method, not the direct equivalent method[1] (IEA, 2008c). Note: RoW = Rest of World.

Despite the fact that as a group industrialized countries consume significantly higher amounts of energy per capita than developing ones, a considerable cross-sectional variation of energy use patterns across countries prevails: while some countries (such as, e.g., Japan) display high levels of per capita incomes at comparably low levels of energy use, others are relatively poor despite extensive energy consumption, especially countries abundantly endowed with fossil fuel resources, in which energy is often heavily subsidized (UNEP, 2008b). It is often asserted that developing and transition economies can ‘leapfrog’, that is, adopt modern, highly efficient energy technologies, to embark on less energy- and carbon-intensive growth patterns compared to the now fully industrialized economies during their phase of industrialization (Goldemberg, 1998). For instance, one study for 12 Eastern European EU member countries finds that between 1990 and 2000, convergence in per capita incomes (measured at purchasing power parity) between fully industrialized and transition economies has been accompanied by significant reductions of energy intensities in the latter (Markandya et al., 2006). For industrialized countries, one hypothesis suggests that economic growth can largely be decoupled from energy use by steady declines in

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[1] Historical energy data have only been available for energy use by economic sector. For a conversion of the data using the direct equivalent method, the different energy carriers used by each economic sector would need to be known.

energy intensity as structural change and efficiency improvements trigger the 'dematerialization' of economic activity (Herman et al., 1990). However, despite the decreasing energy intensities (i.e., energy consumption per unit of GDP) observed over time in almost all regions, declines in energy intensity historically often have been outpaced by economic growth and hence have proved insufficient to achieve actual reductions in energy use (Roy, 2000). In addition, it has been argued that decreases in energy intensity in industrialized countries can partially be explained by the fact that energy-intensive industries are increasingly moved to developing countries (G. Peters and Hertwich, 2008; Davis and Caldeira, 2010) and, as observed energy efficiency improvements are largely driven by shifts to higher quality fuels, they cannot be expected to continue indeterminately (Cleveland et al., 2000; R.K. Kaufmann, 2004).

9.3.1.2 Human Development Index and energy

As already mentioned in Section 9.2.2, the industrialized societies' improvements in the quality of life have so far been mainly based on the exploitation of non-RE sources (while noting the important role of hydropower during the early stages of industrialization, as well as for many developing countries today). Apart from its significance for productive purposes, access to clean and reliable energy constitutes an important prerequisite for fundamental determinants of human development including health, education, gender equality and environmental safety (UNDP, 2007).

Figure 9.3 depicts the correlation between the HDI (see Section 9.2.2) and primary energy use per capita for 135 countries. The graph reveals a positive correlation between energy use and the HDI. In particular, countries with the highest levels of human development are also among the largest energy consumers. For countries with a relatively low energy demand (<84 GJ per capita), the picture is more diverse: while some are constrained to low HDI levels (<0.5), others display medium ones (between 0.5 and 0.8) at comparable energy consumption. With rising levels of energy consumption, saturation of the positive relationship between energy use and HDI sets in (Martinez and Ebenhack, 2008), which means that a certain minimum amount of energy is required to guarantee an acceptable standard of living. Goldemberg (2001) suggests 42 GJ per capita, after which raising energy consumption yields only marginal improvements in the quality of life.

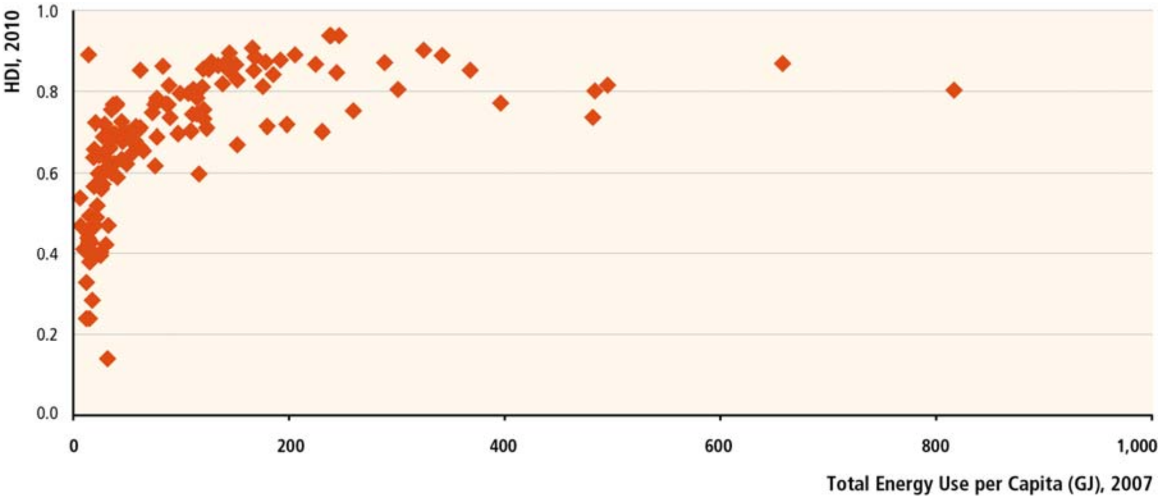

Figure 9.3 | Correlation between total energy use per capita (GJ) and the countries' Human Development Index (HDI). Note that the underlying data on energy use are calculated using the IEA physical content method, not the direct equivalent method.[2] Based on UNDP (2010) and World Bank (2010).

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[2] Historical energy data have only been available for energy use per capita by country. For a conversion of the data using the direct equivalent method, the different energy carriers used by each country would need to be known.

9.3.1.3 Employment creation

According to a recent study prepared by UNEP (2008a), RE already accounts for about 2.3 million jobs worldwide and in many countries job creation is seen as one of the main benefits of investing in RE sources. A study by the German Environment Ministry finds that in 2006, about 236,000 people were employed in RE, up from roughly 161,000 two years earlier (BMU, 2009). Examples of the use of RE in India, Nepal and parts of Africa (Cherian, 2009) as well as Brazil (Goldemberg et al., 2008; Walter et al., 2011) indicate that in many parts of the developing world, RE can stimulate local economic and social development. Numerous governments have included substantial spending on clean energy technologies in their stimulus packages that were put into place in response to the financial and economic crisis (N. Bauer et al., 2009; Bowen et al., 2009). For the USA, one study (Houser et al., 2009) suggested that every USD_{2005} 1 billion spent on green fiscal measures had the potential to create about 33,000 jobs; another one, prepared by the Center for American Progress (Pollin et al., 2008), estimated that a green stimulus of USD_{2005} 90.7 billion could create roughly 2 million jobs. The Council of Economic Advisors to the US administration projects that the USD_{2005} 82 billion spending on clean energy included in the American Recovery and Reinvestment Act will create or safeguard 720,000 job-years through 2012. From a more long-term perspective, many national green growth strategies, for example, in China, Korea, Japan, the EU and the USA (UNEP, 2010), have stressed the deployment of RE as an important contribution to job creation and one study (Barbier, 2009) argues that a ‘Global Green New Deal’ could in the long run create more than 34 million jobs in low-carbon transportation and related activities alone.

Other studies that also observe possible negative employment effects are more critical in this regard (Frondel et al., 2010) and the assertion of positive employment effects is further weakened by disagreements about the methodology used to calculate them (Sastresa et al., 2009). Evaluating the labour market effects of RE policies is in any case a challenging task that requires an assessment of how value chains and production patterns adjust in the mid-term and how structural adjustment and innovative activity respond in the long term (Fankhauser et al., 2008). RE should not be regarded as an instrument that can be employed to cure underlying inefficiencies in labour markets. For a comprehensive assessment, it would be necessary to factor in all social costs and benefits of a given technology (including interactions with labour market frictions) to be able to appropriately compare RE and fossil fuels on a level playing field. This includes the costs of support schemes for RE as well as subsidies for fossil fuels (see Section 9.5.2).

9.3.1.4 Financing renewable energy

An evaluation of the specific benefits of RE discussed in this section can only be undertaken in a country-specific context. Especially for developing countries, the associated costs are a major factor determining the desirability of RE to meet increasing energy demand, and concerns have been voiced that increased energy prices might endanger industrializing countries’ development prospects (Mattoo et al., 2009). Yet, as will be discussed in more detail in Section 9.3.2., RE has been shown to bring about potential cost savings compared to fossil fuels (such as diesel generators) in poor rural areas without grid access (Casillas and Kammen, 2010). Nevertheless, in general the purely economic costs of RE exceed those of fossil fuel-based energy production in most instances (see Sections 2.7, 3.8, 4.7, 5.8, 6.7, 7.8 and 10.5) and further financial barriers to the adoption of RE are discussed in Section 11.4.3.

Overall, cost considerations cannot be discussed independently of the burden-sharing regime adopted, that is, without specifying who assumes the costs for the benefits brought about from reduced GHG emissions, which can be characterized as a global public good (N. Stern, 2007). For instance, the Copenhagen accord recognized that for the period 2010 to 2012 USD_{2005} 26 billion should be made available for climate measures in developing countries (including mitigation and adaptation), and that this sum should be scaled up to USD_{2005} 86 billion per year by 2020 (UNFCCC, 2009). Estimates of mid- to long-term financial flows to developing countries show considerable variation, depending to a high degree on the GHG stabilization level and burden-sharing scheme assumed to be in place. According to estimates assuming a 450 ppm atmospheric CO_2 stabilization scenario with an equal per capita distribution of emission permits, financial inflows related to climate finance could reach up to 10% of GDP for sub-Saharan Africa and up to 5% for India around 2020 (IMF, 2008). Obviously, such sizeable financial inflows can play an important role in supporting the transition towards RE-based energy systems. However, the appropriate governance of substantial financial inflows is also critically important, ensuring that these transfers result in actual SD benefits instead of undermining development by inducing rent-seeking behaviour and crowding out manufacturing activity (Strand, 2009). Insights from the governance of resource rents and aid flows can provide guidance on these issues, for example, by identifying best practices with regard to transparency and revenue management. Hence, this discussion emphasizes again that the decision to adopt RE cannot be based on a single criterion, but has to factor in a variety of aspects, including economic costs, ancillary benefits (such as energy access, energy security and reduced impacts on health and the environment), as well as additional funding possibilities by the means of climate finance.

9.3.2 Energy access

Significant parts of the global population today have no or limited access to modern and clean energy services. From a SD perspective, a sustainable energy expansion needs to increase the availability of energy services to groups that currently have no or limited access to them: the poor (measured by wealth, income or more integrative indicators), those in rural areas and those without connections to the grid. For households, the impacts from polluting and inefficient energy services on women have often been recognized (A. Reddy et al., 2000; Agbemabiese, 2009; Brew-Hammond, 2010).

Table 9.1 provides an estimate of the number of people without access to electricity, which totalled more than 1.4 billion in 2009. The regional distribution indicates that it is entirely a developing country issue, particularly in sub-Saharan Africa and South Asia.

Table 9.1 | Millions of people without access to electricity in 2009 by region; projections to 2015 and 2030 under the IEA *World Energy Outlook 2010*, New Policies Scenario; and percentage of total populations with future access as a result of anticipated electrification rates (IEA, 2010b).

Region	2009			2015	2030	2009	2015	2030
	Rural	Urban	Total	Total	Total	%	%	%
Africa	466	121	587	636	654	42	45	57
Sub-Saharan Africa	465	120	585	635	652	31	35	50
Developing Asia	716	82	799	725	545	78	81	88
China	8	0	8	5	0	99	100	100
India	380	23	404	389	293	66	70	80
Other Asia	328	59	387	331	252	65	72	82
Latin America	27	4	31	25	10	93	95	98
Developing Country*	1,229	210	1,438	1,404	1213	73	75	81
World**	**1,232**	**210**	**1,441**	**1,406**	**1213**	**79**	**81**	**85**

Notes: *Includes Middle East countries, **includes OECD and transition economies.

A recent report from the UN Secretary General's advisory group on energy and climate change (AGECC, 2010) stresses the importance of universal access to modern energy sources by 2030 as a key part of enhancing SD. AGECC also suggests a new understanding of the term 'access', and identifies the specific contributions of RE to SD that go beyond the effects of increased energy access based on grid expansion or fossil technologies like diesel plants. This approach defines energy access as "access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses" (AGECC, 2010) and illustrates the incremental process (Figure 9.4) involved in moving from servicing basic human needs to creating a self-sustaining process of SD.

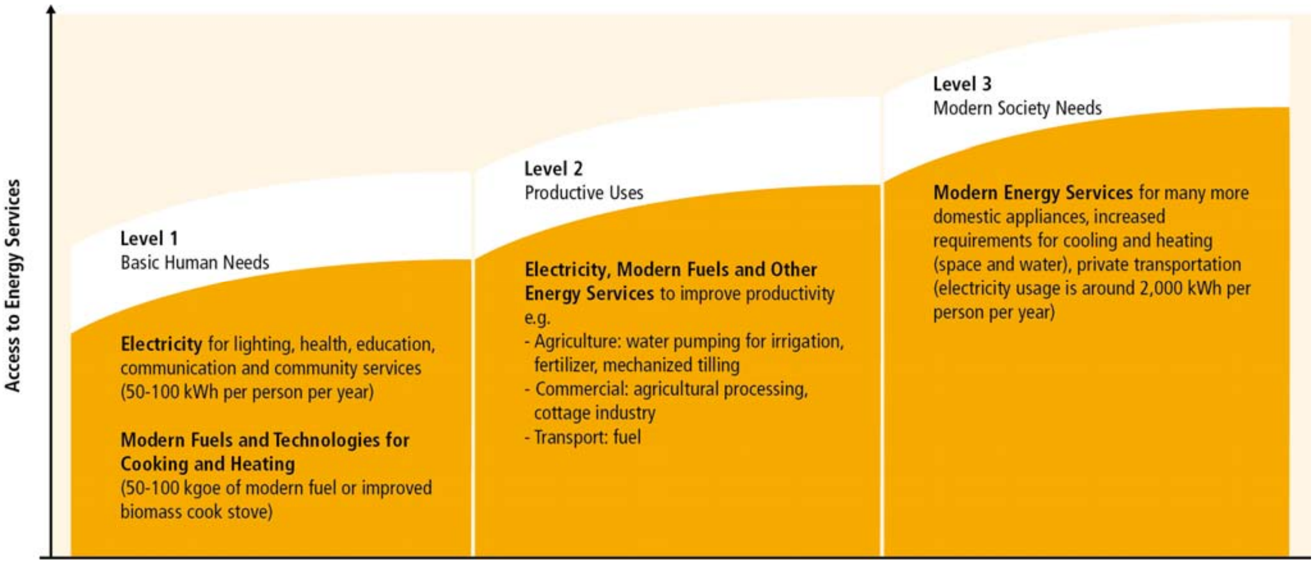

Figure 9.4 | Incremental level of access to energy services (AGECC, 2010; based on IEA data and analysis). Note: kgoe = kilogram(s) of oil equivalent

Even a basic level of energy access, such as the provision of electricity for lighting, communication, healthcare and education, can result in substantial benefits for a community or household, including cost savings. However, AGECC argues for a broader definition of energy access and proposes that energy levels should provide not only for basic services but also for productive uses in order to improve livelihoods in the poorest countries and drive local economic development (see Figure 9.4). For a further discussion of energy access concepts, such as numerical minimum requirements for social and economic criteria, see Modi et al. (2005).

Access issues need to be understood in a local context[3] and in most countries there is a marked difference between electrification in urban and rural areas (Baumert et al., 2005; Bhattacharyya, 2005; World Bank, 2008b; UNDP and WHO, 2009; Brew-Hammond, 2010; IEA, 2010a). While this is especially true in the sub-Saharan African and South Asian regions, statistics show that rural access is still an issue of concern in developing regions with high overall national levels of electrification, illustrating that the rural-urban divide in modern energy services is still quite marked (see Table 9.1).

Decentralized grids based on RE are generally more competitive in rural areas with significant distances to the national grid (Baumert et al., 2005; Nouni et al., 2008; Deichmann et al., 2011) and the low levels of rural electrification offer significant opportunities for RE-based mini-grid systems. The role of RE in providing increased access to electricity in urban areas is less distinct. This relates either to the competitiveness with other grid supply options or to local social and economic issues at household or community levels; here, access is hampered by legal land issues or affordability.

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[3] See also the Earth trends database on electricity access: earthtrends.wri.org/searchable_db/index.php?theme=6.

Today, around 2.7 billion people rely on traditional biomass like wood, charcoal and dung for cooking energy and it is estimated that another half billion use coal (Table 9.2). Uncertainty in these estimates is high, but the span is limited across the different data sources (IEA, 2010a). In addition to the more than 1.4 billion with no access to electricity around another 1.3 billion people still use biomass, kerosene, coal or liquid propane gas (LPG) for energy-demanding services such as cooking despite having access to some form of electricity (Bravo et al., 2008; Karekezi et al., 2008; Dhingra et al., 2009, IEA, 2010b).

Table 9.2 | Number of people (millions) relying on traditional biomass for cooking in 2009 (IEA, 2010b).

Region	Total
Africa	657
Sub-Saharan Africa	653
Developing Asia	1,937
China	423
India	855
Other Asia	659
Latin America	85
Developing Country*	2,679
World**	**2,679**

Notes: *Includes Middle East countries, **includes OECD and transition economies.

More detailed analysis of these statistics is generally hampered by very poor data about energy consumption among the poor in many developing countries. While an increasing number of national censuses include energy-related data, the coverage is still very limited for poor peri-urban and rural households with no official registration or land ownership (GNESD, 2008; Dhingra et al., 2009). The analytical constraints are compounded by the lack of well-defined and generally accepted indicators (IEA, 2010a).

The very dominant, and mainly indoor, use of traditional biomass fuels for cooking purposes has a number of documented negative effects. These include health impacts (Barnes et al., 2009; see Section 9.3.4.3), social effects, like the time spent gathering fuel or the high shares of income paid for small amounts of commercial biomass, and environmental aspects, like deforestation in areas where charcoal and market-based biomass are the dominant fuels.

A major challenge is to reverse the pattern of inefficient consumption of biomass by changing the present, often unsustainable, use to more sustainable and efficient alternatives. As illustrated by Figure 9.5 there is a strong correlation between low household income and use of low-quality fuels, illustrating that it is the poorest parts of the population who are at risk. The introduction of liquid or gaseous RE fuels, such as ethanol gels, to replace solid biomass for cooking could play a critical role whilst improving the health of millions of people (Lloyd and Visagle, 2007). While LPG has already displaced charcoal in some regions, it is a costly option for the majority of poor people and only a few countries have achieved significant penetration (Goldemberg et al., 2004). Replacing biomass or LPG with dimethyl ether produced from biomass shows some potential (Larson and Yang, 2004). The scale of liquid biofuel production required to meet cooking fuel demands is less than that for meeting transport fuel demand (Sections 8.2.4 and 8.3.1).

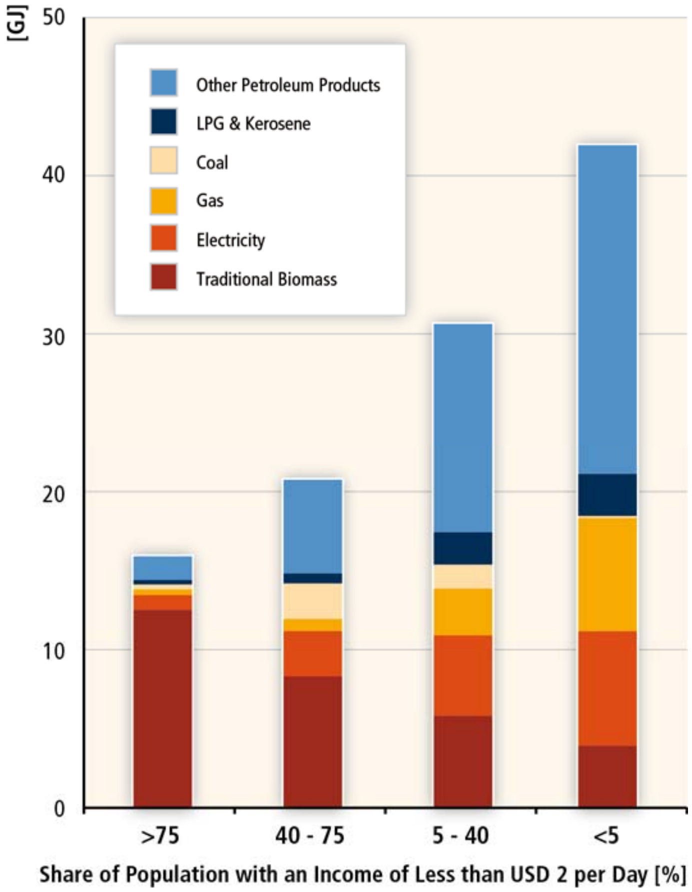

Figure 9.5 | The relationship between per capita final energy consumption and income in developing countries (IEA, 2010b). Data refer to the most recent year available during the period 2000 to 2008. Note: LPG = liquid petroleum gas.

Apart from the specific relevance of RE for electrification in remote areas, it is not well understood how contributions from RE sources can make a specific difference with regard to providing energy access in a more sustainable manner than other energy sources.

A study by the Global Network on Energy for Sustainable Development examined the options for RE technologies in making specific contributions to rural development (GNESD, 2007b). Several non-electrical technologies like using solar energy for water heating and crop drying, biofuels for transportation, biogas and modern biomass for heating, cooling, cooking and lighting, and wind for water pumping, etc. were found to serve priority household and productive energy needs (cooking, water heating, heating, water pumping) in areas with no access to electricity. This is also illustrated by the overview in Table 9.3, which outlines possible ways RE can provide basic energy services in rural off-grid areas. However, many of the options apply equally to the increasing number of slum communities in peri-urban areas where many households are not able to gain legal or economic access to even nearby electricity grids (Jain, 2010).

Table 9.3 | Transition to renewable energy in rural (off-grid) areas (REN21, 2010).

Rural Energy Service	**Existing Off-Grid Rural Energy Sources**	**Examples of New and Renewable Energy Sources**
Lighting and other small electric needs (homes, schools, street lighting, telecom, hand tools, vaccine storage)	Candles, kerosene, batteries, central battery recharging by carting batteries to grid	• Hydropower (pico-scale, micro-scale, small-scale) • Biogas from household-scale digester • Small-scale biomass gasifier with gas engine • Village-scale mini-grids and solar/wind hybrid systems • Solar home systems
Communications (televisions, radios, cell phones)	Dry cell batteries, central battery recharging by carting batteries to grid	• Hydropower (pico-scale, micro-scale, small-scale) • Biogas from household-scale digester • Small-scale biomass gasifier with gas engine • Village-scale mini-grids and solar/wind hybrid systems • Solar home systems
Cooking (homes, commercial stoves and ovens)	Burning wood, dung, or straw in open fire at about 15% efficiency	• Improved cooking stoves (fuel wood, crop wastes) with efficiencies above 25% • Biogas from household-scale digester • Solar cookers
Heating and cooling (crop drying and other agricultural processing, hot water)	Mostly open fire from wood, dung, and straw	• Improved heating stoves • Biogas from small- and medium-scale digesters • Solar crop dryers • Solar water heaters • Ice making for food preservation • Fans from small grid renewable system
Process motive power (small industry)	Diesel engines and generators	• Small electricity grid systems from microhydro, gasifiers, direct combustion, and large biodigesters
Water pumping (agriculture and drinking water)	Diesel pumps and generators	• Mechanical wind pumps • Solar PV pumps • Small electricity grid systems from microhydro, gasifiers, direct combustion, and large biodigesters.

Energy access through some of these technologies allows local communities to widen their energy choices. As such, these technologies stimulate economies, provide incentives for local entrepreneurial efforts and meet basic needs and services related to lighting and cooking, thus providing ancillary health and education benefits. For example, the non-electrical technologies outlined above were found to exhibit a high potential for local job generation and increased economic activity through system manufacture and renewable resource extraction and processing (GNESD, 2007a).

Implementation of RE-based energy access programs is expanding quite rapidly, but research on the sustainability-related aspects is still quite limited and there is hardly any literature on large-scale implementation. Instead, analysis has to rely on a few specific examples of actions where elements of energy access have been provided with a specific focus on the combination of social and productive services utilizing the potential for local job creation through small-scale business development (van der Vleuten et al., 2007; Nouni et al., 2008; Kaundinya et al., 2009; J. Peters et al., 2009; Urmee et al., 2009; Jonker Klunne and Michael, 2010). The assessment and case examples available, however, show that energy access is key for achievement of the MDGs and for economic development in general. RE technologies have the potential to make a significant contribution to improving the provision of clean and efficient energy services. But in order to ensure full achievement of the potential SD benefits from RE deployment, it is essential to put in place coherent, stable and supportive political and legal frameworks. The options for and barriers to such frameworks are further assessed in Chapter 11.

As a final caveat, it should also be noted that different RE facilities, that is, distributed versus central supply, face very different constraints, with the latter experiencing similar barriers as conventional energy systems, that is, high upfront investments, siting considerations, infrastructure and land requirements as well as network upgrade issues. Like for any other new technology, the introduction of RE will also face social and cultural barriers and implementation will need to be sensitive to social structures and local traditions like, for example, diets and cooking habits. There are many examples of improved stove programs failing due to lack of understanding of culture, staple food types and cooking habits (Slaski and Thurber, 2009).

9.3.3 Energy security

In addition to reducing energy consumption and improving energy efficiency, RE constitutes a further option that can enhance energy security. This section assesses the evidence for the potential contribution of RE technologies to energy security goals based on the two broad themes of energy security outlined in Section 9.2.2: availability and distribution of resources, and variability and reliability of energy sources.

The potential of RE to substitute for fossil energy—that is, theoretical and technical RE potentials—is summarized in Section 1.2 and discussed in detail in the respective technology chapters (Sections 2.2, 3.2, 4.2, 5.2, 6.2 and 7.2). Moreover, Section 11.3.3 discusses aspects of energy policies related to energy security.

9.3.3.1 Availability and distribution of resources

The ratio of proven reserves to current production (R/P), that is, for how many years production at current rates could be maintained before reserves are finally depleted, constitutes a popular measure to illustrate potential fossil fuel scarcities. According to this metric, recent estimates suggest that scarcity of coal (with a global R/P ratio of more than 100 years) is not a major issue at the moment, but at the current rate of production, global proven conventional reserves of oil and natural gas[4] would be exhausted in 41 to 45 and 54 to 62 years, respectively (BGR, 2009; BP, 2010; WEC, 2010).[5] While these figures only intend to give a sense of the magnitude of remaining fossil fuel reserves, they do not provide an assessment of when current reserves will actually be depleted. Proper interpretation of R/P ratios has to take many aspects into account, including the methodology of how reserves are classified and calculated, future changes in production and discovery of new reserves, as well as deterioration in the quality of reserves (Feygin and Satkin, 2004). A recent report that includes these factors in the analysis concludes with the projection of a likely peak of conventional oil before 2030 and a significant risk of a peak before 2020 (Sorrell et al., 2009).

As has been highlighted by the IEA (2008b) in its *World Energy Outlook 2008*, accelerated economic growth in many parts of the developing world is likely to raise global energy demand, which could further shorten the lifespan of remaining fossil fuel resources. Even though technological progress allows tapping reservoirs of oil from so-called non-conventional sources (such as, e.g., oil sands), usually large investments are required, which raise extraction costs and the price of oil and gas (Bentley, 2002). In addition, increasing amounts of energy are needed to produce a given quantity of usable energy from depleted conventional as well as from non-conventional reserves. Published estimates of the ratio of energy output-to-input (Energy Return on Energy Invested: EROEI, see Section 9.3.4.) for conventional oil indicate that when the quality of reserves is taken into account there has been a substantial decline over time: while the EROEI reached its maximum of about 19 in 1972, it dropped to roughly 11 (i.e., about 42% lower) in 1997 (Cleveland, 2005). For non-conventional resources the EROEI is even lower (IEA, 2010b; Seljom et al., 2010). Thus, it is not surprising that the fossil fuel industry, particularly in the case of oil, has seen sharp increases in extraction costs over the past decade, although equipment, raw materials and labour demand have also played a role (EIA, 2009). Correlated with the increasing amounts of input energy to extract resources are the lifecycle carbon emissions from these resources.

As there is relatively little overlap between the location of fossil fuel reserves and the place of their consumption, fossil fuels are heavily traded and many countries with relatively scarce endowments rely to a large extent on imports of energy to meet desired levels of consumption. Due to the fact that a substantial share of global energy trade is channelled through a rather small number of critical geographical areas (so-called ‘chokepoints’), it is highly vulnerable to accidents or terrorist attacks and importers face a considerable risk of supply disruption or price hikes (E. Gupta, 2008). Figure 9.6 shows that currently the European Union (EU-27), North America, and Asia and the Pacific region are net oil importers[6] supplying 85, 32, and 61% of their oil consumption from foreign producers, respectively. The EU-27 also relies on imports to meet more than half of its gas consumption, while for the Asia-Pacific region the import share is below 15% and North America almost fully meets demand for gas through domestic production. The Middle East, the Former Soviet Union (FSU), Africa and to some lesser extent Latin America are the most important exporters of oil and gas (for Africa, exports of both oil and gas exceed domestic consumption). Even though the EU-27 and the Middle East also rely on imports of coal,[7] energy security concerns

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[4] Recent improvements in extraction technologies for shale gas and coal-bed methane are expected to result in notable production of natural gas from these non-conventional resources in the near future (IEA, 2008b).

[5] Since 1990, proven conventional reserves of oil and natural gas have moderately grown due to revisions in official statistics, new discoveries and increased recovery factors. However, new discoveries have lagged behind consumption. Ultimately recoverable reserves (which include reserves that are yet to be discovered) are considerably larger than proven reserves; their actual size crucially depends on future oil prices and development costs (IEA, 2008b).

[6] It should be noted that there is considerable heterogeneity within single regions (e.g., while the USA is a net oil importer, Canada is a net exporter).

[7] Coal imports are hard coal; due to high transportation costs, lignite coal is in general not traded.

are less salient: the former possesses reserves that exceed its annual consumption by a factor of more than 90, while for the latter coal only accounts for a marginal fraction of total energy use (BGR, 2009). This particular constellation of pronounced global imbalances in energy trade leads to a situation in which countries that heavily depend on energy imports frequently raise concerns that their energy consumption might be seriously affected by possible supply disruptions (Sen and Babali, 2007).

The spatial distribution of reserves, production and exports of fossil fuels is very uneven and highly concentrated in a few regions. Over 60% of coal reserves are located in just three regions (the USA, China and the FSU (BP, 2010)), and in 2009 China alone accounted for about half of global production of hard coal (IEA, 2010b). Over 75% of natural gas reserves are held by OPEC nations and states of the FSU, and 80% of the global gas market is supplied by the top 10 exporters (IEA, 2010b). This heavy concentration of energy resources, many of which are located in regions in which political events can have an adverse impact on the extraction or export of fossil fuel resources, creates a dependency for importers and raises the danger of energy supply disruptions (E. Gupta, 2008). That said, it should also be noted that exporting countries have a vested interest in maintaining income streams from the continued sale of fossil fuel supplies, so they are unlikely to limit exports for a prolonged period of time.

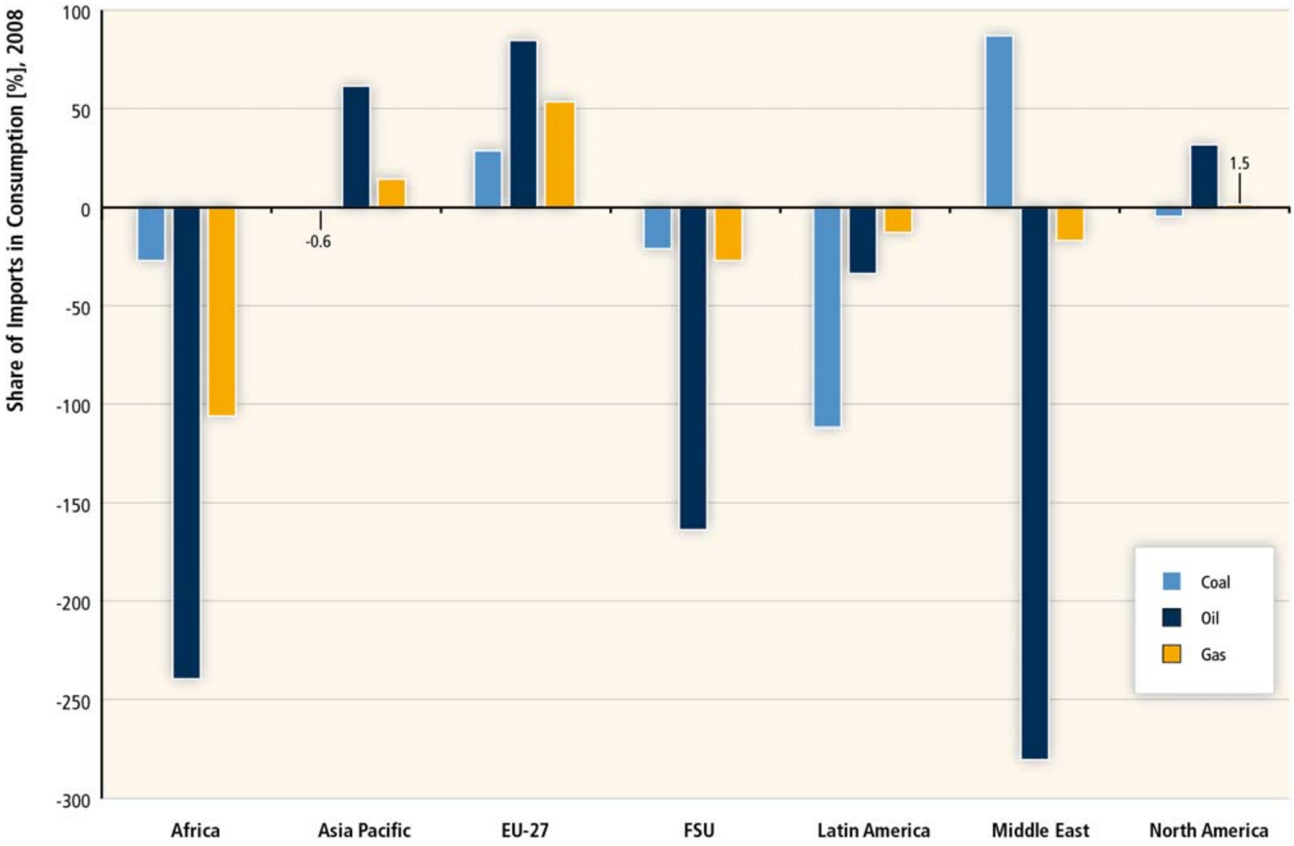

Figure 9.6 | Energy imports as the share of total primary energy consumption (%) for coal (hard coal and lignite), crude oil and natural gas for selected world regions in 2008. Negative values denote net exporters of energy carriers. Based on BGR (2009).

Further, for a number of countries (Moldova, Pakistan, Trinidad and Tobago, Madagascar, India, Ukraine, Tajikistan) the share of energy imports in total imports exceeded 25% for the period 2000 to 2005 and it was as high as 45% for Bahrain and 40% for Sierra Leone (World Bank, 2007b). A related indicator is the share that energy imports constitutes of export earnings and overall GDP. For example, Kenya and Senegal spend more than half of their export earnings for importing energy, while India spends over 45% (GNESD, 2010; Jain, 2010). Such dependence on energy imports exposes the affected economies to a potential risk of price fluctuations. The Energy Sector Management Program (ESMAP) of the World Bank has assessed the impacts of higher oil prices on low income countries and the poor (ESMAP, 2005).[8] Table 9.4, which summarizes these findings, illustrates that oil-importing developing countries are significantly affected by oil price increases and that a rise in oil prices of $\text{USD}_{1999\text{-}2001}$ 10 per barrel might result in GDP losses of almost 1.5% for the poorest countries (with per capita income less than $\text{USD}_{1999\text{-}2001}$ 300). The ESMAP national case studies also showed that the poorest households experienced the highest percentage changes in expenditures for commercial energy purchases of, for example, kerosene, LPG and diesel.

Table 9.4 | Percentage change in GDP resulting from a $\text{USD}_{1999\text{-}2001}$ 10 per barrel rise in oil prices [9] (analytical results grouped by income levels) (ESMAP, 2005).

Net Oil Importers		**Net Oil Exporters**	
Income per capita ($\text{USD}_{1999\text{-}2001}$)	ΔGDP (%)	Income per capita ($\text{USD}_{1999\text{-}2001}$)	ΔGDP (%)
<300	-1.47	<300	+5.21
300–900	-0.76	900–9,000	+4.16
900–9,000	-0.56		
>9,000	-0.44		

For these countries, increased uptake of RE technologies could further be an avenue to redirect foreign exchange flows away from energy imports towards imports of goods that cannot be produced locally, such as high-tech capital goods. For other developing countries that are net exporters of energy, promoting the domestic use of RE can extend the lifetime of their fossil resource base and prolong the time to diversify the scope of economic activities by decreasing the dependence on resource exports while strengthening their manufacturing and service sectors.

Governments frequently try to limit the impacts of international price increases in the short term by adjusting subsidies or providing targeted cash support to the poorest households, rationing supply or forcing supply companies to absorb some of the short-term effects (ESMAP, 2005, 2006, 2008). Since this may have significant effects both on state budgets and companies' abilities to maintain stable delivery (UNEP, 2008b), longer-term responses are focused more on efficiency measures and diversification. In this context, it needs to be noted that import dependencies do not only occur with respect to specific energy sources; the technologies needed for implementation of RE have their own specific risks for potential supply disruptions and price volatility (see Box 9.1).

Box 9.1 | Access to raw materials for future renewable resources deployment.

While renewable resources can be a powerful instrument to mitigate fossil fuel depletion, scarcity of other raw materials may pose constraints to enhanced deployment of RE technologies. Securing access to required scarce inorganic mineral raw materials (IRM), above all precious rare earth and some specialty metals, at reasonable prices is an upcoming challenge for all industries. For the complex renewable energies sector no specific assessment of the structure and quantity of IRM

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[8] It should be noted that the data are based on a large number of country case studies and thus are not necessarily universally valid.

[9] As the grouping of countries in this table does not correspond to any regional grouping, it was not possible to convert monetary values to year 2005 USD due to a lack of appropriate conversion factors.

demand is available. To identify potential areas of concern for future renewable resources deployment, a large set of technologies and possible technology pathways has to be considered; several reports are available as starting points for such analyses (Frondel et al., 2007; Reuscher et al., 2008; Angerer et al., 2009; Ziemann and Schebek, 2010; US DOE, 2010; EC, 2010; Kristof and Hennicke, 2010; Teipel, 2010).

The IRM supply chain has to be understood as a vulnerable system and is subject to various threats. Sources of potential market distortions are concentration processes and political instability of some major mining countries. Currently, 97% of rare earth elements, 60% of indium and 30% of gallium production are located in China, 56% of the global chromium supply is controlled by South Africa and Kazakhstan and 55% of cobalt is mined in politically instable regions in Africa (USGS, 2010).

With some notable exceptions (e.g., silver), future IRM constraints will be caused by imbalances of demand and supply rather than by depletion of geological resources (Angerer, 2010). Some metals are derived as by-products, mostly from ores of major or carrier metals in which they are present in low concentrations. Their production levels depend on the demand for the major metal as the main economic driver of extraction (Hagelüken and Meskers, 2010). Typical by-product metals are gallium, germanium, indium, tellurium and selenium. In some deposits, groups of metals may occur as ‘coupled elements’ without a real carrier metal. Notable examples include the platinum group metals and rare earth elements that generally have to be mined and processed together. In such cases, it may not be economically viable to increase production in response to rising demand for a certain element. As a result, complex price patterns and supply risks emerge. Market tensions also occur in response to unexpected changes in demand, for example, as a result of fast-rising prosperity in emerging and developing countries, or technology breakthroughs that cause a demand surge or drop.

In the future, demands for certain metals are projected to multiply significantly. Indicators that relate raw material demand by emerging technologies in 2030 to today’s total world production show that as a result of expected technical innovations the demand for gallium and neodymium may be 6 and 3.8 times higher, respectively (Angerer et al., 2009; see Table 9.5). Demand drivers for gallium are thin-layer photovoltaics and high-speed integrated circuits, and for neodymium high-performance permanent magnets used in generators of wind turbines and energy efficient electric motors.

Table 9.5 | Estimated global demand for selected metals by emerging technologies in 2030 as a multiple of world production in 2006 (Angerer et al., 2009).

Element	**Multiple**
Gallium	6
Neodymium	3.8
Indium	3.3
Germanium	2.4
Scandium	2.3
Platinum	1.6
Tantalum	1
Silver, Tin	0.8
Cobalt	0.4
Palladium, titanium	0.3

The vulnerability of industrial sectors is especially large if there is no possibility for substitution. Current examples for such a lack of substitutes include chromium in stainless steels (e.g., for tidal power plants), cobalt in wear-resistant super alloys, scandium in lightweight alloys, indium in transparent indium-tin-oxide electrodes for photovoltaic panels and neodymium in strong permanent magnets. At the same time there are also competing uses of raw materials between industries. Cobalt, for instance, is needed for the varied and growing applications of lithium-ion rechargeable batteries, for catalysts in the Fischer-Tropsch process that may be used to produce future synthetic fuels from biomass, and is an essential component of extremely wear-resistant parts in automotive, mechanical and medical engineering. Table 9.6 gives an overview of critical raw materials in some essential components of renewable resources technologies.

Table 9.6 | Critical raw materials content of renewable resources technologies.

Application	**Component**	**Critical raw materials content**
Wind and hydropower plants	Permanent magnets of synchronous generator	Neodymium, dysprosium, praseodymium, terbium
	Corrosion-resistant components	Chromium, nickel, molybdenum, manganese
Photovoltaics	Transparent electrode	Indium
	Thin film semiconductor	Indium, gallium, selenium, germanium, tellurium
	Dye-sensitized solar cell	Ruthenium, platinum, silver
	Electric contacts	Silver
Concentrating solar power (CSP)	Mirror	Silver
Fuel cell-driven electric vehicles	Hydrogen fuel cell	Platinum
	Electric motor	Neodymium, dysprosium, praseodymium, terbium, copper
Biomass to liquid (BtL)	Fischer-Tropsch synthesis	Cobalt, rhenium, platinum
Electricity storage	Redox flow rechargeable battery	Vanadium
	Lithium-ion rechargeable battery	Lithium, cobalt
Electricity grid	Low-loss high-temperature super-conductor cable	Bismuth, thallium, yttrium, barium, copper

An important future contribution to a secure IRM supply is the set-up of effective recycling systems. End-of-life products such as electronics, batteries or catalysts contain in total significant amounts of comparably enriched metals. For RE technologies it might become crucial to develop closed loop recycling concepts from the very beginning. Besides several environmental advantages, this could enhance the supply situation and long-term supply security of scarce raw materials and reduce dependency on (usually more energy intensive) primary supply while mitigating metal price volatility (Hagelüken and Meskers, 2010).

9.3.3.2 Variability and reliability of energy supply

Besides the advantageous properties discussed above, renewable energy sources also possess some drawbacks. The variable long- or short-term availability of some RE due to seasonal, diurnal or weather changes can be addressed by storage and technical balancing to meet heat or power demand changes. In addition, institutional settings for energy markets can be optimized, such as regionally integrated electricity markets in which local fluctuations can be smoothed by means of geographic diversification (Roques et al., 2010), and a range of other solutions including grid flexibility may be implemented (see Section 8.2.1). The solutions to overcome variability constraints on an energy supply system can involve additional costs that should be taken into account when comparing the relative benefits of RE with conventional energy technology projects.

Analysis and operating experience primarily from certain OECD countries suggest that, at least for low to medium levels of wind electricity penetration (defined as up to 20% of total annual average electrical energy demand), the integration of wind energy generally poses no insurmountable technical barriers and is economically manageable. Nevertheless, concerns about (and the costs of) wind energy integration will grow with wind energy deployment and, even at lower penetration levels, integration issues must be actively managed. At low to medium levels of wind electricity penetration, the available literature suggests that the additional costs of managing electric system variability and uncertainty, ensuring generation adequacy and adding new transmission to accommodate wind energy will be system specific but generally in the range of US cents_{2005} 0.7 to 3/kWh. (Section 7.5).

A number of emerging regional power collaborations in East, West and Southern Africa, South and Central America and South East Asia aim to enhance the reliability of electricity grids and therefore local supply. ESMAP (2010) studied 12 sub-regional integration schemes and found that for most schemes energy security was one of the motivating factors. Larger integrated networks may also provide benefits in terms of cost efficiency, trade and more general economic development.

Many developing countries specifically include providing adequate and affordable access to all parts of the population as part of their definition of energy security and in this way link the access and security issues while broadening the concept to include stability and reliability of local supply. While regional interconnections may be an interesting way to ensure better supply security at the national level, it does not automatically 'trickle down' to the poorer segments of the population in terms of increased access or even stable and affordable supply for those who are connected. GNESD (2004) examined the effects of power sector reforms on access levels and found that only when there was strong political commitment to improve access to electricity for poor households did reforms deliver results. An explicit focus on poor households was found essential along with specific protection of funds for electrification.

While electricity connection is often used as a key indicator for access to modern energy services, it is important to underline that household connections have restrictions in terms of capacity, stability and outage problems, as illustrated by the data from the World Bank in Table 9.7.

Table 9.7 | Indicators of the reliability of infrastructure services (World Bank, 2007a).

	Sub-Saharan Africa	Developing countries
Delay in obtaining electricity connection (days)	79.9	27.5
Electrical outages (days per year)	90.9	28.7
Value of lost output due to electrical outages (percent of turnover)	6.1	4.4
Firms maintaining own generation equipment (percent of total)	47.5	31.8

Energy security at the micro level in developing countries may therefore have a number of social and economic effects that go beyond direct impacts of fuel price increases (Jain, 2010). Improving access to affordable and reliable energy supply will therefore not only provide improved energy services, but it may also broadly increase productivity and avoid parallel investments in infrastructure, from small-scale generation equipment to parallel lighting and cooking systems, where most households have at least two different options to hedge against unstable supply. However, decentralized RE is competitive mostly in remote and rural areas, while grid-connected supply generally dominates denser areas where the majority of households reside (Deichmann et al., 2011).

9.3.4 Climate change mitigation and reduction of environmental and health impacts

SD must ensure environmental quality and prevent undue environmental harm. No large-scale technology deployment comes without environmental trade-offs, and a large body of literature is available that assesses various environmental impacts of energy technologies from a bottom-up perspective.

The goal of this section is to review and compare available evidence about the environmental impacts associated with current and near-future energy technologies, including the full supply chain. This review is largely based on literature from lifecycle assessments (LCA). LCA does not attempt to determine a socially optimal energy supply portfolio; its aim is to aid technology comparisons in terms of environmental burden. While the development of sustainable strategies and portfolios needs to be viewed from a top-down, macro-economic and systemic perspective, bottom-up evidence from LCA provides valuable insights about the environmental performances of different technologies across categories. Similarly, the energy payback time (EPT, see Box 9.3) provides a measure for the lifecycle energy efficiency of individual technologies, which is helpful for identifying high-quality energy sources, but must additionally be viewed in the broader economic and social context. As the following sections review the results of hundreds of LCA studies, the major characteristics and challenges of LCA in the context of energy technologies are introduced below (Box 9.2).

Box 9.2 | Lifecycle assessments of energy technologies.

LCA studies provide a well-established and comprehensive framework to compare RE with fossil-based and nuclear energy technologies. LCA methodologies have been evolving for a few decades and are now supported by international initiatives (UNEP and SETAC, 2010) and governed by standards (Cowie et al., 2006; ISO, 2006). Although LCA is increasingly applied to energy technologies, some methodological challenges persist (Udo de Haes and Heijungs, 2007).

The majority of the available literature on energy technologies is based on so-called attributional LCAs, which investigate the environmental impacts associated with the average product or technology lifecycle (Figure 9.7). A resulting key limitation is that changes in the energy system that might result from the decision to install additional renewable capacity are excluded. For instance, for wind power and solar PV, variability and limited predictability leads to an increased need for balancing reserves, and possibly efficiency penalties in the case of fossil power plants providing these reserves (R. Gross et al., 2007; Pehnt et al., 2008; see also Sections 3.5.4 and 7.6.1.3). In contrast, the recently developed approach of consequential LCA considers the marginal effects of implementing a technology, and displacing and changing the operation of other technologies, as reflected by market dynamic interactions between technologies and industries (Rebitzer et al., 2004; Brander et al., 2008; Finnveden et al., 2009). However, consequential LCAs form the minority of studies in the literature, and context dependency precludes the incorporation of the limited results available into the broader assessments presented here. Assumptions and changing characteristics of the background energy system (e.g., its carbon intensity) in turn particularly affect LCAs of most RE technologies, since their lifecycle impacts stem almost entirely from component manufacturing (see Lenzen and Wachsmann, 2004). Further challenges include the potential for double-counting when assessing large interconnected energy systems (Lenzen, 2009), and system boundary problems (Suh et al., 2003; Lenzen, 2008).

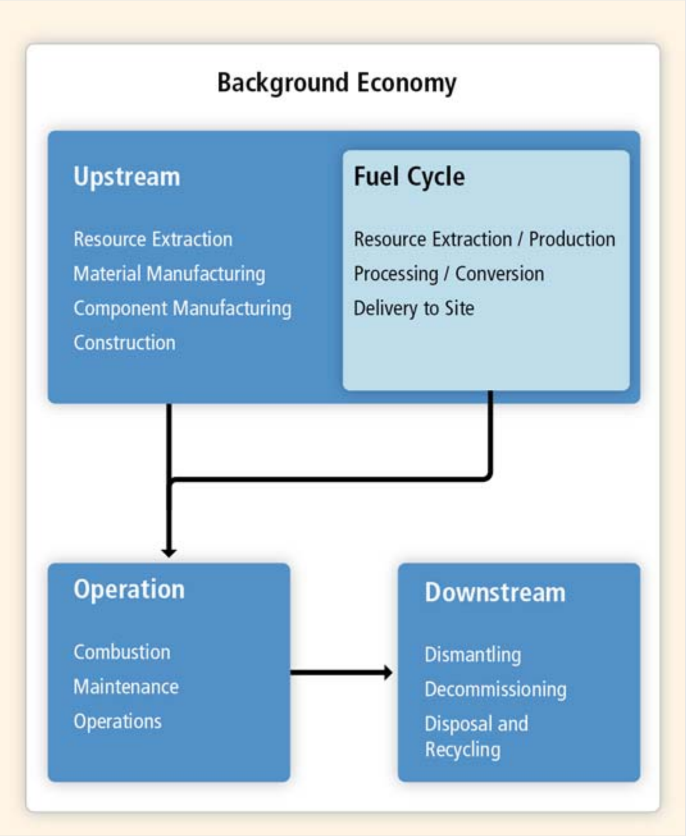

Figure 9.7 | Illustration of generalized lifecycle stages for an energy technology. Fuel cycle applies to fossil and nuclear chains and bioenergy.

Substantial variability in published LCA results (as seen, for example, in Figure 9.8) is also due to technology characteristics (e.g., design, capacity factor, variability, service lifetime and vintage), geographic location, background energy system characteristics, data source type (empirical or theoretical), differences in LCA technique (e.g., process-based LCA or input-output LCA) and key methods and assumptions (e.g., co-product allocation, avoided emissions, study scope). Given these significant caveats, emphasis will be placed on the underlying reasons for uncertainties and variations when describing the results for selected energy technologies.

LCA allows a detailed investigation into the environmental consequences that are associated with manufacture, operation and decommissioning of a specific technology evaluated in the context of the current energy system. In doing so, LCAs complement economic assessments that focus on current costs, for example, the levelized cost of energy (LCOE; see Section 10.5.1). In the same way as future costs of RE technologies might decline (e.g., due to research and development (R&D) and learning by doing; see Section 10.5.2), the way future RE technologies are manufactured, operated and decommissioned might change as well. As a consequence, a comprehensive assessment of different RE expansion strategies should try to take these expected modifications into account. While marginal changes in the background energy system can be addressed by consequential LCA (see Box 9.2), non-marginal changes due to the ongoing evolution of the background systems can be accounted for in scenario analyses (see Sections 10.2 and 10.3). By extending scenario analyses to include lifecycle emissions and the energy requirements to construct, operate and decommission the different technologies explicitly, integrated models could provide useful information about the future mix of energy systems together with its associated lifecycle emissions and the total environmental burden.

It is not possible to cover all relevant environmental impacts[10] associated with energy supply technologies within the scope of this chapter. This section concentrates mostly on electricity generation and liquid transport fuels, as these areas are most frequently reported in the literature, including the technology chapters of this report. Heating and household energy are included in the assessments on air pollution and health, but omitted from most other sections due to a paucity of published work. Regarding the lifecycle impacts of heating fuels, the upstream impacts of fuel extraction and processing are in many cases similar to those of the corresponding transport or electricity generation chains. However, some renewable technologies such as heat pumps or passive solar may exhibit different properties. The discussion of transport fuels focuses on biofuels, as they are currently the only renewable fuels that can be considered mature and available for large-scale application. A discussion of renewable electricity generation for charging of electric battery vehicles, and other future pathways is provided in Section 8.3.1. A broader discussion of technology integration options is provided in Chapter 8.

Data available for different impact categories vary widely regarding the number and quality of sources. GHG emissions are generally well covered (Section 9.3.4.1). A significant number of studies report on air pollutant emissions (Section 9.3.4.2), related health impacts (Section 9.3.4.3) and operational water use (Section 9.3.4.4), but evidence is scarce for (lifecycle) emissions to water, land use (Section 9.3.4.5) and health impacts other than those linked to air pollution. Discussion of impacts on biodiversity and ecosystems is limited to qualitative summaries of potential areas of concern (Section 9.3.4.6), as no quantitative basis for comparison is available. To account for burdens associated with accidents as opposed to normal operation, Section 9.3.4.7 provides an overview about risks associated with energy technologies.

Box 9.3 | Energy payback of electricity generation.

The role of high-quality energy sources in the development of modern civilizations is widely recognized. The energy payback time (EPT) and similar concepts described below provide a measure for energetic efficiency of technologies or fuels. The following characterizes the balance between the energy expended for the manufacture, operation and decommissioning of electricity generating plants (the ‘embodied’ energy) and their energy output in terms of an EPT, that is, the operational time it would take the technology to recover its own embodied energy. For combustion technologies, this includes the energy requirements of fuel extraction and processing, but not the energy content of the fuel itself. The EPT is closely related to other common metrics such as the energy return on energy invested (EROEI) or the energy ratio. The latter quantities depend on assumptions about the expected lifetime of a plant, which is also shown below (see Annex II for definitions and further explanations). For some RE technologies, for example, wind and PV, EPTs have been declining rapidly over the last years due to technological advances and economies of scale. Fossil and nuclear power technologies are characterized by the continuous energy requirements for fuel extraction and processing. This might become increasingly important as qualities of conventional fuel supply decline and shares of unconventional fuels rise (Farrell and Brandt, 2006; Gagnon, 2008; Lenzen, 2008).

In addition to the common causes of variability in estimates of impacts from LCAs (Box 9.2), the ranges in Table 9.8 are mainly caused by variations in:

- fuel characteristics (e.g., moisture content), cooling method, ambient and cooling water temperatures, and load fluctuations (coal and gas);
- uranium ore grades and enrichment technology (nuclear);

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[10] Within this subsection, the term impacts is not used in the strict sense of its definition within the field of LCA.

- crystalline or amorphous silicone materials (PV solar cells);
- economies of scale in terms of power rating (wind); and
- storage capacity and design (concentrating solar).

In addition, the location-specific capacity factor has a major bearing on the EPT, in particular that of variable RE technologies.

Table 9.8 | Energy payback times and energy ratios of electricity-generating technologies. Electricity from biomass is excluded, as the literature almost exclusively documents GHG instead of energy balances for this technology, and mostly covers the biofuel cycle only (Lenzen, 1999, 2008; Voorspools et al., 2000; Lenzen and Munksgaard, 2002; Lenzen et al., 2006; Gagnon, 2008; Kubiszewski et al., 2010).

Technology	**Energy payback time (years)**		**Most commonly stated lifetime (years)**	**Energy ratio $(\mathrm{kWh_e/kWh_{prim}})$**	
	Low value	High value		Low value	High value
Brown coal, new subcritical	1.9	3.7	30	2.0	5.4
Black coal, new subcritical	0.5	3.6	30	2.5	20.0
Black coal, supercritical	1.0	2.6	30	2.9	10.1
Natural gas, open cycle	1.9	3.9	30	1.9	5.6
Natural gas, combined cycle	1.2	3.6	30	2.5	8.6
Heavy-water reactors	2.4	2.6	40	2.9	5.6
Light-water reactors	0.8	3.0	40	2.5	16.0
Photovoltaics	0.2	8.0	25	0.8	47.4
Concentrating solar	0.7	7.5	25	1.0	10.3
Geothermal	0.6	3.6	30	2.5	14.0
Wind turbines	0.1	1.5	25	5.0	40.0
Hydroelectricity	0.1	3.5	70	6.0	280.0

9.3.4.1 Climate change

This section reviews available estimates of lifecycle GHG emissions from renewable and non-renewable electricity generation technologies and liquid transportation fuels. Positive and negative emissions related to land use change (LUC) are omitted from both reviews, and discussed separately, albeit with a focus on biofuels.

LUC-related GHG emissions are potentially relevant to any technology, but are most significant for technologies that transform substantial amounts of land, and induce changes in carbon stocks of that land. For bioenergy systems, LUC impacts could reduce, negate or enhance potential GHG emission reduction benefits depending on the circumstance and assumptions. Methane emissions from submersed biomass or organic sediments may produce substantial emissions for certain hydropower reservoirs. However, the state of the science regarding actual net emissions from hydropower reservoirs is unresolved (see Section 5.6.3 for details). Research on LUC related to resource extraction for fossil fuels, for example, mountaintop-removal coal mining (Fox and Campbell, 2010) or oil production (Yeh et al., 2010), is nascent (Gorissen et al., 2010).

LUC-related GHG emissions are excluded from the reviews for the following reasons:

1) significant gaps in available evidence for the full range of power technologies and fuels evaluated in this section preclude consistent comparisons; and

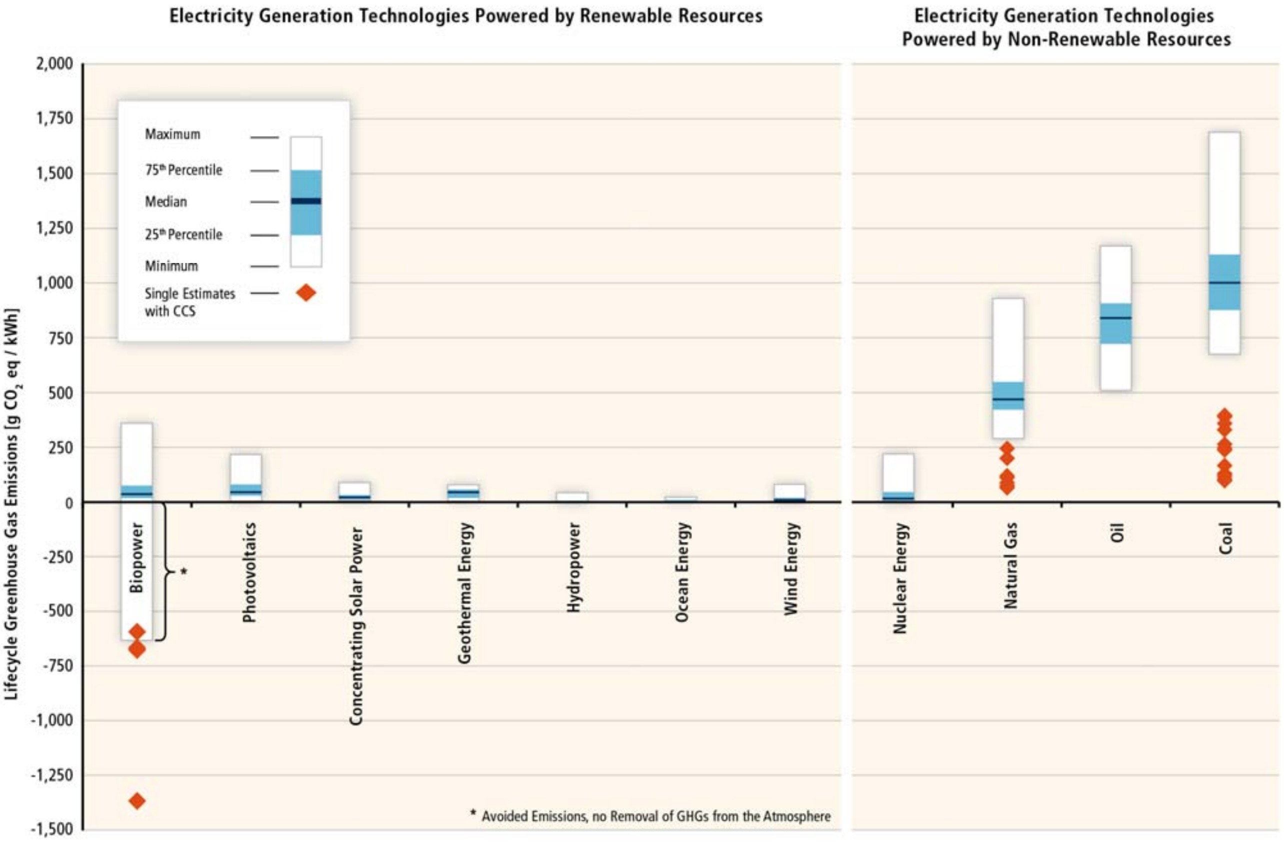
2) uncertainties in estimating GHG emissions from LUC are high relative to the understanding of GHG emissions more directly associated with the manufacture, operation and decommissioning of the technology itself.

Uncertainty in LUC estimates stems from many sources that are currently unresolved and inconsistent, including: modelling and estimation methods; data and modelling resolution (spatial, temporal, categorical); system boundary and vintage; allocation of impacts among primary products, co-products and residues; assumptions about the policy context and market size and characteristics; projections of technological performance, background energy system and comparison reference case; and evaluation time horizon (Cherubini et al., 2009; Kline et al., 2009; Hertel et al., 2010).

Other uncertainties related to estimation of GHG emissions from bioenergy in particular include N_2O emissions from fertilization and soils (Crutzen et al., 2008; E. Davidson, 2009), how technologies perform in practice compared to models and regulations now and in the future, lack of commercial-scale lignocellulosic feedstocks and fuels production, and other potentially significant indirect effects such as rebound effects in energy consumption due to changes in the price of energy after introduction of RE (Rajagopal et al., 2010). These uncertainties—along with the LCA-related caveats discussed in Box 9.2—should be kept in mind when considering the evidence presented in Section 9.3.4.1.

Lifecycle greenhouse gas emissions of electricity generation technologies

This section synthesizes evidence from a comprehensive review of published LCAs covering all regions of the world (literature collection, screening and analytical methods are described in Annex II). Without considering LUC, lifecycle GHG emissions normalized per unit of electrical output (g CO_2eq/kWh) from technologies powered by renewable resources are generally found to be considerably less than from those powered by fossil fuel-based resources (Figure 9.8). Nuclear power exhibits a similar inter-quartile range (IQR; 75th minus 25th percentile values) and median as do technologies powered by renewable resources. The maximum estimate for CSP, geothermal, hydropower, ocean and wind energy is less than or equal to 100 g CO_2eq/kWh and median values for all RE range from 4 to 46 g CO_2eq/kWh, although the number of references examining several of these technologies is small. The upper quartile of the distribution of estimates for photovoltaics and biopower extend 2 to 3 times above the maximum for other RE technologies, as it does for nuclear, mainly owing to differences in background energy system, assumed uranium ore grade (nuclear) and cases of suboptimal production processes (PV, biopower). Nevertheless, only the very highest estimates for biopower overlap with the range of a fossil-fuelled technology, and the central tendencies of all RE are between 400 and nearly 1,000 g CO_2eq/kWh lower than their fossil-fuelled counterparts (without CCS).



Count of Estimates	222(+4)	124	42	8	28	10	126	125	83(+7)	24	169(+12)
Count of References	52(+0)	26	13	6	11	5	49	32	36(+4)	10	50(+10)

Figure 9.8 | Estimates of lifecycle GHG emissions (g CO_2eq/kWh) for broad categories of electricity generation technologies, plus some technologies integrated with CCS. Land-use related net changes in carbon stocks (mainly applicable to biopower and hydropower from reservoirs) and land management impacts are excluded; negative estimates[11] for biopower are based on assumptions about avoided emissions from residues and wastes in landfill disposals and co-products. References and methods for the review are reported in Annex II. The number of estimates is greater than the number of references because many studies considered multiple scenarios. Numbers reported in parentheses pertain to additional references and estimates that evaluated technologies with CCS. Distributional information relates to estimates currently available in LCA literature, not necessarily to underlying theoretical or practical extrema, or the true central tendency when considering all deployment conditions.

Cases of post-combustion carbon capture and storage (CCS) represent the emissions associated with the base technology plus CCS. As expected, their lifecycle GHG emissions are considerably lower than those of the base technology, and for fossil-fuelled technologies, can bring total lifecycle GHG emissions near the range of several RE technologies. Biopower with CCS can display significantly negative GHG emissions (without considering LUC). Because CCS is still not a mature technology,

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[11] 'Negative estimates' within the terminology of lifecycle assessments presented in this report refer to avoided emissions. Unlike the case of bioenergy combined with CCS, avoided emissions do not remove GHGs from the atmosphere.

assumptions regarding the duration of sequestration and leakage rates contribute to the variability seen in Figure 9.8.

The proportion of GHG emissions from each lifecycle stage differs for technologies powered by renewable and non-renewable resources. For fossil-fuelled technologies, fuel combustion during operation of the facility emits the vast majority of GHGs. For nuclear and RE technologies, the majority of GHG emissions are upstream of operation. Most emissions for biopower are generated during feedstock production, where agricultural practices play an important role. For nuclear power, fuel processing stages are most important, and a significant share of GHG emissions is associated with construction and decommissioning. For other renewable technologies, most lifecycle GHG emissions stem from component manufacturing and, to a lesser extent, facility construction. The background energy system that, for instance, powers component manufacturing, will evolve over time, so estimates today may not reflect future conditions.

Variability in estimates of lifecycle GHG emissions from the evaluated technologies is caused both by factors related to methodological diversity in the underlying literature (see Box 9.2), and factors relating to diversity in the evaluated technologies. Expanding on the latter, for combustion technologies (fossil fuels and biopower), variability is most prominently caused by differences in capacity factor (which influences GHG emissions for many other technologies as well), combustion efficiency, carbon content of the fuel, and conditions under which the fuel is grown/extracted and transported. Biopower additionally is affected by assumptions regarding the reference use of the biomass feedstock; for instance, if landfilling of organic material can be avoided, the use of that biomass for power generation can be considered as avoiding methane emissions (seen in the non-CCS, negative emission estimates in Figure 9.8). Variability for PV stems from the rapidly evolving and multiple solar cell designs. For solar, geothermal,[12] ocean and wind technologies, the quality of the primary energy resource at the site significantly influences power output.

The state of knowledge on lifecycle GHG emissions from the electricity generation technologies was found to vary. The following synopses are based on an assessment of the number of references and estimates, the density of the distribution of estimates (IQR and range relative to the median), and an understanding of key drivers of lifecycle GHG emissions. Lifecycle GHG emissions from fossil-fuelled technologies and wind appear well understood.[13] Reasonably well known, but with some potentially important gaps in knowledge and a need for corroborative research, are those for biopower, hydropower, nuclear, some PV technologies and CSP. The current state of knowledge for geothermal and ocean energy is preliminary.

Lifecycle greenhouse gas emissions of selected petroleum fuels and biofuels

In this section, literature-derived estimates of lifecycle GHG emissions for first-generation biofuels (i.e., sugar- and starch-based ethanol, and oilseed-based biodiesel and renewable diesel (RD)), and selected next-generation biofuels derived from lignocellulosic biomass (i.e., ethanol and Fischer-Tropsch diesel (FTD)) are compared. Ranges of emissions for first-generation biofuels represent state-of-the-art technologies and projections of near-term technological improvements while those for next-generation ethanol and FTD from lignocellulosic biomass represent conceptual designs envisioned for commercial-scale biorefineries.

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[12] Also, some existing formations may have high operational emissions of CO_2 due to configuration and high dissolved CO_2 concentrations in geothermal fluids, which are not reflected in LCA literature assessed. See Sections 4.5.1 and 4.5.2 for details

[13] In late 2010, some controversy emerged over potential revisions to the GHG profile of natural gas. Some observers believe that methane leakage associated with upstream production and transport of natural gas is higher than historically categorized. See EPA (2010a) and Lustgarten (2011) for views of this emerging controversy.

Emissions are reported on the basis of 1 MJ of fuel produced and used to propel a passenger vehicle. These results are nearly equivalent to a comparison per vehicle km travelled because the vehicle fuel efficiency (distance travelled per MJ) is virtually unchanged when considering the evaluated biofuels and the petroleum fuels they displace used in the same vehicle (Beer et al., 2002; Sheehan et al., 2004; CARB, 2009). Emissions from direct and indirect LUC are excluded for all fuels, and discussed in the following subsection (see also Sections 2.3.1 and 2.5.3). Readers should refer to Section 8.3.1 for a comparison of lifecycle GHG emissions of various fuels (including hydrogen and electricity) used in different vehicle configurations. Note that electric vehicles could have lower lifecycle GHG emissions compared to vehicles fuelled with existing biofuels if electricity from renewable sources is used, or higher emissions than petroleum-based fuels if carbon-intensive fossil-based power generation is used (Creutzig et al., 2009; van Vliet et al., 2011).

Results from the studies reviewed suggest that, without considering potential LUC-related GHG emissions, first- and next-generation biofuels have lower direct lifecycle GHG emissions compared to petroleum fuels from a variety of crude oil sources (Figure 9.9). By comparison, the range in estimates for biofuels is much wider than that for gasoline and diesel. This can be attributed to many factors, including the types of feedstocks utilized; variations in land productivity, crop management practices, conversion process, and process energy source; uncertainty in N_2O emissions from fertilization; and methodological choices in LCAs, for example, co-product allocation approaches and definition of system boundaries[14] (Williams et al., 2009; Hoefnagels et al., 2010; Cherubini and Strømman, 2011; see also Box 9.2).

Although there is significant overlap in the ranges of lifecycle GHG emissions for virtually all biofuels, not all biofuel systems are equally efficient in reducing GHG emissions compared to their petroleum counterparts. For example, ethanol from Brazilian sugarcane has lower GHG emissions than that produced from wheat and corn (von Blottnitz and Curran, 2007; S. Miller, 2010). Estimates are reasonably comparable for biodiesel derived from rapeseed and soybean (Hill et al., 2006; CONCAWE, 2008; Huo et al., 2009a; Hoefnagels et al., 2010). Without LUC, palm oil biodiesel could have similar lifecycle GHG emissions as rapeseed and soybean biodiesel when the palm plantation and palm oil mill effluent (POME) are properly managed, or higher emissions if methane release from POME is not captured (Beer et al., 2007; CONCAWE, 2008; Wicke et al., 2008; Achten et al., 2010; Hoefnagels et al., 2010). The range in GHG estimates for *Jatropha* biodiesel is comparable to that for palm oil biodiesel (Whitaker and Heath, 2010).

The lack of commercial-scale lignocellulosic feedstocks and fuels production leads to a high degree of uncertainty in estimates of lifecycle GHG emissions for these systems. Uncertainty analysis indicates that the GHG emissions of some projected lignocellulosic biofuel supply chains could be higher than shown in Figure 9.9 assuming a combination of worst-case conditions in different elements of the supply chain (e.g., poorly managed biomass production practices, and energy-intensive biomass pre-processing) (Soimakallio et al., 2009; Hsu et al., 2010). However, lignocellulosic biofuels under well-managed conditions can have lower GHG emissions than grain ethanol and oilseed biodiesel.

The total lifecycle GHG emissions of fuels critically depend on the sign and magnitude of direct and indirect LUC effects, which could potentially negate or exceed any GHG reduction benefit from the displacement of petroleum fuels by biofuels discussed in this section (Berndes et al., 2010).

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[14] Sections 2.3 and 2.5 provide more detailed reviews of biofuel technologies and configurations, including lifecycle GHG emissions.

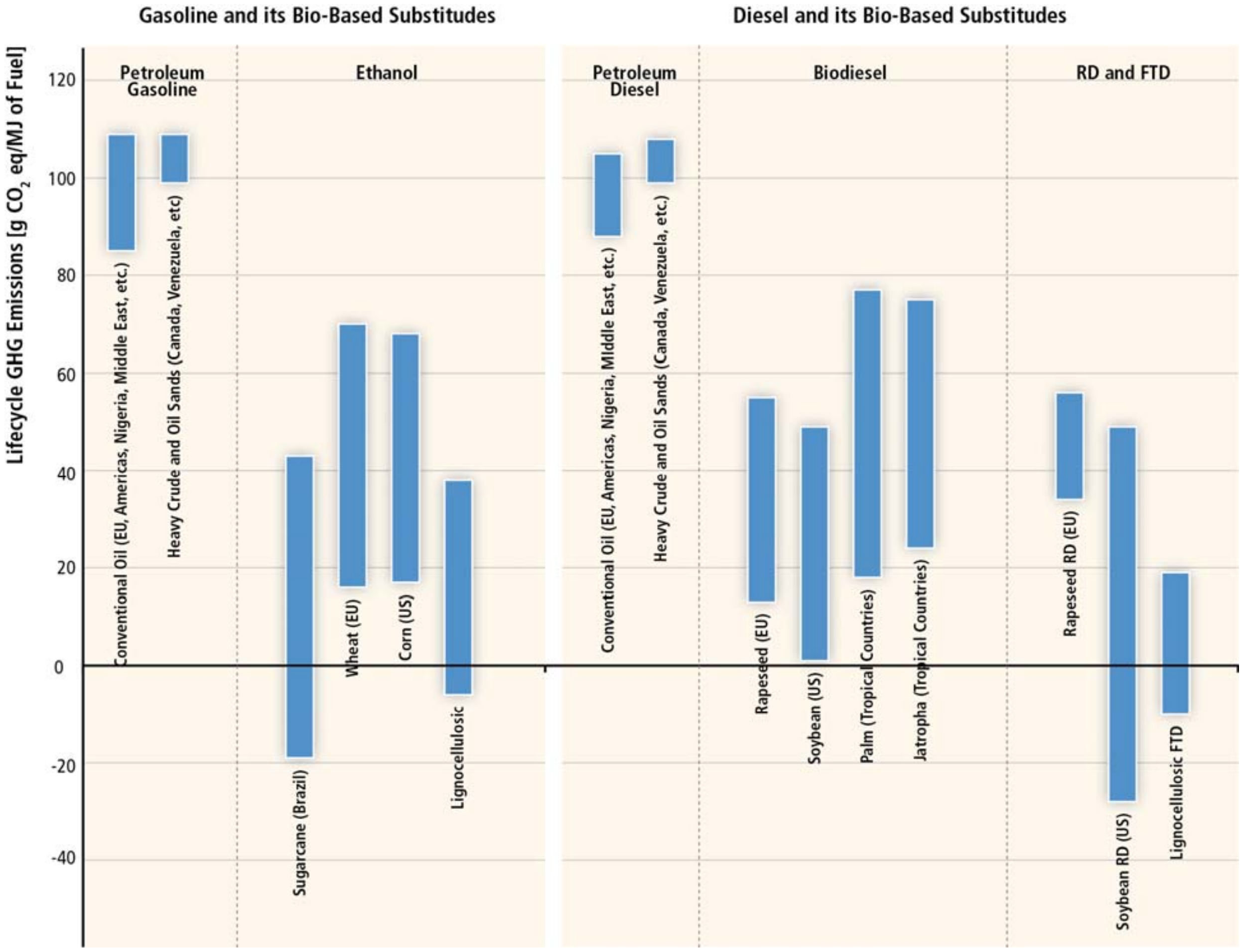

Figure 9.9 | Illustrative ranges in lifecycle GHG emissions of petroleum fuels, first-generation biofuels and selected next-generation lignocellulosic biofuels without considering land use change. (Sources for estimates plotted: Wu et al., 2005; Fleming et al., 2006; Hill et al., 2006, 2009; Beer et al., 2007; Wang et al., 2007; CONCAWE, 2008; Macedo and Seabra, 2008; NETL, 2008, 2009; CARB, 2009; Hoefnagels et al., 2010; Hsu et al., 2010; Kaliyan et al., 2010; Larson et al., 2010; Neely et al 2010). Note: FTD = Fischer-Tropsch diesel; RD = Renewable diesel (RD is different from biodiesel in processing and product properties). For common feedstock and fuel categories shown in both Figure 2.10 and above (e.g., sugarcane ethanol, FTD), the references cited and the ranges of GHG emission estimates are identical.

Land use change-related greenhouse gas emissions and bioenergy

Conversion from one land cover type or use to another directly and indirectly affects terrestrial GHG stocks and flows, and historically has been a significant contributor to global GHG emissions (IPCC, 1996b; Le Quere et al., 2009). Agriculture and forestry systems are important drivers of these land use changes, with energy systems (especially bioenergy but also reservoir hydropower, mining and petroleum extraction) being an additional stressor (Schlamadinger, 1997). While GHG emissions from LUC are difficult to quantify, they are important to investigate and evaluate, since any potential GHG emission reduction benefits from increased use of bioenergy compared to fossil energy sources could be partially or wholly negated when LUC-related GHG emissions are considered.

Direct LUC (dLUC) occurs when bioenergy feedstock production modifies an existing land use, resulting in a change in above- and below-ground carbon stocks. dLUC-related GHG emissions are dependent on site-specific conditions such as the prior land use, soil type, local climate, crop management practices and the bioenergy crop to be grown. In the examples shown in Figure 9.10, the original land use is generally a more important factor in determining dLUC-related GHG emissions than the bioenergy feedstock type planted. The conversion of certain land types (e.g., rainforest and peatland) can lead to very large GHG emissions; conversely, the use of degraded land and sometimes former farmland (e.g., when using lignocellulosic feedstocks) can enhance carbon stocks. Any dLUC-related GHG emissions must be repaid over time before GHG emission reduction benefits for the use of bioenergy can accrue (Gibbs et al., 2008). Results reported in Figure 9.10 are totals averaged over a 30-year time horizon. Not considered in the analyses reviewed here is the time signature of these GHG emissions (an initial pulse followed by a long tail), which is an important determinant of GHG climate impacts.

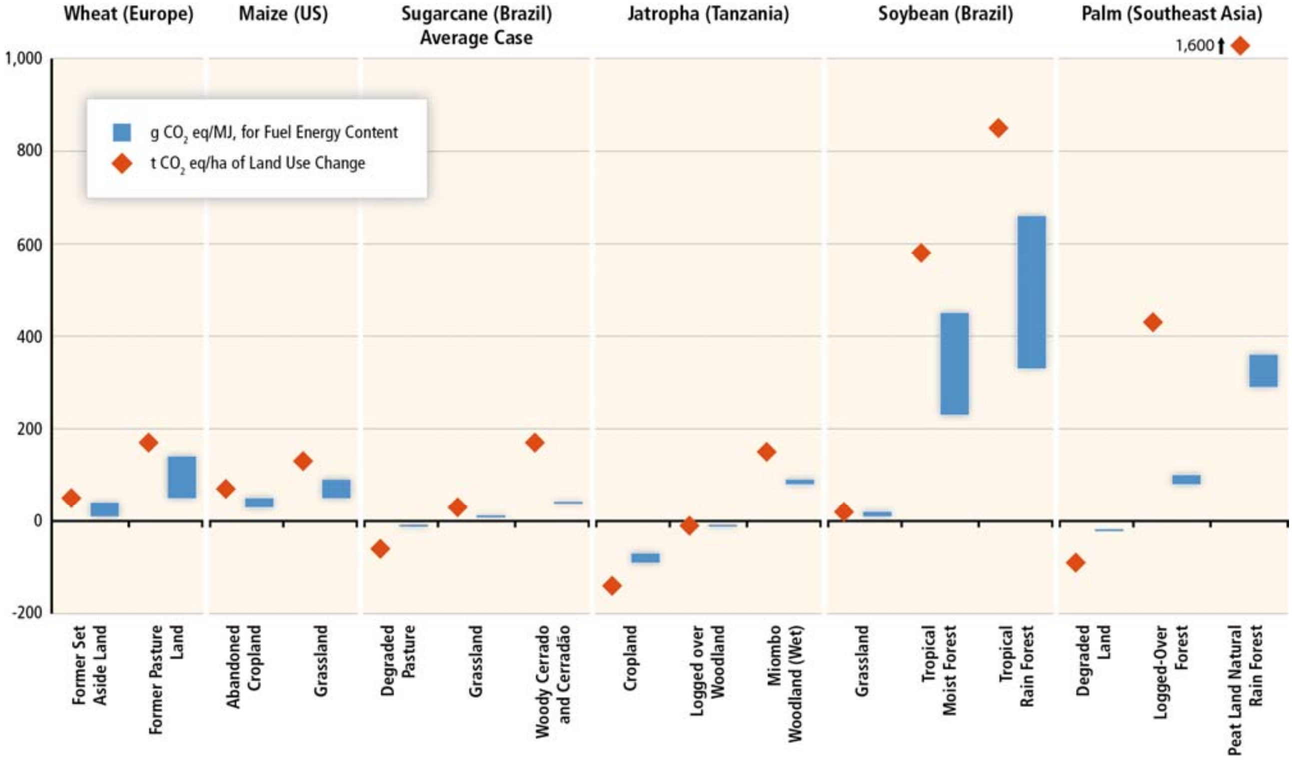

Figure 9.10 | Illustrative direct LUC-related GHG emission estimates from selected land use types and first-generation biofuel (ethanol and biodiesel) feedstocks. Results are taken from Hoefnagels et al. (2010) and Fargione et al. (2008) and, where necessary, converted (assuming a 30-year timeframe) to the functional units displayed using data from Hoefnagels et al. (2010) and EPA (2010b). Ranges are based on different co-product allocation methods (i.e., allocation by mass, energy and market value).

Indirect LUC (iLUC) occurs when a change in the production level of an agricultural product (i.e., a reduction in food, feed or fibre production induced by agricultural land conversion to the production of bioenergy feedstocks) leads to a market-mediated shift in land management activities (i.e., dLUC) outside of where the primary driver occurs. iLUC is not directly observable, and is complex to model and attribute to a single cause. Important aspects of this complexity include model geographic resolution, interactions between bioenergy and other agricultural systems, how the systems respond to changes in market and policy, and assumptions about social and environmental responsibility for actions taken by multiple global actors. For example, estimates of iLUC-induced GHG emissions can depend on how land cover is modelled. Models using greater geographic resolution and number of land cover types have tended to produce lower estimates and tighter uncertainty ranges that those considering just, for example, pasture and forest, at lower resolution (Nassar et al., 2009; EPA, 2010b). Emission estimates also tend to increase if large future bioenergy markets and high growth rates are assumed. Despite similar evaluation methods, Al-Riffai et al. (2010) and Hiederer et al. (2010) report a LUC (direct and indirect) impact of 25 and 43 g CO_2eq/MJ, respectively, for a similar set of biofuels, partly because they evaluated different magnitudes of biofuels market growth (0.3 and 0.9 EJ, respectively).

Despite challenges in modelling iLUC attributable to bioenergy systems, improvements in methods and input biophysical data sets have been made. Some illustrative estimates of representative LUC-related (including d- and iLUC) GHG emissions are reported in Figure 9.11. See Section 2.5.3 for more published estimates and discussion of LUC.

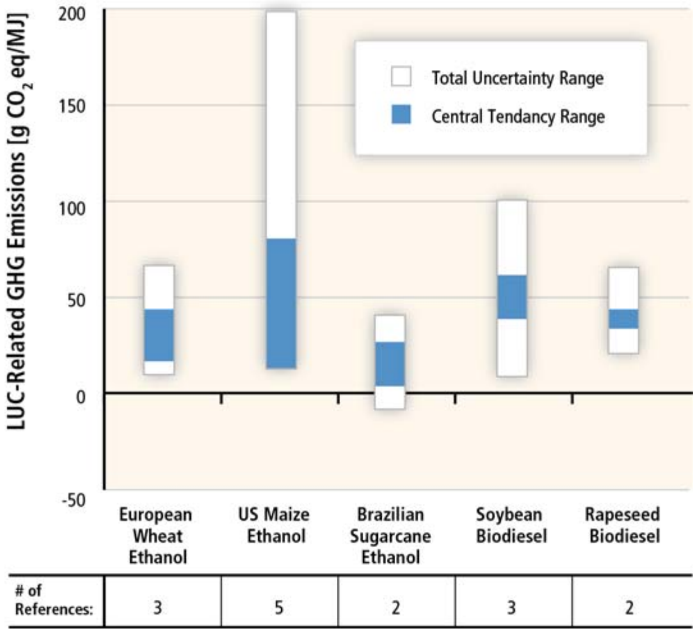

Figure 9.11 | Illustrative estimates of direct and indirect LUC-related GHG emissions induced by several first-generation biofuel pathways, reported here as ranges in central tendency and total reported uncertainty. Estimates reported here combine several different uncertainty calculation methods and central tendency measures and assume a 30-year time frame. Reported under the x-axis is the number of references with results falling within these ranges (Sources: Searchinger et al., 2008; Al-Riffai et al., 2010; EPA, 2010b; Fritsche et al., 2010; Hertel et al., 2010; Tyner et al., 2010).

The wide ranges of even the central tendency estimates reflect the uncertainty and variability remaining in the estimation of LUC-induced GHG emissions from bioenergy systems, but nonetheless point to a potentially significant impact of LUC relative to non-LUC lifecycle GHG emissions for many dedicated bioenergy systems. Thus, it is critical to continue research to improve LUC assessment methods and increase the availability and quality of information on current land use, bioenergy-derived products and other potential LUC drivers. It is also critical to consider ways to mitigate the risk of bioenergy-induced LUC, for instance Agro-Ecologic Zoning systems (EMBRAPA, 2009) coupled with adequate monitoring, enforcement and site-specific bioenergy carbon footprint evaluation; improvement of agricultural management and yields, for example, by intercropping and improved rotations systems; using lower LUC-risk lignocellulosic feedstocks or replacing dedicated biomass with residues or wastes; and promoting the use of degraded or marginal lands or sustainability certification systems (van Dam et al., 2009; Berndes et al., 2010; see Sections 2.2.4, 2.4.5, 2.5.2 and 2.8.4).

9.3.4.2 Local and regional air pollution

This section presents data on selected air pollutants that are emitted by energy technologies and that have the most important impacts on human health as indicated by the World Health Organization (WHO, 2006). These include particulate matter[15] (PM), nitrous oxides (NO_x), sulphur dioxide (SO_2) and non-methane volatile organic compounds (NMVOC). Their dispersion in the atmosphere entails significant impacts at the local and regional scale (up to a few thousand kilometres) (e.g., Hirschberg et al., 2004b). Black carbon, which constitutes a fraction of total PM emissions, and other aerosols can also have impacts on global and regional climate (see Box 9.4). The location-specific impacts from air pollutants depend on exposure, their concentrations in the atmosphere, as well as the concentrations of further pollutants acting as reactants, for example, for formation of secondary particulates (e.g., Kalberer et al., 2004; Andreani-Aksoyoglu et al., 2008; Hallquist et al., 2009). Air pollution also varies significantly between urban and rural areas. Therefore, cumulative lifecycle inventory results, that is, quantities of pollutants emitted per unit of energy delivered, must be interpreted with care regarding conclusions about potential impacts on human health and the environment (Torfs et al., 2007). The following results can only act as basic data for the estimation of specific impacts (see Section 9.3.4.3). Indoor air pollution caused by solid fuels in traditional cookstoves is discussed in Box 9.4 and Section 9.3.4.3.

Box 9.4 | Black carbon and aerosols: Climate effects of air pollutants.

Black carbon (BC) is a short-lived air pollutant formed by incomplete combustion of fossil or biomass fuels. Prime sources of BC are agricultural and forest fires, (diesel) combustion engines, in particular maritime vessels running on heavy oil, and residential use of heating and cooking fuels (Bond et al., 2004; Lack et al., 2008). BC emissions are particularly high in developing countries. BC has detrimental health effects (see Section 9.3.4.3), and can accelerate climate change both through its heat-absorbing properties in the atmosphere, and by reducing the albedo of cloud, snow and ice surfaces (Ramanathan and Carmichael, 2008; Flanner et al., 2009; Lau et al., 2010). BC is emitted together with organic carbon (OC), and other aerosols like sulphates, that have a negative effect on radiative forcing. Therefore, the net warming effect of aerosol emissions from combustion is source- and location-dependent, and still uncertain. Available literature suggests that contained combustion of fossil fuels and residential combustion of solid biomass results in net warming, while the net effects of open combustion (field fires) of biomass sources are negative, due to a higher ratio of reflective OC to absorptive BC aerosols (Bond et al., 2004; M. Jacobson, 2004; Hansen et al., 2005; Koch et al., 2007). Both processes play a prominent role in the formation of atmospheric brown clouds and other processes that exhibit strong regional climate impacts (Ramanathan et al., 2005, 2007), for example, alteration of the Indian Monsoon (Auffhammer et al., 2006) or larger warming in elevated regions of the tropics (Gautam et al., 2009).

BC abatement has been proposed as a significant means not only for climate change mitigation, but also for addressing additional sustainability concerns such as air pollution, inefficient energy services, and related health impacts on the poor (Grieshop et al., 2009). The provision of energy efficient and smoke-free cookers and soot-reducing technologies for coal combustion in small industries could have major benefits by reducing radiative forcing and combating indoor air pollution and respiratory diseases in urban centres (Ramanathan and Carmichael, 2008; see Sections 2.5.4 and 9.3.4.3). A switch from diesel to LPG in the public transport system in Delhi has resulted in net GHG savings and substantial reductions in BC loads (C. Reynolds and Kandlikar, 2008).

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[15] PM emissions are specified as PM_d, where the subscript d indicates the largest diameter (in μm) of the particles that are included. Particles emitted by internal combustion engines are all very small and almost entirely included in the $PM_{2.5}$ measure.

However, it has been suggested that removing the 'masking' effect of *reflective* aerosols through air pollution control measures might accelerate the impacts from already-committed-to warming (Ramanathan and Feng, 2008; Carmichael et al., 2009).

Heat and electricity supply

For space heating and electricity production with fossil fuels and biomass (wood) combustion, the dominant contributor to lifecycle inventory results (per kWh of end-use energy) is the combustion stage, with typically a 70 to almost 100% share of the overall emissions (e.g., Jungbluth et al., 2005; C. Bauer, 2007; Dones et al., 2007) (see Figure 9.12). However, in the case of long distance transport of coal, natural gas, oil and wood fuel, the transport stage might become more important (e.g., C. Bauer, 2007, 2008). In general, natural gas causes the lowest emissions among fossil fuels. Contributions of different sections of the energy chains as well as total emissions vary within orders of magnitude with power plant technology, application of pollution control technologies (flue gas desulphurization, particulate filters, etc.) and characteristics of fuel feedstock applied, as indicated by minimum and maximum values in Figure 9.12.

In the case of space heating, for example, minimum and maximum figures represent the most and least efficient technology options among the datasets evaluated. Additionally, the type of fuel (e.g., wood logs, chips or pellets in case of biomass) affects the results. The figures for solar heating are valid for a certain location in central Europe, and variation in solar irradiation is not considered in the range shown. In the case of fossil electricity generation, the results include country-specific averages for current technology and fuel supply for all European and a few other countries, such as the USA and China. Minimum and maximum values therefore mainly represent the countries with the most and least efficient power plant and pollution control technology, respectively.

The results from this assessment show that non-combustion RE technologies and nuclear power cause comparatively minor emissions of air pollutants, only from upstream and downstream processes. Also, the variations in the results, depending on both technologies applied and site of power generation (in terms of, for example, solar irradiation (Jungbluth et al., 2009) and wind conditions (EWEA, 2004)), are in general much lower for RE and nuclear than for fossil power and heating systems. The potential increase in overall emissions from the power system due to a more flexible operation of fossil power plants in response to feed-in of variable renewable electricity is not taken into account. Although not shown in Figure 9.12, the type of electricity used for the operation of the geothermal heat pump has a significant impact on the performance of this technology (Heck, 2007).

LCA literature including results on air pollution in developing countries is scarce, and available case studies could not be integrated into the results displayed in a consistent way. However, emissions at the higher end of the ranges shown may typically apply to developing economies that use older technologies, have less pollution control measures in place and possibly consume lower-quality fuels. Also, lack of environmental regulation in developing countries results in comparatively higher emissions. Molina and Molina (2004) report outdoor urban air pollution in cities from industry, energy and transport that is a factor of 10 or higher than in developed nations; the location of the emission sources in combination with the prevailing meteorological conditions are important factors in this respect. Air pollution abatement has gained importance since the early 1990s, in particular in China, resulting in a slowdown of sulphur emissions in Asia (Carmichael et al., 2002). The substantial potential of RE to contribute to air pollution abatement has been studied in particular for emerging economies' electricity and transport sectors (Boudri et al., 2002; Aunan et al., 2004; Ramanathan and Carmichael, 2008; Creutzig and He, 2009; see Sections 9.4.4 and 10.6).

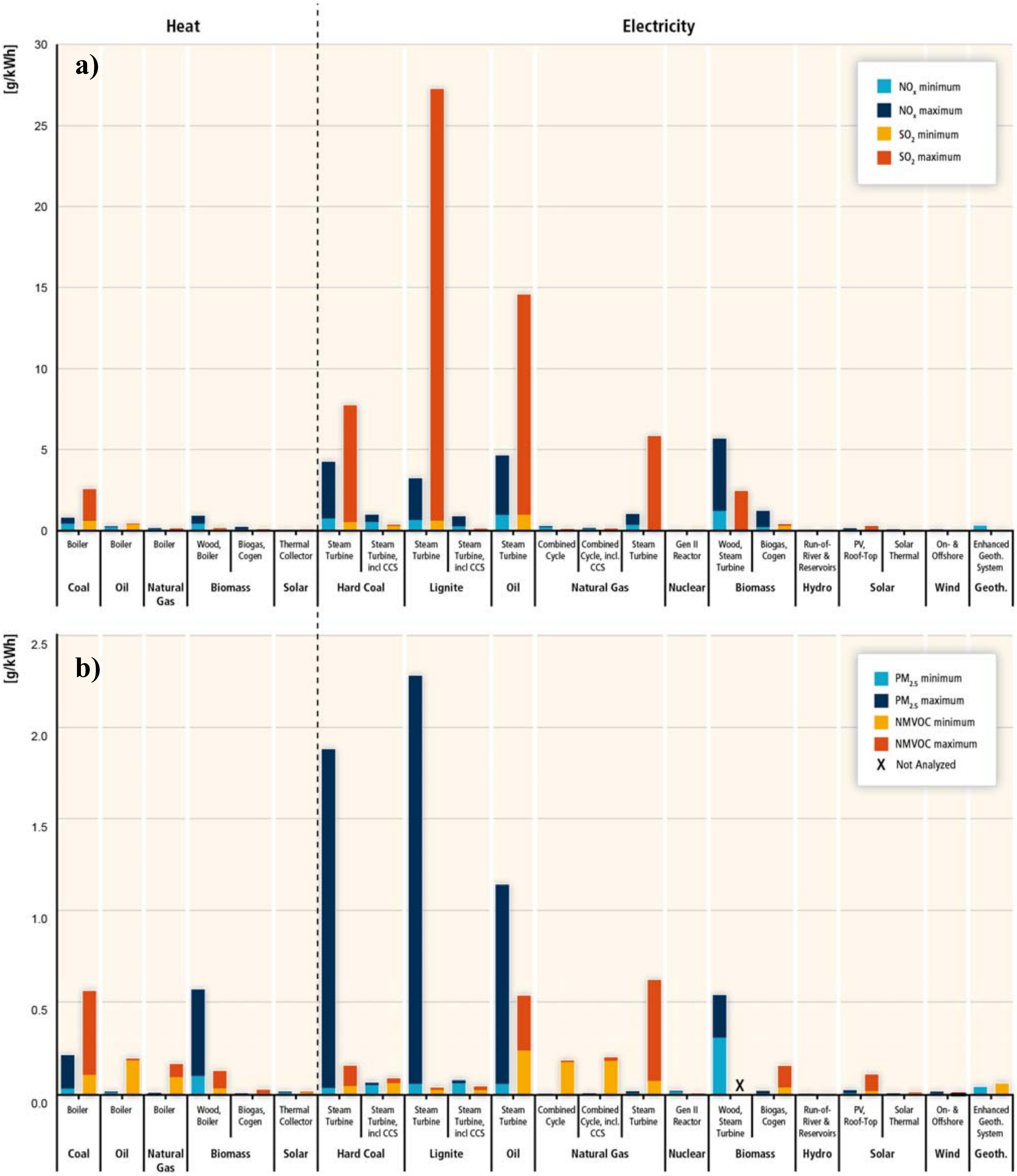


Figure 9.12 | Cumulative lifecycle emissions per unit of energy generated of a) NO_x and SO_2 and b) NMVOC and $PM_{2.5}$ for current heat and electricity supply technologies (C. Bauer, 2008; Viebahn et al., 2008; Ecoinvent, 2009); traditional biomass use not considered. Figures for coal and gas power chains with CCS are valid for near-future forecasts (C. Bauer et al., 2009).

Transport fuels

Under a lifecycle approach, well-to-wheels air pollutant emissions of biomass fuel/vehicle systems differ significantly. These differences are caused by the feedstock used for fuel production, biomass yields, fuel production pathways and technologies, location of biomass growth and harvesting, as well as fuel characteristics and vehicle technologies (von Blottnitz and Curran, 2007; Cherubini and Strømman, 2011).

The use of gaseous fuels—both fossil and biomass origin—tends to reduce air pollution compared to liquid fuels (Zah et al., 2007). The effects of using biomass fuels and bioethanol and biodiesel blends on tailpipe emissions have been examined by numerous authors with varying results (Schifter et al., 2004, 2011; Niven, 2005; Coelho et al., 2006; Fernando et al., 2006; Goldemberg et al., 2008; Graham et al., 2008; Pang et al., 2008; Coronado et al., 2009; Costa and Sodré, 2009; Demirbas, 2009; Hilton and Duddy, 2009; Roayaei and Taheri, 2009; Yanowitz and McCormick, 2009; Yoon et al., 2009; Zhai et al., 2009; Park et al., 2010). Fuel blends, combustion and ambient temperatures as well as additives play a decisive role in air pollutant formation (Lucon et al., 2005; Coelho et al., 2006; Graham et al., 2008; Ginnebaugh et al., 2010). Overall, the studies tend to agree that carbon monoxide (CO) and hydrocarbon emissions are reduced by use of both ethanol and biodiesel blends compared to gasoline and diesel, respectively, while NO_x emissions seem to be higher. Increased NO_x and evaporative emissions from oxygenates of biofuel blends can lead to higher concentrations of tropospheric ozone (Schifter et al., 2004; Agarwal, 2007). Increased aldehyde emissions have been reported for bioethanol in Brazil, which are less toxic than the formaldehydes originating from fossil fuels (Goldemberg et al., 2008; Graham et al., 2008; Anderson, 2009). Second-generation and future biofuels are expected to improve performance, when the combustion system is specifically adapted (Pischinger et al., 2008; Ußner and Müller-Langer, 2009).

Notter et al. (2010) and Zackrisson et al. (2010) suggested that future electric or fuel cell vehicles (see Section 8.3.1) offer a substantial potential for reductions in air pollution (as well as other environmental burdens) if electricity or hydrogen from RE sources is used as the energy carrier.

Shifting emissions from urban to less-populated areas can result in less exposure and therefore reduced impacts on human health (see Section 9.3.4.3). Despite increases in total emissions, some bioethanol blends used in flex-fuel vehicles in Brazil contributed to reductions of up to 30% in urban emissions, as most emissions originated from farming equipment, fertilizer manufacture and ethanol plants located in rural areas (Huo et al., 2009b). Similarly, the formation of secondary pollutants as aerosols and ozone in towns might be reduced, depending on atmospheric conditions including background concentrations of pollutants.

9.3.4.3 Health impacts

The most important energy-related impacts on human health are those associated with air pollutant emissions by fossil fuel and biomass combustion (Ezzati et al., 2004; W. Paul et al., 2007). Air pollution, even at current ambient levels, aggravates morbidity (especially respiratory and cardiovascular diseases) and leads to premature mortality (Table 9.9;,Cohen et al., 2004; Curtis et al., 2006). Although the health effects of ambient air pollution result from a complex mixture of combustion products and are therefore difficult to attribute to a certain source or pollutant, negative effects have been most closely correlated with three species of pollutants in epidemiological studies: fine PM, SO_2, and tropospheric ozone (Ezzati et al., 2004; Curtis et al., 2006). Significant reductions in mass emissions of pollutants by deployment of RE should yield increased health benefits, and opportunities for policy measures combining climate change and (urban) air pollution mitigation are increasingly recognized (see Sections 9.4.4.1, 10.6 and 11.3.1).

Table 9.9 | Health impacts of important air pollutants (adapted from Bickel and Friedrich, 2005).

Primary Pollutants [1]	**Secondary Pollutants** [2]	**Impacts**
particles (PM_{10}, $PM_{2.5}$, black carbon)		cardio-pulmonary morbidity (cerebrovascular and respiratory hospital admissions, heart failure, chronic bronchitis, upper and lower respiratory symptoms, aggravation of asthma), mortality
SO_2	sulphates	like particles[3]
NO_x	nitrates	morbidity, like particles[3]
NO_x+VOC	ozone	respiratory morbidity, mortality
CO		cardiovascular morbidity, mortality
Polyaromatic Hydrocarbon		cancers
Lead, Mercury		morbidity (neurotoxic and other)

Notes: [1] Emitted by pollution source, [2] created by chemical reactions in the atmosphere, [3] lack of specific evidence, as most available epidemiological studies are based on mass PM without distinction of components or characteristics.

Household environmental exposures, including indoor air pollution (IAP) from the combustion of solid heating and cooking fuels, generally decline with increased development, whereas community-level exposures have been found to increase initially, and then gradually decline, with important distinctions between rural and urban areas (Smith and Ezzati, 2005; HEI, 2010). Exposure to IAP from the combustion of coal and traditional biomass is recognized as one of the most important causes of morbidity and mortality in developing countries (Bruce et al., 2002; Ezzati et al., 2004; Smith and Ezzati, 2005; Zhang and Smith, 2007). For example, comparative quantifications of health risks showed that in 2000, more than 1.6 million deaths and over 38.5 million disability-adjusted life-years (DALYs) were attributable to indoor smoke from solid fuels (WHO, 2002; Smith and Mehta, 2003; Smith et al., 2004; Torres-Duque et al., 2008). Figure 9.13 illustrates the magnitude of the health problems associated with IAP, which is projected to exceed other major causes of premature deaths (e.g., HIV/AIDS, malaria and tuberculosis) by 2030 (IEA, 2010a).

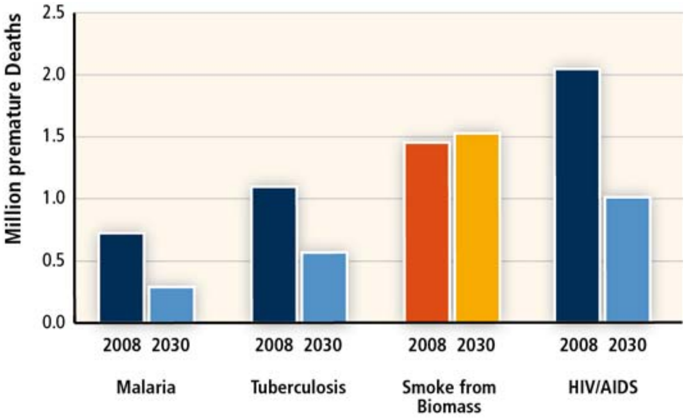


Figure 9.13 | Premature deaths from household air pollution and other diseases in 2008 and projected for 2030 (IEA, 2010a).

Many health problems like chronic obstructive pulmonary disease, cataracts and pneumonia are most severe for women and children, which are most exposed to indoor emissions (Smith et al., 2000; Pokhrel et al., 2005; Barnes et al., 2009; Haines et al., 2009; UNDP and WHO, 2009), and generally affect the poorest segment of the population (see Section 9.3.2).

In traditional uses, biomass-based fuels yield worse results with respect to contaminant concentrations than charcoal or coal (Kim Oanh and Dung, 1999; Bailis and Cutler, 2004; Zhang and Smith, 2007). Mitigation options—besides the more costly switch to cleaner fuels (see Section 9.3.2)—for health impacts from IAP include improved cookstoves (ICS), ventilation and building design and behavioural changes (Smith et al., 2000; Bruce et al., 2004; Mehta and Shahpar, 2004; Palanivelraja and Manirathinem, 2010). Modern bioenergy technologies (ICS, biogas) can provide health benefits without fuel switching (Smith et al., 2007; Bailis et al., 2009), as well as additional environmental and social advantages (Haines et al., 2009) (see Section 2.5.7.2).

Non-combustion-related health impacts

Health impacts from energy technologies other than those described above can be regarded as relatively minor. Table 9.10 provides an overview of areas of concern for RE technologies as identified in this report.

Table 9.10 | Overview of potential impacts on human health by RE technologies as reported in Sections 2.5, 4.6, 5.6 and 7.6. For solar and ocean technologies, no impacts were identified.

RE Technology	Potential Health Concerns
Bioenergy	Depending on feedstock and agricultural management, direct and indirect exposure to agrochemicals and derivatives like pesticides or nitrates, or smoke due to residue burning may cause local impacts Health impacts related to air pollutant emissions by combustion*
Geothermal Energy	For some operations, hydrogen sulphide emission may cause local impacts
Reservoir Hydropower	Standing water bodies can lead to spread of vector-borne diseases in tropical areas Concentrations of population and migrant workers during construction of large dams may cause public health concerns
Wind Energy	Nuisance from noise and flickering

* see previous subsection for details

For nuclear power, radiotoxicity of spent fuels and uranium tailings, including windblown radioactive dust dispersal, and radon gas from the mining stage are the most prominent health concerns (OECD/NEA, 2002; Abdelouas, 2006; Al-Zoughool and Krewski, 2009). Increased cancer risk for residents, particularly children, near nuclear power plants has been studied with contrasting results in different countries (Ghirga, 2010).

9.3.4.4 Water

Water is a critical and highly localized resource with multiple and competing uses, including energy. The condition and amount of water resources in a given location will influence the selection, design and performance of an energy technology; impacts from energy technologies will also vary geographically and temporally. Hence, implications for the water-energy nexus must be considered within a SD context. Literature holistically evaluating the impacts of energy technologies on water resources is limited, especially from a lifecycle perspective. While some broad conclusions can be drawn from the evidence presented in the following sections, additional research is needed to confirm many of the results and fill existing knowledge gaps.

In 2006, the energy and industrial sectors accounted for 45% of freshwater withdrawals in Annex I countries and 10% of freshwater withdrawals in non-Annex I countries (Gleick, 2008). As lesser-developed countries industrialize and improve access to energy services, additional freshwater resources may be required to meet the water demands of increased energy production. However, various metrics indicate that many developing countries already experience water scarcity problems, and climate change may exacerbate water stress (Rijsberman, 2006; IPCC, 2008; Dai, 2011). Thermal power plants may be especially vulnerable to conditions of water scarcity and climate change due to their continuous water requirements. Also, hydropower and bioenergy are highly dependent on water availability, and exhibit potentials for both increased competition for and mitigation of water scarcity (see Sections 2.5.5.1 and 5.10).

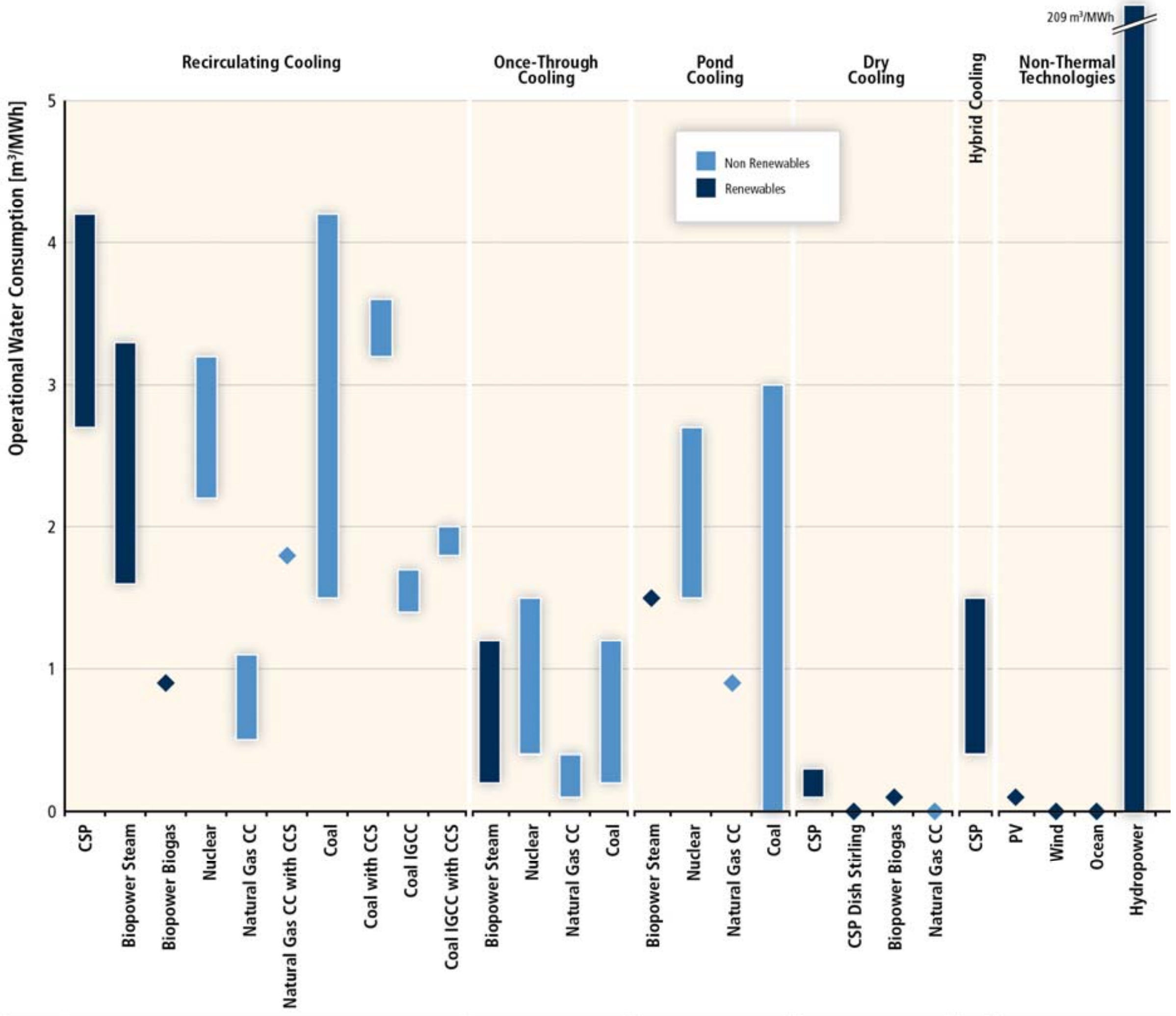
Operational water use and water quality impacts of electricity generation

Electricity sector impacts involve both water withdrawal and consumption. Water withdrawal is the amount of water removed from the ground or diverted from a water source, while consumption is the amount of water that is lost through evaporation, transpiration, human consumption and incorporation into products (Kenny et al., 2009). Both metrics have an important impact on local water availability, and often with trade-offs such that using existing technology only one impact can be reduced at a time. Water consumption by industry and power plants, while accounting for less than 4% of global water consumption, is an important consideration for water-scarce regions; this is particularly relevant in the context of future resource development, with water being effectively removed from the system and not available for other uses, for example, agriculture or drinking water (Shiklomanov, 2000).

While water is used throughout the lifecycle of most technologies, operational cooling needs for thermal power plants result in the withdrawal and consumption of more water than any other lifecycle phase, with the exception of biomass feedstock production (Fthenakis and Kim, 2010). Figure 9.14 depicts the variability in operational water consumption rates associated with electricity generation units and cooling technologies. Water consumption varies widely both within cooling technology categories, but especially across categories. The choice of cooling system is often site-specific and based on water availability, local environmental regulations or quality impacts, parasitic energy loads, costs, or other considerations (J. Reynolds, 1980; Bloemkolk and van der Schaaf, 1996). Non-thermal technologies, with the exception of hydropower, are found to have the lowest operational and lifecycle withdrawal and consumptive water use values per unit electricity generated (Tsoutsos et al., 2005; Fthenakis and Kim, 2010). Substantial evaporation can occur from hydroelectric reservoirs, yet reservoirs often provide other beneficial services besides power production (e.g., flood control, freshwater supply, and recreation), and allocation schemes for determining water consumption from various reservoir uses can significantly influence reported water consumption values (Gleick, 1993; LeCornu, 1998; Torcellini et al., 2003). Research may be needed to determine the net effect of reservoir construction on evaporation in a specific watershed. Data shown in Figure 9.14 are from studies of US systems only, but represent a wide range of technology vintages and climatic conditions, both of which can affect water use rates (B. Miller et al., 1992), and thus their results are applicable and comparable to water use rates in other countries (EC, 2006).

Data for geothermal energy are not included in Figure 9.14 because in most situations, geothermal fluids are utilized for cooling before reinjection, and therefore no freshwater is consumed (Franco and Villani, 2009; see Section 4.5.3). Depending on technology, resource type and cooling system used, geothermal operational water consumption can range from near zero up to 15 m^3/MWh (Fthenakis and Kim, 2010).

Reduced water levels or higher temperatures in water bodies may require once-through cooled thermal power plants, which withdraw large volumes of water but consume comparatively little, to run at lower capacities or to shut down completely (Poumadère et al., 2005). Addressing this vulnerability by utilizing recirculating cooling technologies, which withdraw less water, could lead to increases in water consumption (Figure 9.14), reductions in plant-level thermal efficiencies and increases in operating and installed costs (Tawney et al., 2005). Ambient air temperature increases may lead to reduced plant-level thermal efficiency and cooling system performance, resulting in higher water use rates (B. Miller et al., 1992; Turchi et al., 2010). Thermal power plant vulnerability can be reduced by utilizing alternative water sources, such as municipal wastewater, or by utilizing a dry-cooling system, yet there are cost, performance and availability trade-offs and constraints (EPRI, 2003; Gadhamshetty et al., 2006). Reservoirs and river levels may also be affected by climate change, altering water availability and hydropower performance capabilities and output (Harrison and Whittington, 2002; IPCC, 2008).



N:	18	4	1	5	4	1	16	2	7	3	1	3	3	9	1	1	1	7	11	2	1	2	4	2	2	1	4
Sources:	11	3	1	5	4	1	8	1	2	1	1	3	3	4	1	1	1	2	4	2	1	2	2	2	2	1	2

Figure 9.14 | Ranges of rates of operational water consumption by thermal and non-thermal electricity-generating technologies based on a review of available literature (m^3/MWh). Bars represent absolute ranges from available literature, diamonds single estimates; n represents the number of estimates reported in the sources. Note that upper values for hydropower result from few studies measuring gross evaporation values, and may not be representative (see Box 5.2). Methods and references used in this literature review are reported in Annex II.

Notes: CSP: concentrating solar power; CCS: carbon capture and storage; IGCC: integrated gasification combined cycle; CC: combined cycle; PV: photovoltaic.

Electricity generation units can affect water quality through thermal and chemical pollution. During normal operation, electricity generation units with once-through cooling systems can elevate the temperature of water bodies receiving the cooling water discharge, which can negatively affect aquatic ecosystems and reduce fish yields (Kelso and Milburn, 1979; Barnthouse, 2000; Poornima et al., 2005; Greenwood, 2008; Kesminas and Olechnoviciene, 2008; Shanthi and Gajendran, 2009). Deposition of air pollutant emissions from the combustion of fossil fuels to water bodies can also affect water quality (Larssen et al., 2006). Hydroelectric facilities can impact both temperature and dissolved oxygen content of the released water while also altering the flow regime, disturbing ecosystems and disrupting the sediment distribution process (Cushman, 1985; Liu and Yu, 1992; Jager and Smith, 2008; see Section 5.6). Tidal energy facilities located at the mouths of estuaries could affect the hydrology and salinity of estuaries and ocean thermal energy conversion technologies can alter local water quality through the accidental release of toxic chemicals, such as ammonia and chlorine (Pelc and Fujita, 2002; Vega, 2002; see Section 6.5). Geothermal facilities can affect both surface and ground water quality through spillage of geothermal fluids at the surface during operation, leakage from surface storage impoundments, and through contamination of nearby freshwater wells (Brophy, 1997; Dogdu and Bayari, 2004; see Section 4.5).

Water use of upstream processes

Water use in upstream processes (see Figure 9.7) can be high for some energy technologies, particularly for fuel extraction and biomass feedstock production (Fthenakis and Kim, 2010). Specifically, unconventional fossil fuel (e.g., oil shale, shale gas) exploration and processing techniques can have significantly greater water use rates than conventional exploration techniques, and may require freshwater to be imported from other watersheds (GAO, 2010; Kargbo et al., 2010; Parfitt, 2010; Veil, 2010). Further research is necessary to determine water use as a function of output energy content of the extracted fuel in unconventional production to facilitate comparison to other conventionally produced fuels.

Biomass feedstock may be used for electricity generation or converted into liquid fuels. To account for both naturally variable precipitation and irrigation freshwater required in feedstock production, the water footprint metric is used (Gerbens-Leenes et al., 2009). The water footprint of feedstock production is highly dependent on feedstock type, geographic region and local climatic conditions, and crop management practices (Berndes, 2002, 2008; Gerbens-Leenes et al., 2009; Wu et al., 2009; Harto et al., 2010; Stone et al., 2010). These factors may change from year to year, and the water footprint for an individual case may differ substantially from the global average. Estimates of water footprints for biomass grown for multiple purposes can also vary significantly due to the choice of allocation method (S. Singh and Kumar, 2011).

The current water footprint of biomass feedstock production for electricity generation is approximately 70 to 400 times greater than operational water consumption requirements for thermal power plants (Gerbens-Leenes et al., 2009; S. Singh and Kumar, 2011). The current global average water footprint (weighted by production mass) of biofuel feedstock production ranges from about 60 to 600 litres per MJ fuel (Gerbens-Leenes et al., 2009). Biodiesel feedstock water footprints are nearly two to four times greater than the water footprint for ethanol crops, because oilseed crops are less water efficient (Gerbens-Leenes et al., 2009; S. Singh and Kumar, 2011). Refining and processing biofuels require around 0.1 to 0.5 litres of water per MJ fuel, which is far less than feedstock production requirements but still considerably higher than those of conventional petroleum products (Berndes, 2002; King and Webber, 2008; Wu et al., 2009; Harto et al., 2010; S. Singh and Kumar, 2011).

Without proper management, increased bioenergy production could therefore increase competition for water in critical areas (see Section 2.5.5.1; Dornburg et al., 2008; Berndes, 2010; Fingerman et al., 2010). However, the proportion of irrigation freshwater to total water consumed varies considerably, and the relationship between vegetation and hydrological processes at the landscape scale is complex. Certain feedstock production systems may drive land use towards systems with higher water productivity and decreased water competition, as, for example, woody crops grown in multi-year rotations. Some perennials can improve water retention functions on degraded lands, and considerable water efficiency gains are possible with improved agricultural management.

Quality impacts of upstream processes

Feedstock production, mining operations and fuel processing can also affect water quality (Larssen et al., 2006). Effluent from coal mining can degrade local water quality by lowering pH and increasing concentrations of solids and heavy metals; leachate water from overburden dumps can also have high metal concentrations (Tiwary, 2001). Effluent from uranium mining for nuclear fuel can increase concentrations of uranium, radium, selenium, molybdenum and nitrate in surrounding surface- and groundwater (R.F. Kaufmann et al., 1976; van Metre and Gray, 1992; Au et al., 1995; Voitsekhovitch et al., 2006; Carvalho et al., 2007). Radioactive water contamination can also occur from reprocessing of spent nuclear fuel, although releases can be greatly reduced through effective regulation (EC, 1999; Suzuki et al., 2008; Yamada and Zheng, 2008). Operational oil tanker discharges (i.e., dumping of oil during tanker cleaning operations) are a continuous source of water pollution (Jernelöv, 2010; Rogowska and Namiesnik, 2010). Most countries have established strict limits and safety standards to prevent water pollution, yet this does not always prevent accidents (see Section 9.3.4.7).

If conventional row-cropping production methods are used, bioenergy feedstock production can have water quality impacts from fertilizer and pesticide use similar to other row crops, yet second-generation feedstocks in many regions require lower chemical inputs for production than non-energy row crops (Paine, 1996; McLaughlin and Walsh, 1998; Lovett et al., 2009). Discharges of organic distillery wastes can pollute local water bodies, but can be reduced through existing anaerobic digestion technologies (Giampietro et al., 1997; Wilkie et al., 2000)

9.3.4.5 Land use

Most energy technologies have substantial land requirements when the whole supply chain is included. However, literature reporting lifecycle estimates for land use by energy technologies is scarce. The limited evidence available suggests that lifecycle land use by fossil energy chains can be comparable and higher than land use by RE sources (Hirschberg et al., 2006; Fthenakis and Kim, 2009).

A variety of metrics has been used in the literature to describe and compare land requirements by the dominating stage of different RE technologies, that is, the area occupied by the generating facility or cultivated for biomass feedstock. Examples are area occupied (m^2/kW) and percent effective land use (Trieb et al., 2009; Rovere et al., 2010) or land footprint (m^2 per capita) (Denholm and Margolis, 2008). Aspects that need to be considered for a proper interpretation and comparison of land requirements include:

- properties and conditions of the land required (e.g., arable land or brown-fields, close or remote to centres of demand);
- quality of land use (exclusive or allowing for multiple use); and

- duration and reversibility of the land transformation (former land use/cover, reclamation times).

In particular, the assessment of environmental impacts of land transformation is very complex, with many methodological challenges yet to be solved (Dubreuil et al., 2007; Scholz, 2007). These include issues such as landscape fragmentation (Jordaan et al., 2009), impacts on life support functions and ecosystem services, impacts on naturalness of areas, like regeneration times after different types of use, and impacts on biodiversity (Lindeijer, 2000; Scholz, 2007; Schmidt, 2008) (see Section 9.3.4.6).

For fossil energy chains and nuclear power, land use is dominated by upstream and downstream processes (see Figure 9.7), depending on type of mining operations or extraction (e.g., onsite, leaching, surface or underground mining), quality of mineral deposits and fuel, and supply infrastructure (Hirschberg et al., 2006; Fthenakis and Kim, 2009; Jordaan et al., 2009). As a result of high ash content, waste disposal sites contribute significantly to land use of coal fired power stations (Mishra, 2004; NRC, 2010). Aboveground land transformation of nuclear power chains has lower ranges than do fossil fuel chains. However, the necessity of maintaining future disposal sites for high-level radioactive waste shielded from access for very long time spans (10,000 to 100,000 years) can increase the occupational land use of nuclear facilities substantially (Gagnon et al., 2002; Fthenakis and Kim, 2009).

For most RE sources, land use requirements are largest during the operational stage. An exception is the land intensity of bioenergy from dedicated feedstocks, which is significantly higher than for any other energy technology and shows substantial variations in energy yields per hectare for different feedstocks and climatic zones. If biomass from residues or organic wastes is used, additional land use is small (see Section 2.3.1).

To the extent that solar PV and solar thermal installations can be roof-mounted, operational land use is negligible, while for central PV plants and CSP design considerations can influence extent and exclusiveness of the land use (Tsoutsos et al., 2005; Denholm and Margolis, 2008; see Section 3.6.1). Geothermal generation has very low aboveground direct land use, but it increases considerably if the geothermal field is included for risk of land subsidence (Evans et al., 2009). The conservation of scenic landscapes and outstanding natural features, and related conflicts with tourism may arise as areas of concern (see Section 4.5.3.3). Similarly, the obstruction of landscape views both on- and offshore has emerged as an issue for wind energy (see Section 7.6.3.2).

Run-of-river hydropower has very low lifecycle land use, while the values for reservoir hydropower differ greatly depending on the physical conditions of the site (Gagnon et al., 2002). The impoundment and presence of a reservoir stands out as the most significant source of impacts (Egré and Milewski, 2002), with social issues such as involuntary population displacement or the destruction of cultural heritage adding a critical social dimension (see Sections 9.5.1 and 5.6.1.7). In the case of multipurpose reservoir use, inundation effects cannot be exclusively attributed to electricity generation (see Section 5.10). For wind, wave and ocean or tidal current energy, spacing between the facilities is needed for energy dissipation. Thus, the total land or ocean area transformed is quite large, but secondary uses such as farming, fishing and recreation activities are often feasible (Denholm et al., 2009; M. Jacobson, 2009), though constrained access for competing uses may be an issue for certain ocean technologies (see Section 6.5.2).

To conclude, it should be noted that land requirements for the establishment and upgrade of distribution and supply networks of future energy systems may be substantial, and may increase in the future with rising shares of variable renewable sources.

9.3.4.6 Impacts on ecosystems and biodiversity

Closely connected to land use are (site specific) impacts on ecosystems and biodiversity. Energy technologies impact ecosystems and biodiversity mainly through the following pathways:

- direct physical destruction of habitats and ecosystems in the case of reservoir creation and alteration of rivers, surface mining, tidal barrages, waste deposits and land use changes from, for example, forest or grasslands to managed lands;
- fragmentation of habitats, degradation of ecosystems and disturbance of certain species, for example, by infrastructure, harvesting operations or modifications in the built environment; and
- deterioration of habitats due to air and water pollution.

While the latter is largely associated with fossil energy technologies and mining (M. Jacobson, 2009), thermal pollution, which is affecting aquatic life, constitutes a serious concern for all thermal technologies. Potential impacts of severe accidents in the extraction stage of fossil fuels can also be relevant (see Sections 9.3.4.4 and 9.3.4.7).

The assessment of impacts on biodiversity are not part of LCA methodologies, and even though efforts are made to establish and integrate indicators into the context of LCA (e.g., (Schmidt, 2008), no framework for the comparison of lifecycle impacts of different energy chains is currently available. An overview of potential concerns associated with RE technologies is provided in Table 9.11, followed by a short description of the status of knowledge. A broader discussion including potential benefits and mitigation measures is available in the technology chapters (see Sections 2.5.5, 3.6.1, 4.5.3, 5.6.1, 6.5.2, 7.6.2 and 7.6.5).

Table 9.11 | Overview of potential negative impacts and concerns regarding ecosystems and biodiversity related to RE technologies as reported in Chapters 2 through 7 of this report; in depth discussion of technology-specific impacts and appropriate mitigation measures can be found in Sections 2.5.5, 3.6.1, 4.5.3, 5.6.1, 6.5.2, 7.6.2 and 7.6.5.

Bioenergy (dedicated feedstocks)	Loss of high quality natural habitats by conversion to managed lands, pressure on conservation areas, effects on agro-biodiversity and wildlife by agricultural intensification, soil degradation, eutrophication and pesticide emissions to aquatic habitats, introduction of invasive or genetically modified species
Bioenergy (residues)	Residue removal may lead to soil degradation, loss of woody debris habitats in forestry systems
Solar PV (field installations)	Disturbance through installation stage, plant community change due to shading effects
CSP	Disturbance of fragile desert ecosystems
Geothermal	Impacts of hazardous chemicals in brine fluids in case of surface disposal, modifications of habitats in conservation areas
Hydropower (general effects)	Alteration of littoral, riverine and lentic ecosystems, interference with fish migratory routes, reduced access to spawning grounds and rearing zones, change in sediment loads of the river
Hydropower (typical for reservoirs)	Habitat and special biotope loss through inundation (change of terrestrial to aquatic and riverine to lentic ecosystems), impacts of changes in chemical composition and water temperature (downstream), changes in seasonal flow and flooding regimes, extirpation of native species/introduction of non-native species, alteration of the hydrological cycle downstream
Ocean Tidal Barrage	Alteration of marine and coastal ecosystems, changes in water turbidity, salinity and sediment movements in estuary affecting vegetation, fish and bird breeding spaces

Ocean Salinity Gradient	Brackish waste water impacts on local marine and riverine environment
Ocean (Ocean Thermal Energy Conversion)	Up-welling effect of nutrient rich water to surface may impact aquatic life
Ocean (Wave energy, ocean and tidal current)	Rotating turbine blades, noise, vibration and electromagnetic fields may impact sensitive species (elasmobranchs, marine mammals), disturbance of pelagic habitats and benthic communities
Wind (Onshore)	Disturbance of air routes of migratory birds, collision fatalities of birds/raptors and bats, avoidance or displacement from an area, reduced reproduction
Wind (Offshore)	sound waves during construction may negatively affect marine mammals, disturbance of benthic habitats

Scientific evidence regarding the impacts of RE technologies on biodiversity varies: for bioenergy, both local impacts of different feedstock production systems and consequences of large-scale deployment have been studied. There is evidence for both positive and negative local impacts of different feedstock production and management systems (including use of organic residues) on biodiversity (e.g., Semere and Slater, 2007; Firbank, 2008; Fitzherbert et al., 2008; Baum et al., 2009; Lovett et al., 2009; Schulz et al., 2009; Fletcher et al., 2011; Riffell et al., 2011). However, the exploitation of large bioenergy potentials is considered a reason for concern, with potential impacts on already fragmented and degraded areas that are rich in biodiversity and provide habitat for endangered and endemic species (e.g., Firbank, 2008; Sala et al., 2009; WBGU, 2009; Dauber et al., 2010; Beringer et al., 2011; see Sections 2.2.4., 2.5.5, 9.4.3.5, and 9.4.4). The overall impacts of bioenergy on biodiversity will also depend on the balance between the long-term positive effects of reduced future climate change, and the short-term negative effects of land use change (Dornburg et al., 2008).

For site-specific effects, ample evidence largely based on environmental impact assessments is available for hydropower (e.g., Rosenberg et al., 1997; Fearnside, 2001; IUCN, 2001; see Section 5.6), and to a certain extent for on- and offshore wind farms (see Section 7.6.2) and some solar technologies (e.g., Tsoutsos et al., 2005). Less evidence is available for geothermal energy, and the variety of marine and tidal devices—other than tidal barrages—are in a too early stage of development to assess their biodiversity effects. However, the long-term and population-level consequences of large-scale deployment need further research for all energy technologies.

9.3.4.7 Accidents and risks

The comparative assessment of accident risks associated with current and future energy systems is a pivotal aspect in a comprehensive evaluation of energy and sustainability. 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., 2004a; Burgherr et al., 2008), purposefully malicious action (e.g., Giroux, 2008), and human errors (e.g., Meshakti, 2007; Ale et al., 2008). This section compares risks from accidents of different energy technologies on the basis of objective information for the probability of an event and the consequences of that event, focusing on societal risk measures (e.g., Jonkman et al., 2003). Impacts from normal operation, intentional actions, and violations of ethical standards, as well as voluntary versus involuntary risks and aspects of risk internalization in occupational safety are not covered. Additional risks related to large-scale deployment of renewable technologies are also discussed.

The risks of energy technologies to society and the environment occur not only during the actual energy generation, but at all stages of the energy supply chain (Hirschberg et al., 1998; Burgherr and Hirschberg, 2008). It had already been recognized in the early 1990s that accidents in the energy sector form the second largest group of man-made accidents worldwide, however in terms of completeness and data quality their treatment was not considered satisfactory (Fritzsche, 1992). In response to this, the Energy-Related Severe Accident Database (ENSAD) was developed, established and is continuously updated by the Paul Scherrer Institute (e.g., Hirschberg et al., 1998, 2003; Burgherr and Hirschberg, 2008). The results presented here are focused on so-called severe accidents because they are most controversial in public perception and energy politics. A detailed description of the methodological approach is given in Annex II.

First, two complementary, fatality-based risk indicators are evaluated to provide a comprehensive overview. Fatalities were chosen because fatality data is typically most reliable, accurate and complete (Burgherr and Hirschberg, 2008); reducing risks to acceptable levels often includes fatalities since they are amenable to monetization (Viscusi, 2010); and actual or precursor events can provide an estimate for the maximum fatality potential of a technology (Vinnem, 2010). The fatality rate is based on the expected number of fatalities which occur in severe (≥5 fatalities) accidents, normalized to the electricity generation in GW-years. The maximum consequences are based on the maximum number of fatalities that are reasonably credible for a single accident of a specific energy technology.

Figure 9.15 shows risk assessment results for a broad range of currently operating technologies. For fossil energy chains and hydropower, OECD and EU 27 countries generally show lower fatality rates and maximum consequences than non-OECD countries. Among fossil chains, natural gas performs best with respect to both indicators. The fatality rate for coal in China (1994 to 1999) is distinctly higher than for the other non-OECD countries (Hirschberg et al., 2003; Burgherr and Hirschberg, 2007), however, data for 2000 to 2009 suggest that China is slowly approaching the non-OECD level (see Annex II). Among large centralized technologies, modern nuclear and OECD hydropower plants show the lowest fatality rates, but at the same time the consequences of extreme accidents can be very large. Experience with hydropower in OECD countries points to very low fatality rates, comparable to the representative Probabilistic Safety Assessment (PSA)-based results obtained for nuclear power plants, whereas in non-OECD countries, dam failures can claim large numbers of victims. Until 2010,[16] two core-melt events have occurred in nuclear power stations, one at Three Mile Island 2 (TMI-2, USA, 1979) and one at Chernobyl (Ukraine, 1986) (see Annex II). However, the Chernobyl accident is neither representative of operating plants in OECD countries using other and safer technologies, nor of today's situation in non-OECD countries (Hirschberg et al., 2004a; Burgherr and Hirschberg, 2008). New Generation III reactors are expected to have significantly lower fatality rates than currently operating power plants, but maximum consequences could increase due to the tendency towards larger plants (see Annex II). All other renewable technologies exhibit distinctly lower fatality rates than fossil chains, and are fully comparable to hydro and nuclear power in highly developed countries. Concerning maximum consequences, those renewable sources clearly outperform all other technologies because their decentralized nature strongly limits their catastrophic potential. However, it is important to assess additional risk factors of RE that are currently difficult to fully quantify, but could potentially impede their large-scale deployment (see Table 9.12).

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[16] A third core-melt event that occurred in Fukushima, Japan, in March 2011 is not included in the current analysis.

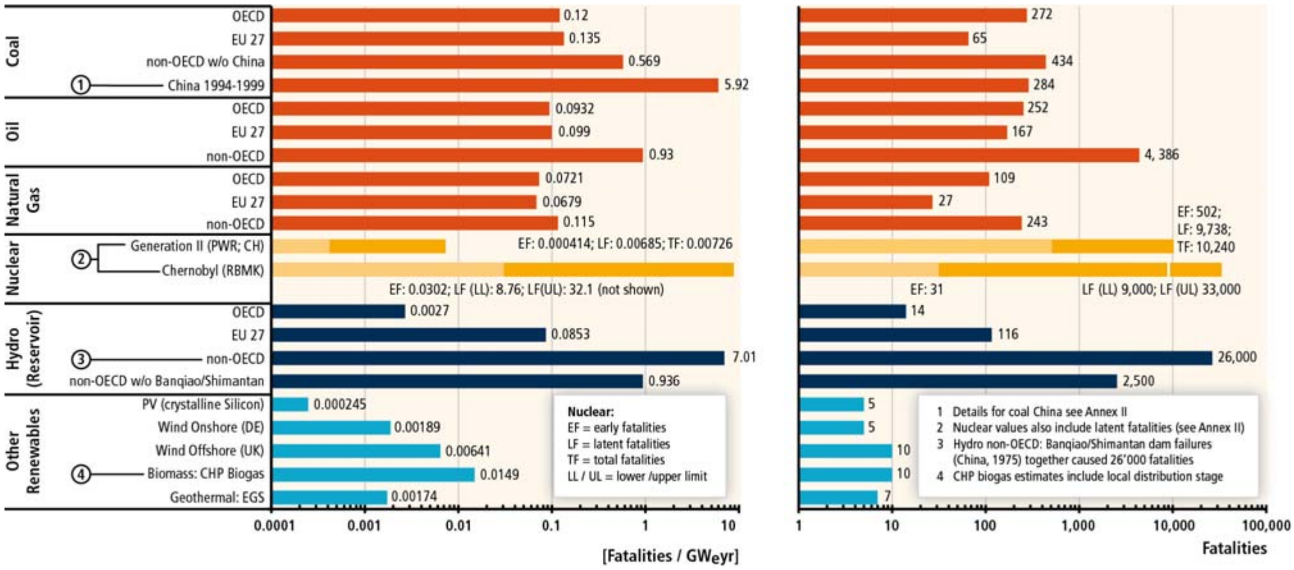

Figure 9.15 | Comparison of fatality rates and maximum consequences of currently operating large centralized and decentralized energy technologies. Fossil and hydropower is based on the ENSAD database (period 1970 to 2008); for nuclear PSA is applied; and for other renewable sources a combination of available data, literature survey and expert judgment is used. See Annex II for methodological details. Note: RBMK = reaktor bolshoy moshchnosty kanalny,a boiling water-cooled graphite moderated pressure tube type reactor; PWR = pressurized-water reactor; CHP = combined heat and power; EGS = Enhanced Geothermal Systems.

Accidents can also result in the contamination of large land and water areas. Accidental land contamination due to the release of radioactive isotopes is only relevant for nuclear technologies (Burgherr et al., 2008). Regarding accidental releases of crude oil and its refined products into the maritime environment, substantial improvements have been achieved since the 1970s due to technical measures, but also to international conventions, national legislations and increased financial liabilities (Burgherr, 2007; Knapp and Franses, 2009; Kontovas et al., 2010). Still, accidental spills from the extraction and production of petroleum fuel are common and can affect both saline and freshwater resources (Kramer, 1982; Jernelöv, 2010; Rogowska and Namiesnik, 2010). Also, very disastrous events like the one of the drilling platform Deepwater Horizon (Gulf of Mexico, 2010; 670,000 t spill: Lubchenco et al., 2010) cannot be excluded in future. Furthermore, increased extraction of deep offshore resources (e.g., Gulf of Mexico, Brazil) as well as in extreme environments (e.g., the Arctic) provides an additional threat of accidents with potentially high environmental and economic impacts. Spills of chemicals can also occur via hydraulic fracturing during shale natural gas and geothermal operations, which can potentially result in local water contamination (Aksoy et al., 2009; Kargbo et al., 2010). Additional research is needed in this area as experience grows.

Table 9.12 and the following overview summarize a variety of risk aspects that are not amenable to full quantification yet because only limited data and experience are available or they cannot be fully covered by traditional risk indicators focusing mainly on consequences. The impact of induced seismicity from enhanced geothermal systems (EGS) has already been the cause of delays, and two major EGS projects in the USA and Switzerland were even permanently abandoned (Majer et al., 2007; Dannwolf and Ulmer, 2009). With the accelerating expansion of offshore wind parks, the risk analysis of ship collisions with offshore wind turbines and the subsequent implementation of risk-reducing measures becomes an import aspect; although the frequency of occurrence is low, the consequences could be large (Christensen et al., 2001; Biehl and Lehmann, 2006). With the installation of large renewable capacities in geopolitically less stable regions, threats to RE infrastructure (including the grid) and supply may become an important factor, including intentional supply cuts as well as physical or cyber attacks by non-state actors (e.g., sabotage, terrorism) (Lacher and Kumetat, 2010). Key issues for bioenergy include potential competition with food production and use of water resources (e.g., Koh and Ghazoul, 2008; see Sections 2.5.7.4 and 9.3.4.4). Despite numerous prototype installations and a few small commercial projects, tidal and wave power technologies are still at a relatively early stage of development, therefore their potential impacts and risks are yet rather poorly understood (Westwood, 2007; Güney and Kaygusuz, 2010; Langhamer et al., 2010; Shields et al., 2011).

Table 9.12 | Overview of selected additional risk aspects for various energy technologies.

Risk aspect	Affected technologies and references
Induced seismicity, subsidence	Oil and gas production, coal mining (Klose, 2007, 2010b; Suckale, 2009); hydropower reservoirs (H. Gupta, 2002; Kangi and Heidari, 2008; Klose, 2010a; Lei, 2010); geothermal (Bommer et al., 2006; Majer et al., 2007; Dannwolf and Ulmer, 2009); carbon capture and storage (IPCC, 2005; Benson, 2006; Holloway et al., 2007; Bachu, 2008; Ayash et al., 2009).
Resource competition	Bioenergy (Koh and Ghazoul, 2008; Ajanovic, 2011; Bartle and Abadi, 2010) reservoir hydro (Wolf, 1998; Sternberg, 2008; McNally et al., 2009).
Hazardous substances	Relevance for PV requires sector downscaling to allocate appropriate share of consequences (see Annex II) (Coburn and Cohen, 2004; Bernatik et al., 2008). In the case of geothermal, groundwater contamination may occur (Aksoy et al., 2009)
Long-term storage (public acceptance)	Disposal of nuclear waste (Adamantiades and Kessides, 2009; Sjöberg, 2009); carbon capture and storage (IPCC, 2005; Huijts et al., 2007; Ha-Duong et al., 2009; Wallquist et al., 2009).
Proliferation	Nuclear (Toth and Rogner, 2006; Yim, 2006; Adamantiades and Kessides, 2009).
Geopolitics, terrorist threat	Security and energy geopolitics of hydrocarbons and renewable sources (e.g., solar thermal) (Le Coq and Paltseva, 2009; Giroux, 2010; Toft et al., 2010; Lacher and Kumetat, 2010). Pirate attacks on oil/gas tankers (Hastings, 2009; Hong and Ng, 2010).

In conclusion, accident risks of renewable technologies are not negligible, but their decentralized structure strongly limits the potential for disastrous consequences in terms of fatalities. However, various additional risks, complementing a purely fatality-based approach, should also be considered as outlined above because they may play an important role in public debate (e.g., risk aversion) and decision making (e.g., policies).

9.4 Implications of (sustainable) development pathways for renewable energy

In contrast to Section 9.3 that focused on the impacts of current and emerging renewable energy (RE) systems on the four sustainable development (SD) goals assessed in this chapter (for a conceptual description of these SD goals see Section 9.2), this section addresses SD pathways and future RE deployment. It will thus incorporate the intertemporal concerns of SD (see section 9.2.1).

However, only a few regional analyses address RE specifically in the context of SD pathways.[17] Even though these results indicate a positive relationship between SD pathways and RE deployment in general, they only offer limited insights with respect to the four goals that were discussed in Section 9.2. In addition, they are not explicit about the specific socioeconomic and biophysical constraints in terms of SD. Furthermore, they neglect complex global interrelations between different technologies for different energy services that significantly shape the future pathway of the global energy sector and its wider socioeconomic and environmental implications. Since the interaction of SD and RE deployment pathways[18] cannot be anticipated by relying on a partial analysis of individual energy technologies (see Section 9.3), the discussion in this section will be based on results from the scenario literature, which typically treats the portfolio of technological alternatives in the framework of a global or regional energy system.

The vast majority of the long-term scenarios reviewed in this section (and in Chapter 10) were constructed using computer-based modelling tools that capture, at a minimum, the interactions between different options for supplying, transforming and using energy. The models range from regional energy-economic models to integrated assessment models that couple models of global biogeophysical processes with models of key human systems including energy, the economy and land use. The value of these models in creating long-term scenarios, and their potential for understanding the linkages between SD and RE in particular, rests on their ability to explicitly consider interactions across a broad set of human activities (e.g., generating industrial emissions as well as leading to changes in land use and land cover), at global and regional scales, over annual to decadal to centennial time scales. Consistent with Chapter 10, these models are referred to as 'integrated models' for the remainder of the discussion in this section, since they do not look at individual technologies in isolation but rather explore the linkages between technologies, and between the energy system, the economy and other human and natural systems. Though integrated models are designed to be descriptive rather than policy prescriptive, they do offer policymakers insights into their actions that would otherwise be unavailable from focusing solely on traditional disciplinary research alone.

Integrated models have been used for many years to produce the sorts of detailed characterizations of the global energy system necessary to examine the role of RE in climate stabilization and its economic competition with other energy sources. These models also have a capability, to varying degrees, to examine issues related to the four SD goals laid out in Section 9.2. Models also vary in the degree to which they represent the biogeophysical processes that govern the fate of emissions in the atmosphere. Most models address some subset of human activities and interactions with ecosystems, but they do not in general capture feedbacks from other parts of the Earth system. In some cases, these feedbacks can be substantial.

While integrated models are powerful tools of analysis, and they will likely serve as the primary means to generate long-term scenarios in the near future, they are continually under development. Some of these developments will be relevant to the representation of sustainability concerns in future scenarios. Important areas of development include: improving their representation of

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[17] In a scenario analysis for India, for example, Shukla et al. (2008) found that the share of RE is higher for mitigation scenarios that include additional sustainability policies (47 versus 34% of primary energy). For Japan, several backcasting studies analyzing low-carbon society roadmaps emphasize the need for both supply-side and demand-side options including an increasing share of RE (Fujino et al., 2008; Suwa, 2009).

[18] As already discussed in Section 9.2, pathways are thus primarily understood as scenario results that attempt to address the complex interrelations among SD on the one side and the different energy technologies on the other side at a global scale.

resources and technology[19] to utilize them (including end-use technologies) to conserve energy resources; improving the representation of international and interregional trade; increasing both spatial and temporal resolution; allowing for a better representation of the distribution of wealth across the population; incorporating greater detail in human and physical Earth system characterization (e.g., water and the hydrological cycle), including climate feedbacks and impacts and adaptation to climate change; incorporating uncertainty and risk management; and exploring an increasingly diverse and complex policy environment.

Before turning to specific results, several caveats are in order. Although there has been some attempt at standardization among models, these are by no means 'controlled experiments'. For example, the models produce very different business-as-usual projections based upon non-standardized assumptions about a variety of critical factors, such as technology, population growth, economic growth, energy intensity and how the energy system will respond to changes in energy prices. These assumptions can have a profound effect on the energy system and welfare losses in mitigation scenarios. Even parameters that tend to be the focus of the analyses often differ across models, such as constraints on nuclear and CCS. Moreover, some but not all models use 'learning curves', that is, RE or other technology costs are assumed to decline as capacity grows. Additionally, some models allow for biomass plus CCS. As this technology option generates negative emissions, it can ease the transformation process and reduce the costs of mitigation (Wise et al., 2009; Edenhofer et al., 2010; Luckow et al., 2010; Tavoni and Tol, 2010; van Vuuren et al., 2010b). All of this leads to considerable variation among models. Importantly, however, the models basically agree on many fundamental insights (see Section 10.2).

This section will be structured along the lines of the four SD goals laid out in section 9.2: 1) social and economic development; 2) energy access; 3) energy security; and 4) climate change mitigation and reduction of environmental and health impacts. The section will give an overview of what can be learned from the literature on long-term scenarios with respect to the interrelation between SD pathways and RE. The aim of this section is twofold: first, to assess what long-term scenarios currently have to say with respect to SD pathways and the role of RE; and second, to evaluate how the modelling tools used to generate these scenarios can be improved to provide a better understanding of sustainability issues in the future.

9.4.1 Social and economic development

This section discusses the relationship between RE deployment and social and economic development in long-term scenarios. The integrated models used to generate these long-term scenarios generally take a strong macro-perspective and therefore ignore aspects like life expectancy or leisure time that would be relevant for alternative welfare indicators compared to GDP, such as the HDI (see Section 9.3.1). Therefore, this section will focus strongly on economic growth and related metrics. In general, growth of GDP by itself is an insufficient measure of sustainability (Fleurbaey, 2009). Most of the scenarios that are covered in Chapter 10 impose an upper limit on future cumulative GHG emissions. However, this report does not discuss to what extent the different carbon constraints are consistent with a policy avoiding dangerous climate change. Therefore, economic growth can only be used as an indicative welfare measure in the context of different stabilization pathways.

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[19] Unfortunately, until recently, such analyses have tended to pay insufficient attention to RE technologies and, indeed, to technology in general. The technological detail of the integrated models used to develop these scenarios is continually under development, and most of the models reviewed here and in Chapter 10 capture substantial improvements in the representations of technology with respect to the modelling capabilities available a decade ago.

9.4.1.1 Social and economic development in scenarios of the future

There has been an enormous amount of analysis over the past two decades on the costs of reducing GHG emissions (see, e.g., IPCC, 1996a, 2001, 2007b). This work is typically based on cost-effectiveness analysis, in which the costs and means to meet a particular goal are explored, rather than cost-benefit analysis, in which the costs and benefits of mitigation and adaptation over centennial time scales are considered simultaneously, and a primary objective is to determine the optimal pattern of mitigation and adaptation over time. In cost-effectiveness studies, a long-term social goal is assumed, for example, limiting atmospheric GHG concentrations to no more than 450 ppm CO_2 equivalent. The limitation of emissions, concentrations, or more generally radiative forcing is used to study the most cost-effective pattern of emission reductions. These analyses are typically based on a variety of socioeconomic, technological and geopolitical assumptions extending over periods of decades to a century or more. When a constraint is imposed on GHG emissions, very often welfare losses are incurred. A variety of measures are used, ranging from direct estimates of social welfare loss to the more common aggregate measures such as GDP or consumption (a major component of GDP) foregone. Other concepts of welfare, as discussed in Section 9.3.1, for example, are usually not considered. Thus, at the heart of such calculations are assumptions about the availability and costs of, and GHG emissions generated by, those technologies used to satisfy energy demands—with and without a GHG constraint.

The scenario review in Chapter 10 gives an impression of possible welfare implications of RE. First note that, not surprisingly, GDP reductions are associated with a GHG constraint, independent from a particular technology portfolio. That is to say, mitigation in general decreases economic growth, at least in scenarios that do not consider the feedbacks from a changing climate, as is the case with the majority of the integrated scenarios that exist to date.

Second, by limiting the options available for constraining GHGs, GDP losses increase. It follows that economic development will be lower when the ability to deploy RE technologies is limited. A wide range of analyses over the last decade have explored the welfare implications of varying assumptions about the costs, performance and, more recently, the availability of RE (e.g., Kim Oanh and Dung, 1999; L. Clarke et al., 2008, 2009; Luderer et al., 2009; Edenhofer et al., 2010) for different levels of GHG stabilization. All of these studies have demonstrated that more pessimistic assessments of RE costs, performance and availability increase the costs of mitigation. Indeed, recent research indicates that very ambitious climate goals are not only more expensive, but may not be possible to achieve without a full portfolio of options, including RE. For example, several of the models in Edenhofer et al. (2010) could not find a feasible solution to reach a 400 ppm CO_2eq goal when constraining RE technologies to their baseline levels. The availability of bioenergy coupled with CCS is particularly important for meeting very aggressive climate goals (Azar et al., 2010; Edenhofer et al., 2010; van Vuuren et al., 2010b). More generally, scenarios do not find a clear indication that RE is more or less important in reducing costs than nuclear energy or fossil energy with CCS. For example, four of six models analyzed in Edenhofer et al. (2010) and Luderer et al. (2009) found that the economic costs of constraining RE were higher than those of constraining nuclear and fossil energy with CCS, however, of a comparable order of magnitude (see Figures 10.10 and 10.11 in Chapter 10). When other low-carbon energy technologies are constrained, not surprisingly, the share of primary energy provided by RE increases (see also the analysis provided in Chapter 10 and Figure 10.6). At the same time, higher mitigation costs result in decreasing overall energy consumption.

Looking at different sectors, a number of studies (Edmonds et al., 2006; L. Clarke et al., 2007, 2009; Fawcett et al., 2009; Luderer et al., 2009) have shown that the electricity sector can be more easily decarbonized than transportation due to the fact that many low-carbon options are available, including RE, nuclear energy and CCS. The result even proves to be robust when different low-carbon technologies are constrained as well as for developed and developing countries. The transportation sector proves to be more difficult to decarbonize and shows a significant share of fossil fuels in all models in the long term up to 2100. This can be explained by a lack of low-cost alternatives to oil (see also Section 9.4.3 on energy security), such as biofuels or the electrification of the transport sector (see, e.g., Turton and Moura, 2007 and Chapter 8). Many recent studies, for example, L. Clarke et al. (2009), include models that consider a wide range of passenger and commercial transport options such as electric vehicles and electric-hybrid vehicles. The development of a low-cost electric vehicle technology would make it easier and cheaper to reduce emissions in the transport sector (see, e.g., US DOT, 2010).

Although global average indicators of welfare are valuable for exploring the general relationships among RE, climate mitigation and economic growth, a great deal of interest centres not on global totals, but on the relative performance of developing and emerging economies. An important question is how mitigation in general and RE in particular influence economic growth.

Mitigation scenarios provide general insights into this issue. Overall, the same fundamental lessons about RE, mitigation and economic growth observed in global analyses are also found in analyses of developing countries. The economic growth effects are generally found to be larger in non-Annex I countries than in the Annex I countries. This is due to assumptions about more rapid economic growth and an increasingly large and dominant share of GHG mitigation over time in non-Annex I countries. Building upon the analysis in Chapter 10, Figure 9.16 shows the share of non-Annex I countries in global RE deployment for different RE sources, indicating that most future RE deployment is expected to take place in the developing world (Krey and Clarke, 2011). This is particularly important because developing countries have yet to go fully through their industrialization process. Even with huge advances in energy efficiency, their development process is likely to still involve substantial growth in energy consumption. The key challenge of deploying a carbon-free energy system in developing countries is to overcome the higher LCOEs of RE (and other low-carbon technologies) compared to current market prices (see Annex III). Successfully meeting this challenge could lead to leapfrogging the emission-intensive development paths that developed countries have taken so far.[20]

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[20] For a more detailed discussion of leap-frogging see also Section 9.5.2.

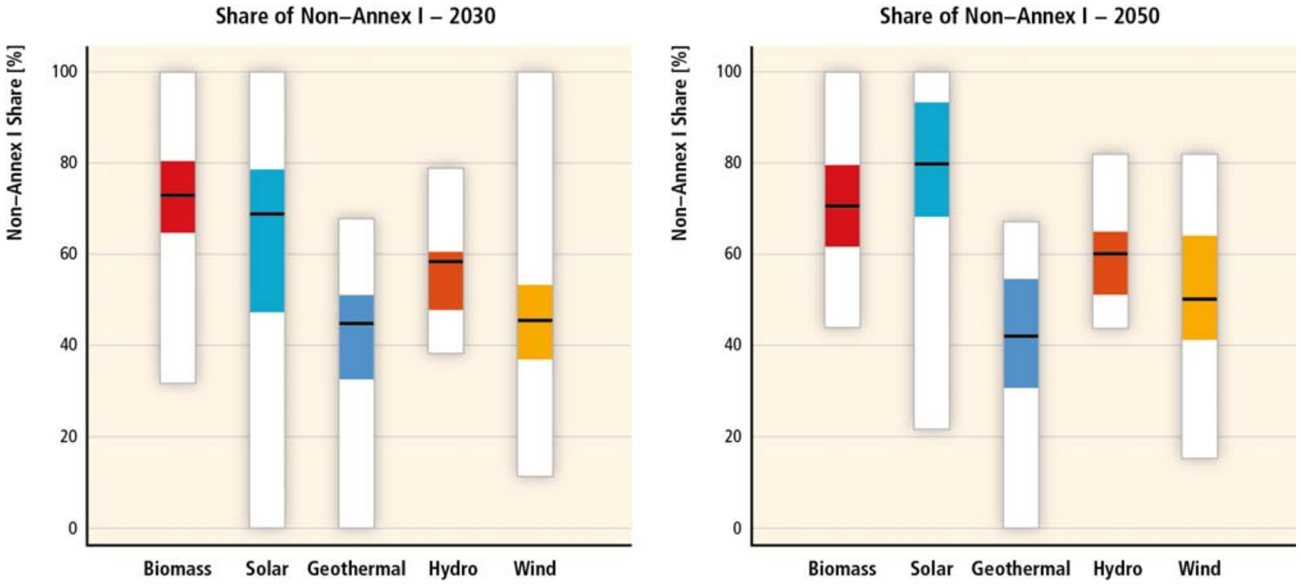

Figure 9.16 | Share of Non-Annex I countries in the global deployment of different RE sources in long-term scenarios by 2030 and 2050. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the white surrounding bars correspond to the total range across all reviewed scenarios (adapted from Krey and Clarke, 2011).

When all regions mitigate using the same economically efficient carbon price path, the resulting technology portfolio is independent of the allocation of emissions allowances (Coase, 1960). However, regional emissions mitigation will vary, depending on many factors such as technology availability, economic growth and population. When tradable allowances are allocated, each region's total cost is the sum of its mitigation costs plus (or minus) the value of permits that are purchased from (sold to) other regions. Total costs are thus reduced relative to domestic mitigation costs for permit sellers and increased for permit buyers, even though the global price of carbon is independent of the permit allocation.

If emissions mitigation obligations are distributed regionally and no trading is permitted, there is no reason to believe that marginal costs of emissions mitigation will be equal across regions and sectors, which in turn would impact the regional technology portfolio. In such circumstances, global total costs will be higher as compared to a situation where marginal costs are equal, for any given global emission mitigation level. However, the regional distribution of costs will depend on the particular assignment of mitigation obligations both initially and over time (Weyant, 1993; Edmonds et al., 1999; Scott et al., 2004; Luderer et al., 2009).

9.4.1.2 Research gaps

It should be stressed that the models used for the analyses mentioned above generally provide an incomplete measure of welfare losses because they focus on aggregate measures such as GDP or consumption losses. As noted in Section 9.2, GDP is considered by most economists as an inadequate measure of welfare. However, the use of other welfare indicators, such as, for example, life expectancy or leisure time, is difficult in the current set of integrated models. Also, losses are measured at the economy-wide level, which—although correlated with per capita GDP losses—can be misleading. Finally, the models do not give an indication of the distribution of wealth across the population. Is it concentrated among 'a few' or distributed more evenly across 'the many'?

Beyond the general insights presented in Section 9.4.1.1, particularly with respect to RE and other energy technologies, scenarios do not generally provide strong assessments of many of the forces that might make developing countries behave differently than developed countries; for example, differences in physical and institutional infrastructure and the efficiency and effectiveness of economic markets. The modelling structures used to generate long-term global scenarios generally assume perfectly functioning economic markets and institutional infrastructures across all regions of the globe, discounting the special circumstances that prevail in all countries, for example, in developing countries where these assumptions are particularly tenuous. These sorts of differences and the influence they might have on social and economic development among countries should be an area of active future research.

9.4.2 Energy access

9.4.2.1 Energy access in scenarios of the future

One of the fundamental goals of SD is the expansion of energy services, produced more cleanly, to those people who have only limited access to these services today (Goldemberg et al., 1985). While sustainable energy development comprises a number of elements (see Section 9.2; IPCC, 2000), this section focuses particularly on what different energy scenarios say about the future availability of energy services to different populations. Such services include basic household-level tasks (e.g., cooking, lighting, water heating, water collection, space heating, cooling, refrigeration); transportation (personal and freight); and energy for commerce, manufacturing and agriculture.

Integrated models have been used to evaluate and explore possible future energy systems for over three decades, but it is only in the last decade that analyses of energy access have been implemented in these models. Most, though not all, early versions of integrated models were based on the information and experiences of industrialized countries; energy systems of developing countries were often assumed to behave likewise, although some exceptions paid particular attention to differences between developed and developing regions (Shukla, 1995). In addition, for integrated modelling the data of industrialized countries were historically extrapolated to low-income countries, with no change in the underlying assumptions, to assess scenarios for developing countries. However, fundamental differences remain between the energy systems of developing countries and those of currently industrialized countries. As such, models grounded in developed country experience, and using developed country data, often fail to capture important and determinative dynamics in, for example, the choices to use traditional fuels, informal access to the electricity grid, informal economies, and structural changes in domestic economies, all of which exert a demonstrably large effect on access in many parts of the world (van Ruijven et al., 2008).

Although these factors are important for analyzing both the energy systems of developing countries and the dynamics of energy access, only a handful of integrated models explicitly account for them. A comparison study of 12 well-known integrated models by Urban et al. (2007) shows that there has been progress in addressing these issues for application in developing country contexts. All models covered electrification—though not all explicitly—and most models had implemented the use of traditional biomass and urban/rural dynamics. However, many of the models still lacked important factors such as potential supply shortages, informal economies, and investment decision making. Some of these issues are being implemented into revised models. For example, to understand how to avoid supply shortage during the peak hours, a higher temporal resolution and daily load curves to allow dynamic pricing of electricity were added to a MARKAL model of South Africa (Howells et al., 2005). Similarly, to reflect an aspect of the informal economy in fuel choices, a non-commercial 'inconvenience cost', related to using fuels, was added to MESSAGE (Ekholm et al., 2010). Several groups have attempted to increase the distributional resolution, and thereby to capture behavioural heterogeneity, by dividing populations into rural and urban categories, as well as diverse income groups (van Ruijven, 2008; Ekholm et al., 2010).

Nevertheless, much more work remains ahead as models of energy access are typically limited to specific regions or countries due to lack of data or process resolution. Another obstacle is the relative difficulty of representing alternative pathways to receiving modern energy services, and specifically whether the models are really able to capture and analyze the range of distributed RE options: if models focus only on larger grid supply or cooking fuel, they only cover a part of the energy access issue.

While model resolution of energy access is improving, it remains imperfect for understanding rural dynamics. Nevertheless, it seems likely that rural populations in developing countries will continue to rely heavily on traditional fuel to satisfy their energy needs in the near future (see Table 9.1). Income growth is expected to alleviate some of the access issues, but linking this growth with fuel transitions carries much uncertainty. For example, a scenario analysis of India's energy system in 2050 showed more than a 10% difference in the future electrification rate depending on whether the Gini coefficients[21] approach the level of present day Italy or China (van Ruijven, 2008). To achieve a high penetration of modern energy, it is vital to put effective policies in place and to trigger major investments.

Electrification, whether by grid extension or off-grid distributed generation, is capital intensive and requires large investment. The IEA estimates that an investment of USD_{2005} 558 billion from 2010 to 2030 is needed for universal modern energy access by 2030, of which USD_{2005} 515 billion, or USD_{2005} 24 billion per year on average, is needed to accomplish universal electricity access. If developing countries are not able to secure finance for electrification, the number of people without electricity is going to stay around the level of today (IEA, 2010b). During the build-up of new energy infrastructure, the combination of the availability of the low-cost traditional biomass and high initial investment cost for LPG will continue to make fuelwood and other forms of traditional biomass the main source of energy for cooking. Policies might induce higher penetration, but the structure of economic incentives must be calibrated to the local economic situation. A scenario analysis of cooking fuel in India by Ekholm et al. (2010) shows that without financing, a 50% subsidy for LPG is required for full penetration by 2020, but only a 20% subsidy is needed if improved financing for the purchase of appliances is also offered.

Having access to modern energy is not a guarantee to the path of SD. First, a shift to modern energy may be simply a shift to fossil fuels, which is not sustainable in the long run. Second, the distribution of energy use within a country with respect to income is an essential element of understanding access. For example, some countries have relatively equitable access to electricity (Norway, the USA), while others have highly unequal access depending on income (Kenya, Thailand) (A. Jacobson et al., 2005). Third, the use of RE can also have its own set of environmental or health impacts (see Section 9.3.4). However, to secure a sustainable use of energy, measures to alleviate the overall environmental burden while providing access to modern energy are essential. One aspect of such a shift would be an increasing fraction of energy supplied by RE technologies, both grid and decentralized. In addition, there is a social aspect of energy use, which relates to concerns that forced shifts to RE could affect household budgets and macroeconomic costs. In an analysis by Howells et al. (2005) on future rural household energy consumption in South Africa, a shift to electricity outside of lighting and entertainment services only occurred in the scenario which included health or other externalities from local combustion emissions.

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[21] The Gini coefficient is a numerical measure for the degree of inequality of income.

9.4.2.2 Research gaps

Any sustainable energy expansion should increase availability of energy services to groups that currently tend to have less access to them: the poor (measured by wealth, income or more integrative indicators), those in rural areas, those without connections to the grid, and women (UNDP/UNDESA/WEC, 2000). From a development perspective, the distribution in the use and availability of energy technologies, and how they might change over time, is of fundamental importance in evaluating the potential for improvement in access (Baer, 2009). Since expanding access requires multiple changes in technology and the way services are delivered, understanding the starting distribution as well as the changes over time is necessary to evaluate the potential increase in access in one scenario relative to another. A second confounding factor in using model output to evaluate changes in access is the inability of many models to capture social phenomena and structural changes that underlie peoples' utilization of energy technologies.

These two aspects—lack of distributional resolution and structural rigidity—present particular challenges for integrated models. Models have historically focused much more on the technological and macroeconomic aspects of energy transitions, and in the process have produced largely aggregated measures of technological penetration or energy generated by particular sources of supply (Parson et al., 2007). Such measures can, of course, be useful for making broad comparisons, such as the relative share of low-carbon energy across countries. However, an explicit representation of the energy consequences for the poorest, women, specific ethnic groups within countries, or those in specific geographical areas, tends to be outside the range of current global model output.

Future modelling efforts could potentially address some of the problems highlighted in this section. Currently, access can be only estimated via proxies for aggregate statistics. However, the relationships between these aggregate statistics and access are clearly not consistent across countries and could change over time. Therefore, if access is a concern, then integrated models should incorporate the elements most likely to illuminate changes in energy access. Explicit representation of traditional fuels, modes of electrification, and income distribution could add some resolution to this process. More fundamentally, linking these to representation of alternate development pathways could provide a more comprehensive view of the possible range of options to provide access. For example, a dramatic expansion of distributed off-grid electricity generation coupled with efficient devices raises the possibility that large grid connectivity may not remain as fundamental a driver of access as it has been in the past. RE has historically been construed as relatively expensive in developing countries, but cost reductions and energy security concerns have in some cases recast it as a potentially useful source of supply in energy system studies (Goldemberg et al., 2000). RE, which is valuable in remote places due to the conversion of natural energy sources onsite, could play a major role in such scenarios (see Section 9.3.2).

9.4.3 Energy security

As noted in Sections 9.2 and 9.3.3, energy security, like SD, suffers from a lack of either a well-formed quantifiable or qualitative definition. In many countries, energy security is often taken to be inversely related to the level of oil imports. The focus on oil results from the fact that many countries are potentially vulnerable to supply disruptions, with many developed countries having experienced an oil supply disruption during the Organization of the Petroleum-Exporting Countries (OPEC) oil embargo of the mid-1970s. However, despite its importance, the real concern is not necessarily about oil, but about the vulnerability and resilience to sudden disruptions in energy supply and consequent price implications in general.

All other things being equal, the more reliant an energy system is on a single energy source, the more susceptible the energy system is to serious disruptions. This is true for energy security concerns with respect to both availability and distribution of resources, and the variability and reliability of energy sources, as discussed in Sections 9.2 and 9.3.3. At the same time, it is important to note that diversity of supply is only beneficial to the extent that the risks of disruptions are equal across sources. To the extent that risks are not equal, it is generally beneficial to rely more heavily on those sources with the lowest and most uncorrelated risks. The following discussion will address how RE influences energy security in scenarios of the future by focusing on diversity of supply and thereby energy suppliers' market power, particularly looking at the oil market; then the variability in energy supply associated with RE in the context of energy security will be assessed.

9.4.3.1 Energy security in scenarios of the future

Availability and distribution of resources: Diversity of supply and oil markets

RE deployment levels generally increase with climate change mitigation in long-term scenarios, leading to a more broadly diversified energy portfolio. To the extent that RE deployment in mitigation scenarios thus reduces the overall risk of disruption, this represents an energy security benefit. With fossil fuels continuing to dominate the energy system absent GHG mitigation (Grubb et al., 2006; L. Clarke et al., 2009), this would be particularly beneficial for regions with fossil fuel demand that can only be met by increasingly scarce or concentrated supplies.[22] Yet, market power in resource markets is typically not represented in large integrated models. This subsection thus focuses on the ability of RE to displace oil—the fossil fuel that is commonly perceived to cause the biggest energy security concerns, which are also triggered by the high price volatility (see Section 9.3.3).

The role of RE in reducing energy supply disruptions by diversifying energy supply will vary with the energy form. Hydropower, solar, wind, geothermal and ocean energy are often associated with electric power production, though some of these technologies also contribute to other end-use sectors. Reducing oil demand by increasing RE supplies in the electricity sector depends on the ability of electricity to supplant oil. This result is seen in mitigation scenarios for the buildings and industrial sectors and is caused by increasingly favourable relative electricity prices (as compared to fossil fuels). The demand for liquid fuels in the transport sector, however, is highly inelastic at present. Relatively little substitution of electricity for oil occurs without technology forcing or a technology breakthrough that makes electric power options competitive with liquid fuel transport options. This could only change if electric vehicle technology improves sufficiently in the future (see Sections 9.4.1 and 8.3.1).

Bioenergy, in contrast, is a versatile RE form that can be transformed into liquid fuels that can compete directly with liquid fossil fuels. In reference scenarios, liquids derived from biomass garner market share. The interaction between bioenergy and oil consumption is potentially sensitive to both policy and technology; the presence of a carbon price, for example, increases bioenergy's competitive advantage. However, the sector in which bioenergy is utilized depends strongly on whether or not CCS technology is available. Without CCS, bioenergy is used predominantly as a liquid fuel, whereas the availability of bioenergy with CCS shifts its use towards power generation—resulting in negative net carbon emissions for the system (Luckow et al., 2010; see Figure 9.17). Other studies show comparable results (van Vuuren et al., 2010b).

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[22] The concentration of energy supplies in the hands of a small number of sellers means that that a small group has the potential to control access. Diversification of the set of suppliers is one possible response to reduce the potential for energy supply disruptions.

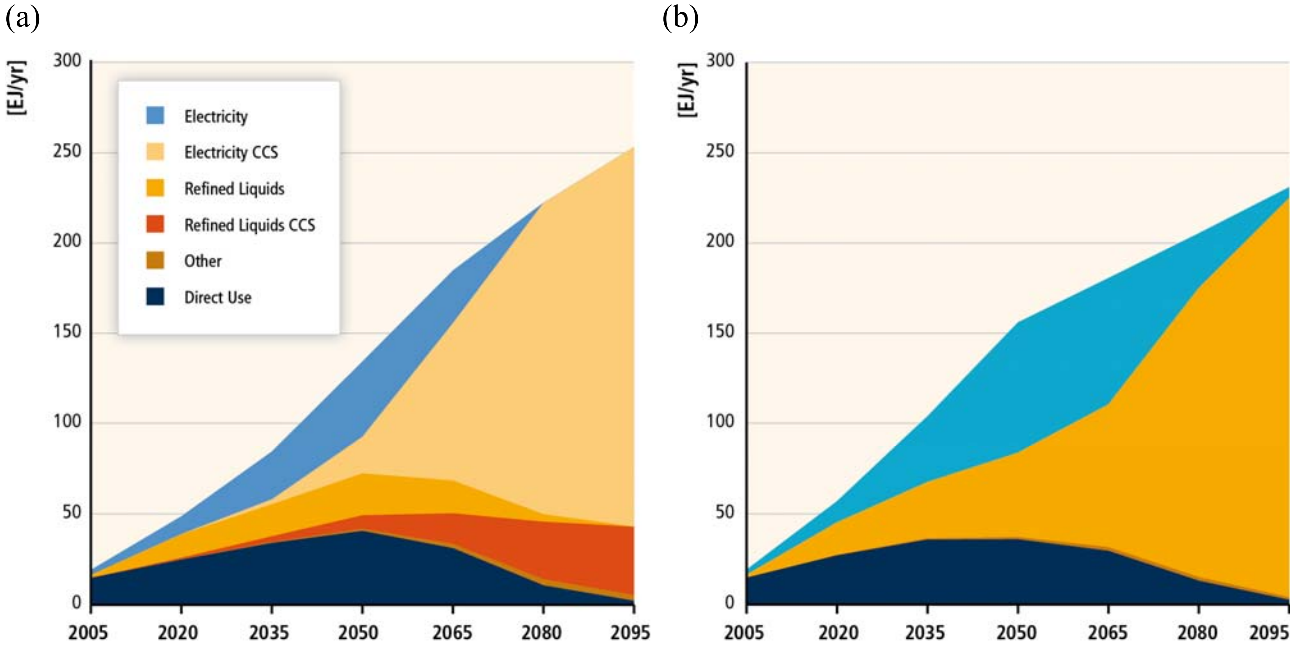

Figure 9.17 | Biomass consumption by use with (a) and without (b) CCS for a 450 ppm climate stabilization scenario using the GCAM model (Luckow et al., 2010).

The emergence of bioenergy to supplant oil does not necessarily mean a reduction in the market power and volatility that surround markets for liquid fuels. While models generally assume that the emergence of bioenergy as a major energy form would take place in a market characterized by a large number of sellers with relatively little market power, this is by no means certain. If the bioenergy market were characterized by a small number of sellers, then buyers would be exposed to the same type of risk as is characteristic of the global oil market. However, this sort of risk-to-portfolio linkage is simply not explored by existing mitigation scenarios and a future bioenergy market might entail precisely the same volatility concerns as the current oil market.

The interaction between bioenergy production and food prices is another critical issue, since the linkage of food prices to potentially volatile energy markets has important implications for SD (see Section 2.5.7.4). A number of authors have critically assessed this relationship (Edmonds et al., 2003; Gurgel et al., 2007; Runge and Senauer, 2007; Gillingham et al., 2008; Wise et al., 2010) and some highlighted the importance of the policy environment and in particular the valuation of terrestrial carbon stocks (Calvin et al., 2009; Wise et al., 2009). Emissions mitigation policies that cause large bioenergy markets to form would clearly benefit the sellers of bioenergy and in general the owners of land, which would be more valuable. However, higher food prices clearly hurt the poor, even in scenarios with generally rising incomes. Burney et al. (2010) and Wise et al. (2009) also show the importance of traditional crop productivity in reducing GHG emissions due to the resulting higher biomass availability. Absent continued improvements in agricultural crop yields, bioenergy production never becomes a significant source of RE (Wise et al., 2010).

In the scenarios examined in Chapter 10, the consumption and price of oil do not change as significantly with more stringent mitigation as, for example, the consumption and price of coal. This more modest change in oil consumption is partly due to the fact that oil is primarily consumed in the transportation sector. Alternatives to oil, such as biofuels and electric vehicles, if included in the current generation of models, are still expensive and might have adverse impacts (e.g., first-generation biofuels, see Sections 9.4.1 and 2.5). These scenarios therefore do not see as dramatic differences between the baseline and policy scenarios with respect to cumulative oil consumption as they do for the consumption of coal. Compared to the baseline scenarios from Chapter 10, cumulative oil consumption decreases by 20% in the 440 to 600ppm CO_2 stabilization scenarios (Category III and IV, see Table 10.2) and by 40% in low stabilization scenarios (Category I and II, 400 to 440ppm CO_2) (see Figure 9.18a).

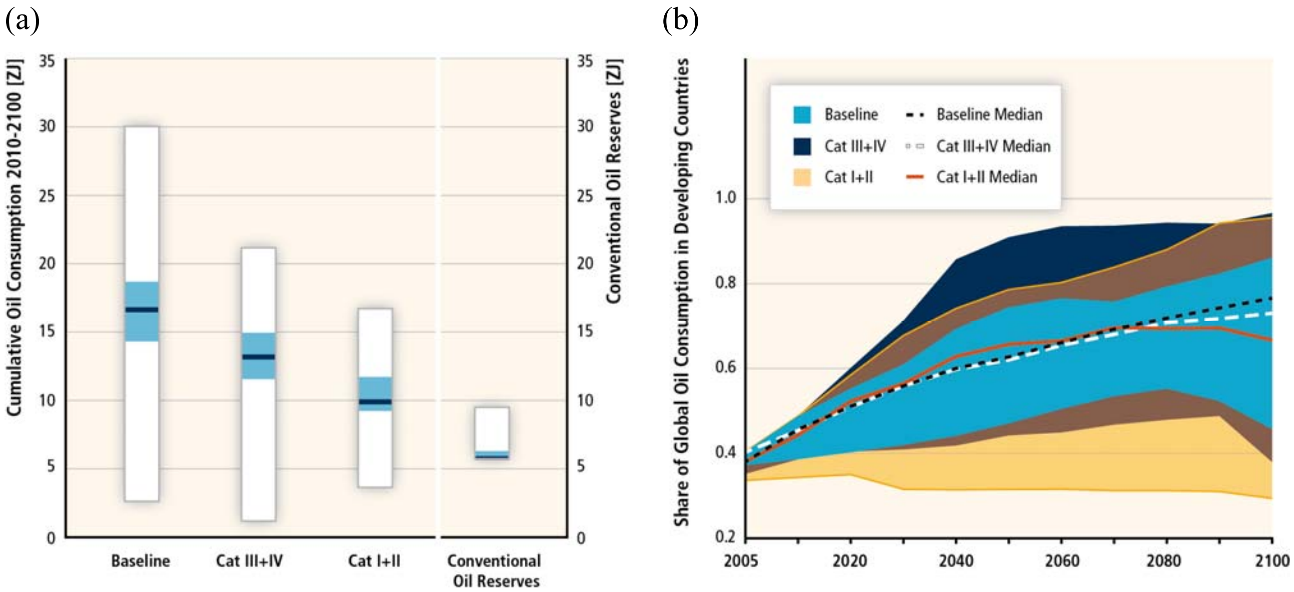

Figure 9.18 | a) Conventional oil reserves compared to projected cumulative oil consumption (ZJ) from 2010 to 2100 in scenarios assessed in Chapter 10 for different scenario categories: baseline scenarios, category III and IV scenarios and low stabilization (category I+II) scenarios. The thick dark blue line corresponds to the median, the light blue bar corresponds to the inter-quartile range (25th to 75th percentile) and the white surrounding bar corresponds to the total range across all reviewed scenarios. The last column shows the range of proven recoverable conventional oil reserves (light blue bar) and estimated additional reserves (white surrounding bar) (Rogner, 1997).[23] b) Share of global oil consumption in non-Annex I countries for different scenario categories over time, based on scenarios assessed in Chapter 10.

To the extent that imports also decline, countries would be less vulnerable to oil supply disruptions than in a reference scenario. However, as discussed above, a move to bioenergy does not necessarily imply fewer liquid fuel supply disruptions in so far as bioenergy is a globally traded good. With oil still playing a major role in the mitigation scenarios of Chapter 10, energy security discussions concerning oil supply disruptions will thus remain relevant in the future. For developing countries, the issue will become even more important, as their share in global total oil consumption increases in nearly all scenarios, independent of the GHG concentration stabilization levels (Figure 9.18b).

Furthermore, in scenarios that stabilize CO_2 concentrations, carbon prices generally rise to the point where unconventional oil supplies, such as oil shales, are more limited in supply compared to the baseline scenario (see, e.g., Figure 9.18a). On the one hand, this effect would limit the environmental concerns (such as water pollution) that are generally associated with unconventional oil production. On the other hand, depending on a country's domestic resource base, this could

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[23] According to Rogner (1997), proved recoverable reserves are between 5.7 and 6.3 ZJ. In addition to that, estimated additional reserves range between 2.6 and 3.2 ZJ. This is in line with more recent estimates for proved recoverable reserves of conventional crude oil and natural gas liquids of 1,239 billion barrels (or 7.3 ZJ) (WEC, 2010). The total consumption of oil goes far beyond that in most scenarios reviewed in Chapter 10, which directly implies the use of unconventional reserves.

increase (decrease) energy supply vulnerability for countries with (without) endowments of coal and unconventional liquids.

The effect of a GHG emissions constraint with respect to conventional oil is also notable in terms of consumption timing. Because conventional oil is relatively inexpensive to produce, the immediate suppression in demand, imports and the oil price to suppliers (consumer prices rise), is offset by an increase in oil use in later years. In other words, the effect of the cap in a CO_2 concentration stabilization scenario is to lower the peak in oil production and shift it further into the future. This has the effect of reducing near-term oil imports and increasing oil consumption in later years. As the allowable long-term CO_2 concentration declines, this effect is overwhelmed by declining cumulative allowable emissions (see, e.g., Bollen et al., 2010).

Energy security policies also have a noteworthy effect on RE and GHG emissions. A static general equilibrium model for the EU, which analyzed trade flows to and from the FSU, showed that policies to subsidize the domestic production of bioenergy simultaneously reduced fossil fuel CO_2 emissions and oil imports (Kuik, 2003). However, these policies were not seen as a cost-effective option for achieving climate goals in this study.

Variability and reliability of RE

Another source of energy supply vulnerability is exposure to unpredictable disruptive natural events. For example, wind power is vulnerable to periods of low wind. Other energy forms such as solar power or bioenergy are also susceptible to unusual weather episodes. Increased reliance on electricity generated from RE could have implications for grid stability and requires further research (see Section 8.2.1).

An important method for addressing energy supply stochasticity is holding stocks, which act to buffer the system (see Section 9.2.2). An increase in the role of bioenergy would likely lead to the creation of bioenergy stocks—either in the form of stocks of solid fuel or bioenergy liquids—as a hedge against uncertainty of supply.

RE forms such as wind, solar, geothermal and wave energy, which produce electricity, are generally not easily stored in their natural forms or as electricity. Energy supply variability can be reduced by increasing the geospatial diversity of supply. Additional efforts to increase system reliability will likely add costs and involve balancing needs (such as holding stocks of energy), the development of complementary flexible generation, strengthening network infrastructure and interconnections, energy storage technologies and modified institutional arrangements including regulatory and market mechanisms (see Sections 8.2.1 and 7.5).

9.4.3.2 Research gaps

The relationship between RE and energy security is characterized by numerous research gaps ranging from the lack of a clear quantifiable definition of energy security to the scarce scenario literature focusing on the relationship between RE and energy security. Consideration of energy security commonly focuses on the most prominent of energy security issues in recent memory, for example, disruptions to the global oil supply and security issues surrounding nuclear energy production. However, energy security issues go well beyond these aspects. For example, the supply of rare Earth metals and other critical inputs could constrain the production of some (renewable) energy technologies (see Box 9.1). These broader concerns as well as options for addressing them, e.g., recycling, are largely absent from future scenarios of mitigation and RE.

An important aspect of deploying RE sources at a large scale is their integration into the existing supply structure. Systems integration is most challenging for the variable and to a degree unpredictable electricity generation technologies such as wind power, solar PV and wave energy. A first-order proxy for the challenges related to systems integration is therefore the share of different variable and unpredictable RE sources at the global level (see also Figure 10.9). Again, those scenarios with high proportions of wind and solar PV electricity in the grid implicitly assume that any barriers to grid management in this context are largely overcome, for example, through electricity storage technologies, demand-side management options, and advances in grid management more generally (see Section 8.2.1). This is a strong assumption and managing storage, balancing generation, grid improvement and demand-side innovation will be essential to balancing variable RE generation and ensuring grid reliability. Improving the spatial and temporal resolution of integrated models to better reflect issues with respect to the integration of RE sources into the grid is an area of ongoing research (see also Section 9.4.4.2).

9.4.4 Climate change mitigation and reduction of environmental and health impacts

In addition to evaluating alternate scenarios with respect to the potential contribution to energy access and energy security, any assessment of energy futures under SD criteria must include a comparison of the environmental impacts of energy services. Fundamentally, reductions in environmental impacts can be derived from increases in the efficiency of providing services, changes in behaviour or shifting to lower-impact sources of supply.

9.4.4.1 Environmental and health impacts in scenarios of the future

As existing models include explicit representation of energy efficiency and energy supply mix, the scenarios they produce provide information on both of these dimensions of sustainability. In addition, several models have included explicit representation of factors that are linked to environmental or health impacts. For example, combustion of sulphur-containing coal without control technology can generate pollutants that are important at local and regional levels (e.g., sulphur oxides). This raises the possibility that a move away from sources of combustion would generate benefits not only via reductions in GHG emissions but also via reductions in local air pollution (see Section 9.3.4.2). Several models include sulphate pollution and therefore provide the basis for some estimation of the health or ecosystem consequences of this combustion by-product (van Ruijven et al. 2008). For example, van Vuuren et al. (2007) highlight the co-benefits in the form of reduced NO_x and SO_2 emissions when replacing fossil fuels with renewable sources and CCS. In standard scenarios, however, the link between regional pollutants and consequences is not explicit. Bollen et al. (2009) addressed this question by performing a cost-benefit analysis (using the MERGE model) that included both GHG and PM reductions. They found that climate policy can help drive improvements in local air pollution but that air pollution reduction policies do not necessarily drive reductions in GHG emissions. In addition, the external benefits were greatest when external costs of health effects due to particulate emissions and impacts of climate change were internalized (see Sections 9.3.4.3 and 10.6.4). Shrestha and Pradhan (2010) performed a broader co-benefits analysis within a specific country case, linking the MARKAL model to a model of Thailand’s energy system. They found similarly that climate policy would lower the impacts from coal combustion.

Another implication of some potential energy trajectories is possible diversion of land to support biofuel production. While this has been a topic of intense discussion, many models have until recently not supported explicit links between energy supply options and land use. Early attempts to address the links were focused on trade-offs across energy supply and food production (Yamamoto et al., 2001) or used existing scenarios as a basis for estimating future bioenergy use (Hoogwijk and Faaij 2005). Subsequently, these approaches were combined by embedding bioenergy modules directly into integrated models (Gillingham et al., 2008). To date, substantial literature has, for example, become available related to emissions from indirect land use change (see Sections 9.3.4.1 and 2.5.3) (Yamamoto et al., 2001; Edmonds et al., 2003; McCarl and Schneider, 2003; Tilman et al., 2006; Searchinger et al., 2008; Calvin et al., 2009; Melillo et al., 2009; Wise et al., 2009). Wise et al. (2009) and Melillo et al. (2009) found that deforestation, land diversion and N_2O emissions were driven by biofuels expansion without proper policies in place. In both investigations, what might ostensibly have been seen as a 'sustainable' energy scenario (i.e., the increasing use of biofuels) was shown to have potential consequences that contravened the principles of SD.

Model scenarios can be useful in demonstrating scenarios of potentially unanticipated (or at least unquantified) environmental benefits as well as scenarios of unanticipated or unquantified environmental costs. However, a variety of approaches in addition to modelling are underway (e.g., Croezen et al., 2010), and other aggregate measures that could be amenable to analysis under current scenarios include, for example, water use intensity of energy (m^3/MWh) and land use (ha/MWh). These could be linked to other dimensions of sustainability, such as loss of biodiversity or changes in food security, though the appropriate treatment of this link is not defined.

9.4.4.2 Research gaps

Unfortunately, aside from the linkages discussed above (land use (change), SO_2 and PM emissions), the existing scenario literature does not explicitly treat the many non-emissions-related environmental elements of sustainable energy development such as water use, (where only very broad and non-technology-specific studies are available from the literature; see, e.g., Hanasaki et al., 2008; Shen et al., 2008) and the impacts of energy choices on household-level services or indoor air quality. These environmental aspects of sustainability depend to a much greater degree on the distribution of energy use and how each energy technology is used in practice. Analyzing this with the existing models might be difficult since models have been designed to look at fairly large world regions without looking at income or geographic distribution (see Section 9.4.2.2). Existing scenarios, rather, enable users to compare the outcomes of different possible 'futures' (L. Clarke et al., 2007; O'Neill and Nakicenovic, 2008) by allowing easy comparisons of aggregate measurements of sustainability—for example, national or sectoral GHG emissions. Although some models have also begun to allow for comparison across smaller geographic scales of impact, such as for regional air pollution and land use change, some environmental impacts remain opaque in the scenarios produced to date: the distribution of the use of traditional fuels, for example, can matter significantly for the health of billions of people (Bailis et al., 2005). In addition, most models face challenges in modelling local ecosystem impacts because of the small scales involved in many ecosystem processes. There is currently extensive discussion about the feasibility of and mechanisms for achieving finer resolution in space and time in future scenarios, not only for physical and ecosystem changes but also for social, demographic and economic factors (Moss et al., 2010). Some integrated assessment models have addressed issues of smaller scale through downscaling. However, these downscaling methods have been applied primarily to variables like emissions and demographics (Bengtsson et al., 2006; Grübler et al., 2007; van Vuuren et al., 2007, 2010a). Because the downscaling was focused on informing other questions, it does not meaningfully resolve questions about local sustainability. Finally, many models do not explicitly allow for an assessment of lifecycle impacts of the technologies used in different scenarios. What these impacts are, whether and how to compare them across categories, and whether they might be incorporated into future scenarios would constitute useful areas for future research.

9.5 Barriers and opportunities for renewable energies in the context of sustainable development

Pursuing a RE deployment strategy in the context of SD implies that all environmental, social and economic effects are taken explicitly into account. Integrated planning, policy and implementation processes can support this by anticipating and overcoming potential barriers to and exploiting opportunities of RE deployment. Barriers that are particularly pertinent in a SD context and that may either impede RE deployment or result in trade-offs with SD criteria are discussed in Section 9.5.1.[24] Section 9.5.2 focuses on how the integration of RE policies and measures in strategies for SD at various levels can help overcome such barriers and create opportunities for RE deployment that more fully meet SD goals.

9.5.1 Barriers

Integration of RE policymaking and deployment activities in SD strategy frameworks implies the explicit consideration of inter-linkages (synergies and trade-offs) with the three pillars of SD and related SD goals (see Section 9.2.1). In this way, RE policies as well as project planning, construction and operation are rooted in the specific social, economic and environmental context and support the strategic development objectives of a given society or project location. They should also remain aligned with multilateral environmental agreements. This section looks at some of the main socio-cultural, information and awareness, and economic barriers to RE deployment in a SD context addressed in the literature. For each category of barriers, links are provided to potential environmental, social or economic concerns that should be taken into account during RE policy development and deployment.

9.5.1.1 Socio-cultural barriers

Most communities have traditionally viewed RE applications as environmentally friendly and a high level of general public support for RE is documented in available studies and opinion polls (Devine-Wright, 2005; McGowan and Sauter, 2005; Wolsink, 2007b; BERR, 2008). However, public support of RE at the generic level does not necessarily translate into active support and acceptance of RE at the local implementation level, where RE deployment is often associated with direct impacts for individuals and groups (Painuly, 2001; Bell et al., 2005; Wustenhagen et al., 2007).[25] Increased public resistance to large, new installations has, for example, been experienced in many countries, often beyond the narrow ‘not in my backyard’ type of opposition (Wolsink, 2007b; Devine-Wright, 2009).

Socio-cultural barriers or concerns with respect to the deployment of RE and its potential SD trade-offs have different origins and are intrinsically linked to societal and personal values and norms (Sovacool and Hirsh, 2009). Such values and norms affect the perception and acceptance of RE technologies and the potential impacts of their deployment by individuals, groups and societies (GNESD, 2007b; Sovacool, 2009; West et al., 2010). From a SD perspective, barriers may arise from inadequate attention to such socio-cultural concerns, which include barriers related to behaviour; natural habitats and natural and human heritage sites, including impacts on biodiversity and ecosystems (see Sections 2.5.5.2 and 9.3.4.6); landscape aesthetics; and water/land use and

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[24] Barriers are addressed in many chapters of the report. Chapter 1 provides a general overview of barriers to RE development and implementation, categorizing the barriers as socio-cultural, information and awareness, economic, and institutional. The technical chapters (2 to 7) cover the technology-specific barriers, with Chapter 8 addressing energy system lock-in and RE integration. Barriers to policymaking and financing are covered in Chapter 11.

[25] Local opposition to renewable energy projects may also depend on methods used to gather public opinion (van der Horst, 2007).

water/land use rights (see Section 9.3.4.4 and 9.3.4.5) as well as their availability for competing uses. These barriers are briefly discussed below.

Deployment of RE technologies may be associated with *behavioural* implications that challenge social and cultural values, norms and perceptions (Painuly, 2001; S. Reddy and Painuly, 2004; GNESD, 2007b; Chaurey and Kandpal, 2010). In India, for example, multi-criteria analysis of domestic cooking devices (Pohekar and Ramachandran, 2006) reveals that behavioural concerns[26] are second most important in determining consumer preferences for cooking devices, only surpassed by technical criteria. Behavioural concerns limit uptake not only of the relatively new and technically advanced solar cookers. They also offer an important explanation for the non-use of installed improved fuelwood cook-stoves in India, where only 6 million out of a total of 23 million installed improved fuelwood stoves were found to be functional (Neudoerffer et al., 2001; Pohekar and Ramachandran, 2006). Similar findings regarding the significance of behavioural barriers for dissemination and use of improved cookstoves are found for other developing countries (Ben Hagan, 2003; Zuk et al., 2007; Bailis et al., 2009). Behavioural barriers to new RE technologies and systems may be relatively small as long as the transition seeks to emulate existing practices and properties of current technologies. However, they tend to increase with the extent of changes in behaviour or consumption levels (Kumar et al., 2009; Petersen and Andersen, 2009).

Although applicable, the precautionary principle is not always utilized to minimize impacts on *natural habitats and natural and human heritage sites* (Rylands and Brandon, 2005; Hreinsson, 2007; Nandy et al., 2007; S. Clarke, 2009; Hennenberg et al., 2010; Wolsink, 2010). This has led to public resistance to various types of RE development projects. Public perception of impacts related to *aesthetics* of altered landscapes associated with wind power developments in OECD countries is a barrier that is extensively analyzed in the literature (Wolsink, 2000, 2007b, 2010; Upreti, 2004; Jobert et al., 2007; Wustenhagen et al., 2007). Attitudes towards offshore wind farms visible from shore depend on, for example, the type and frequency of beach use with regular visitors perceiving coastal landscapes as more pristine resources and thus less suited for industrial usage (Ladenburg, 2010). See also Section 8.2.1.3 on public opposition with regard to new network infrastructure.

Displacement and resettlement of communities in project developments that involve large quantities of *land*, such as large-scale hydropower, may be significant (Richter et al., 2010). The World Commission on Dams (2000) estimates that worldwide, 40 to 80 million people have been displaced by large dams. This figure increases significantly when the associated impacts of alterations in river flows and freshwater *ecosystems* on downstream populations are included (Richter et al., 2010). Although more recent figures on the number of people affected by hydropower developments are available at the individual project and country level,[27] aggregate statistics seem to be limited to the 2000 report by the World Commission on Dams. Large-scale hydropower projects are in addition often associated with trade-offs related to competing uses of water, for example, for water supply for domestic and industrial purposes, flood control and irrigation (Moore et al., 2010). Resettlement of populations affected by large-scale hydropower developments is intrinsically linked to the issue of *land use rights* of indigenous people (Bao, 2010; Moore et al., 2010; Ölz and Beerepoot, 2010) and associated with complex resettlement and compensation issues (Chen, 2009; Mirza et al., 2009). For example, insufficient economic compensation may be offered to affected populations or to those affected by externalities such as

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[26] Related to ease of operation; types of dishes cooked; cleanliness of utensils; need for additional cookstove; motivation to buy; taste of food; and aesthetics.

[27] See, for example, factsanddetails.com/china.php?itemid=323&catid=13&subcatid=85#01 for information on dams and hydropower in China and www.gms-eoc.org/CEP/Comp1/docs/Vietnam/Hydropower/SocialImpact.pdf for Vietnam.

losses in cultural heritage (Cernea, 1997; World Commission on Dams, 2000; Bao, 2010; Brown and Xu, 2010). Land use issues arising from commercial-scale energy crops are another area of increasing attention (IIED, 2009). Occupational concerns regarding human and labour rights, such as working conditions in field crop projects, are important to consider in this context (ILO, 2010). Finally, food security is another important social concern (see Section 2.5.7.4) to which certification schemes are paying increased attention (see Section 2.4.5).

Public awareness and acceptance is, as indicated above, an important element in the need to rapidly and significantly scale-up RE deployment to help meet climate change mitigation goals. Large scale implementation can only be undertaken successfully with the understanding and support of the public (Zoellner et al., 2008). This may require dedicated communication efforts related to the achievements and the opportunities associated with wider-scale applications (Barry et al., 2008). At the same time, however, public participation in planning decisions as well as fairness and equity considerations in the distribution of the benefits and costs of RE deployment play an equally important role and cannot be side-stepped (see below and Section 9.5.2.2; Wolsink, 2007b; Malesios and Arabatzis, 2010).

9.5.1.2 Information and awareness barriers

A common argument to promote RE projects is their contribution to poverty reduction, with local communities benefiting from employment opportunities, skills development, investment opportunities and technology transfer (see Sections 9.3.1.3 and 11.3; UN, 2002; GNESD, 2004, 2007a,b, 2008; Goldemberg and Teixeira Coelho, 2004; Modi et al., 2006; Goldemberg et al., 2008; UNEP, 2008a; Barbier, 2009). Many RE pilot projects in developing countries give anecdotal evidence of the role that renewable sources can play in energy-poor communities (Karekezi and Kithyoma, 2003; Mondal et al., 2010). However, if the local community does not perceive these benefits, or their distribution is considered inequitable, project acceptance may be problematic (Upreti, 2004; Gunawardena, 2010; see Section 11.6.4). In developing countries, limited technical and business skills and absence of technical support systems are particularly apparent in the energy sector, where awareness of and information dissemination regarding available and appropriate RE options among potential consumers is a key determinant of uptake and market creation (Painuly, 2001; Ölz and Beerepoot, 2010). This gap in awareness is often perceived as the single most important factor affecting the deployment of RE and development of small and medium enterprises that contribute to economic growth. Ignoring the informational and perception concerns associated with decentralized units can often result in abandoned or dysfunctional systems (Werner and Schaefer, 2007).

In cases where the proprietary ownership of RE technology is in the hands of private sector companies and the diffusion of technologies also typically occurs through markets in which companies are key actors (Wilkins, 2002), there is a need to focus on the capacity of these actors to develop, implement and deploy RE technologies. Therefore, the importance of increasing technical and business capability as a part of capacity building (Section 11.6.6)—at the micro or firm level—needs to be addressed (Lall, 2002; Figueiredo, 2003).

Attitudes towards RE are shaped by more than knowledge and facts. Norms and values are important to consider, as illustrated in Section 9.5.1.1, and may affect public and personal perceptions of the implications of RE for consumption as well as for deeply held values regarding trust, control and freedom (Sovacool, 2009; Walker et al., 2010). This implies that attitudes towards RE in addition to rationality are driven by emotions and psychological issues (Bang et al., 2000; Devine-Wright, 2009). To be successful, RE deployment and information and awareness efforts and strategies need to take this explicitly into account (Jager, 2006; Nannen and van den Bergh, 2010;

Litvine and Wüstenhagen, 2011), particularly as barriers to information and awareness may have implications for RE uptake, markets, uncertainty and hence capital costs (Painuly, 2001; Ölz and Beerepoot, 2010).

9.5.1.3 Market failures and economic barriers

The economics of RE are discussed in nearly all chapters of this report (Chapters 2 through 7 in cost sections, Chapter 10 on externalities, Chapter 11 on policy case studies). To assess the economics of RE in the context of SD, social costs and benefits need to be explicitly considered. RE should be assessed against quantifiable criteria targeted at cost effectiveness, regional appropriateness, and environmental and distributional consequences (C. Gross, 2007; Creutzig and He, 2009). From a social perspective, a level economic playing field is required to support rational RE investment decisions. This implies that market distortions, such as taxes and subsidies and their structure, as well as market imperfections and failures must be considered carefully with respect to their implications for the deployment of RE and the internalization of social costs, such as damages from GHG emissions, health, and environmental costs (Rao and Kishore, 2010; see Sections 9.5.2 and 10.6).

Grid size and technologies are key determinants of the *economic viability* of RE and of the competitiveness of RE compared to non-RE. Appropriate RE technologies that are economically viable are often found to be available for expanding rural off-grid energy access (Bishop and Amaratunga, 2008; Ravindranath and Balachandra, 2009; Thompson and Duggirala, 2009; Deichmann et al., 2011; see Section 9.3.2). For smaller off-grid applications, there is some evidence that several RE technologies, including wind, mini-hydro and biomass-electric, can deliver the lowest levelized generation costs of electrification, that is, including the levelized costs of transmission and distribution (ESMAP, 2007). Several RE technologies, including biomass (particularly biogas digesters and biomass gasifiers), geothermal, wind and hydro, are also potentially the least-cost mini-grid generation technology (ESMAP, 2007).[28] However, non-renewable power generation technologies remain more economically viable than RE in many contexts (van Alphen et al., 2007; Cowan et al., 2009). This is particularly the case for most large grid-connected applications, even with increases in oil price forecasts (ESMAP, 2007) and when likely RE technology cost reductions over the next 20 years are considered (Deichmann et al., 2011).

Assessments of the economic viability of RE are based on and subject to assumptions regarding the *availability and cost of the renewable resource*. The lack of adequate resource potential data directly affects uncertainty regarding resource availability, which may translate into higher risk premiums by investors and project developers, as appears to be the case with geothermal electricity development in Indonesia (Ölz and Beerepoot, 2010). An emerging area of attention relates to the potential impacts of climate variability and climate change on energy services and resources, where the timing and availability of RE resources are immediately impacted (World Bank, 2011). Impacts of climate variability and extreme events (e.g., hurricanes and typhoons, heat waves, floods, and droughts) on energy services and resources are already being experienced. In Eastern Africa, for example, where power supply is heavily reliant on hydropower, recent droughts were associated with estimated annual costs of the order of 1 to 3.3% of annual GDP (Eberhard et al., 2008; Karekezi et al., 2009). For issues related to the higher costs of RE due to their variable availability, see Section 8.2.

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[28] Mini-grid applications are village- and district-level isolated networks with loads between 5 and 500 kW.

In cases where deployment of RE is viable from an economic perspective, other economic and financial barriers may affect the deployment of RE. High upfront costs of investments, including high installation and grid connection costs, are examples of frequently identified barriers to RE deployment (Painuly, 2001; Limmeechokchai and Chawana, 2007; Kassenga, 2008; Mathews, 2008; Monroy and Hernandez, 2008; Rao and Kishore, 2010; Green and Vasilakos, 2011). Particularly in low-income countries, high upfront costs of RE technologies may inhibit uptake by consumers. Consumers may prefer to keep the initial cost low rather than minimizing the operating costs, which run over a longer period of time, or they may have no choice if they lack access to cash and/or credit (S. Reddy and Painuly, 2004). Hence, the successful uptake of RE technologies depends to some degree on the choice and set-up of the dissemination model, such as donations, cash sales, consumer credits or fee-for-service schemes (Nieuwenhout et al., 2000).

Policy and entrepreneurial support systems are needed along with RE deployment to stimulate economic growth and SD and catalyze rural and peri-urban cash economies (O. Davidson et al., 2003). Investments are, for example, required to ensure availability of the technical capacity required to operate and maintain the systems, which is a significant barrier for harnessing available RE sources in developing countries (Ölz and Beerepoot, 2010). A new set of thinking is also gradually emerging, treating RE as an integral component of a market-based energy economy and more strongly involving the private sector (GNESD, 2007b, 2008).

High upfront costs may also reflect high-risk perceptions of investors and a general lack of financing instruments as well as fragmented or underdeveloped financial sectors (Brunnschweiler, 2010). In this way, anecdotal evidence from South East Asia suggests that a lack of experience with and understanding of RE systems among financial institutions and investors leads to low participation by national financiers, which may increase the cost of capital for RE projects through higher risk premiums (see Section 11.4.3). In Indonesia, biomass-based power projects are viewed as facing additional hurdles linked to a general lack of experience in bioenergy project development and related feedstock supply issues among banks and national investors (Ölz and Beerepoot, 2010).

The effects of the timing of the stream of costs and benefits from RE investments lead to a trade-off with respect to sustainability, for example in cases where decision makers in developing countries have to choose between investments in non-RE with shorter payback time, but higher external costs, and RE investments with longer payback time, but higher positive externalities for example, for job creation, health, GHG emission reduction, etc. Barriers to RE financing are also addressed in Sections 9.3.1.4 and 11.4.3.

Externalities result from market distortions and are central when RE deployment is addressed in the context of SD. The structure of subsidies and/or taxes may, for example, favour non-RE with adverse implications for the competitiveness of RE (see Section 9.5.2.1). Similarly, existing grid networks and engineering capacities will advantage some forms of energy over others, with implications for the path dependency of energy deployment (see Section 11.6.1). Path dependencies may lock in societies into energy or infrastructure options that may be inferior in terms of cost efficiency or accumulated social costs in the long term (Unruh, 2000). In many cases, internalization of environmental externalities has considerable effects for the levelized costs of RE technologies (Cowan et al., 2009; Harmon and Cowan, 2009; Fahlen and Ahlgren, 2010) and subsequently their non-inclusion presents a barrier for RE deployment. Internalization of damage costs resulting from combustion of fossil fuels into the price of the resulting output of electricity could, for example, lead to a number of renewable technologies being financially competitive with generation from coal plants (Owen, 2006; see Section 10.6). Similar conclusions were reached for PV mini-grids for three remote rural regions in Senegal, where levelized electricity costs from PV technologies were found to be lower than the cost of energy from grid extension when environmental externalities are taken into account (Thiam, 2010).

A number of recent studies include several social and environmental sustainability indicators in assessing and ranking energy options. In addition to GHG emissions, these sustainability indicators include land requirements, water consumption, social impacts and availability of renewable sources, providing additional insight into potential barriers for RE deployment in a sustainability context (Afgan et al., 2007; Becerra-Lopez and Golding, 2008; Brent and Kruger, 2009; Evans et al., 2009; Brent and Rogers, 2010; Browne et al., 2010; Carrera and Mack, 2010; see Section 9.5.2.1).

9.5.2 Opportunities

Strategies for SD at international, national and local levels as well as in private and nongovernmental spheres of society can help overcome barriers and create opportunities for RE deployment by integrating RE and SD policies and practices. At international and national levels strategies include: removal of mechanisms that are perceived as to work against SD; mechanisms for SD that internalize environmental and social externalities; and integration of RE and SD strategies. At the local level, SD initiatives by cities, local governments, and private and nongovernmental organizations can be drivers of change and contribute to overcome local resistance to RE installations.

9.5.2.1 International and national strategies for sustainable development

The need for cross-sectoral SD strategies has been articulated at the multilateral level since the 1972 Stockholm Conference on the Human Environment (Founex Committee, 1971; Engfeldt, 2009). The concerns were reinforced in the goals of Agenda 21 (UNCED, 1992), aiming at the adoption of strategies to harmonize these different sectoral processes (Steurer and Martinuzzi, 2007). In the Johannesburg Plan of Implementation adopted at the World Summit on Sustainable Development in 2002, governments were called upon with a sense of urgency to substantially increase the global share of RE and to take immediate steps towards national strategies for SD by 2005 (UN, 2002). In the formulation of such National Sustainable Development Strategies (NSDS), countries have usually prioritized strategic policy areas and concrete objectives for which national circumstances and international commitments required swift action, such as limiting climate change and increasing the use of RE (OECD, 2002; UNDESA, 2008). Such prioritization may contribute to productivity, income growth, health and education, gender equality, reduced social impacts associated with energy extraction, human development, and macroeconomic stability and governance (World Bank, 2001). RE technologies, in particular, can add other benefits (see Section 9.3). In addition, integrating RE policy into NSDS provides a framework for countries to select specific policy instruments, to incorporate concerns of other countries into their own, and to align with international policy measures (OECD, 2002).

Removal of mechanisms that work against sustainable development

The removal of fossil fuel subsidies has the potential to open up opportunities for more extensive use or even market entry of RE. It decreases the artificially widened competitive advantage of fossil fuels and may free spending on fossil fuel subsidies to be redirected to R&D and deployment of RE technologies. With the 2009 G-20 Summit having agreed to phase out ‘inefficient fossil fuel subsidies’ over the medium term (G-20, 2009), this may offer some co-benefits for RE technologies. A report by the IEA, OECD and World Bank (2010), prepared for the subsequent G-20 Summit, finds that government support of fossil fuels is geographically concentrated. In 2009, 37 economies, mainly non-OECD, accounted for more than 95% of fossil fuel subsidies worldwide representing a total value of USD_{2005} 268 billion.[29] Government support of fossil fuels is predominant in economies where supported energy carriers are abundant, for example, Iran and Saudi Arabia.[30] Supported fuels are mainly oil (USD_{2005} 108 billion) and natural gas (USD_{2005} 73 billion), and may also implicitly cover electricity (USD_{2005} 82 billion), if largely generated by these fuels. In contrast, global coal subsidies are comparatively small at only USD_{2005} 5 billion.

A general concern when reforming these subsidies is how they affect the poor; they need to be carefully designed as low-income households are likely to be disproportionally affected (IEA, 2010b). However, subsidies are often regressive and there is a substantial benefit leakage to higher-income groups (Del Granado et al., 2010). For example, in Iran the richest 30% percent consume 70% of all government support (Nikou, 2010), and in Indonesia the bottom 40% of low-income families reap only 15% of all energy subsidies (IEA, 2008a). By and large this includes most supported fuels, for instance, electricity in several African countries (Angel-Urdinola and Wodon, 2007), LPG in India (Gangopadhyay et al., 2005) and petroleum products worldwide (Coady et al., 2010). In the case of kerosene, however, the picture is less clear and subsidies are relatively better targeted (Coady et al., 2004).

Accordingly, reforming subsidies towards the use of RE technologies should necessarily go along with addressing the specific needs of the poor. In order to do so, two general directions appear suitable. The first direction is expanding rural electrification, as poor households tend to live in areas without electricity service (Angel-Urdinola and Wodon, 2007). Successful programs have been initiated in Ethiopia and Vietnam (IEA/OECD/World Bank, 2010), and the phase-out of concurrent fossil fuel subsidies may create further incentives for business activities (Barnes and Halpern, 2001). Increasing electrification could be complemented with additional support for RE technologies in centralized power supplies, which would then also become available to the poor. Second, if electrification is not viable or better low-cost options exist, RE off-grid technologies are an alternative. In Nepal, for example, financial aids have significantly increased the awareness levels in adopting RE off-grid technologies and the willingness to pay for electricity (Mainali and Silveira, 2011). Moreover, for domestic lighting in India, solar photovoltaics and modern bioenergy systems are better options in rural areas compared to traditional kerosene-based lighting (Mahapatra et al., 2009).

It is likely that many more such opportunities exist, but to identify potential gains for RE and evaluate efficiency further case-specific analysis is needed. Without such analysis it is neither clear that RE technologies directly benefit from a phase-out of fossil fuel subsidies, nor whether the phase-out as such is potentially harmful.

The importance of *eliminating barriers to trade in RE supplies and associated technologies* as part of a broader strategy to reduce dependence on more-polluting and less secure energy sources has been stressed in several studies and events. This is the case for, among others, PV, wind turbines and biofuels (Steenblik, 2005; Lucon and Rei, 2006; OECD, 2006). As outlined in Section 2.4.6.2, barriers to the market penetration and international trade of bioenergy include tariff barriers, technical standards, inappropriately restrictive sustainability criteria and certification systems for biomass and biofuels, logistical barriers, and sanitary requirements. More generally, the elimination or reduction of barriers to trade can facilitate access to RE and other environmental goods that can contribute to climate change mitigation by fostering a better dissemination of technologies at lower costs. Elimination of both tariffs and non-tariff barriers to clean technologies could potentially result in a 14% increase in trade in these products (WTO, 2010).

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[29] Even though the underlying price gap approach has some limitations, it may serve as a first estimate.

[30] For more information on subsidy rates see www.iea.org/subsidy/index.html.

As parties to the Kyoto Protocol of the UN Framework Convention on Climate Change develop and implement policies and measures to achieve GHG concentration stabilization, compatibility with World Trade Organization (WTO) rules could become a recurrent issue. More generally, the nexus of investment rules inside and outside the WTO with the climate regime needs further attention (Brewer, 2004). Interactions that are the most problematic include the potential use of border measures to offset cross-national differences in the energy costs of goods, Clean Development Mechanism (CDM) and Joint Implementation projects in relation to the WTO subsidies agreement, efficiency standards in relationship to the WTO technical barriers agreement and carbon sequestration in relationship to the WTO agriculture agreement (Tamiotti et al., 2009).

Mechanisms for sustainable development that internalize environmental and social externalities

There is a constant need for mechanisms for SD that internalize environmental or social externalities. Diffusion of RE technologies is driven by policies and incentives that help overcome high upfront costs and lack of a level playing field (Rao and Kishore, 2010). However, when external costs (see Section 10.6) are included, the relative advantage of renewable energies is highlighted—especially regarding GHG emissions (Onat and Bayar, 2010; Varun et al., 2010). Incorporating external costs requires good indicators. A methodological limitation found in studies of different energy production systems is their use of an insufficient number of comparable sustainability indicators, which may lead to biases and flaws in the ranking of energy sources and technologies against sustainability (Brent and Kruger, 2009; Eason et al., 2009; Kowalski et al., 2009). Although multi-criteria decision analysis and approaches contribute significantly, it is recognized that appraising the contribution of RE options to SD is a complex task, considering the different aspects of SD, the imprecision and uncertainty of the related information as well as the qualitative aspects embodied that cannot be represented solely by numerical values (Cavallaro, 2009; Michalena et al., 2009; Donat Castello et al., 2010; Doukas et al., 2010).

The CDM established under the Kyoto Protocol is a practical example of a mechanism for SD.[31] RE to substitute for fossil fuels constitutes 61% of projects and 35% of expected Certified Emission Reductions by 2012 under the CDM (UNEP Risø Pipeline, 2011).The CDM is widely acknowledged as one of the most innovative features of the Kyoto Protocol with the involvement of 69 developing countries in the creation of a global carbon market worth billions of US dollars. It is, however, also widely known that its contribution to sustainable and low-carbon development paths in host countries is questionable (Figueres and Streck, 2009). CDM projects are submitted for sustainability screening and approval at the national level by the Designated National Authority (DNA; see also Sections 11.5.3.3, 11.6,11.6.6.1). There is, however, no international standard for sustainability assessment to counter weaknesses in the existing system of sustainability approval (Olsen and Fenhann, 2008b). Thus, DNAs have an important role in meeting national SD priorities—as well as in attracting investment (Winkler et al., 2005). Literature reviews of the CDM (Paulsson, 2009) and its contribution to SD (Olsen, 2007) find that one of the main weaknesses of the market mechanism is that of cheap emission reduction projects being preferred over more expensive projects that often are associated with higher SD benefits (Sutter and Parreño, 2007). Voluntary standards exist, such as the Gold Standard and the Climate, Community and Biodiversity Standards, that aim to attract investors who are willing to pay a premium for emission reductions with guaranteed co-benefits (Nussbaumer, 2009). The Gold Standard applies to RE and energy efficiency projects, where the most common RE projects are wind, biogas, biomass energy, hydro, landfill and solar. These labelled projects, however, make up a small share of the total volume of

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[31] The CDM has the twin objectives of promoting SD in developing countries and assisting developed countries to achieve their emission reduction targets cost-effectively.

CDM projects and as voluntary standards, they are successful in rewarding high-quality projects rather than improving low- or unsustainable projects (Wood, 2011). As input to the negotiations for a post-2012 climate regime, much literature has addressed how to reform the CDM to better achieve new and improved mechanisms for SD (Hepburn and Stern, 2008; Olsen and Fenhann, 2008a; Wara, 2008; Figueres and Streck, 2009; Schneider, 2009). Ideas include an up-scaling of mitigation actions through sector no-lose targets (Ward, 2008), introduction of new sectoral approaches (Marcu, 2009), differentiation of developing country eligibility for CDM crediting (Murphy et al., 2008) and structural changes for the CDM to contribute to long-term benefits for a low-carbon economy (Americano, 2008).

Mechanisms for SD may also be addressed from a wider perspective than sustainability assessments. The idea that developing countries might be able to follow more sustainable, low-carbon development pathways than industrialized countries have is particularly attractive. Such decisions are both political and societal, but depend intrinsically on the understanding of the concept of leapfrogging (see Box 9.5).

Box 9.5 | Leapfrogging.

‘Leapfrogging’ relates to the opportunity for developing countries to avoid going through the same pollution intensive stages of industrial development as industrialized countries have experienced in the past (see Annex I for definition). Three different types of ‘environmental leapfrogging’ are distinguished: leapfrogging within overall development pathways, leapfrogging within industrial development, and leapfrogging in the adoption and use of technologies. A sufficient level of absorptive capacity is at the core of successful leapfrogging; it includes the existence of technological capabilities to instigate and manage change and the support of appropriate national and international institutions (Sauter and Watson, 2008).

Any leapfrogging strategy involves risks, but latecomer countries can benefit if initial risks of developing new products and establishing markets have been borne in ‘frontrunner’ countries. Once a market is established, developing countries can catch up through rapid adoption of new technologies and/or the development of manufacturing capacity. More radical innovation—due to a shift in technological paradigms—can provide additional ‘windows of opportunity’ for developing countries. Different factors have been identified for the success of this process and since there is no standard model of development, trial-and-error learning needs to be accepted as part of leapfrogging strategies (Hobday, 2003; Sauter and Watson, 2008). Technological leapfrogging in RE has been reported by several studies (L. Clarke et al., 2007; Moreno et al., 2007; R. Singh, 2007; Tarik-ul-Islam and Ferdousi, 2007; Karakosta et al., 2010; Reiche, 2010; Saygin and Cetin, 2010), although current energy technologies may prevent the energy sector from being as conducive to leapfrogging as other sectors like information technology (World Bank, 2008a). Overall, experience has shown that the embarkment on a fundamentally cleaner development pathway needs to be accompanied by ongoing and targeted policy support and guidance, improved institutional capabilities and far-reaching political will in both developing and developed countries (Perkins, 2003; Gallagher, 2006).

Integrating renewable energy and sustainable development strategies

Opportunities for RE to play a role in national strategies for SD can be approached in two ways: 1) by integrating SD and RE goals into development policies and plans such as budgeting processes and Poverty Reduction Strategy Plans; and 2) by development of sectoral strategies for RE contributing to goals for green growth, low-carbon and sustainable development.

Though the idea of *National Sustainable Development Strategies (*NSDS) was born at the international level, the actual implementation of strategies takes place at the national level. By

2009, 106 countries corresponding to 55% of Member States to the United Nations had reported to the Commission on Sustainable Development that they were implementing an NSDS. The overall idea of NSDS is to integrate principles for SD such as the three pillars of sustainability, participation, ownership, comprehensive and coordinated policymaking, as well as targeting, resourcing and monitoring (i.e., the measurement and monitoring of development outcomes) into a country’s existing development process (George and Kirkpatrick, 2006). NSDS should not be a new, separate strategy but are meant to integrate SD concerns into a country’s existing governance and decision-making framework. As countries differ in their institutional, developmental and geographical conditions no blueprint exists for NSDS, but generally they are structured into three levels: 1) major goals and policy areas such as dealing with climate change and energy security; 2) concrete objectives and issues such as transport, energy efficiency and RE; and 3) aims and actions such as implementing a RE strategy, liberalizing energy markets or using the CDM to support small RE power projects (UNDESA, 2008). When it comes to implementation of NSDS, however, the record of progress has been limited (George and Kirkpatrick, 2006). Volkery et al. (2006) found that many countries are still at early stages of learning and a key challenge is coordination of NSDS with other strategy processes such as the national budget, sectoral and sub-national strategy processes. In most countries, the NSDS provides a summary of existing strategies and as such it works as a post-rationalization rather than an overarching framework guiding and stimulating new action (George and Kirkpatrick, 2006; Volkery et al., 2006). Compared to the rich institutional landscape for economic cooperation and development, the institutional landscape for SD is still relatively small but may be improved through better ownership of SD strategies central to government.

RE strategies for low-carbon, green and sustainable development are increasingly important as a means to achieve goals such as GHG concentration stabilization, energy security, energy access for the poor and the creation of green jobs (IEA, 2010b; SARI, 2010; Lund et al., 2011; see Section 9.3). Policy targets for RE can be helpful to mobilize people and resources and to monitor progress. By 2010, more than 85 countries worldwide had adopted policy targets for the share of RE; typically 5 to 30% for electricity production. Examples of targets for final energy are 15% by 2020 in China, 20% by 2020 in the EU and 100% by 2013 in the small island states of Fiji and Tonga (REN21, 2010). The policy targets are specific to RE but represent important elements in overall strategies for low-carbon, green and sustainable development (UN, 2005b; SARI, 2010; Offer et al., 2011).

Essentially, RE strategies describe the challenges and possible solutions of phasing out unsustainable fossil fuels and technologies while phasing in RE systems (Lund, 2007; Verbruggen and Lauber, 2009). To harness the full potential of RE sources, major technological changes are needed along with policies and regulation to ensure a sustainable, effective and efficient use of energy sources and technologies. To ensure the sustainable use of RE sources and technologies, detailed scientific differentiation and qualification of renewable electricity sources and technologies is required to assess the huge diversity in the field (Verbruggen and Lauber, 2009). Further methodological development of sustainability criteria for, indicators for, and assessments of RE sources and technologies based on their attributes (such as types, density, variability, accessibility, scale, maturity, costs etc.), would allow improved fine-tuned regulation for sustainable RE solutions (Verbruggen and Lauber, 2009). In Norway, environmental concerns have led to a more sustainable use of hydropower (see Box 9.6).

Box 9.6 | Sustainable hydropower in Norway.

For about a century, hydropower, ‘the white coal of Norway’, has been a strong driving force in the industrialization of the country (Skjold, 2009). By early 2010, installed capacity was about 29 GW and the average annual generation was about 122 TWh, meeting 98 to 115% of Norway's annual electricity demand, depending on rainfall (NVE, 2009). After intense exploitation during the 1970s and 1980s, newly heightened environmental awareness led to a period of relative standstill in the development of hydropower plants in general, and in 1973 the Norwegian government adopted its initial national protection plan (today there are four in total). As a result, approximately 400 rivers are now protected. In 1986, the first version of a master plan for hydropower was passed; it categorizes potential projects according to economic and technical viability, but also strongly emphasizes potential environmental and social conflicts (Thaulow et al., 2010). Of the estimated feasible potential of 205 TWh of hydropower from Norway's rivers, 122 TWh are utilized, 46 TWh are protected, and about 37 TWh are sorted into acceptable/not acceptable projects in the National Master Plan for hydropower (Thaulow et al., 2010). The last 30 years have seen improved environmental and social impact assessment procedures, guidelines and criteria, increased involvement of stakeholders, and better licensing procedures; all efforts to make hydropower more sustainable for the long term.

9.5.2.2 Local, private and nongovernmental sustainable development initiatives

At the local level, cities and local governments in alliance with business and citizen interests can be drivers of change for RE deployment (REN21, 2009). In response to enabling framework conditions at international and national levels, cities and local governments can independently use their legislative and purchasing power to implement RE initiatives in their own operations and the wider community (see Section 11.6). Typically, local policy initiatives are motivated by sustainability goals such as low GHG concentration stabilization, the share of renewable electricity production or total energy consumption (Ostergaard and Lund, 2010). Other types of local RE policies and SD initiatives are urban planning that incorporates RE, inclusion of RE in building codes or permitting, regulatory measures such as blending of biofuels, RE in municipal infrastructure and operations and voluntary actions to support RE and serve as a role model for business and citizens (REN21, 2009). To share experiences and inspire local actions a range of networks and initiatives have emerged such as the World Mayors and Local Governments Climate Protection Agreement, the Local Government Climate Roadmap, Solar Cities, 100% renewable energy regions, ICLEI's Local Renewables Initiative, the European Green Cities Network, Green Capital Awards and many others. Common to these initiatives is a broad recognition of the local SD benefits RE may bring (del Rio and Burguillo, 2008, 2009), such as a local supply of energy, saving energy and money, creating local jobs and involving the private sector in playing a role in providing RE services (Hvelplund, 2006).

Involvement of community-based organizations can mitigate local opposition to RE installations by facilitating local ownership and sharing of benefits (Rogers et al., 2008; Zografakis et al., 2009). The creation of local energy markets can provide opportunities for local private investors (Hvelplund, 2006) and thereby ensure public acceptance of integrating an increasing number of local RE installations (windmills, solar panels, biogas plants etc.) into the energy system. Positive impacts on the local economy further improve public attitudes towards RE developments (Jobert et al., 2007; Maruyama et al., 2007; Aitken, 2010; Warren and McFadyen, 2010). Case studies evaluating the success of wind energy projects in France and Germany found that the familiarity of the developer with local circumstances and concerns (Jobert et al., 2007) as well as transparency, provision of information and participation of the local population in the planning process from the early stages on (Wolsink, 2007a) are crucial factors for public acceptance. In the context of developing countries, this also includes the empowerment of rural women in order to seek the best solutions for community energy needs (Omer, 2003; Oikonomou et al., 2009; A. Singh, 2009).

9.6 Synthesis

The renewable energy (RE) technologies discussed in this report will play an increasingly important role in the world energy system over the next several decades. Mitigation of climate change caused by the combustion of fossil fuels provides one key motivation for a drastic transformation of the world energy system. Additional factors pointing towards the desirability of increasing reliance on RE include concerns about uneven distribution and future supply scarcity of fossil fuel resources, the affordable provision of modern energy services and reductions of burdens on the environment and human health. Given the heavy reliance of modern societies on fossil fuels, any proposed transformation pathway must be carefully analyzed for feasibility and its implications for SD.

In order to be seen as advancing SD, any energy technology has to contribute to a number of SD goals. In the context of this report, these have been identified as social and economic development, energy access, energy security, and the reduction of adverse impacts on health and the environment. To date, RE has often been claimed to advance these four goals and the assessment of this chapter has focused on validating these assumptions. In the following sections, the theoretical concepts and methodological tools used in the analyses are briefly presented. Building on that, results from the bottom-up and integrated assessments of Sections 9.3 and 9.4 are combined to provide clear insights into where the contribution of RE to SD may remain limited and where it shows significant potential.

9.6.1 Theoretical concepts and methodological tools for assessing renewable energy sources

SD has predominantly been framed in the context of the three-pillar model, that is, the contribution to economic and social development and environmental protection. SD is also oriented along a continuum between the weak and strong sustainability paradigms, which differ in assumptions about the substitutability of natural and human-made capital. RE technologies can be evaluated within both concepts: the contribution of RE to the development targets of the three-pillar model and the prioritization of goals according to the weak and strong sustainability framework. As such, SD concepts provide useful frameworks for policymakers to assess the contribution of RE to SD and to formulate appropriate economic, social and environmental measures.

The assessments carried out in this chapter are based on different methodological tools, including bottom-up indicators derived from attributional lifecycle assessments (LCA) or energy statistics, dynamic integrated modelling approaches, and qualitative analyses. Naturally, each of these assessment techniques comes with its own set of limitations. For example, general conclusions from results of individual LCAs are thwarted by potential system boundary problems, differences in technology and background energy system characteristics, geographic location, data source type and other central methods and assumptions. Yet LCA provides a standardized framework for comparison, and bottom-up evidence allows valuable insights about environmental performances of different technologies across categories. In a complementary approach, scenario results of global integrated models were analyzed to derive conclusions about the contribution of RE deployment to the named SD goals within a macro-economic and systemic perspective. However, any interpretation of these results needs to be accompanied by the recognition that integrated models in existence today were generated around a relatively specific set of tasks. These relate to understanding the effects of policy or economics on the energy portfolios of fairly large world regions and the emissions trajectories implied by changes in those energy portfolios over time. While expanding the models beyond these tasks can be challenging, there is room for improving treatment of sustainability in the future. For example, questions relating to the ability of integrated models to accurately represent cultural dimensions of energy use and the impact of non-price policies on behaviour and investment are not resolved.

One of the key points that emerged from the literature assessment is that the evaluation of energy system impacts (beyond GHG emissions), climate mitigation scenarios and SD goals has for the most part proceeded in parallel without much interaction. Effective, economically efficient and socially acceptable transformations of the energy system will require a much closer integration of results from all three of these research areas. While the assessment carried out within the context of this report generated a number of important insights, it also disclosed some of these shortcomings. For example, it highlights the need for the inclusion of additional boundaries (e.g., environmental) and more complex energy system models within an integrated model framework to improve the representation of specific local conditions, variability or biophysical constraints. However, it is also evident that for the multi-dimensional challenge of integrating RE and SD, no single global answer is possible. Many solutions will depend strongly on local and regional cultural conditions, and the approaches and emphases of developing and developed countries may also be different.

9.6.2 Social and economic development

The energy sector has generally been perceived as key to economic development with a strong correlation between economic growth and expansion of energy consumption. Historically, increased energy use has also strongly correlated with growth in GHG emissions. While considerable cross-sectional variation of energy use patterns across countries prevails, the correlation is confirmed by both analyses of single measures such GDP as well as composite indicators such as the Human Development Index. Developing and transition economies may have the opportunity to ‘leapfrog’ to less energy- and carbon-intensive growth patterns. This requires strong policy and institutional frameworks, as experiences show that rapid economic growth can outpace any declines in energy or carbon intensity.

The contribution of RE to social and economic development may differ between developed and developing countries. To the extent that developing countries can avoid expensive energy imports by deploying economically more efficient RE technologies, they can redirect foreign exchange flows towards imports of other goods that cannot be produced locally. However, generation costs of RE today are generally higher than current energy market prices, although further cost reductions are expected. In poor rural areas lacking grid access, RE can already lead to substantial cost savings today. Creating employment opportunities and actively promoting structural change in the economy are seen, especially in industrialized countries, as goals that support the promotion of RE.

Results from the scenario literature highlight the role of RE for cost-efficient mitigation efforts in the long run—particularly for low-GHG stabilization levels. In developing countries, for which large-scale integrated models suggest a higher share of global RE deployment over time, RE may help accelerate the deployment of low-carbon energy systems. Climate finance is expected to play a crucial role in providing the funding required for large-scale adoption of RE.

9.6.3 Energy access

Enhancing access to clean, reliable and affordable energy sources is a key part of SD and RE has potential to contribute significantly to this goal. Currently, around 1.4 billion people have no access to electricity and about 2.7 billion rely on traditional biomass for cooking (Section 9.3.2). Access to modern energy services is an important precondition for many fundamental determinants of human development, including health, education, gender equality and environmental safety. Even at basic levels, substantial benefits can be provided to a community or household, for example, by improved lighting, communication or healthcare opportunities. In developing countries, decentralized grids based on RE have expanded and improved energy access in rural areas with significant distances to the national grid. In addition, non-electrical RE technologies offer opportunities for direct modernization of energy services, for example, using solar energy for water heating and crop drying, biofuels for transportation, biogas and modern biomass for heating, cooling, cooking and lighting, and wind for water pumping (see Table 9.3). Model analyses confirm that income growth tends to lead to increased energy access, but this is also dependent on the level of income distribution within a society. If developing countries are able to secure dedicated financing for enhanced energy access and apply tailored policies, the number of people with access to modern energy services can expand more rapidly.

9.6.4 Energy security

The role of RE in shaping economies' energy security is complex and depends on the development level of a given country. For example, for developing and transition economies, RE can make a contribution to economizing foreign exchange reserves and help to increase the reliability of energy services. For many developing countries, the definition of energy security specifically includes the provision of adequate and affordable access to all parts of the population and thus exhibits strong links to energy access aspects. Hence, the definition of energy security, that is, the risk of supply disruptions, is broadened from resource availability and distribution of resources, and variability of supplies, to include the reliability of local energy supply.

Scenario analysis confirms that RE can help to diversify energy supply and thus enhance energy security. Local RE options can substitute for increasingly scarce or concentrated fossil fuel supplies, diversifying energy supply and diminishing dependence on a small number of suppliers. As long as RE markets (e.g., bioenergy) are not characterized by concentrated supply, this may help reduce economic vulnerability to price volatility. However, due to the variable output profiles of some RE technologies, technical and institutional measures appropriate to local conditions are often necessary to minimize new insecurities. Also, supply constraints of certain inorganic raw materials may affect enhanced deployment of RE.

The degree to which RE can substitute for liquid fossil fuels used in transport will depend on technology, market and institutional developments. Even with these advances, oil and related energy security concerns will likely continue to play a dominant role in the global energy system of the future.

9.6.5 Climate change mitigation and reduction of environmental and health impacts

RE technologies can provide important environmental benefits compared to fossil fuels, including reduced GHG emissions. Maximizing these benefits often depends on the specific technology, management and site characteristics associated with each RE project. While all energy technologies deployed at scale will create environmental impacts—determined in large measure by local implementation decisions—most RE options can offer advantages across categories, in particular regarding impacts on climate, water resources and air quality. The environmental advantages of RE over other options are not always clear-cut. Significant differences exist between technologies, and some might potentially result in difficult SD trade-offs.

In particular, bioenergy has a special role. It is the only RE based on combustion, leading to associated burdens such as air pollution and cooling water needs. Other impacts from bioenergy production may be positive or negative and relate to land and water use, as well as water and soil quality. These require special attention due to bioenergy's inherent connection to agriculture, forestry and rural development. The net effects of bioenergy production, in particular in terms of lifecycle GHG emissions, are strongly influenced by land and biomass resource management practices, and the prior condition of the land converted for feedstock production. While most models do not yet include land use and terrestrial carbon stocks, those scenarios that have focused on direct and indirect land use change highlight the possible negative consequences for SD. These result from high expansion rates without proper policies in place and large future bioenergy markets, and can lead to deforestation, land diversion and increased GHG emissions. Proper governance of land use, zoning and choice of biomass production systems are key to achieving desired outcomes.

RE has the potential to significantly reduce local and regional air pollution from power generation and associated health impacts. Scenarios that explicitly address regional air pollutants, for example, PM and sulphur emissions, found that climate policy can lead to important co-benefits in that area. Indoor air pollution caused by the use of solid fuels in traditional systems is a major health problem at a global scale, and improved technologies and fuels could also address other SD concerns. Careful decisions based on local resources are needed to ensure that water scarcity does not become a barrier to SD, and that increasing access to energy services does not exacerbate local water problems. Non-thermal RE technologies (e.g., wind and PV) can provide clean electricity without putting additional stress on water resources, whereas operational water needs make thermal power plants and hydropower vulnerable to changes in water availability. While accident risks of RE technologies are not negligible, their often decentralized structure strongly limits the potential for disastrous consequences in terms of fatalities. However, dams associated with some hydropower projects may create a specific risk depending on site-specific factors.

Insights from the modelling approaches show that integrated assessment models might be well suited to include some important environmental indicators in addition to GHG emissions (e.g., air pollutant emission, water use), but may be challenged by addressing localized impacts, for example, related to energy choices at the household level. Resulting scenarios could be useful to demonstrate unanticipated or unquantified environmental benefits or costs.

9.6.6 Conclusions

The previous sections have shown that RE can contribute to SD and the four goals assessed in this chapter to varying degrees. While benefits with respect to reduced environmental and health impacts may appear more clear-cut, the exact contribution to, for example, social and economic development is more ambiguous. Also, countries may prioritize the four SD goals according to their level of development. To some extent, however, these SD goals are also strongly interlinked. Climate change mitigation constitutes in itself a necessary prerequisite for successful social and economic development in many developing countries.

Following this logic, climate change mitigation can be assessed under the strong SD paradigm, if mitigation goals are imposed as constraints on future development pathways. If climate change mitigation is balanced against economic growth or other socioeconomic criteria, the problem is framed within the paradigm of weak SD, allowing for trade-offs between these goals and using cost-benefit type analyses to provide guidance in their prioritization.

However, the existence of uncertainty and ignorance as inherent components of any development pathway, as well as the existence of associated and possibly ‘unacceptably high’ opportunity costs (Neumayer, 2003), will make continued adjustments crucial. In the future, integrated models may be in a favourable position to better link the weak and strong SD paradigms for decision-making processes. Within well-defined guardrails, integrated models could explore scenarios for different mitigation pathways, taking account of the remaining SD goals by including important and relevant bottom-up indicators. According to model type, these alternative development pathways might be optimized for socially beneficial outcome. Equally, however, the incorporation of GHG emission-related LCA data will be crucial for a clear definition of appropriate GHG concentration stabilization levels in the first place.

Despite the potential existence of several technically, economically and environmentally feasible development pathways, it is the human component that will ultimately define the success of any such strategy. Important barriers, especially in the SD context, are those relating to socio-cultural and information and awareness aspects. In particular, barriers intrinsically linked to societal and personal values and norms will fundamentally affect the perception and acceptance of RE technologies and related deployment impacts by individuals, groups and societies. Dedicated communication efforts, addressing these subjective and psychological aspects in the same manner as the more objective opportunities associated with wider-scale RE applications are therefore a crucial component of any transformation strategy. Local SD initiatives by cities, local governments, and private and nongovernmental organizations can act as important drivers of change in this context.

Local initiatives, however, also need to be embedded in coherent SD strategies at the national level. The clear integration of SD and RE goals into development policies and the development of sectoral strategies for RE can provide an opportunity for contributing to goals for green growth, low-carbon and sustainable development, including leapfrogging.

9.7 Gaps in knowledge and future research needs

This chapter has described part of the interactions between SD and RE and focused on SD goals such as social and economic development, energy access, energy security, climate change mitigation and the reduction of environmental and health impacts. An assessment of indicators related to these goals has revealed several gaps in knowledge.

Beginning with the more conceptual discussion of SD, there is a tremendous gap between intertemporal measures of human well-being (sustainability) and measurable sub-indicators that needs to be narrowed. In addition, possibilities for relating the two opposite paradigms of sustainability, weak and strong sustainability, need to be explored. One possibility would be to allow for nonlinearities, tipping points, and uncertainty about nonlinearities in intertemporal measures, or to provide formal guidelines for consideration of the precautionary principle. In the context of this report, this also means that specific indicators of weak sustainability like genuine savings, ISEW or GPI, but also those of strong sustainability (e.g., land use boundaries) need to be statistically and logically related to RE indicators.

Apart from the definitions and indicators, data that are necessary to assess sustainability and RE are insufficiently available. There is a clear need for better information and data on energy supply and consumption for non-electrified households and also low-end electricity consumers. Furthermore, there is a need for analysis of RE-based mini-grid experiences for improving access and for the energy security implications of regional power integration. The electrification of the transport sector and its implications for energy security, environmental impacts and GHG emissions also deserves attention.

Many aspects of the assessment of environmental impacts of energy technologies require additional research to resolve key scientific questions, or provide confirmatory research for less contentious but also less-studied aspects. Two key issues regarding GHG emissions caused by energy technologies are direct and indirect land use change. For RE technologies, these issues mainly concern the production of biomass for bioenergy systems and hydropower impoundments, but land use change associated with some non-RE technologies deserve investigation as well (e.g., carbon emission from soils exposed by mountaintop removal coal mining). Several energy technologies are lacking substantial or any studies of lifecycle GHG emissions: geothermal, ocean energy and some types of PV cells. Water use has not been consistently or robustly evaluated for any energy technology across its lifecycle. The state of knowledge about land use, especially when considered on a lifecycle basis, is in a condition similar to water. For both, metrics to quantify water and land use need consensus as well as substantial additional study using those metrics. More is known about air pollutants, at least for the operation of combustion systems, but this knowledge has not been well augmented on a lifecycle basis, and the interpretation of air pollutant emissions on a lifecycle basis needs to be enhanced since the important effects of pollutants should not be summarized by summing masses over time and space. For LCAs as a whole, heterogeneity of methods and assumptions thwarts fair comparison and pooling of estimates from different studies. Ex post facto harmonization of the methods of previous research (and meta-analysis) and perhaps stronger standards guiding the conduct of new LCAs is critical to clarifying results and producing robust estimates.

Assessments of the scenario literature have provided some useful insights on how SD pathways will interact with RE and vice versa. However, in the past, models have focused on the technological and macro-economic aspects of energy transitions and the evaluation of SD pathways therefore mostly needs to rely on proxies that are not always informative. One major difficulty is the models' macro perspective, while some issues for SD are relevant at a micro and regional level. Thus, when focusing more specifically on different SD criteria, major drawbacks can be found for all of them:

- With respect to sustainable social and economic development, the scenario literature has a strong focus on consumption and GDP. Even though models address multiple criteria for welfare, they are generally not sufficiently specific to inform about distributional issues. Differentiations between income groups, urban and rural populations and so on are difficult to make.
- The distribution and availability of energy services, and how they change over time, are aspects that are not broadly included in most energy-economy models so far, which makes the evaluation of energy access challenging.
- Regarding energy security, the current representation of the grid structure in most of the models does not allow for a thorough analysis of possible difficulties related to large-scale integration of RE. Possible barriers are mostly assumed to be overcome without difficulties, particularly when thinking of storage and variability issues that might occur. Possible co-benefits of renewable sources, such as growing diversity of supply and possibilities to electrify rural areas, are also poorly covered in the literature as, for example, fuel supply risks are usually not taken into account in the models.
- The existing scenario literature does not give an explicit treatment to many non-emissions-related aspects of sustainable energy development, for example, water use, biodiversity impacts, or the impacts of energy choices on household-level services or indoor air quality. In addition to that, regarding Section 9.3.4 of this chapter, emissions are generally not treated over the lifecycles of technology choices, which might be an interesting aspect of future research.

In conclusion, knowledge regarding the interrelations between SD and RE in particular is still very limited. Finding answers to the question of how to achieve effective, economically efficient and socially acceptable transformations of the energy system will require a much closer integration of insights from social, natural and economic sciences (e.g., through risk analysis approaches) in order to reflect the different dimensions of sustainability. So far, the knowledge base is often limited to very narrow views from specific branches of research, which do not fully account for the complexity of the issue.

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