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Global Energy and Climate Outlook 2018: Sectoral mitigation options towards a low-emissions economy

Global context to the EU strategy for long-term greenhouse gas emissions reduction

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Contents

Abstract

This report analyses global transition pathways to a low Greenhouse Gas (GHG) emissions economy. The main scenarios presented have been designed to be compatible with the 2°C and 1.5°C temperature targets put forward in the UNFCCC Paris Agreement, in order to minimise irreversible climate damages. Reaching these targets requires action from all world countries and in all economic sectors. Global net GHG emissions would have to drop to zero by around 2080 to limit temperature increase to 2°C with respect to pre-industrial times (by around 2065 for the 1.5°C limit). The analysis shows that this ambitious low-carbon transition can be achieved with robust economic growth, implying small mitigation costs. Results furthermore highlight that the combination of climate and air policies can contribute to improving air quality across the globe, thus enabling progress on the UN Sustainable Development Goals for climate action, clean energy and good health. Key uncertainties in future pathways related to the availability of future technological options have been assessed for Carbon Capture and Sequestration (CCS) and bioenergy. If CCS technologies would not develop, a 2°C pathway would have a similar mitigation trajectory in the first half of the century as a 1.5°C scenario with CCS.

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Executive summary

This report analyses global transition pathways to a low Greenhouse Gas (GHG) emissions economy that is compatible with the 2°C and 1.5°C temperature targets put forward in the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement.

Policy context

The 2015 UNFCCC Paris Agreement set the goal to limit global warming to well below 2°C above pre-industrial levels and aim for 1.5°C. In October 2018, the Intergovernmental Panel on Climate Change (IPCC) presented a special report related to the 1.5°C objective. In 2023 the UNFCCC parties will assess the progress made in the first global stocktaking. Furthermore, parties are invited to submit long-term low GHG emissions development strategies by 2020. In preparation for this process, the European Commission has prepared a Long-Term Strategy for the evolution of the European Union’s energy and climate objectives. This report offers the international context within which the EU’s contribution can be assessed.

Key conclusions

The scenarios elaborated in this study show possible pathways to mitigate global warming to 2°C and below by the end of the century. These consistent scenarios illustrate that mitigating climate change to such levels is technically possible while having a moderate reliance on bioenergy resources and carbon removal technologies such as biomass with carbon capture and sequestration (BECCS). Analysis shows that this transition is compatible with robust economic growth and also provides significant co-benefits for reducing air pollution.

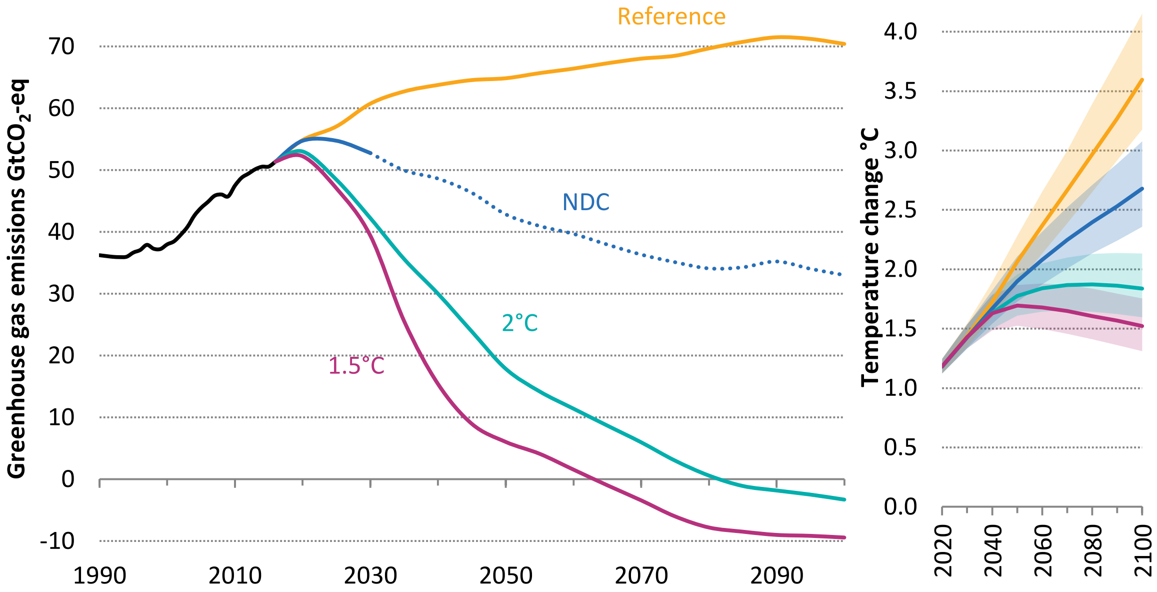
This transition is based on three main levers, all of them requiring immediate and strong action: (i) a substantial, cross-sectoral increase in energy efficiency by decoupling economic growth from energy consumption; (ii) a strong shift of energy carriers towards electricity; and (iii) a deep decarbonisation of the energy system. A transition compatible with 1.5°C would imply more reductions, in particular during the next three decades.

Total energy-supply-related expenditure needs would remain similar across scenarios, but the composition shifts more towards power sector investments. More expenditure would be needed for investment in infrastructure, especially in the power sector and for demand-side energy efficient investments, while operational costs would drop, following the declining trend of fossil fuels consumption.

Main findings

Current temperature levels are already 1°C above pre-industrial times; and today's emissions and energy consumption trends are not on track to meet either the 2°C or the 1.5°C targets. However, this study shows that the targets are technically possible at relatively low cost for the overall economy. The global GDP is estimated to be 0.4%–1.3% lower in 2050, compared to a global cumulative economic growth of 128% between 2020 and 2050. The global energy system and energy consumption patterns would have to undergo a profound and immediate transformation to sustain unprecedented levels of global annual decarbonisation rates between 6.1 and 9.0%/year over 2015–2050, compared to 1.9%/year over 1990–2016.

Figure ES 1. Global GHG emissions and global average temperature change (with median probability)



Note: The NDC scenario assumes that the global average rate of decarbonisation implied by the NDCs in 2020–2030 is maintained over 2030–2050.

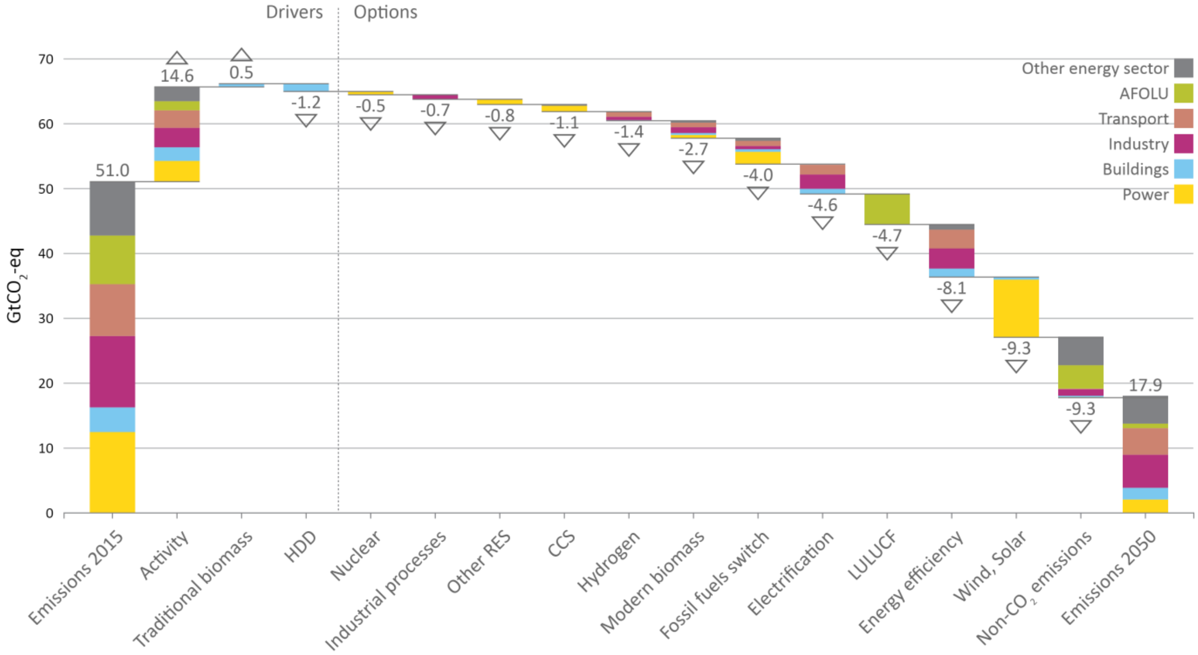
Source: POLES-JRC 2018; MAGICC online.

The 2°C objective would trigger in-depth changes to the energy system. Total global GHG emissions in 2050 would be cut by half compared to their 1990 level. Net GHG emissions would drop to zero around the year 2080. A stronger climate objective of 1.5°C would result in accelerated mitigation efforts in the 2020–2040 decades in particular, reaching global net zero GHG emissions globally around the year 2065.

Key mitigation options as a share of total mitigation over 2015–2050 for the central 2°C scenario include the increase of the use of renewable energy sources (27%), reduction of non-CO_2 emissions (20%, about a third of which are due to the decrease in fossil fuel demand in all demand sectors), improved energy efficiency (17%), electrification in final energy demand (10%) and land use (10%).

Results furthermore highlight that the combination of climate and air policies can contribute to improving air quality across the globe, enabling concurrent progress in the UN Sustainable Development Goals for climate action, clean energy and good health.

Figure ES 2. Drivers of GHG emissions growth and mitigation, 2015–2050, 2°C scenario, World



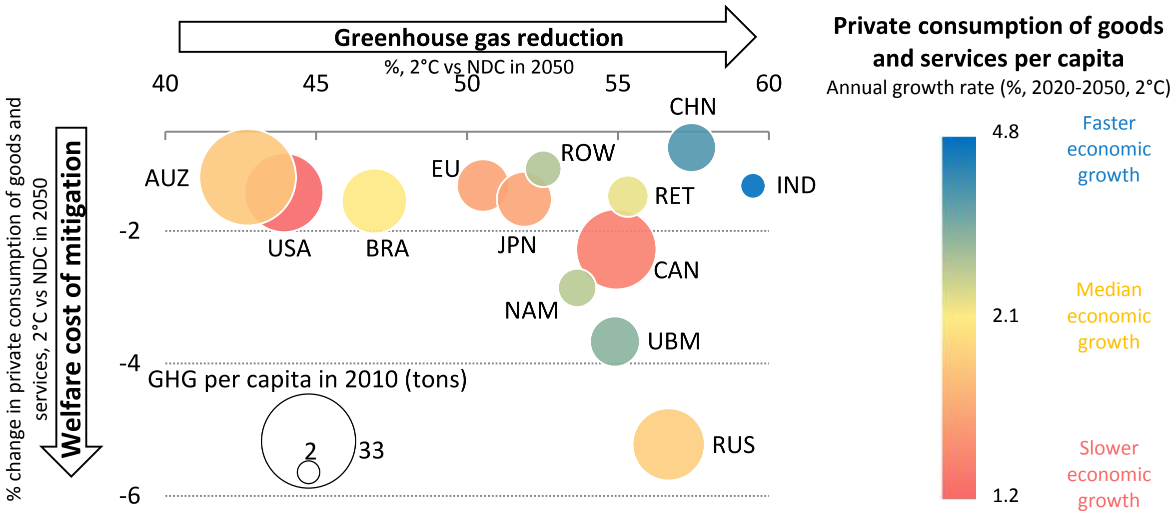
Notes: "AFOLU": Agriculture, Forestry and Other Land Use. "Activity": emissions growth due to the growth of population and the economy, and to associated income-based consumption (industrial value added, transport traffic, dwelling size, electricity consumption). "Traditional biomass": refers to the phase-out of traditional biomass for reasons other than climate, resulting in an energy demand gap that has to be met by other fuels. "HDD": emissions prevented by the evolution in time of heating degree-days due to global warming. "CCS": emissions prevented by carbon capture and sequestration. "Fossil fuels switch": refers to shifts from high-carbon content towards lower-carbon content within the fossil fuel mix (generally from coal to natural gas) and towards synthetic methane. "Non-CO_2": includes emissions from agriculture, industry and other sources (including the reductions from fossil fuel extraction and transport directly related to the decrease in the use of fossil fuels in all energy demand sectors). "Hydrogen", "Biomass", "Electrification": emissions prevented by the use of these fuels in final demand sectors (emissions for their production distributed in the other options here).

Source: POLES-JRC 2018.

The key sensitivity studies carried out in this report show that a 2°C scenario where Carbon Capture and Sequestration (CCS) technologies are excluded has a similar mitigation trajectory in the first half of the century as a 1.5°C scenario with CCS. The analysis of the impact of a wider availability of biomass for energy shows that decarbonisation would have lower costs and biomass combined with CCS would double its potential. However, the expected impact on land use would be more substantial, possibly with significant trade-offs for biodiversity.

According to the analyses conducted, the cost of the efforts to limit global warming would not jeopardise a sustained and continued economic growth. The comparison of the economic impacts across regions between the NDC and the 2°C scenarios indicates that long-term decarbonisation goes hand in hand with high yearly per capita consumption growth rates in fast-growing low and middle-income countries. Striving for higher ambition levels than the Nationally Determined Contributions (NDCs) can be done at relatively low costs. While GDP and consumption are expected to decline relative to the NDC scenario in 2050, investment will increase to build the capital stock required for a low emission economy. Fossil fuel industry output and investment in the 2°C scenario will decline and about 20 million jobs in the global fossil fuel industry would shift to cleaner sectors of the economy.

Figure ES 3. The economic impact of 2°C climate policy relative to the NDC scenario across regions



Source: JRC-GEM-E3 2018.

Related and future JRC work

This report is the fourth edition of the Global Energy and Climate Outlook (GECO). It contributes to the JRC work in the context of the UNFCCC policy process and IPCC assessment reports. This edition offers an international context to the policy proposal on the EU strategy for long-term GHG emissions reduction.

Quick guide

The report uses quantitative energy-economy modelling to build several scenarios aiming to limit global warming to 2°C and 1.5°C. The central 2°C scenario is presented in more detail. The implications of technological availability are highlighted for CCS and bioenergy. Section 2 presents these scenarios. GHG emissions projections are presented in section 3. Section 4 provides an in-depth analysis of mitigation options used by sector of activity: industry, buildings, transport, power generation, agriculture and land use. Sections 5 and 6 analyse the overall impacts of climate policies on energy markets and air pollutants. Finally, section 7 provides details on the macroeconomic impact of these climate policies.

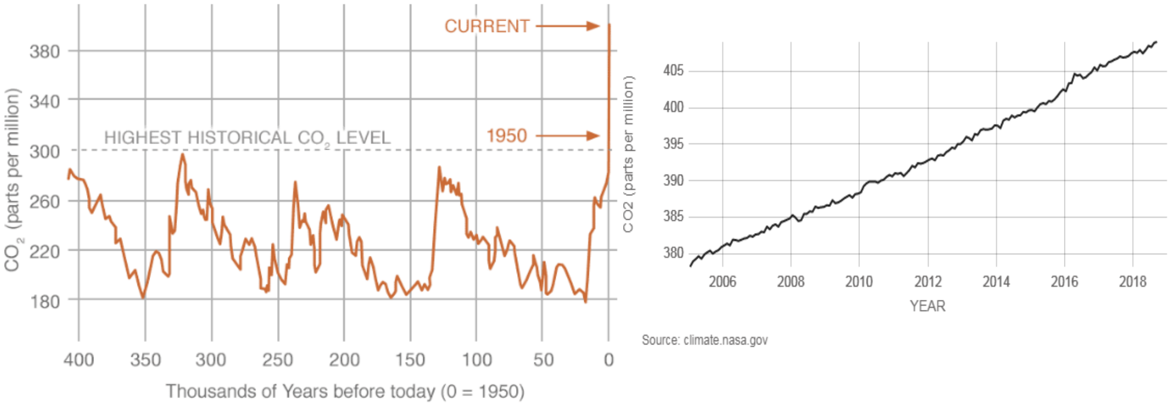
1 Introduction: Towards a sustainable future

1.1 Global emissions and changing climate

In April 2018, the Mauna Loa Observatory in Hawaii recorded an average concentration of atmospheric carbon dioxide (CO_2) above 410 parts per million (ppm) (National Oceanic and Atmospheric Administration, 2018). This was the highest monthly average in recorded history, and according to ice core records it is the highest value in at least the last 400,000 years (see Figure 4 and Figure 5). Global averaged CO_2 atmospheric concentration reached 405 parts per million (ppm) in 2017 (Blunden, et al., 2018), up from 402.9 ppm in 2016 (Blunden & Arndt, 2017). The global growth rate of CO_2 has nearly quadrupled since the early 1960s, with no sign of deceleration.

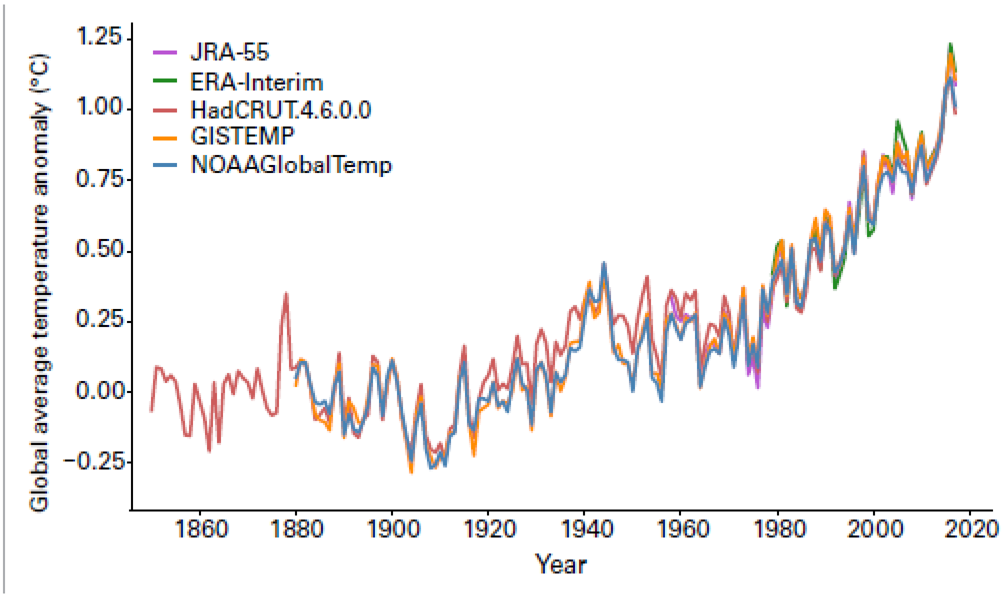
The dominant greenhouse gases (GHGs) present in the Earth's atmosphere (CO_2, CH_4 and N_2O) also reached new record highs in concentrations, caused by human activities such as fossil fuels combustion, industrial processes, agriculture and land use. As of 2017, GHG concentrations were 45% above pre-industrial levels [i.e. since 1750, (World Meteorological Organization, 2017)] (Figure 4). In addition, the speed of accumulation of GHGs in the atmosphere has been record-breaking since the industrial age: the growth rate of atmospheric CO_2 over the past 70 years is nearly 100 times larger than that at the end of the last ice age. Such abrupt changes in the atmospheric levels of CO_2 concentrations are totally unprecedented.

Figure 4. Proxy indirect measurements historical data reconstruction from ice cores (left); direct measure for the atmospheric concentration of CO_2 2005–2018 (right)



Source: (NASA, 2018).

Figure 5. Global mean temperature anomalies, with respect to the 1850–1900 baseline, for the five global datasets



Source: UK Met Office Hadley Centre.

1.2 The need for collective and concerted action

The scientific community presently agrees that human activities have caused approximately 1.0°C of global warming above pre-industrial times, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (high confidence) (IPCC, 2018). This would cause serious disruptions to ecosystems, society, and economies, with different timescales and levels of damage. The severity of the global climate change threat is widely acknowledged by scientists, society, corporations, and all kinds of stakeholders on a global scale. According to a recent Eurobarometer survey, three out of four European citizens consider climate change to be a very serious problem [(European Commission, 2018), (Pewshter, 2018)] (1).

Since the Kyoto Protocol — the international treaty that committed state parties to reduce GHGs emissions — went into effect in 2005, global energy-related CO_2 emissions have increased by around 20% as of 2016 [(PBL, 2017), (IEA, 2017)]. As the observed changes in climate over the last few decades are already having wide-ranging impacts on ecosystems, economic sectors, security, human health and well-being on a global level, more ambitious climate policies should be implemented urgently and globally.

Climate adaptation can reduce the adverse consequences of ongoing climate change, as well as harness any beneficial opportunities, but a quick and deep decarbonisation cannot be circumvented to avoid moving into scenarios in which the response of the planetary systems would entail a severe damage to nature and socio-economic systems, that is, above all else, irreversible.

The rationale for ambitious climate mitigation efforts is related to the expected and observed damages due to the already ongoing climate change. Climate change impact mechanisms are multifaceted, and are already acting along many transmission chains from the biophysical to the socio-economic level. The evidence gathered in The Stern Review (Stern, 2007) showed that "*ignoring climate change will eventually damage*

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(1) According to this barometer, "92% of EU citizens see climate change as a serious problem and 74% see it as a 'very serious' problem". By contrast, results of a similar US survey shows only 56% of Americans see climate change as a threat.

economic growth"; the Review also pointed out that "*the benefits of strong and early action far outweigh the economic costs of not acting*".

On the other hand, climate change actions on mitigation and adaptation have considerable economic consequences that need to be assessed and quantified, in order to implement the policies needed in a cost-effective manner, enhance the preparedness and capacity of all governance levels to respond to ongoing climate change and improve coordination.

1.3 Recent action and wider sustainability issues

The year 2015 saw the endorsement at the United Nations (UN) level of two major international agreements: the Sustainable Development Goals (SDGs) and the Paris Agreement of the United Nations Convention on Climate Change (UNFCCC).

The Paris Agreement entered into force in November 2016, expressing the UNFCCC countries' objective to collectively "*Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels*" (UN, 2015). It has already been ratified by more than 170 parties and is a crucial step in setting an international mechanism for reinforcing climate mitigation efforts.

The SDGs are a collection of 17 global goals on world governance, most of them affecting the sustainability of biophysical and socio-economic systems. While climate change is an SDG in its own right (SDG13: Climate action), it has intense interactions with other SDGs such as:

- SDG2: Zero hunger (see section 4.6 on agriculture and land)
- SDG3: Good health and well-being (see section 6 on air pollutants)
- SDG6: Clean water and sanitation
- SDG7: Affordable and clean energy
- SDG12: Responsible consumption and production (see section 4.3 on industry and Box 11 on circular economy)

The SDGs and the Paris Agreement underline the interconnectedness and deep links amongst many aspects of human activities with the environment: indeed a long-term strategy of the development of human societies can only be approached by taking into account holistically the multiple dimensions of sustainable development. As such, environmental limits are established on the basis of the maximal acceptable impact of human activity on the environment to prevent future damage and to guarantee the durability of human activity itself by some self-regulation mechanisms, and thus to avoid uncontrolled negative consequences that could jeopardise the continuity and progress of human societies (Steffen, et al., 2018). It is therefore vital to anticipate different pathways to reach sustainable growth within the environmental limits.

1.4 Contribution of this report

This report focusses on the portfolio of actions that can be undertaken globally in all the key sectors affecting climate change. The work underlying this report has informed the process of writing the Long-Term Strategy of the EU (2018).

Although the countries' pledges under the Paris Agreement Nationally Determined Contributions (NDCs) initiate a break with historical GHG emissions trends (Kitous, et al., 2016), deeper cuts in emissions would be required globally. Postponing emissions reductions can significantly increase the cost of mitigation in the future as it would require more drastic solutions, given all the uncertainties concerning future economic growth and technological innovation. A realistic pathway also has to take into account the time it would take for the transition to a less carbon-intensive economy to take place, and the time lags to be associated with the implementation of policies in the various sections of the economy across world regions, each of them with different characteristics and response times to policy incentives.

This report focusses on a central 2°C scenario over the century. Further analyses are illustrated with scenario variants showing possible alternatives that might affect the feasibility of the climate and sustainability goals. This report deals primarily with the decarbonisation of the energy system; however it also provides quantitative analyses of all the branches of the economy relevant to GHG emissions and sinks, and considers the interaction of climate action with air quality and health in particular.

The report is organised as follows:

- Section 2: A description of the central 2°C scenario.
- Section 3: Historical global trend and projections of GHG emissions,
- Section 4: A special focus on mitigation strategies sector-wise: buildings, industry, transport, power generation, agriculture and land use.
- Section 5: Historical trends and projections of primary energy demand, fuel prices and energy trade.
- Section 6: The impact of the climate and energy policies on the emissions of air pollutants.
- Section 7: The macro-economic impacts of climate mitigation; the economic analysis, covering energy system costs, GHG mitigation policy costs as well as co-benefits from air pollution reduction, including health.

This report is complemented by detailed regional energy and GHG balances and economic balances (see companion documents (2)).

Box 1. Differences with GECO 2017 and other reports

This report mainly presents scenarios with high mitigation (2°C, 1.5°C warming) rather than focussing on no additional policies (Kitous, et al., 2017) or announced objectives (GECO 2017 INDC) scenarios. Total mitigation and options are presented as efforts to be made across two points in time (e.g. 2015 to 2050) instead of as a comparison of two scenarios at one point in time (e.g. Reference compared to 2°C scenarios). The 2°C warming scenarios presented here aim at a global mean temperature increase of 2°C with a 67% probability, based on the online MAGICC 6 model (Meinshausen, et al., 2011); the temperature increase in the GECO 2017 B2C scenario was lower (below 2°C with 80% probability). The 1.5°C scenario presented in this GECO report has a 50% probability of reaching 1.5°C warming by 2100.

The modelling using the POLES-JRC model (Després, et al., 2018) was updated, notably in oil and gas supply, wind, solar and load representation, electricity storage, buildings energy consumption by end-use, as well as some technologies representation (carbon capture and sequestration infrastructure development, direct air capture of CO_2 (DACCS), synthetic methane production). Agriculture and land use emissions and other parameters were updated, as well as technology costs and socio-economic assumptions. (Annex 3).

Global warming potential figures presented use the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) 100-year values (GECO 2017 used values from the second assessment report).

Nuclear energy is accounted as primary electricity.

The scenarios in this report were finalised in October 2018.

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(2) Available at http://ec.europa.eu/jrc/geco

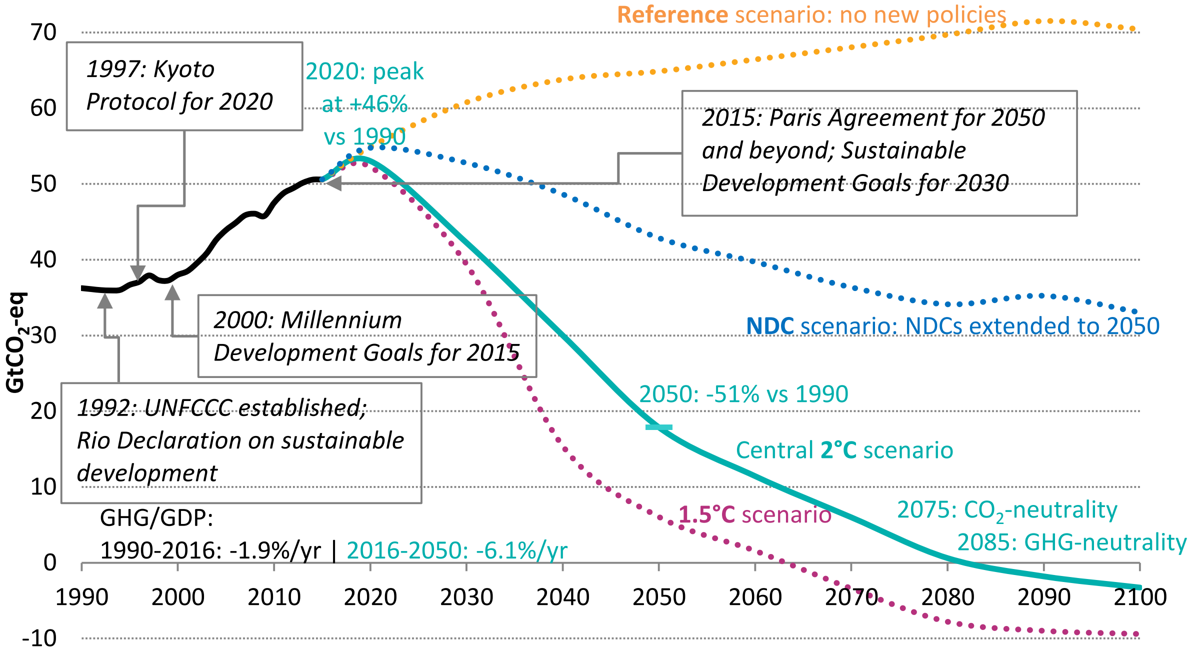
This study closely follows the publication of a companion report (Esmeijer, et al., 2018). In that report, very similar POLES-JRC scenarios are presented (scenarios were finalised in July 2018). The scenarios differ in some modelling elements (land use emissions directly use outputs from the GLOBIOM-G4M model instead of national GHG inventories; the efficiency potential of aviation and maritime bunkers has been reviewed; oil and gas production costs were reviewed). 1.5°C scenarios differ in their speed of transition towards a low-GHG economy, i.e. scenarios in this GECO 2018 report are allowed more time to initiate the transition.

2 Scenarios presentation

The main scenario presented hereafter is a global mitigation pathway in which the immediate strengthening of climate action from 2018 reduces emissions to levels consistent with a likely chance of meeting the long-term goal of a temperature increase over pre-industrial times below 2°C. It reflects the need for a global transition towards a low-emission economy development pattern. An appropriate climate simulation tool is being used in order to evaluate the impact of radiative forcing changes (MAGICC 6.0, (Meinshausen, et al., 2011)).

Figure 6 shows the GHG emissions reduction needed to reach the 2°C target, along with reference and 1.5°C trajectories (Box 2). This budget is reached through a progressively increasing carbon value starting from 2018, considering a carbon price differentiation between regions to account for each country's financial capacity and response flexibility. Mitigation strategies should be massively and quickly adopted, leading to a drastic reduction of global GHG emissions. The scenario also aims to assess the probability of reaching or overshooting the 2°C as well as quantifying the likelihood of risks and opportunities associated to it.

Figure 6. Global GHG emissions in the Reference, central 2°C and 1.5°C scenarios



Note: The NDC scenario assumes that the global average rate of decarbonisation implied by the NDCs in 2020–2030 is maintained over 2030–2050. This report mainly describes the central 2°C scenario.

Source: POLES-JRC 2018.

With the GHG and air pollutant emissions (3) of the central 2°C scenario, the global mean surface temperature would have an overall 64% probability of staying below 2°C throughout the century (4). More precisely, of stabilizing to around 1.9°C by 2060 and reaching 2.0°C by 2100 (Figure 7).

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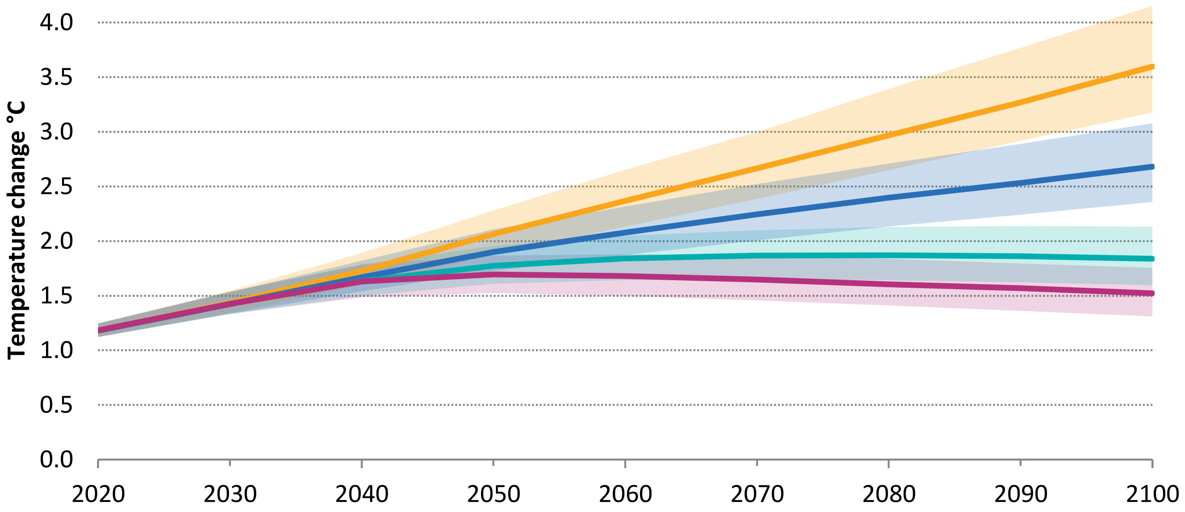
(3) Much of air the pollutant emissions would be reduced by direct control measures or as a co-benefit of climate policies (section 6). As a consequence, the cooling effect of certain pollutants would be reduced compared to current levels.

(4) Using the long-term climate model simulation MAGICC, http://live.magicc.org, (Meinshausen, et al., 2011)

Figure 7. Global average temperature change with 67% probability in the Reference, central 2°C and 1.5°C scenarios



Note: Plain lines note medians. Shaded areas represent 25%–75% probability. The 1.5°C scenario has a 47% probability of being below 1.5°C at the end of the century. See Box 2 for scenarios definition.

Source: MAGICC online

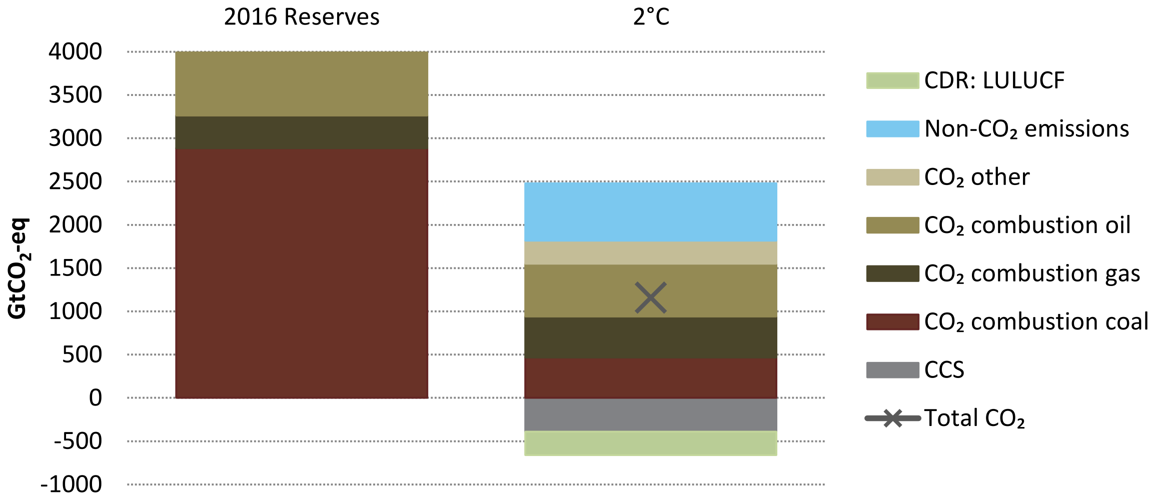
Under this scenario, total cumulated carbon dioxide equivalent emissions over 2011–2100 reach about 1,150 $GtCO_2$ (Figure 8), which is compatible with the 2°C warming objective ([5]).

GHG emissions are the result of gross GHG emissions (fossil fuel combustion, industrial processes, agriculture, waste) and CO_2 removal (CDR: carbon dioxide removal) in the form of Land Use, Land-use Change and Forestry (LULUCF) net sinks and carbon capture and sequestration (CCS). The contribution of each of these sources is illustrated in Figure 8, showing the significant role of coal phase-out, non-CO_2 abatement and CCS deployment as important options for achieving the goal of a temperature increase of below 2°C. In particular, technologies like biomass combustion with carbon capture and sequestration (BECCS) would allow CO_2 removals through using biomass energy (BE) – assumed to be carbon neutral – combined with CCS. The availability of this technology at affordable costs could be key in limiting temperature change to below 2°C or even further.

In the central 2°C scenario, the LULUCF sector would become carbon-neutral around 2030 at the global level, with significant differences in how this sector contributes to emissions balances across countries and regions.

([5]) This carbon budget falls within the range of literature on this subject. From (IPCC, 2014) Table TS.1, cumulative CO_2 emissions 2011–2100 (and likelihood of staying below 2°C over the 21st century): 630–1,180 $GtCO_2$ (likely, 66–100%); 960–1,430 $GtCO_2$ (more likely than not, 50–100%); 990–1,550 $GtCO_2$ (about as likely as not, 33–66%).

Figure 8. Cumulated GHG emissions from 2011 and emissions sources, and current (2016) fossil fuel reserves converted into emissions, in the central 2°C scenario



Source: POLES-JRC 2018.

The main technical and socioeconomic assumptions (see Annex 3) for the central 2°C scenario are:

- **Biodiversity concerns** limit biomass availability to a rather conservative potential (below 200 EJ/year) on a global scale for energy uses (Figure 88).
- A moderate availability and use **of CO_2 capture and sequestration technologies** (Figure 60).
- Further **techno-economic improvements** for all new technologies (including renewable, batteries and electric vehicles (EV)).
- Conservative expectations for **nuclear** electricity generation.
- Significant improvements of **energy intensity** in key energy-intensive economic sectors.
- The **electrification** trend of final energy demand accelerates its pace in virtually all energy-consuming sectors.
- Sectoral **climate policies** are put in place, leading to a country-dependent mix of policies, including an economy-wide carbon tax, sectoral taxes on energy products and sectoral-relevant measures.

Box 2. Alternative scenarios

Where necessary, projections from a **Reference scenario** are presented as a counterfactual case to the central 2°C scenario. The Reference scenario corresponds to a world where no additional policies are implemented compared to what was legislated as of the end of 2017; energy and emissions projections are driven by market forces and technological learning. In particular, it does not pursue the policies put forward in countries' NDCs nor does it attempt the deep decarbonisation of the 2°C or 1.5°C scenarios.

The **NDC scenario** is also used as a benchmark. It assumes that unconditional and conditional NDCs are reached in 2025-2030, and that effort is extended beyond. The global average rate of decarbonisation implied by the NDCs in 2020–2030 is maintained over 2030–2050. Beyond 2050, carbon prices across countries converge to the lead carbon price attained in 2050.

Throughout this report, key figures from alternative scenarios are presented to illustrate possible low-carbon futures that differ from the central 2°C scenario.

In particular, the **1.5°C scenario** is defined with the same parameters as the central 2°C scenario but aims at more aggressively GHG emissions reductions in order to achieve a lower temperature change at the end of the century, with a 2011–2100 carbon budget compatible with a 50% chance of achieving that objective according to MAGICC 6 of 500 $GtCO_2$ (6). In this scenario, the temperature peaks at about 1.7°C around the middle of the century and decreases to 1.5°C by 2100 (with 50% probability). The 1.5°C scenario is examined in the following sections: Box 6, Box 8, Box 9, Box 12, Box 16, Box 21, Box 23.

Other alternative scenarios differ with the central scenario on specific parameters of resource or technological availability:

- 2°C with **ambitious biomass** use (Box 24)

- 2°C **without the use of CCS** technologies (Box 7)

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(6) The scientific literature for scenarios with a high probability of keeping global warming below 1.5°C by 2100 refers to cumulated CO_2 emissions over 2011–2100 ranging from 90 to 415 $GtCO_2$ (see (Rogelj, et al., 2015), (IPCC, 2014): TS.3.1.2). More recent estimates of the remaining budget for limiting warming to 1.5°C point to cumulated CO_2 emissions over 2018–2100 ranging from 450 (two-thirds chance) to 650 $GtCO_2$ (even chance) (see (IPCC, 2018)); this report's 1.5°C scenario uses a target budget of 240 $GtCO_2$ for 2018-2100. The 2011–2017 CO_2 emissions are estimated at 260 $GtCO_2$.

3 Historical trends and projections for greenhouse gas emissions

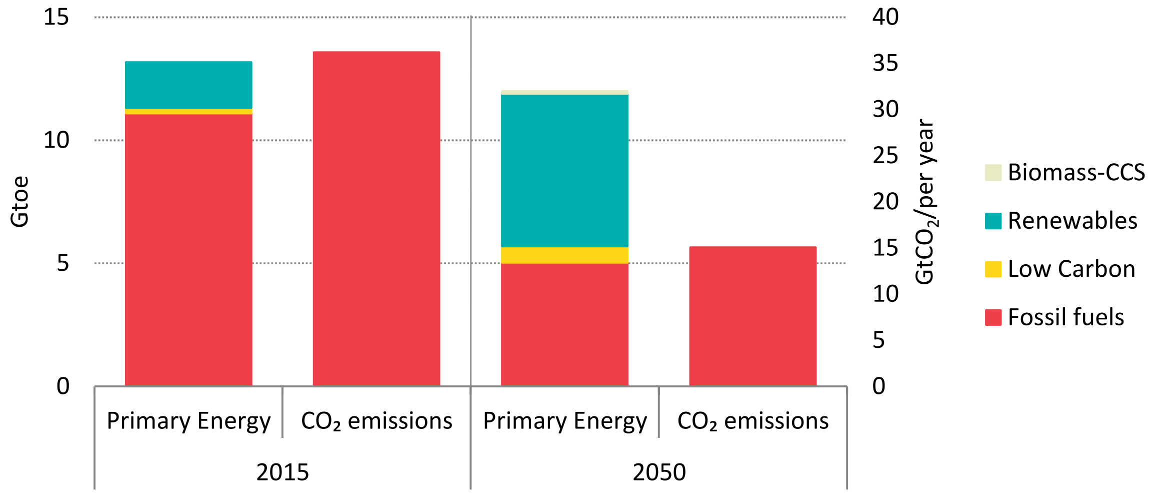
This section reports the main historical trends on GHG emissions and the corresponding future projections across the different world regions and main countries. Focus is put on the largest contributors to GHG emissions and those with higher mitigation potential. An overview of the GHG emissions intensity at the global and regional levels is provided related to the main energy and economic drivers, such as population, income growth and economic structure. Furthermore, final energy demand by end-use and by sector is analysed as the largest contributors to GHG emissions.

3.1 Global GHG emissions by sector

For the central 2°C scenario, GHG emissions would have to be limited close to their current level (around 51.4 $GtCO_2$-eq in 2016) (7) and peak in the immediate future at 53 $GtCO_2$-eq annually in 2020 (Figure 11). Total emissions would decrease thereafter, to half their 1990 level by mid-century, 20 $GtCO_2$-eq annually, before decreasing towards GHG-neutrality by the end of the century.

Most GHG emissions are generated in processes involving the combustion of fossil fuels in the energy system. In the central 2°C scenario, primary energy demand in 2050, 12 Gtoe, would be relatively in the same range as the one in 2015, 13.1 Gtoe, but with the associated CO_2 emissions reduced by 64%. Therefore, the primary energy mix would have experienced an in-depth structural change, shifting from 84% of fossil fuel combustion with unabated emissions in 2015 to 42% by 2050 (Figure 9).

Figure 9. Primary energy (left) and associated CO_2 emissions from energy (right) for the central 2°C scenario



Note: Renewables excludes BECCS. Nuclear is accounted as primary electricity.

Source: POLES-JRC 2018.

A decomposition of GHG emissions by sector and by gas is shown in Figure 10.

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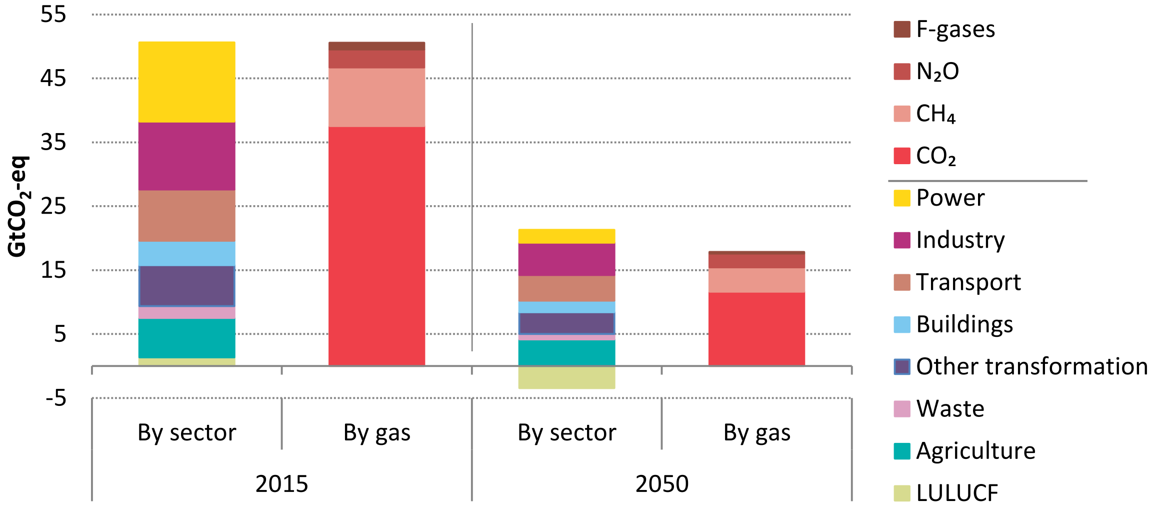
(7) GHG emissions from the different gases are aggregated into CO_2-equivalent values, using the 100-year global warming potentials of the IPCC Fourth Assessment Report (IPCC, 2007).

Figure 10. World GHG emissions in the central 2°C scenario by sector and by gas, 2015 and 2050



Note: Figures for transport include emissions of international aviation and maritime bunkers.

Source: POLES-JRC 2018.

Historically, the power sector has been the largest emitting sector. It is projected to remain as the dominant emitting sector in the medium term (2030), ahead of industry and transport, followed by agriculture, buildings and waste.

In terms of early action by 2020, the non-power energy supply sector would be very responsive to the policies put in place, especially given the relatively higher abatement potential in non-CO_2 gases (e.g. reduction of fugitive emissions and flaring in the production of fossil fuels). In addition, the LULUCF sector would become carbon-neutral early in the 2020–2030 decade. Next, the power sector would also react strongly to the implemented policies and could reach full decarbonisation at the world level by 2050, with emissions starting to decline from 2020 and even becoming negative beyond 2050 (thanks to the combined use of biomass and CCS). This would leave the bulk of the remaining emissions after 2030 to sectors more difficult to decarbonise, such as transport, industry and agriculture.

3.2 Global GHG by region

Historically, the developed economies have contributed more to global climate change, having been mostly accountable for the existing concentration of GHG in the atmosphere since 1950. A handful of countries ([8]) in the world are responsible for 80% of the accumulated CO_2 of the last half century.

However, the geographical distribution of GHG emissions has shifted in recent decades. While developed countries are moving away from coal, and towards cleaner natural gas and renewables, the strong growth of developing countries has led to an increase in their GHG emissions.

However, with the ambitious climate policies assumed in the central 2°C scenario, all regions must drastically reduce their emissions. In the central 2°C scenario, regions develop their economies while also implementing strong climate policies, adopting a conservative use of biomass resources and boosting low-carbon technologies. The

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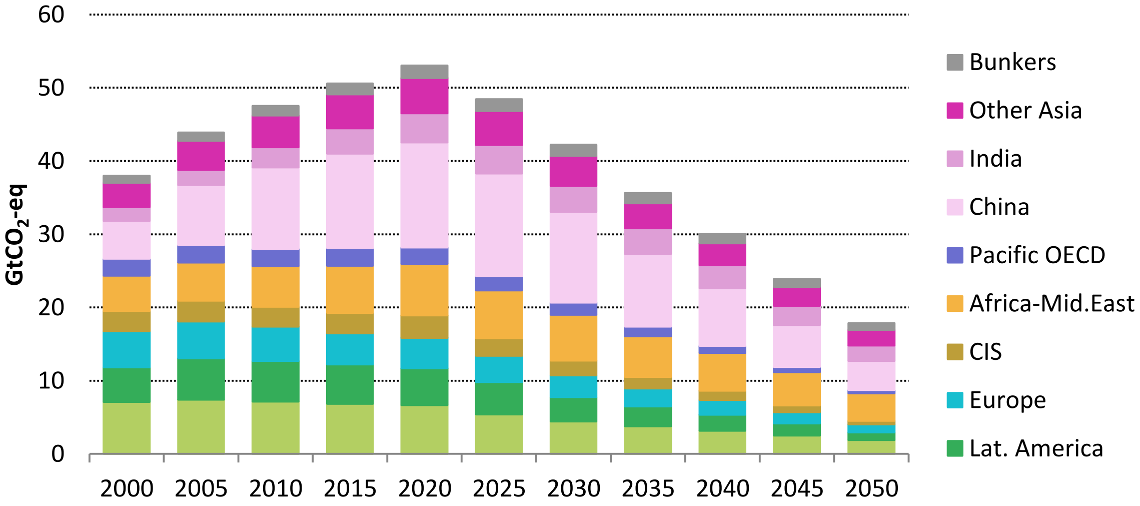
([8]) For the period 1950–2014, 10 countries were responsible for 70% of cumulated emissions: Italy (1.8%), France (2.2%), Canada (2.2%), Great Britain (3.2%), Russian Federation (3.5%), India (3.6%), Japan (4.8%), Germany (7.5%), China (15.6%) and the United States (25.6%) (http://cdiac.ess-dive.lbl.gov/trends/emis/meth_reg.html).

regional distribution of GHG emissions is foreseen to change over time (Figure 11). The growing share of Asia would represent about 50% of global GHG emissions from 2030 onwards; in particular, China and India alone would represent 22% and 12% in 2050, respectively. Africa and the Middle-East would also experience a continuous increase, representing about 20% of the total by mid-century. North America, Europe and Pacific, which still represent about 27% of the total in 2015, would fall to 19% in 2050, followed by CIS (3%) and Latin America (6%), both with slightly decreasing shares, by 2050. International air and maritime bunkers' share would see a rise from 3% in 2015 to 5% by 2050.

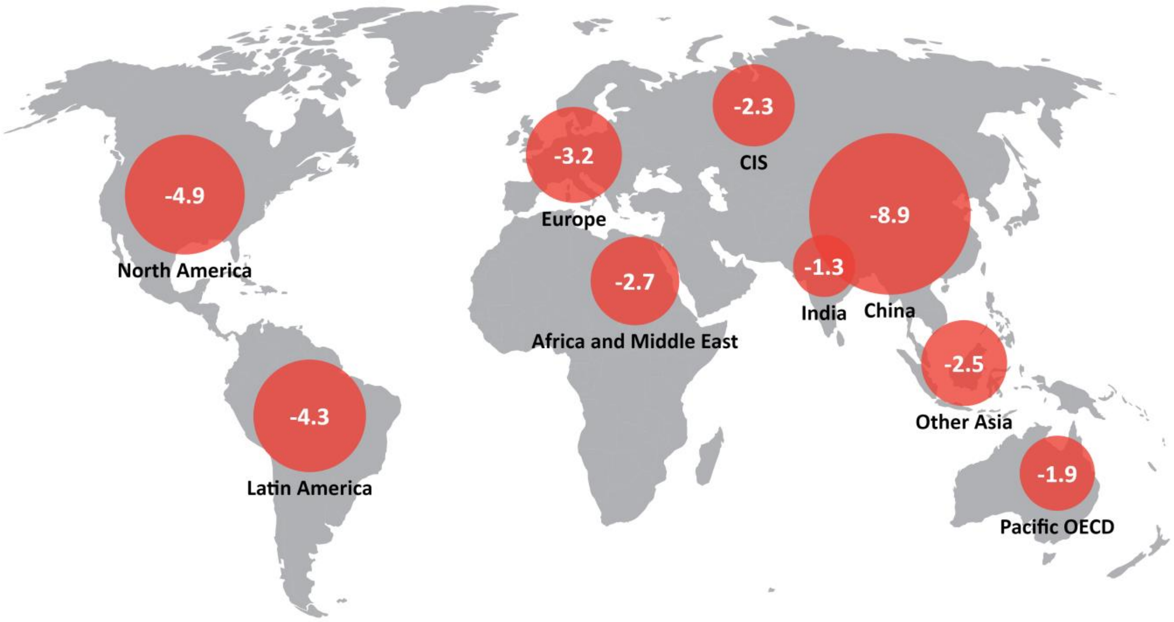
Figure 11. Regional distribution of GHG emissions, in the central 2°C scenario



Source: POLES-JRC 2018.

As seen in Figure 12, global efforts to limit temperature change to below 2°C would be distributed across regions. An important part of emission reductions would take place in emerging economies, in particular China. For each region/country, the mitigation potential would drive the emissions peak years and levels. The different mitigation paths are the result of each region's economic development, natural resources and climate policies (see Annex 4 for details on how climate policies have been implemented across regions).

Figure 12. GHG emissions variation over 2015–2050 by world region ($GtCO_2$-eq), in the central 2°C scenario



Source: POLES-JRC 2018.

Box 3. EU28 GHG emissions reduction trajectory for the central 2°C and 1.5°C scenarios

The European Union has been taking ambitious climate action since the 1990s. EU GHG emissions show a continuous decreasing trend since then; in pathways coherent with the global 2°C and 1.5°C objectives where cost-effectiveness and equity were taken into account (see section 2), this trend is continued or reinforced throughout the projection period.

Annual GHG emissions for the EU28 countries account for 1 and 0.2 $GtCO_2$-eq/year for the 2°C and 1.5 scenarios respectively. Both scenarios share the same annual reduction rate for the 1990–2015 period, -1%/year. But the 1.5° scenario would experience a stronger emissions reduction from 2030 onwards, with -8%/year annual rates for the 2015–2050 period, while the central 2°C scenario would reach values of around -3.9%/year.

Overall, the EU28 would reduce its emissions by 80% and 95% in 2050 in the central 2°C and the 1.5°C scenarios, respectively (this would be pushed to 96% in a 1.5°C case with high biomass availability). GHG neutrality would be reached in approximately 2075 and 2055 in the 2°C and 1.5°C scenarios, respectively (2065 and 2050 for CO_2 neutrality, respectively).

3.3 GHG emissions decomposition

A customary instrument to analyse the GHG emissions dynamics at either the global or regional levels is the well-known Kaya decomposition or Kaya identity (Kaya, 1990), Box 4.

Box 4. Kaya identity

The well-known Kaya decomposition splits the dynamics of GHG emissions into the product of four main drivers/indicators: population (POP), gross domestic product (GDP) per capita (GDP/POP), energy intensity of the economy (E/GDP) and GHG intensity of energy (GHG/E), according to the identity:

$$\boldsymbol{GHG = POP * \frac{GDP}{POP} * \frac{E}{GDP} * \frac{GHG}{E}}.$$

Population: Provides the demographic scale effect – at a fixed structure of the economy and the energy system, increasing the population will on average increase emissions;

GDP per capita: Describes an economic scale effect – at fixed levels of the population and for a given structure of the energy system, increasing the economic activity in GDP terms will ceteris paribus increase emissions;

Primary energy intensity of the GDP: Captures the multiple structural effects contributing to the evolution of the average consumption of the primary energy of the economy. It evolves as a result of both structural changes of the economy (moving towards more or less energy-intensive activities), technological progress (at a given economic structure, using more efficient equipment), non-energy measures (better logistics, insulation, etc.) and behavioural effects (awareness affecting habits, etc.).

GHG intensity of primary energy: Captures the fuel mix structural effect – all the above parameters being equal, changing the energy mix towards less carbon-intensive energy sources will reduce GHG emissions. This term depends, in particular, on the flexibility to switch towards less carbon-intensive energy technologies.

The first two indicators are inherently increasing under normal assumptions, as there is long-term demographic growth in almost all regions, and there is economic growth in all regions analysed. Therefore, for emissions to be reduced over a certain time period, the last two indicators have to overcompensate for the growth of the other two: by reducing the energy intensiveness of GDP and/or by reducing the carbon intensiveness of the energy mix.

The Kaya identity can be used (9) to illustrate and relate the changes of GHG emissions with respect to demographic trends, income per capita, energy intensity and carbon intensity. Figure 13 presents such decomposition, in two successive steps for the periods 1990–2015 and 2015–2050, for the world as an aggregate and for the OECD and non-OECD as regions.

At the world level, the GHG emissions' increase between 1990 and 2015 is sustained by the socioeconomic drivers, with energy and carbon intensities barely compensating for the per capita wealth effect. Regional differences are strong, with emissions from non-OECD regions being largely driven by economic development (growth in GDP per capita). However, developed regions show a structural change of their economies towards less energy-intensive sectors [(Klaassen, et al., 2015); (Cohen, et al., 2018)], along with lower population growth rates.

Over the projection period of 2015–2050 in the central 2°C scenario, the need to limit the four indicators is straightforward, as all are requested to slow down after 2020. Two key indicators, the energy intensity of the economy and the GHG emissions intensity of energy were already decreasing from 1990, with average global annual ratios of -

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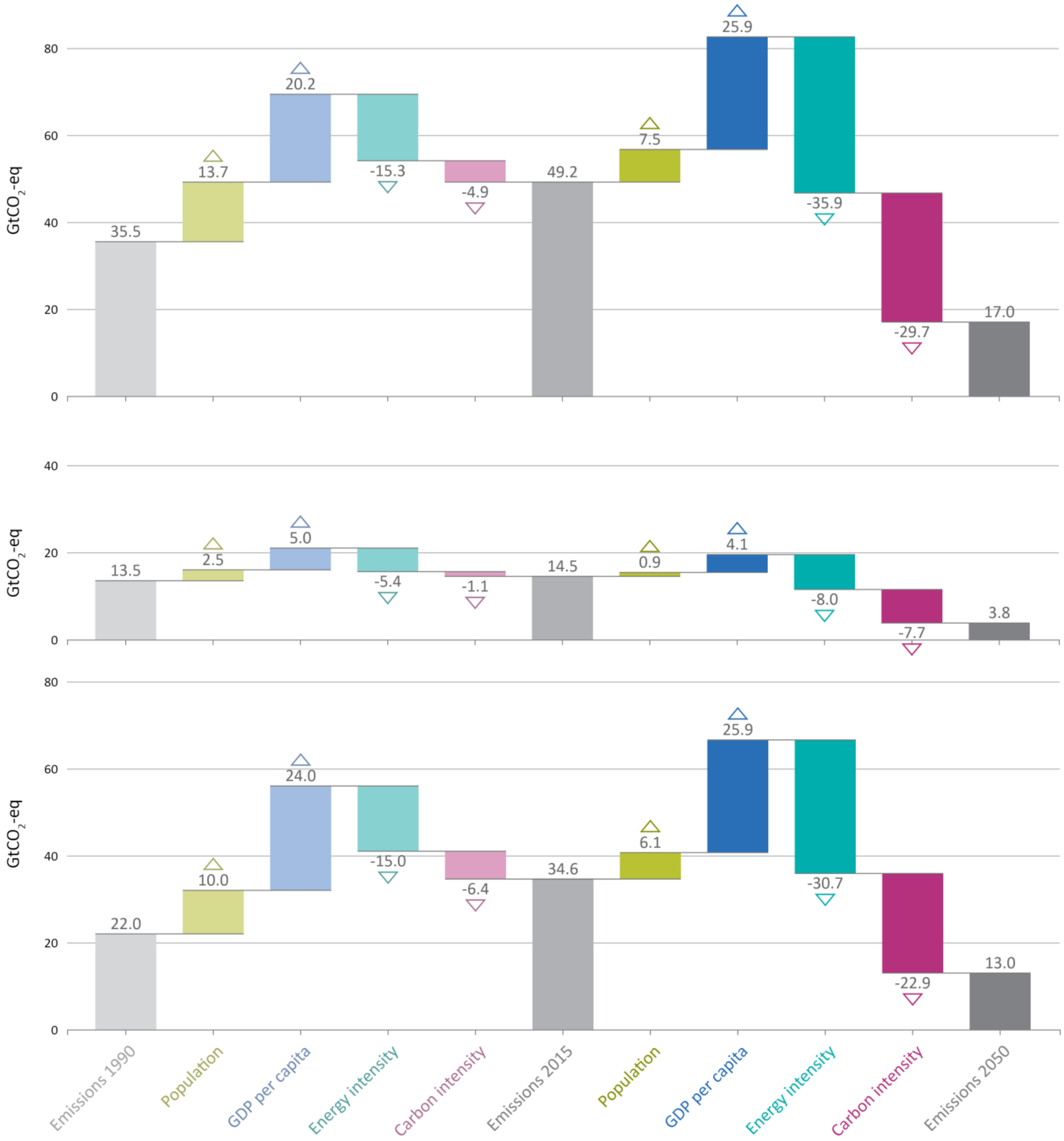
(9) Using the Logarithmic Mean Divisa Index (Ang, 2004)

1.4%/year and −0.2%/year, respectively. However, for the climate change objective to be achieved, the declining trend for both of them should be intensified, tripling at least these annual declining rates up to 2050. These dynamics would translate to a decrease of energy intensity, at an average of -6%/year over 2015–2050 (vs. -1.4% per year in 1990–2015), an increased electrification of final demand (36% in 2050 vs. 16% in 2015) and large changes in the primary energy mix (phase out of coal, reduction of oil and gas after 2020). Thus, the mitigation effort inverts the growth of GHG emissions in all regions of the world, although the evolution of socioeconomic factors is very heterogeneous. Non-OECD regions are expected to maintain higher paces of economic growth rates, which would induce a significant growth in emissions – a phenomenon that is less visible in OECD regions, with economies much less driven by physical capital accumulation and demographically-pushed internal consumption, and more relying on technological development and service sectors.

Figure 13. Decomposition of GHG emissions following the Kaya identity, 1990–2015 and 2015–2050 (World top, OECD middle and non-OECD bottom), in the central 2°C scenario



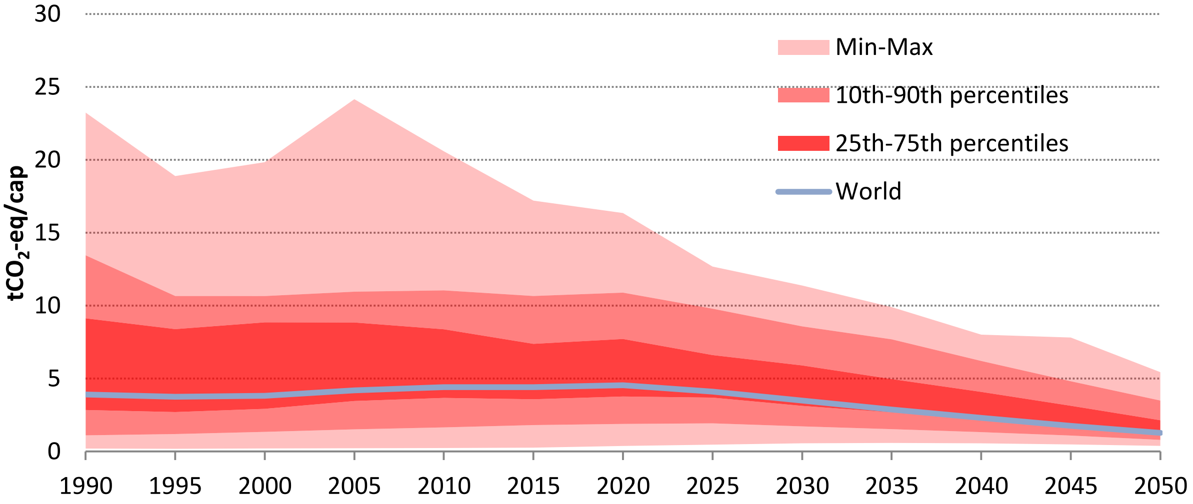
Source: POLES-JRC 2018.

Global per capita energy consumption and emissions per capita were almost flat (or even slightly growing) in the 2005–2015 decade, and would need to decrease at a pace of -0.9%/year and -3.7%/year, respectively, to 2050. This would represent a very considerable structural change within the energy sector, drastically reducing the emissions related to fossil fuel use. All regions would show strong improvements of the energy intensities of their economy, for technological reasons (see sector-wise mitigation trends in section 4) but also due to the changing structure of the economies (see section 7) and human behaviour. Finally, and as opposed to the historic period, the massive reduction of the GHG intensity of the primary energy mix plays a major role in mitigating GHG emissions over the period 2015–2050. This holds true worldwide, although strategies may be very different across regions, depending for example on region-specific energy resource endowments.

More specifically:

Emissions per capita: In the central 2°C scenario, country development patterns and the mitigation effort would result in a convergence over time of emissions per capita in all world regions (Figure 14). World emissions per capita would reach around 2.0 tCO_2-eq per capita in 2050, i.e. at around the same level as some of the least developed countries in 2015. For instance, emissions per capita for major emitting countries would start decreasing before 2020. The world emissions per capita were slightly increasing over the historical period, evolving between 5 and 6 tCO_2-eq/cap, and would evolve to a peak in 2020, and from that point onwards would decrease constantly.

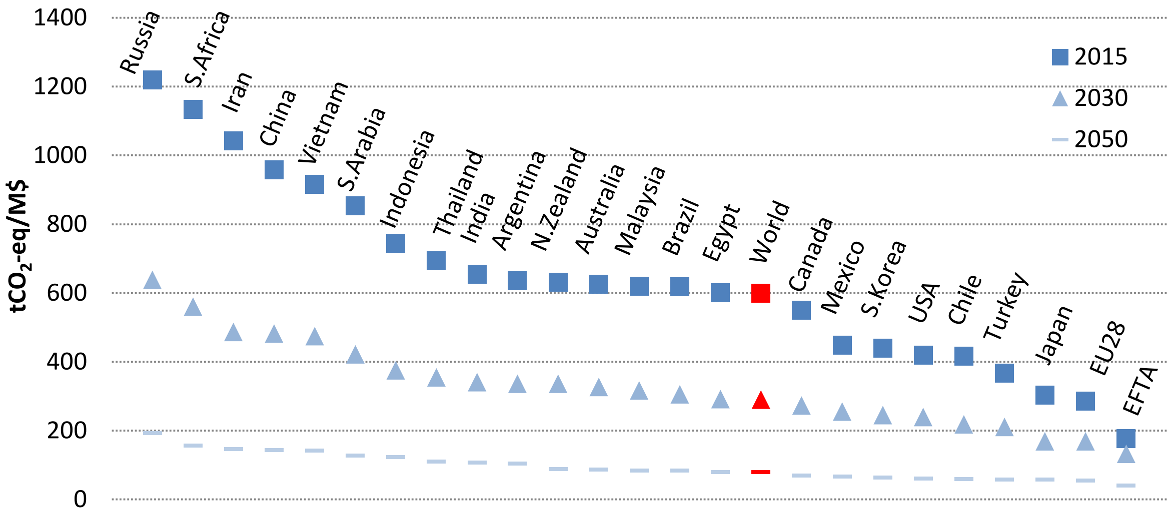
Figure 14. World regions aggregation of the GHG intensity per capita, in the central 2°C scenario



Source: POLES-JRC 2018.

Emissions intensity of GDP: A plot of the emissions intensity of the GDP across large emitting countries in the central 2°C scenario shows a global convergence over time (Figure 15). In purchasing power parity (ppp) terms, for comparability across countries, the emissions intensity would decrease to lower than 200 tCO_2-eq/M$ for all countries in 2050, i.e. below the level of some of the best-performing economies of 2015. World GHG intensity (excluding LULUCF emissions) would be more than halved between 2015 and 2030 (from around 600 to 260 tCO_2-eq/M$), and more than halved again between 2030 and 2050 to reach around 77 tCO_2-eq/M$.

Figure 15. Evolution of GHG intensity of GDP for major economies, in the central 2°C scenario

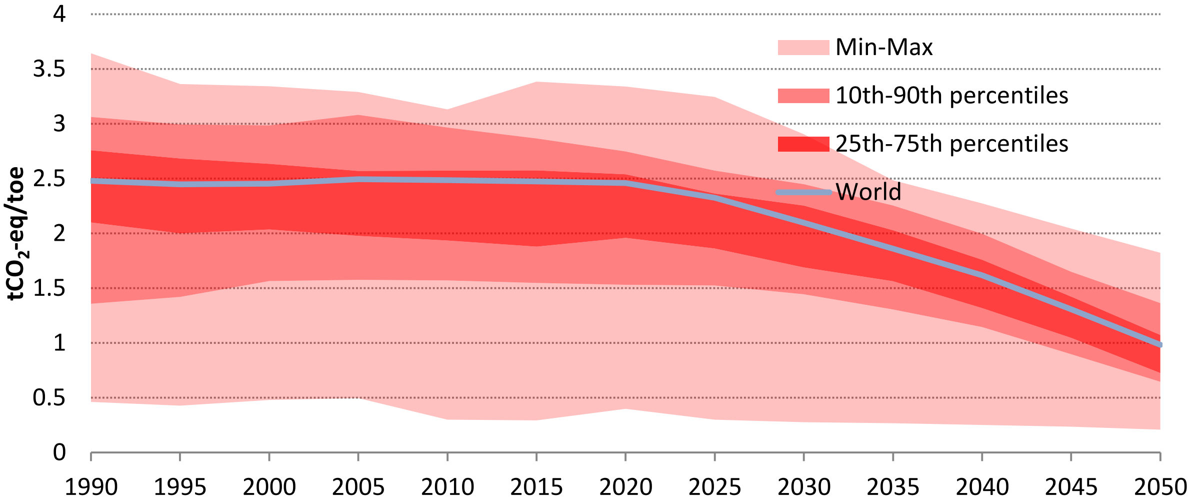


Note: Figures exclude LULUCF emissions; GDP in ppp. Individual countries with ISO3 codes; for regions see section on regional definitions. EU28 includes both OECD and non-OECD member states.

Source: POLES-JRC 2018.

GHG intensity of primary energy mix: A plot of CO_2-eq over primary energy consumption is shown in Figure 16. It can be seen that the decarbonisation of the primary energy began in the early nineties, with only India outside this trend up to 2000.

Figure 16. World regions average energy-related tCO_2-eq emission per primary energy produced, historical data 1990–2015, central 2°C scenario projection 2015–2050

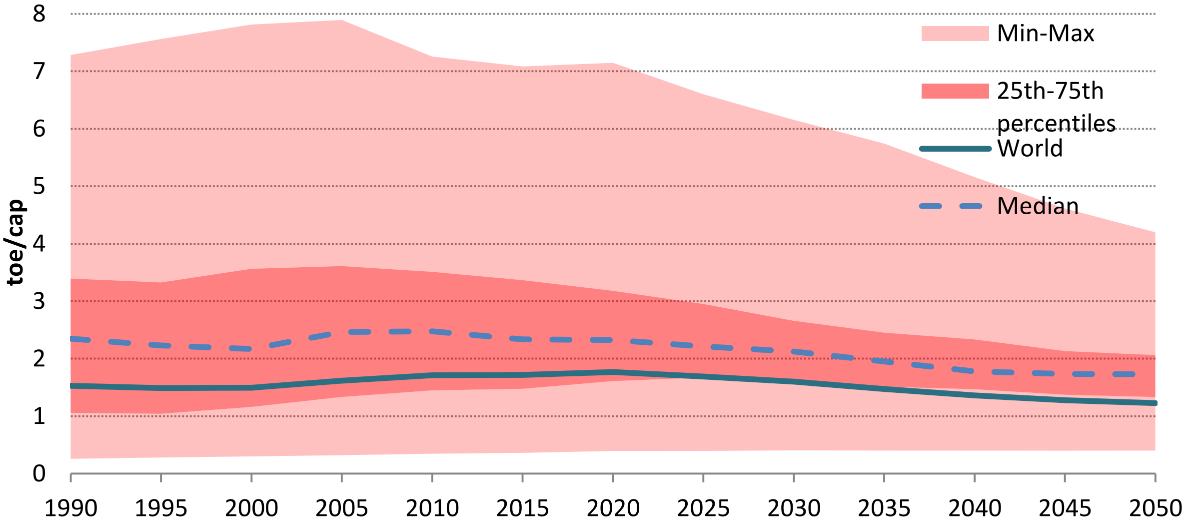


Source: POLES-JRC 2018.

In the central 2°C scenario, the GHG intensity of primary energy drops at a compound annual growth rate of -2.6%/year over the projection period. This energy decarbonisation effort leads to a convergence of emissions per capita across countries over time, with compound annual growth rates (CAGRs) ranging from 0.6%/year to -4.5%/year. This effort is more evenly distributed than the reduction of primary energy requirements, and highlights the major role played by the decarbonisation of the energy system in the central 2°C scenario.

Primary energy per capita: A plot of the resulting primary energy consumption per capita is presented in Figure 16. Higher total energy consumption in developed economies draws the world median to higher than the world average.

Figure 17. World regions primary energy consumption per capita, historical data 1990- 2015, central 2°C scenario projection 2015–2050



Source: POLES-JRC 2018.

Box 5. GHG emissions and energy in 2100

The decarbonisation effort would have to continue in the second half of the century in order to stabilise the temperature rise. The world would become carbon-neutral in 2075 and GHG-neutral in 2085 in the 2°C scenario.

Under this assumption, the second half of the century would see the expansion of negative emissions technologies to counter the accumulation of emissions in the atmosphere from the positive emissions that would be very difficult to mitigate. LULUCF would continue to be a net sink, rising to 5 $GtCO_2$ annually in 2100; biomasses associated with CCS and DACCS would provide much-needed mitigation, rising to 7 and 3.5 $GtCO_2$ annually in 2100. The residual emissions in 2100 (Table 1) would mainly be non-CO_2 emissions from agriculture and CO_2 emissions from diffuse sources (small industry not coupled with CCS, industrial processes, gas for peaking power plants, heavy road vehicles and international bunkers).

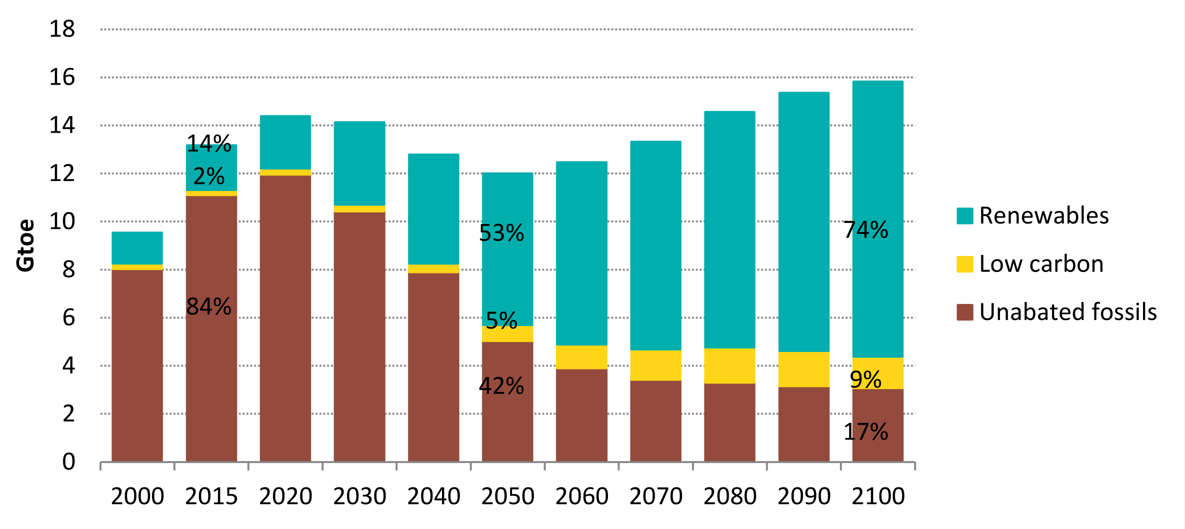
Table 1. Remaining emissions in 2100, in the central 2°C scenario

Remaining emissions in 2100 ($GtCO_2$-eq)	**12.8**
Total non-CO_2, of which:	4.3
Agriculture	3.3
Total CO_2, of which:	8.5
Power	2.0
Industry	1.7
Transport	1.8
Sinks in 2100 (GtCO2)	16.1
LULUCF	5.2
BECCS	7.4
DACCS	3.5

Source: POLES-JRC 2018.

As shown in Figure 18, with considerable energy efficiency efforts already achieved in the first half of the century, which would decrease total energy demand over 2020–2050 (1.2 toe/cap in 2050 versus 1.8 toe/cap in 2015), continued economic growth and rising living standards would drive total energy demand upwards once more (to about the same level as 2015 in 2100 with a population stabilised at 9.5 billion). Energy demand per capita would rise slightly, as a consequence of (still) increasing demand in non-OECD regions but decreasing demand in OECD regions. After exceeding half of primary energy supply in 2050, renewables would represent nearly three quarters of primary energy demand by 2100.

Figure 18. World primary energy demand, 2000–2100, in the central 2°C scenario



Note: Nuclear is accounted as primary electricity.

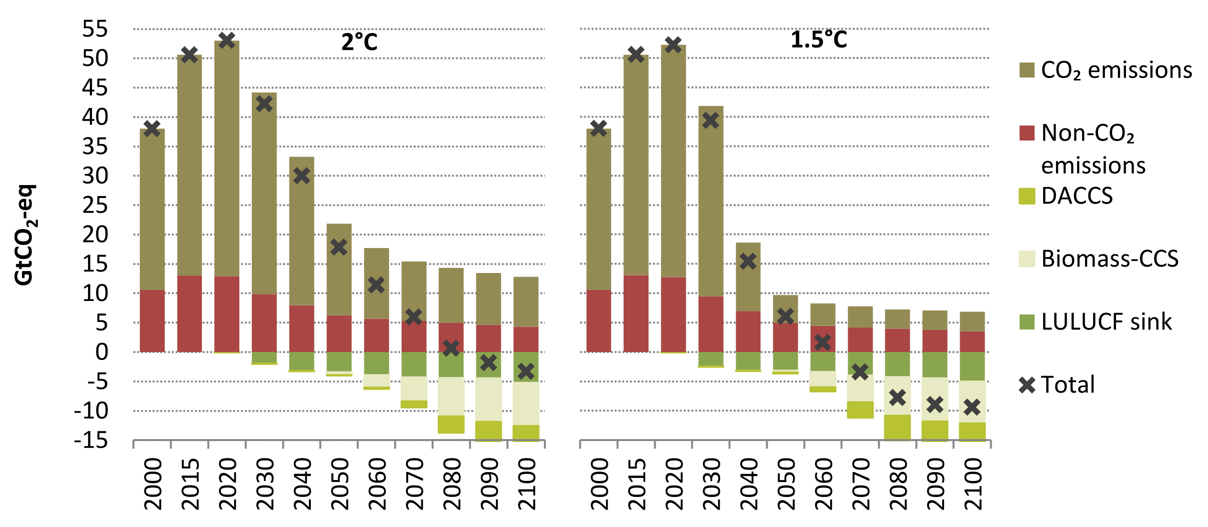
Source: POLES-JRC 2018.

Box 6. GHG emissions and energy in the 1.5°C scenario

Limiting global warming to 1.5°C by 2100 would require a GHG emissions path that would include very ambitious reductions compared to the 2°C case. It seems to be difficult for non-CO_2 GHG emissions to be further reduced at affordable costs beyond what would be achieved in the 2°C scenario. Negative emissions technologies would be restricted by wider constraints (biodiversity limits to biomass use; saturation of LULUCF sink; energy cost of DACCS, consuming 10% of world electricity from 2080) and they would not be mobilised much more than in the 2°C scenario. Thus, the difference would have to be made up by CO_2 emissions, which would entail a faster and deeper decarbonisation of the global energy system compared to the picture presented in the central 2°C scenario. CO_2 emissions cuts would have to be extremely ambitious as early as the 2030s, with total CO_2 emissions reduced by 60% in one decade. The 2030s and 2040s are two critical decades to stay within a 1.5°C-compatible carbon budget. Within this timeframe, world CO_2 emissions should drop by 10%/year (3%/year in the 2°C case). After that, CO_2 emissions would be reduced at an average pace of 2%/year (vs. 1.7%/year in the 2°C case between 2040–2100).

Beyond those critical decades, carbon and GHG neutrality would be reached in 2055 and 2065, respectively, anticipating the 2°C scenario by 20 years. This would be achieved mainly by further reducing CO_2 emissions: they would amount to 5 $GtCO_2$ per year in 2050 (versus 15 $GtCO_2$ in the 2°C) and 2 $GtCO_2$ in 2100 (versus 7 $GtCO_2$).

Figure 19. Emissions and negative emissions technologies in the 2°C and 1.5°C scenarios, World



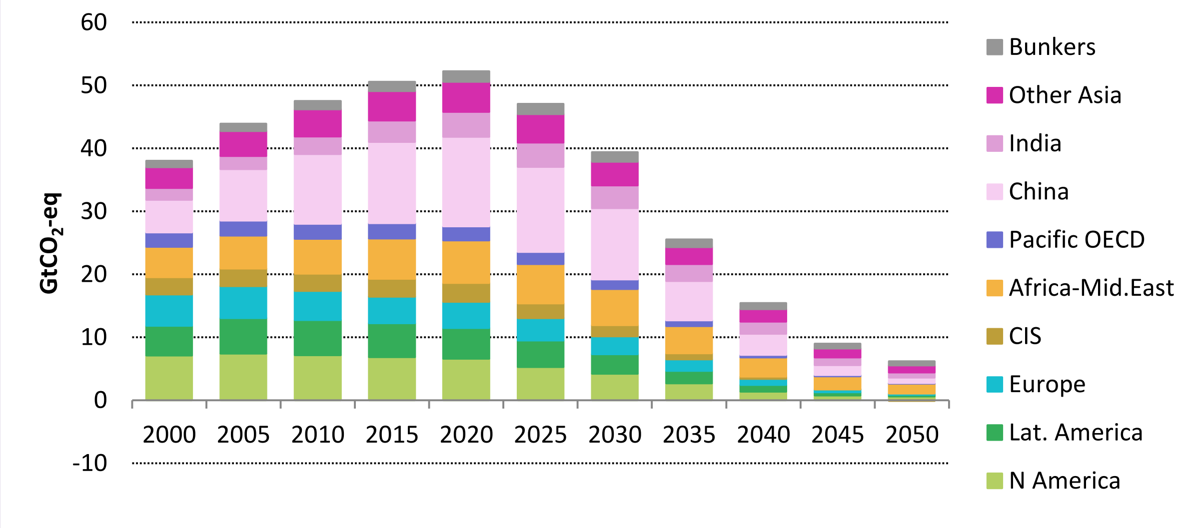
Note: CO_2 emissions are net of the emissions captured by CCS associated with coal and gas (which do not result in net negative emissions).

Source: POLES-JRC 2018.

A considerable effort in reducing and optimising energy consumption would be required to achieve such challenging emissions abatements, beyond the already ambitious levels of efficiency and fuel substitution described in the 2°C scenario (Figure 19). This would mainly be achieved by reducing the energy consumption of fossil fuels, with most of the differences with the 2°C scenario achieved in the 2030s and 2040s. In 2050, world energy demand would drop to 1.0 toe/cap/year, 20% lower compared to the 2°C scenario. Total energy consumption would rise again in the second half of the century due to the increased population sustained by low carbon and renewables and economic growth, similar to the 2°C scenario. The deployment of CCS with coal and gas (near-net-zero emissions technologies) would only be marginally higher than in the 2°C scenario, as a higher value would be given to CCS with biomass (negative emissions).

The additional effort to put world GHG emissions on a 1.5°C path has to be achieved by all regions (Figure 20, compared to Figure 11), further reducing emissions from 50% to more than 100%, depending on the region, in 2050.

Figure 20. Regional distribution of GHG emissions, in the 1.5°C scenario



Source: POLES-JRC 2018.

4 Global mitigation options: A sector-wise view

This section provides insight into the mitigation strategies by branch of economic activity. There is a special focus on CO_2, as this is the most important GHG gas and also the one with the longest lifetime of presence in the atmosphere.

4.1 Mitigation options over the entire economy

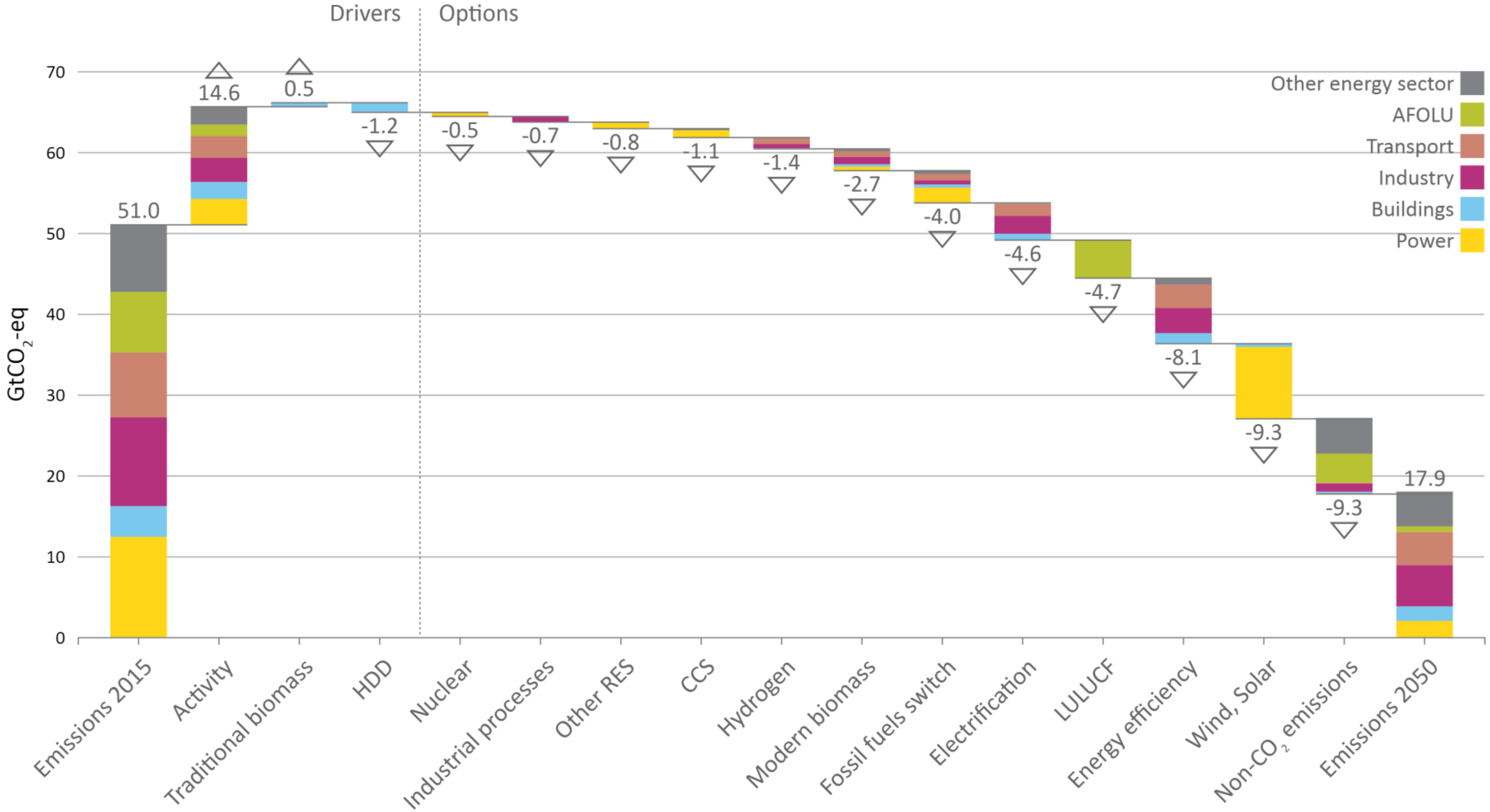
The central 2°C targets are associated with a great number of mitigation challenges that can be summarised as the need to decarbonise the economy. Transitioning to a low-carbon economy, based on the reduction of GHGs, is driven by a shift of the energy system towards carbon-free energy sources, a large diffusion of renewables, especially in the power sector, and increased energy efficiency in buildings, transport and industrial sectors. A further shift in social behaviour can also have a great impact on reducing GHG missions, decreasing growth in energy demand ([10]).

An overview of the mitigation options adopted by the 2°C scenario is presented in Figure 21, where the top four mitigation drivers are: increasing the use of renewable sources, energy efficiency, reduction of non-CO_2 emissions and electrification. They are detailed in the sections below ([11]).

([10]) Social and behaviour changes, as diet change or urban design towards green cities, are beyond the scope of this report.

([11]) Contributions are counted by the relative size of mitigation options only (i.e. between the level of 2015 plus emissions drivers, and the level of 2050).

Figure 21. Drivers of GHG emissions growth and mitigation in the central 2°C scenario, 2015–2050, World



Notes: “AFOLU”: Agriculture, Forestry and Other Land Use. “Activity”: emissions growth due to the growth of population and the economy, and to associated income-based consumption (industrial value added, transport traffic, dwelling size, electricity consumption). “Traditional biomass”: refers to the phase-out of traditional biomass for reasons other than climate, resulting in an energy demand gap that has to be met by other fuels. “HDD”: emissions prevented by the evolution in time of heating degree-days due to global warming. “CCS”: emissions prevented by carbon capture and sequestration. “Fossil fuels switch”: refers to shifts from high-carbon content towards lower-carbon content within the fossil fuel mix (generally from coal to natural gas) and towards synthetic methane. “Non-CO_2”: includes emissions from agriculture, industry and other sources (including the reductions from fossil fuel extraction and transport directly related to the decrease in the use of fossil fuels in all energy demand sectors). “Hydrogen”, “Biomass”, “Electrification”: emissions prevented by the use of these fuels in final demand sectors (emissions for their production distributed in the other options here).

Source: POLES-JRC 2018.

4.1.1 Increased participation of renewable sources

The use of renewable sources ([12]) would be the largest contributor to mitigation over 2015–2050 (27%). Renewables would increase their share in all sectors (Figure 22). They are used in final energy demand either directly (solar thermal; geothermal, heat pumps; direct biomass combustion) or as indirect inputs to energy carriers (wind, solar, hydro, and biomass combustion in power generation and biomass inputs into liquid biofuels production).

In the industrial sector, renewables would come to represent nearly half (45%) of energy sources in 2050, on a near equal footing with fossil fuels, principally thanks to an increased participation of renewable electricity and biomass as a fuel for heat. The energy-intensive industries would be the most challenging to increase their uptake of renewables. The prevailing mechanisms foreseen are a higher consumption of renewable-based electricity which would displace fossil thermal energy, and the substitution of fossil thermal fuels by biomass fuels for other high-enthalpy processes where electrification would be difficult, enabling an even deeper decarbonisation of industry.

The transport sector exhibited the lowest share in renewables in 2015 among all sectors (3%), and would remain so despite a high growth in renewables penetration (36% in 2050). The share of transport fuel from renewable energy sources in 2050 would be dominated by biomass (liquid biofuels), followed by renewable electricity.

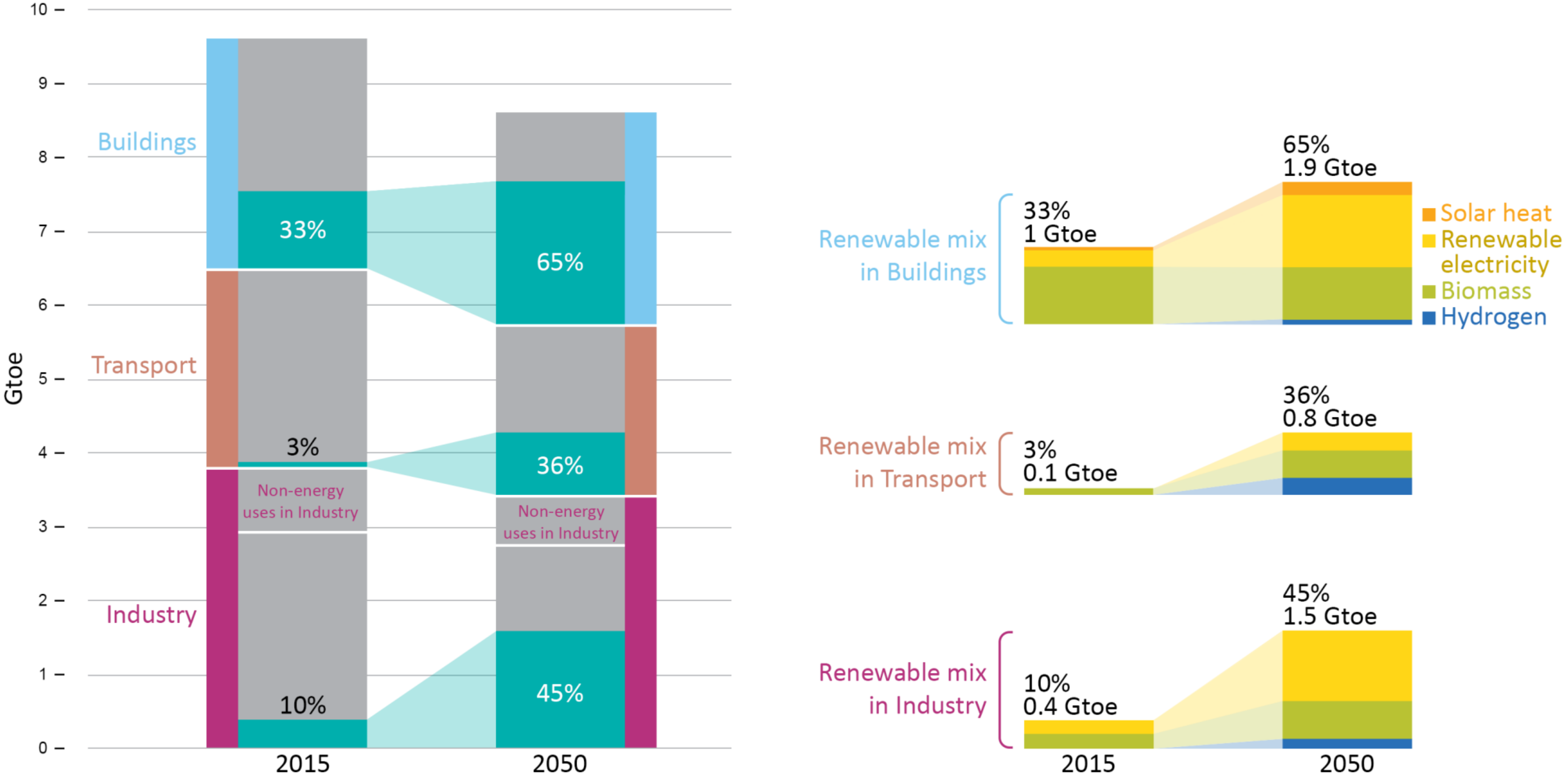
The buildings sector accounted and would continue to account for the largest renewable share (33% in 2015, 65% in 2050). This would occur in spite of a progressive phase-out of traditional biomass in several developing countries in favour of more efficient and cleaner fuels, such as renewable electricity and modern biomass.

The rapid deployment of renewables would be most notable in power generation, where their share would rise from 23% in 2015 to above 50% during the early 2030s, possibly reaching 71% in 2050 thanks to ambitious climate policies.

The decomposition of final energy consumption by end-use (Figure 23) shows the relative ease with which some uses adopt renewables compared to others, with electric processes and appliances being the easiest and most rapid (consisting only of electricity consumption), followed by heat uses (mostly biomass) and finally mobility (biomass first and then electricity).

([12]) Renewables in Figure 21: wind, solar, biomass, other RES.

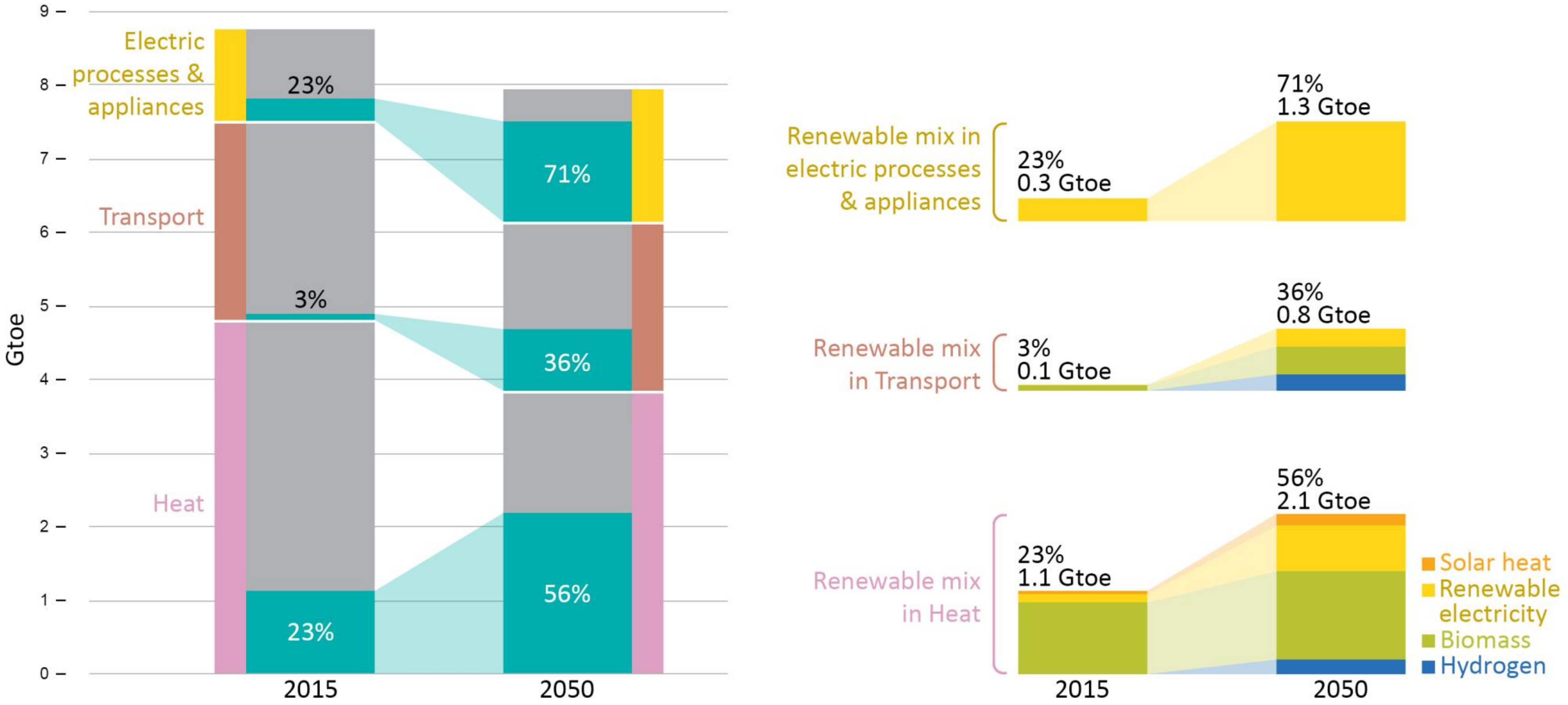
Figure 22. Share of renewables by sector in the central 2°C scenario, 2015–2050, total and decomposition of the renewable share



Note: The renewables share contains direct renewables in final demand (biomass, biofuels, solar heat) and the part of energy carriers produced with renewables (electricity, hydrogen district heating). Figures for buildings include energy used in the residential, commercial and agriculture sectors (was 2040, 870 and 190 Mtoe in 2015, respectively).

Source: POLES-JRC 2018.

Figure 23. Share of renewables by end-use in the central 2°C scenario, 2015–2050, total and decomposition of the renewable share



Note: Renewables share contains direct renewables in final demand (biomass, biofuels, solar heat) and the part of energy carriers produced with renewables (electricity, hydrogen district heating). Figures for transport include energy consumption of international aviation and maritime bunkers.

Source: POLES-JRC 2018.

4.1.2 Energy efficiency

Energy efficiency has one of the largest impacts on mitigating the CO_2 emissions of the central 2°C scenario (17% of the total mitigation over 2015–2050) (see Figure 21). Energy efficiency gains are expected to play a key role across all sectors from 2015 to 2050. The underlying reason is that energy efficiency is one of the most cost-effective ways to reduce emissions. This would involve improvements in appliance efficiency, building insulation, turbomachinery performance and efficiency gains by the electric powertrains versus internal combustion engine (ICE) road vehicles for transport. The key role of energy efficiency also stresses the importance of not only decarbonising energy use but also speeding up the decoupling process of energy use with economic and energy services outputs.

4.1.3 Non-CO_2 emissions mitigation

The most important non-CO_2 GHG gases are methane (CH_4), nitrous oxide (N_2O) and GHG fluorinated gases (F-gases). The overall GHG emissions mitigation from these non-CO_2 gases would represent about 20% of the total mitigation over 2015–2050 ([13]).However, about a third of these reductions are due to the decrease in fossil fuel extraction and transport, which is directly related to the decrease in the use of fossil fuels in all energy demand sectors.

Anthropogenic methane emissions mitigation in industry and energy would be a relatively low-hanging fruit by 2030. Other energy supply prove to be particularly flexible, with reductions quickly taking place in fugitive CH_4 emissions in coal, oil and gas production and gas transport when the climate policies are put in place. This is further reinforced by the decreasing primary production of fossil fuels due to the decreasing demand for these fuels. Improving waste management practices also offers a great potential (Le Fevre, 2017). See section 4.6.1 for more on methane mitigation.

Low-cost abatement options for N_2O are available in industry, wastewater and agriculture (intensification of livestock production systems in large farms) (Winiwarter, et al., 2018). See section 4.6.2 for more on nitrous oxide mitigation.

The industrial sector also includes reductions from hydrofluorocarbons (HFCs), which are subject to the Kigali Agreement of the Montreal Protocol, which, if implemented, would yield significant reductions. See section 4.3.3 for more on HFCs mitigation.

4.1.4 Electrification

In the central 2°C scenario, electrification for final energy demand would be placed as the fourth emissions mitigation driver. This mechanism would account for 10% of the total mitigation effort over the 2015–2050 period.

Electricity in final energy demand is not emitting; energy use and associated emissions in its productions are accounted in the power sector. As such, electrification can reduce the overall emissions of the economy when it is accompanied by the decarbonisation of the power sector in a synergistic way. Electrification is presented here as a mitigation option for final demand sectors; the corresponding increase of electricity demand faced by the power sector is accounted in the "Activity" category of Figure 21.

All final energy demand sectors would experience a strong electrification (Figure 24) Electricity represented 18% of global final energy demand in 2015, and would reach a share of 34% in 2050. In absolute terms, electricity demand would grow at 1.8%/year from 2015 to 2050, from about 20,000 TWh in 2015 and almost doubling by 2050 to 34,000 TWh.

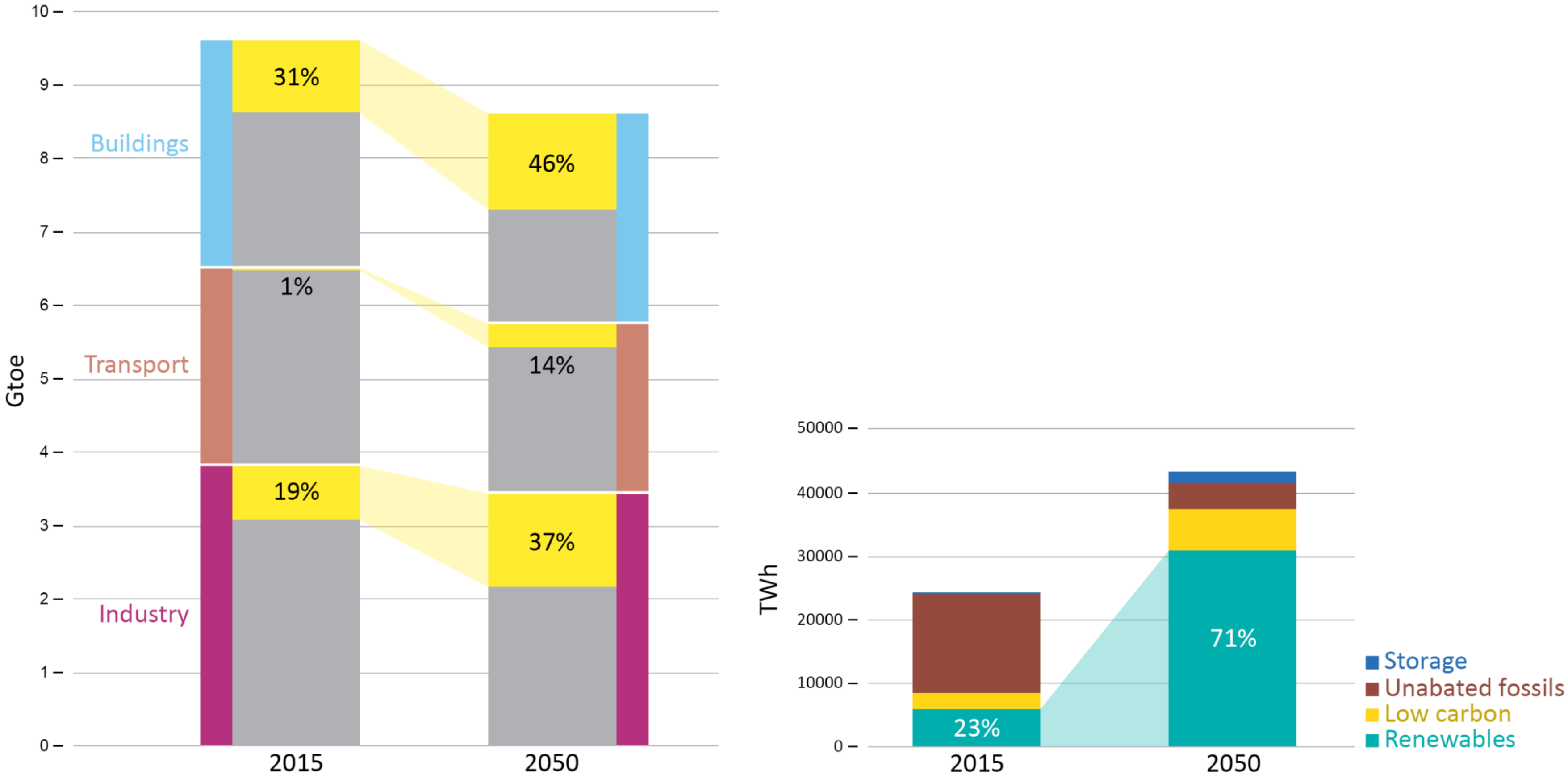
([13]) The projections for agriculture and land use metrics in this report were made by soft-linking the specialised model GLOBIOM (IIASA, 2017) with the energy system model POLES-JRC.

In absolute terms, the rise in electricity demand would be most pronounced in industry, where it is expected to double its volume by 2050 with respect to 2015.

However, in relative terms, the transport sector would experience the largest increase in electricity consumption (a 14-fold increase from 2015 to 2050), due to the emergence of electro-mobility, which is starting from very low levels today.

Electricity demand in buildings is projected to increase by 36% by 2050, due to strong growth in electric space heating and cooling (most notably via heat pumps) and in other electric appliances.

Figure 24. Electrification by sector and power generation mix in the central 2°C scenario, 2015–2050



Note: Figures for industry include non-energy uses of energy fuels. Figures for transport include energy consumption of international aviation and maritime bunkers. Figures for buildings include energy used in the residential, commercial and agriculture sectors (was 2,040, 870 and 190 Mtoe in 2015, respectively).

Source: POLES-JRC 2018.

4.1.5 Land use, land use change and forestry

Land can act as a natural carbon sink, with carbon stored in the soil and above-ground biomass (forest, plants). In the central 2°C scenario, improved management of land and more efficient forest practices, in the form of a drastic reduction of deforestation and an increased effort in afforestation, would account for 10% of the total mitigation effort over 2015–2050 ([14]). If managed and regulated appropriately, the LULUCF sector could become carbon-neutral as early as 2020–2030, being a key sector for emissions reductions beyond 2025. These developments would occur with the simultaneous expansion of the use of biomass as an energy source, and thus an increase in the surfaces of managed forests for its provision.

An important feature of LULUCF activities is their potential reversibility, meaning that the accumulated carbon stock would be potentially non-permanent. This increases the importance of appropriate management and regulation practices for this sector.

4.1.6 Fossil fuel switch

The GHG intensity of energy is strongly influenced by the average carbon content of fossil fuel. The switch of coal and oil towards gas as well as towards synthetic methane (non-emitting in its final use in transport) would account for 9% of the total mitigation over 2015–2050. The majority would take place in the power sector and transport, with about 1.9 $GtCO_2$ and 0.8 $GtCO_2$, respectively, while buildings and industry represent around 0.5 $GtCO_2$ each.

This gives a higher weight to natural gas in a shrinking market. When combining fossil fuel switch with efficiency and electrification, the total volume of natural gas consumption would still decrease over the period 2030–2050.

4.1.7 Carbon capture and sequestration

While the technological bricks of carbon capture and sequestration already exist, the technical complexity of a complete system makes these solutions risky and costly. Given the current lack of carbon price and of lasting political support, this report assumes that CCS will not be fully commercial before 2030.

However, among the complete set of measures necessary for the implementation of the strong mitigation scenarios studied here, the support for CCS becomes key in the longer run, particularly beyond 2050 (Box 18).

Box 7. Anticipating different futures: What if CCS does not develop?

CCS technologies could be key in tackling CO_2 emissions reduction, but high costs, serious technical uncertainties and a potential lack of support from civil society, especially for CO_2 transport and underground storage, could mean that CCS might not be able to play a significant role in CO_2 mitigation. For that reason, an alternative scenario (2°C – no CCS) is presented in this box, without CCS deployment up to 2100; this scenario is otherwise similar to the central 2°C scenario in that it mobilises other mitigation options to reach the 2°C objective.

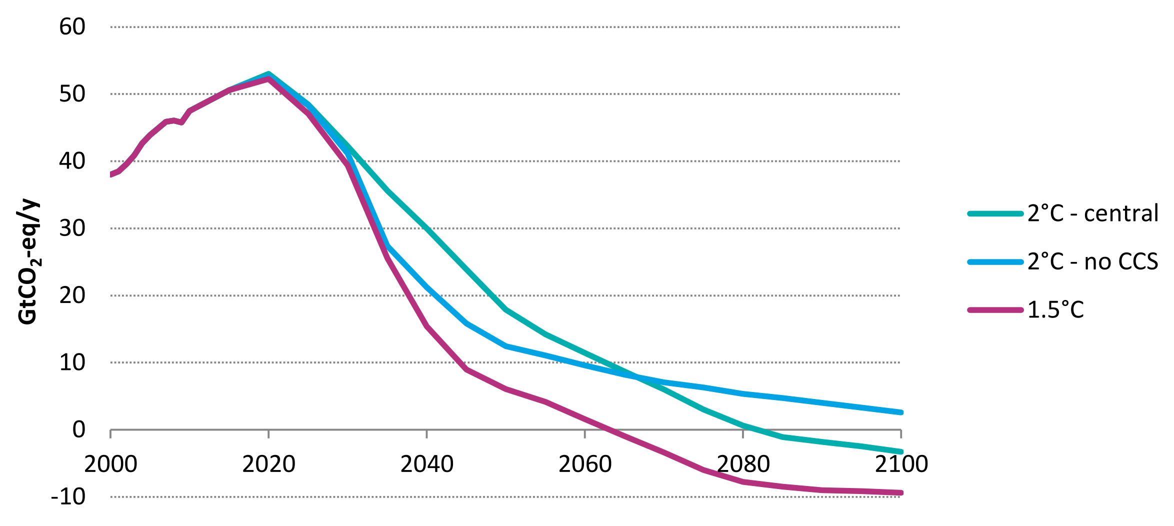
In the central 2°C scenario, CCS technologies would start to be implemented by 2040 and would reach 12 $GtCO_2$/year by 2100. CCS allows for significant emission reductions in the second half of the century; all of this mitigation potential would have to be met in a different way in the no-CCS scenario. The exclusion of CCS technologies from the mitigation options leaves LULUCF sinks as the only negative emissions possibility for the no-CCS scenario. This would force a stronger reduction of emissions already before 2050 in order to compensate the higher CO_2 emissions in the second half of the century(

([14]) The projections for agriculture and land use metrics in this report were made by soft-linking the specialised model GLOBIOM (IIASA, 2017) with the energy system model POLES-JRC.

Figure 25).

The resulting mitigation effort in the no-CCS scenario is similar to that in the 1.5°C scenario for the period 2015–2035. Uncertainty over the use of CCS technologies would thus have a significant impact on the ambition of climate policies that would have to be adopted in the immediate future.

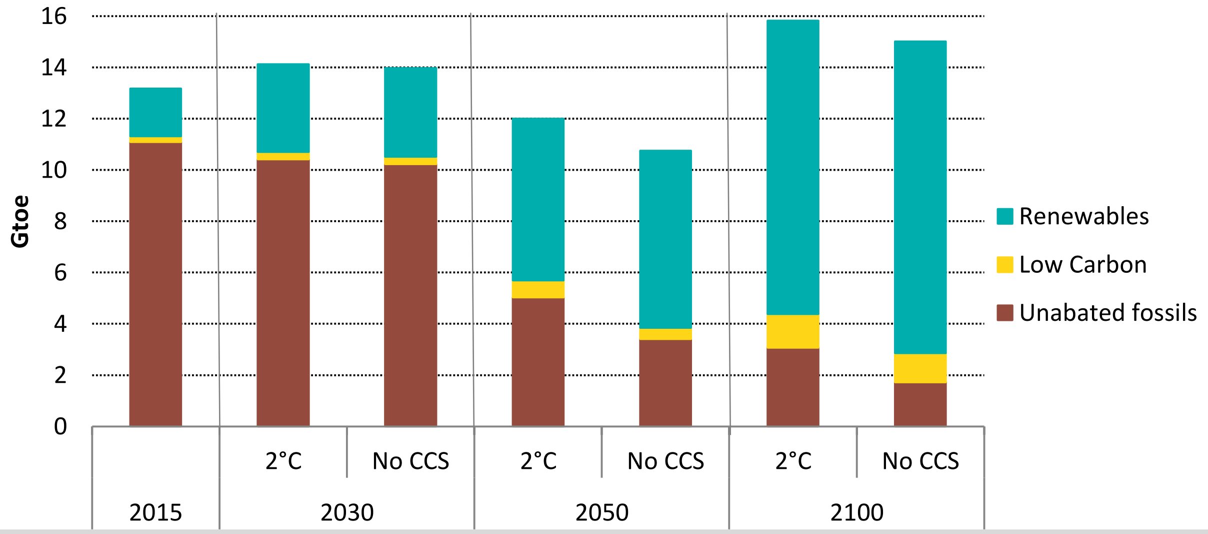
Figure 25. Annual total GHG emissions for the central 2°C, no CCS and 1.5°C scenarios



Source: POLES-JRC 2018.

Figure 26 illustrates the primary energy demand and fuel type, for the central and alternative scenario up to 2100. The total primary energy demand is lower by the no-CCS scenario already in 2030 and during the whole period; the lack of CCS would thus have to be anticipated and higher energy efficiency efforts would have to be undertaken early on in the no-CSS scenario (total demand 9% lower in 2050). In addition, in the no-CCS scenario decarbonisation is accelerated: unabated fossil fuels contract faster (3.4 Gtoe in 2050 vs 5.2 Gtoe in the central 2°C scenario) and renewables expand more both in share and total volumes (7.0 Gtoe in 2050 vs 6.4 Gtoe in the central 2°C scenario). The share of renewables is 6 to 10% higher in the no-CCS scenario throughout 2050–2100. Due to relatively lower energy efficiency efforts, unabated fossil fuels still represent 21% of the energy system in 2100 in the central 2°C scenario, compared to just 11% in the no CCS scenario.

Figure 26. The fuel mix and primary energy demand for the central 2˚C and the no-CCS scenarios



Source: POLES-JRC 2018.

Box 8. Sector-level electrification and renewables penetration in the 2°C and the 1.5°C scenarios

Compared to the central 2°C scenario, the electrification rate of final sectors would reach similar levels by 2050 in the 1.5°C scenario. On the other hand, the share of renewables would increase from approximately half to two thirds of the total end-use consumption (Table 2).

Table 2. Electrification and renewables in end-use sectors, central 2°C and 1.5°C scenarios

	2050 – central 2°C			**2050 – 1.5°C**		
	Final energy consumption (Gtoe)	Electricity share	Renewables share	Final energy consumption (Gtoe)	Electricity share	Renewables share
Industry	3.4	37%	45%	2.7	36%	65%
Transport	2.3	14%	36%	1.5	14%	38%
Buildings	2.9	46%	65%	2.6	52%	77%
Total	**8.6**	**34%**	**49%**	**6.8**	**37%**	**64%**

Note: Renewables share contains direct renewables in final demand (biomass, biofuels, solar heat) and the part of energy carriers produced with renewables (electricity, hydrogen district heating). Figures for industry include non-energy uses. Figures for transport include international aviation and maritime bunkers.

Source: POLES-JRC 2018.

However, taking into account the feedback in activity levels and further energy efficiency improvements, the absolute levels of electricity and renewables consumption in the 1.5°C scenario would be rather similar in 2050. Therefore, it is mainly fossil fuel consumption which would be impacted downwards by stronger climate policies. At the sectorial level, industrial activity and transport would be more impacted in terms of final energy consumption, notably with an additional reduction of one third of consumption in transport. The participation of renewables would grow in all demand sectors, in particular in industry and buildings; in transport the additional mitigation would principally be achieved via further energy efficiency rather than additional renewables.

A similar trend could be observed in the power sector, where absolute renewable generation from renewables would reach comparable levels in 2050 in the central 2°C and 1.5°C scenarios. The 12% decrease in total power generation in the 1.5°C scenario in 2050 would be achieved by further reducing production from fossils (-65% compared to the central 2°C scenario) and other low-carbon sources (-42%) (Table 3).

Table 3. Power generation in the central 2°C and 1.5°C scenarios

	2050 - central 2°C		**2050 - 1.5°C**	
	Power generation (TWh)	Share	Power generation (TWh)	Share
Unabated fossils		10%		4%
Renewables		71%		78%
Other low carbon		15%		10%
Storage		4%		8%
Total	**43,000**	**100%**	**38,000**	**100%**

Source: POLES-JRC 2018.

4.2 Mitigation options for the Buildings sector

The buildings sector, consisting of households and commercial/services buildings, in 2015 accounted for 30% of the global energy consumption and 8% of the total CO_2 emissions.

Table 4. Summary table for the buildings sector, central 2°C scenario

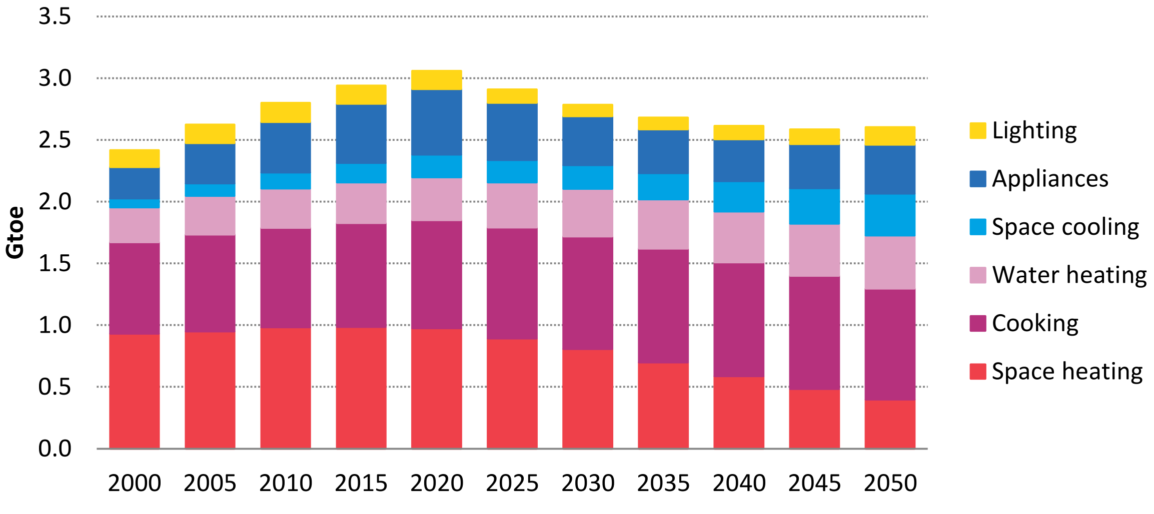
Buildings in transition	**2015**	**2050**
Residential surfaces (Gm^2)	149	303
Annual market for new and renovated residential (% of total surfaces)	4.3%	4.4%
Total buildings energy use (Gtoe)	2.9	2.6
of which generated onsite (distributed electricity and solar heat)	2%	22%
CO_2 emissions ($GtCO_2$)	2.9	1.4
% of total CO_2	(8%)	(11%)
Electrification (% of energy use)	32%	46%
dwellings with heat pumps (% of dwellings' heating systems)	0%	20%
Direct renewable participation (% of energy use)	28%	40%
excluding traditional biomass	5%	24%
distributed PV as % of electricity	2.2%	33%

Note: Direct renewable participation refers to biomass, solar thermal heat and rooftop PV.

Source: POLES-JRC 2018.

Consumption arises from burning fuels or from electricity use for space heating, cooking and water heating, as well as electricity use exclusively for space cooling, lighting and appliances. Of these uses, space heating (33%) and cooking (29%) made up the majority of final energy consumption in buildings in 2015 (Figure 27).

Figure 27. Buildings energy consumption per end-use in the central 2°C scenario, World

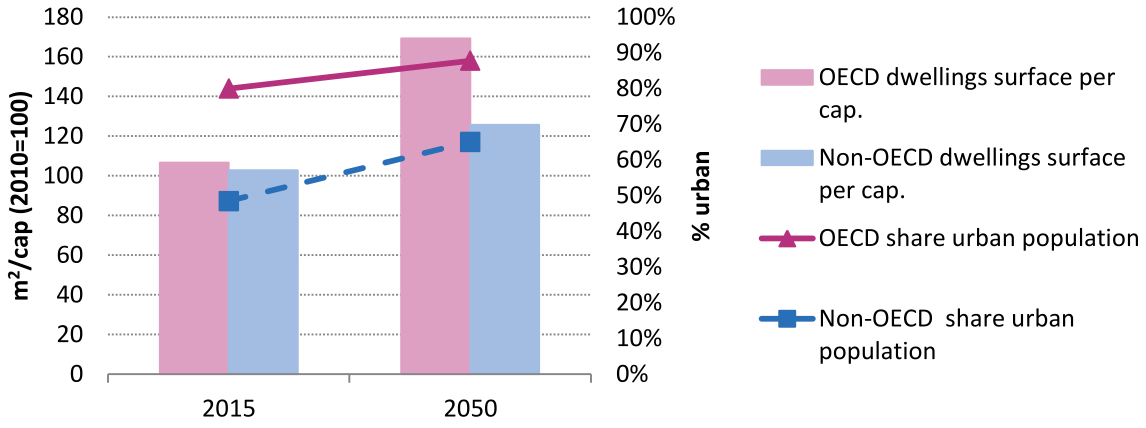


Source: POLES-JRC 2018.

Globally, total energy consumption in buildings grew from 2000 to 2015 by a rate of 1.3%/year, with most of the growth coming from space cooling (5.4%/year) and appliances (4.3%/year) (see Figure 27).

In the coming decades, the buildings sector will face the challenges of providing adequate housing, electricity access and improved cooking facilities to billions of people in developing countries; in addition, population growth, migration to cities and increasing comfort requirements related to wealth increase worldwide will all contribute to increasing energy needs in buildings. By mid-century, on average, the population will be more urban and will reside in larger dwellings (Figure 28), and will be increasingly employed in the services sector. The implementation of strong climate and energy efficiency policy will be key in shaping how the energy needs of residential and commercial buildings are met.

Figure 28. Average dwellings surface per capita (bars, left axis) and share of urban population (lines, right axis), OECD and non-OECD, in the central 2°C scenario

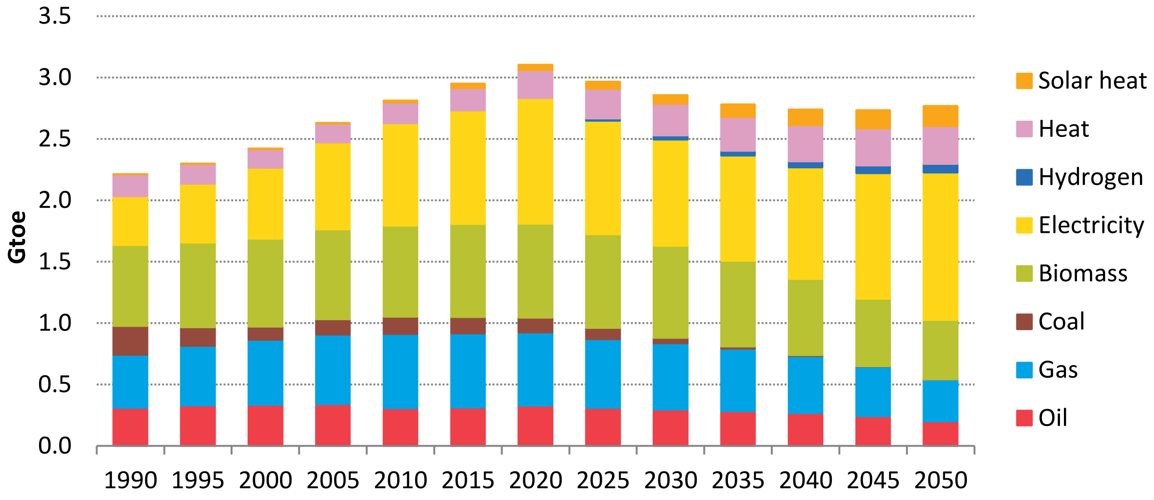


Source: POLES-JRC 2018.

In the central 2°C scenario, buildings' final energy consumption worldwide is expected to reach a plateau and stabilise in the coming decades. Energy consumption should continue growing at a decelerated pace up to 2020 (0.8%/year). This would be followed by a decade of decrease (-0.9%/year over 2020–2030) then of stabilisation (-0.3%/year over 2030–2050). This trend would mainly be the result of a broad diffusion of energy efficiency solutions and changes in the energies used for space heating and cooking; indeed, by 2050 space heating would only make up 15% of energy consumption, superseded by cooking (35%).

Large changes are projected for the energy mix of buildings (see Figure 29).

Figure 29. Buildings energy consumption per fuel, 2015 and 2050, in the central 2°C scenario World

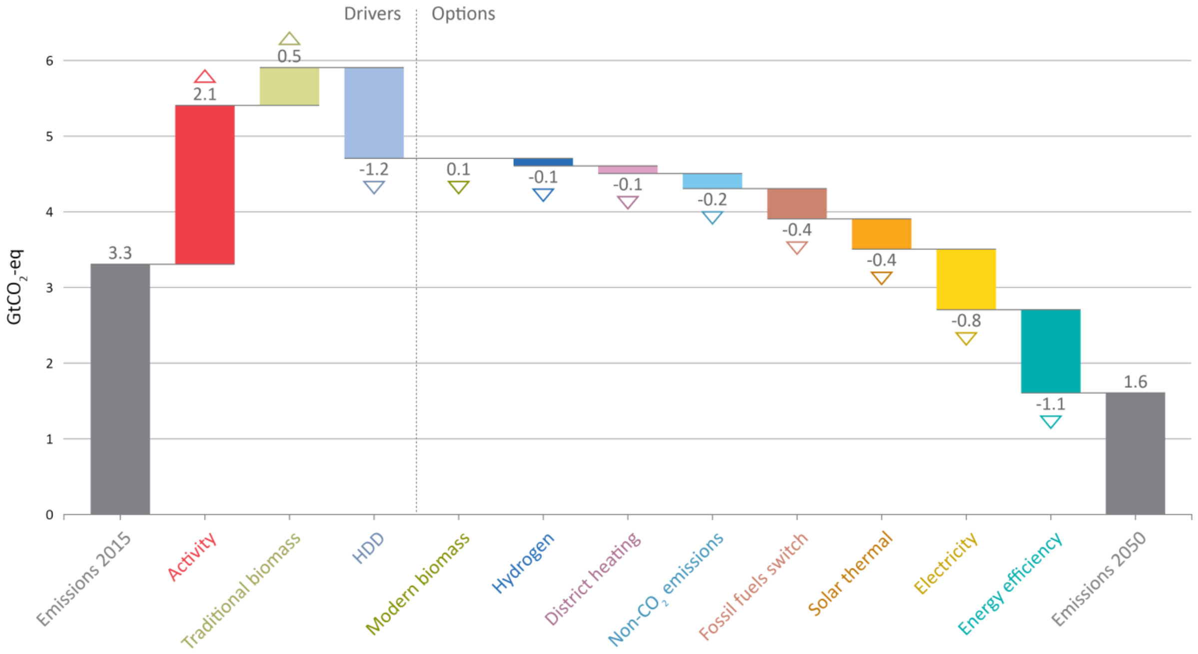


Source: POLES-JRC 2018.

In 2015, the buildings sector energy was dominated by electricity (32%) followed by traditional biomass (26% of the total) and natural gas (21%). In the central 2°C scenario, the total share of fossil fuels is projected to decrease from 36% to 21% over 2015–2050. Electricity is projected to become the main fuel consumed, providing nearly half (46%) of the energy in 2050.

The GHG emissions mitigations options adopted by the buildings sector in the central 2°C scenario are presented in Figure 30.

Figure 30. Buildings GHG mitigation options from 2015 to 2050 in the central 2°C scenario, World



Notes: "Activity": emissions growth due to the growth of population and income, and to associated increase in living standards (dwelling size, cooking and water heating needs). "Traditional biomass": refers to the phase-out of traditional biomass for reasons other than climate, resulting in an energy demand gap that has to be met by other fuels. "HDD": emissions prevented by the evolution in time of heating degree-days (15)."Fossil fuels switch": refers to shifts from high-carbon content towards lower-carbon content within the fossil fuel mix (from coal and oil to natural gas).

Source: POLES-JRC 2018.

4.2.1 Space heating and cooling: Energy efficiency potential and effect of climate change

The largest potential in emissions mitigation and energy consumption reduction in buildings comes from energy used in space heating, which is a concern for countries in higher latitudes – essentially OECD countries, CIS countries, and China.

The technology solution to realise this potential exists and is well demonstrated. Recent advances in insulation in buildings, heating and cooling technologies, design practices and know-how coupled with behavioural change can achieve a reduction in the energy requirements of individual new or existing buildings, largely cost-effectively or sometimes even at net negative cost (IPCC, 2014). Likewise, new construction and a retrofit of very low- and zero-energy buildings are also taking place, often at little marginal investment cost, typically paying back well within the building lifetime. According to (Lucon, et al., 2014) retrofitting for detached single-family homes can achieve a 50–70% reduction in total energy use, while in multi-family housing a number of projects have obtained 80–90% reductions in space heating requirements.

In addition to technologies and architecture, behaviour and lifestyle have a major effect on buildings' energy use; a three- to fivefold difference in energy use (IPCC, 2014) has been shown for the provision of similar building-related energy service levels.

Different energy policies, such as building energy codes, including net-zero energy buildings, tax and purchase incentives, energy labels, and increasing public awareness about new technologies, have been implemented by countries, motivated not only by climate concerns but also by energy resource savings and efficiency. However, fast-growing countries, such as China, India and Iran, still show considerable growth in GHG

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(15) The evolution of CDD results in higher consumption of electricity, which is treated in section 4.5.

emissions and energy consumption, which can be linked to the absence of strong policy and its implementation.

In the central 2°C scenario, with the implementation of strong energy and climate policies, investments in building shell insulation would be necessary to decrease useful energy needs; over 4% of the housing stock would be replaced or renovated each year as a world average. Investments in new and renovated buildings would need to rise to 165 bn$/year over 2015–2050 on average, a tenfold increase compared to the 2000–2015 period.

As a consequence, energy consumption for space heating is projected to decrease strongly from its 2015 level of 980 Mtoe to 400 Mtoe in 2050. That is, an average annual reduction of 2.6%/year. The average energy consumption for space heating per surface in residential buildings would decrease from 55 kWh/m^2 in 2015 to 11 kWh/m^2 in 2050, as a global average.

Due to climate change, population-weighted heating degree-days needs (HDD) are expected to decrease on a global level by a quarter between 2015 and 2050, therefore reducing the thermal energy needs for space heating. The evolution of heating and cooling degree-days (CDD) is the only impact of climate change that was included in the energy and emissions projections in this study ([16]); although strictly speaking, it cannot be considered as an emission mitigation measure, it is a key driver behind the reduction of emissions of the buildings sector.

As a result of all these trends, consumption of space heating fuels decreases over time. This is particularly the case for gas: despite its lower carbon content compared to the other fossil fuels, it will be displaced by electricity as a main final energy carrier. After a strong increase as a heating fuel from 300 Mtoe in 1990 to 400 Mtoe in 2015, becoming the main heating fuel with a 40% share in 2015, it would decrease to 60 Mtoe in 2050. The use of hydrogen as a combustion fuel only very partially mitigates this decrease (about 10 Mtoe in 2050), due to the considerable additional investments that would be needed to create a hydrogen distribution network to go beyond what can be achieved by mixing hydrogen with methane using the current network (up to 15% by volume).

This transformation is accompanied by the penetration of electric heat pumps as a key technology that is both highly efficient and non-emitting (from the end-use point of view). Despite an overall decreasing final consumption of electricity for space heating, electric heat pumps would come to equip 20% of households by 2050 (30% for OECD countries). Another mitigation option is the use of centralised heating systems in dense urban areas, which mutualise infrastructure costs and minimise losses, along with the use of biomass instead of coal and gas to minimise emissions. However, the indoor and ambient air quality associated with biomass combustion is a concern that might drive the arbitrage in choosing heating systems (see section 4.2.6).

Conversely, CDD are expected to increase by a quarter over the 2015–2050 period, thus significantly increasing the electricity needs for space cooling ([17]). Electricity for space cooling is the buildings' energy use that grows the most strongly, at 2.2%/year, on average, worldwide.

([16]) HDD and CDD figures were taken from the ISI-MIP project and were supplied by (Hempel, et al., 2013) (Hempel, S., Frieler, K., Warszawski, L., Schewe, J., Piontek, 2013) (Warszawski, et al., 2014).

([17]) This indirectly results in more GHG emissions in the power sector.

4.2.2 Cooking: from traditional to modern fuels

Currently (2015), it is estimated that buildings energy consumption for cooking amounts to approximately 840 Mtoe, the majority of which is traditional biomass ([18]) (83% of traditional biomass is consumed in cooking). For countries with a widespread use of traditional biomass (in particular the rural areas of China, India, South and South-East Asia, Sub-Saharan Africa), a significant challenge is the phase-out of this traditional biomass and its substitution with modern fuels; this is independent of climate change concerns and is more related to health issues (sanitation, air quality) and sustainability (environmental degradation that can accompany the use of traditional biomass). In recent years, China has operated a shift from approximately 200 Mtoe of traditional biomass for all uses in the 1990s to approximately 80 Mtoe in 2015, mostly substituting it with modern cook stoves and heaters using gas (natural gas or biogases).

In the central 2°C scenario, traditional biomass for all uses, globally, is projected to progressively decrease from approximately 670 Mtoe in 2015 to 420 Mtoe in 2050 (and from 550 to 355 Mtoe for traditional biomass for cooking specifically).

Coal for cooking uses is also projected to be phased out, accelerated by climate policies. While traditional biomass will still represent 40% of energy for cooking by 2050, modern fuels will make up a larger market share, with gas at 21% and electricity at 20%. As a consequence, the phase-out of traditional biomass might result in increased emissions unless accompanied by climate policies.

Overall energy for cooking consumption is projected to increase at a moderate pace, 0.2%/year over 2015–2050, reflecting a growing population and the increase of efficiency in the switch to modern fuels.

4.2.3 Water heating: Tapping the solar potential

An increasing population and rising living standards should drive energy needs for water heating upwards in the future. Total global energy use for water heating is projected to increase at a low rate of 0.8%/year over 2015–2050.

In 2015, gas and oil made up 60% of the fuels used for water heating, followed by electricity and solar heaters. Solar heaters and electric heaters are two non-emitting technologies that are projected to develop in the central 2°C scenario, rising to supply half of water heating energy needs by 2050.

4.2.4 Appliances and lighting

Electricity-specific uses of energy in buildings have presented a strong growth in the past two decades, reflecting rising living standards and the spread of consumer goods, from about 4,600 TWh to 7,300 TWh over 2000–2015. Energy-efficient appliances, energy-efficient lighting and the smart management of appliances can reverse this trend despite the substantial expected increase of equipment rates around the world ([19]). A large part of these gains can be reached with the adoption of currently best available technologies in all world regions.

In the central 2°C scenario, these uses of electricity are projected to decrease to 6,200 TWh by 2050.

([18]) Modern biomass: pellets, bricks, processed agricultural waste, etc. Traditional biomass: solid biomass (non-marketed wood, agricultural residues, animal dung) used mostly for cooking but also space heating, with pre-modern techniques (stone oven, indoor open-fire pit) that result in low efficiency (about 20%) and high air pollution.

([19]) However, the energy consumption associated with the wider use of information and communications technologies (ICT) will lead to higher electricity consumption; the net effect of this trend is not quantified in this report.

4.2.5 Electricity in buildings: Towards smart management and self-generation

Given recent technological evolutions, it is becoming progressively cost-effective to generate electricity with distributed means, notably with rooftop photovoltaics. This tendency should result in in-depth changes in the way the electricity market is structured, given the complex interactions of intermittent decentralised generation with the centralised transport grid.

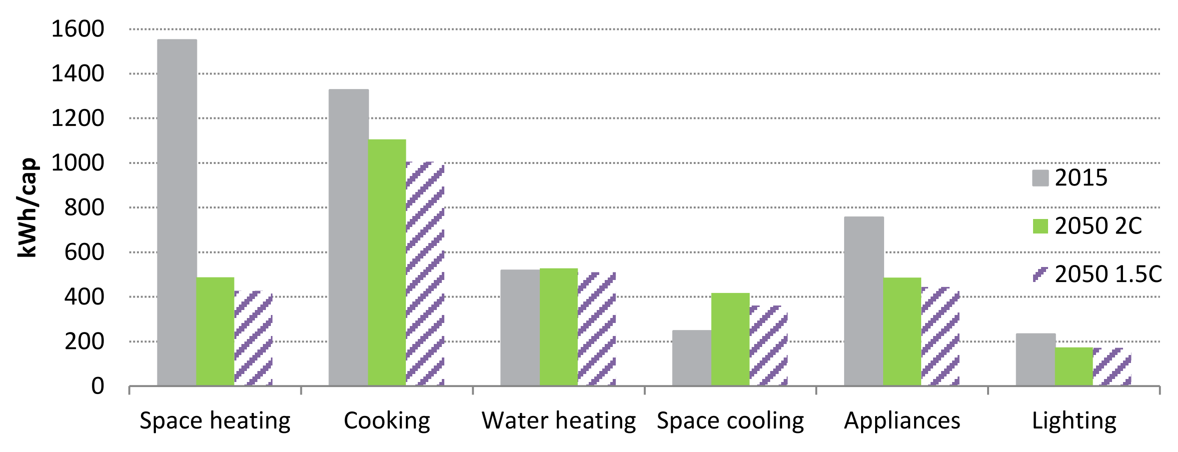
Distributed Photovoltaics (PV) produced about 3% of buildings' electricity needs globally in 2015. The central 2°C scenario projects that this would rise to about a third of buildings' electricity needs by 2050 – i.e. the equivalent of three quarters of the electricity consumption of all appliances, and amounting to 4,200 GW of new installed capacity over 2015–2050. In addition, the simultaneous diffusion of ICT-enhanced technologies such as electric batteries (stationary or in vehicles, see section 4.4) and appliances that can be programmed for load-shifting (limited to 5% of the load in this scenario) could result in even less need to reinforce the central power transmission network. As such, individual buildings would not be self-sufficient; however, urban areas could resemble an ecosystem of interconnected electricity islands.

Box 9. Buildings in the 1.5°C scenario

Buildings emissions in the 1.5°C scenario in 2050 would be half those of the central 2°C scenario, i.e. 0.7 $GtCO_2$. This would be achieved thanks to energy efficiency improvements for end-uses, in particular in buildings insulation, thereby narrowing somehow the market niche within which hydrogen can develop in the 2°C case. This would result in total energy use that would be 9% lower than in the central 2°C scenario in 2050, and a total investment in insulation that would be sensibly higher (+17%) over the 2030–2050 period. In addition, emissions would be further decreased thanks to a challenging near-complete phase-out of fossil fuels, to a deeper decarbonisation through electrification (53% of total consumption) and modern biomass (5%).

The decomposition by use in the buildings sectors is represented in Figure 31.

Figure 31. Energy consumption per capita in buildings, per end-use, 2015, 2050 in the central 2°C and 1.5°C scenarios, World



Source: POLES-JRC 2018.

Box 10. Buildings energy use in 2100

Given the uncertainties about the long-term evolution of technology and the unpredictability of innovation related to consumer goods, it is difficult to project buildings energy use to the end of the century. Values mentioned here are inherently exploratory.

By 2100 in the central 2°C scenario, all buildings would be near-zero energy buildings. Space heating energy needs would have decreased to just 1 kWh/m^2, making just 2% of the total. Most of the energy demand would come from space cooling (36%) and appliances (26%), both still increasing uses due to rising living standards in particular in low latitudes regions (South and Southeast Asia, Sub-Saharan Africa). Most energy needs would be met by electricity (85% of the total, a third of which is generated onsite) and solar heat (6%).

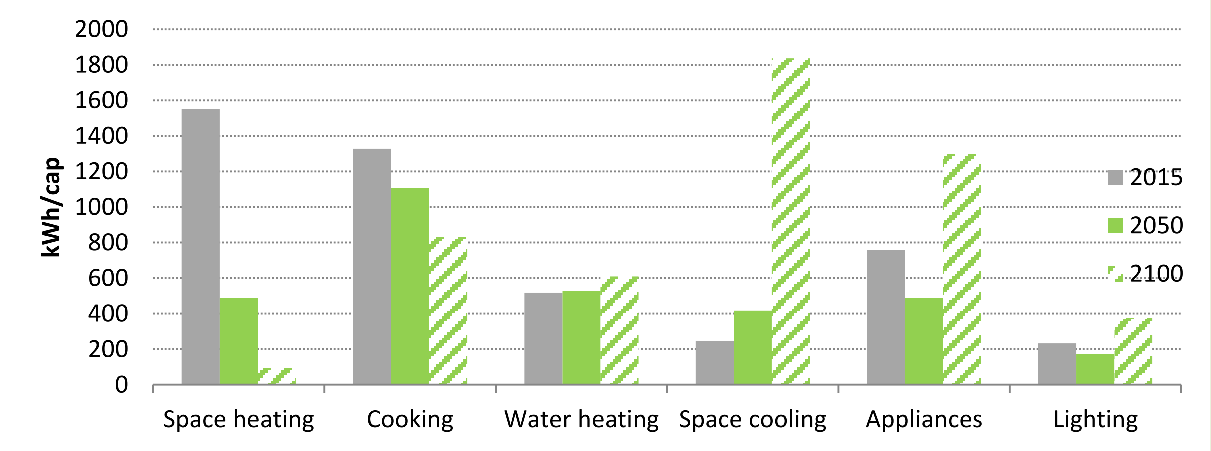
Excluding appliances, energy consumption per capita would be at a broadly similar level to today (3800 kWh/cap in 2100 vs 3900 kWh/cap in 2015), however, with a wholly different technology and fuel mix, and with basic energy needs met for all of the world's population.

Hydrogen use would be very limited; it could play a significant role in the energy mix if the upfront investments are made to create the proper distribution network, thereby mitigating some of the needs of insulation investments. However, in this scenario insulation investments are driven by mostly private actors with a 15% discount rate.

The combined effect of the trends per end-use is summarised in

Figure **32**.

Figure 32. Energy consumption per capita in buildings, per end-use, 2015, 2050 and 2100, in the central 2°C scenario, World



Source: POLES-JRC 2018.

4.2.6 Air pollutants emissions in buildings: $PM_{2.5}$

The buildings sector is responsible for a large proportion of particulate matters and carbon monoxide emissions, with historical shares of around 35–40%, which would remain quite stable by 2050 in the central 2°C scenario. VOCs emissions would also be important, with one fifth of the total in 2010 stable throughout the projection period. Buildings' contributions to SO_2 and NO_x emissions would be lower, with respectively 5 and 8–9% of the total (Table 5).

Table 5. Air pollutants emissions from buildings in the central 2°C scenario, volumes and shares of total, World

	2010		**2030**		**2050**	
	Emissions (Mt)	Share of total	Emissions (Mt)	Share of total	Emissions (Mt)	Share of total
SO_2	5	5%	3	5%	1	5%
NO_x	10	8%	8	9%	3	9%
$PM_{2.5}$	16	39%	13	34%	7	36%
CO	166	35%	146	35%	66	34%
VOC	24	22%	22	21%	12	22%

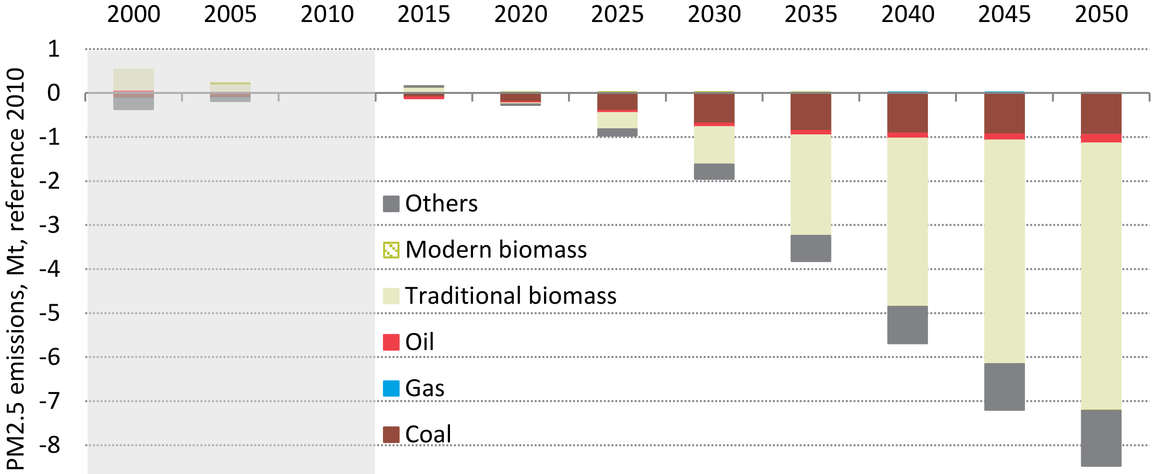
Source: POLES-JRC 2018.

$PM_{2.5}$ emissions are a major concern in the buildings sectors; they are linked to fuel combustion for space and water heating and cooking. Coal and traditional biomass uses are major emitters of particulates, and are the source of major health impacts, including cardiovascular and respiratory illnesses, allergies and asthma (Vicente & Alves, 2018).

Therefore, the transformation of the energy system induced by climate policies, as well as the targeted phase-out of traditional biomass are expected to bring significant co-benefits in terms of $PM_{2.5}$ emissions in the residential and services sector.

The $PM_{2.5}$ emissions change by source compared to 2010 is presented in Figure 33. The bulk of the abatement would be related to lowered emissions from biomass (-6 Mt in 2050 compared to 2010), followed by coal and other sources (including agriculture, waste and other various sources).

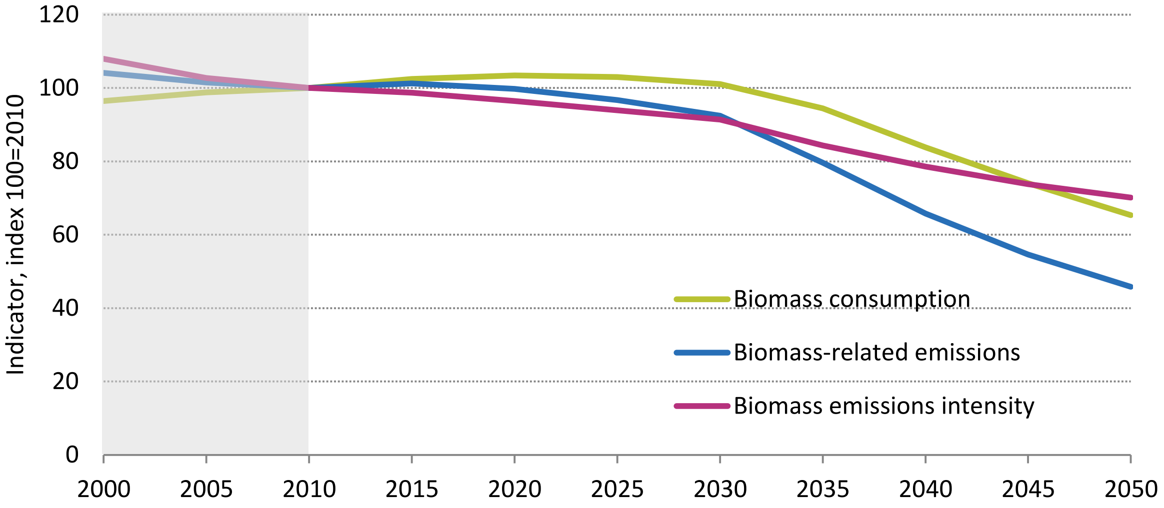
Figure 33. $PM_{2.5}$ emissions changes by source, buildings, central 2°C scenario



Source: POLES-JRC 2018.

The decomposition of biomass-related PM emissions (Figure 34) shows the reduction of emission factors between 2010 and 2030, due to tightening regulations and a progressive phase-out of traditional biomass, although the total biomass consumption of buildings would be slightly increasing. After 2030, the drop of biomass consumption would contribute to reducing emissions further, to obtain an abatement of annual emissions of more than 50% in 2050 with respect to 2010.

Figure 34. Decomposition of biomass-related $PM_{2.5}$ global emissions for buildings, central 2°C scenario



Source: POLES-JRC 2018.

4.3 Mitigation options for the Industrial sector

The world industrial sector accounted in 2015 for 39% of the global energy consumption and 21% of the total GHG emissions. GHG emissions from industry involve fossil fuels burned onsite at facilities for heat and electricity; a lot of the mitigation effort would be concentrated on these emissions. However, more than half of industrial emissions are also emissions coming from the processes themselves, either in the form of CO_2 (e.g. limestone calcination in cement production) or non-CO_2 (e.g. perfluorocarbons (PFCs) from the anode effect in primary aluminium reduction); mitigating these emissions is more challenging, as they are intrinsic to the processes involved in converting raw materials into semi-finished goods.

Table 6. Summary table for the industrial sector, central 2°C scenario

Industry in transition		**2015**	**2050**
Value added (tn$)		23	61
Total industry final energy consumption, for energy and for non-energy uses (Gtoe)		2.9 0.8	2.7 0.6
Electrification (% of energy use)		25%	46%
Direct renewable participation (% of energy use)		7%	14%
CO_2-energy emissions ($GtCO_2$) % of total CO_2-energy		6.1 19%	2.2 18%
Other GHG emissions ($GtCO_2$-eq)	Industrial processes CO_2	3.0	2.3
	Non-CO_2	1.1	0.3

Note: Direct renewable participation refers to biomass.

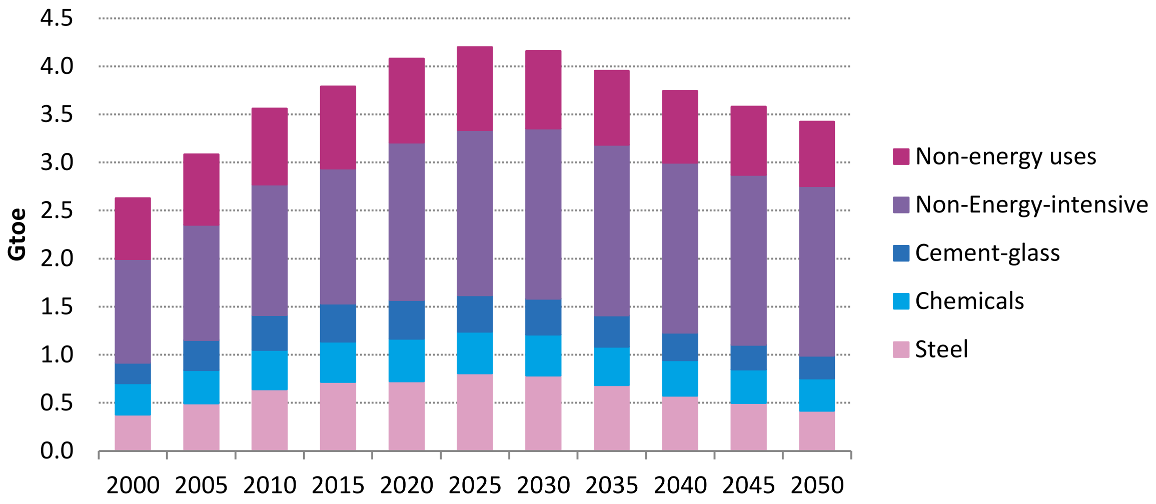
Source: POLES-JRC 2018.

The industrial sector uses a variety of energy sources. Currently, most industries purchase electricity from electric utilities or independent power producers. Some industrial facilities generate electricity for use at their plants using fuels that they purchase or the residues from their industrial processes. A few produce electricity with solar photovoltaic systems located on their premises. Some of them sell a part of the electricity they generate. The industrial sector could increasingly combine a co-generation of heat and electricity with increased exchanges of excess heat or electricity, and thus reduce waste by-products while also becoming a flexibility option for the electric grid.

Furthermore, the industrial sector uses energy fuels for non-energy uses, as primary raw materials for the production of chemical fertilisers and plastics. This consumption is directly related to the amount of goods to be produced, driven mostly by population and economic growth (and moderately impacted by the evolution of energy prices). Therefore, fuel consumption for non-energy uses can only be partially limited. Such an example is nitrogen-based fertiliser production, which is stabilised (+2% in 2050 compared to 2010) due to improved fertiliser management while still satisfying the food needs of a growing population and reaching the objectives of the SDG on reducing hunger. The oil converted into polymers is non-emitting, however oil consumption for polymers production could also be reduced by increasing recycling and substituting oil with biomass as a source of hydrocarbons. Indeed, this prevents the GHG emissions across the oil and gas supply chain that would occur from energy self-consumption at the well or fugitive emissions in transport. As a consequence, the petrochemical industry might come under pressure to mitigate its emissions by substituting oil and gas as a raw material. All in all, fuels employed in non-energy uses are projected to reach 0.6 Gtoe in 2050 in the 2°C scenario, compared to 0.8 Gtoe in 2015.

As for the energy uses for industry, in the central 2°C scenario they are projected to peak around 2025 and stabilise in 2050 at their 2010 level, around 2.7 Gtoe, compared to 2.9 Gtoe in 2015 (Figure 35).

Figure 35. Industry energy consumption, central 2°C scenario, World



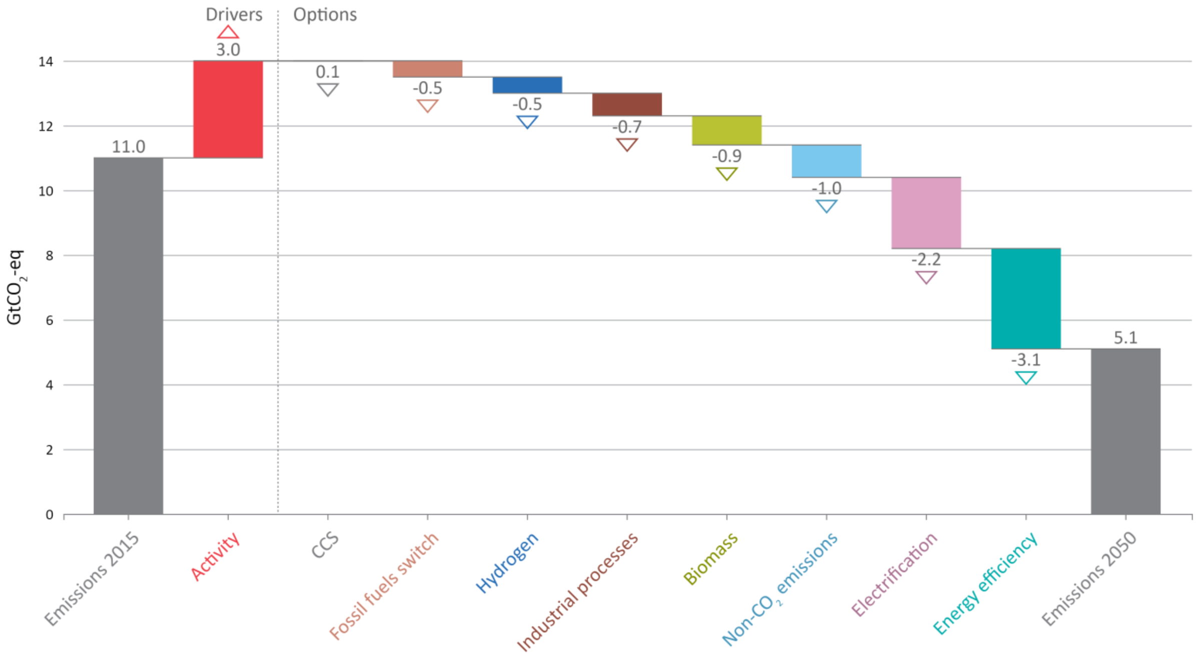
Source: POLES-JRC 2018.

Energy-intensive industries, grouped here in three broad subsectors as iron and steel, chemicals and non-metallic minerals (cement, glass), made up most of the energy consumption in 2015 (52%) for only a quarter of the value added of industry. As energy-intensive industries, they will be most subject to pressure to mitigate their emissions; their share in total industry energy consumption is projected to decrease to 36% by 2050.

Energy use in the other industrial sectors is projected to increase significantly as economic growth spurs demand for manufactured goods in all world regions.

The GHG emission mitigation options adopted by the industrial sector in the 2°C scenario are presented in Figure 36.

Figure 36. Industry GHG mitigation options from 2015 to 2050, central 2°C scenario, World



Notes: "Activity": emissions growth due to the growth of population and the economy (industrial value added). "CCS": emissions prevented by carbon capture and storage. "Fossil fuels switch": refers to shifts from high-carbon content towards lower-carbon content within the fossil fuel mix (generally from coal and oil to natural gas). "Hydrogen", "Biomass", "Electrification": emissions prevented by the use of these fuels (emissions for their production accounted elsewhere). "Industrial processes": reduction of CO_2 emissions due to direct mitigation and process change.

Source: POLES-JRC 2018.

4.3.1 Efficiency and fuel mix

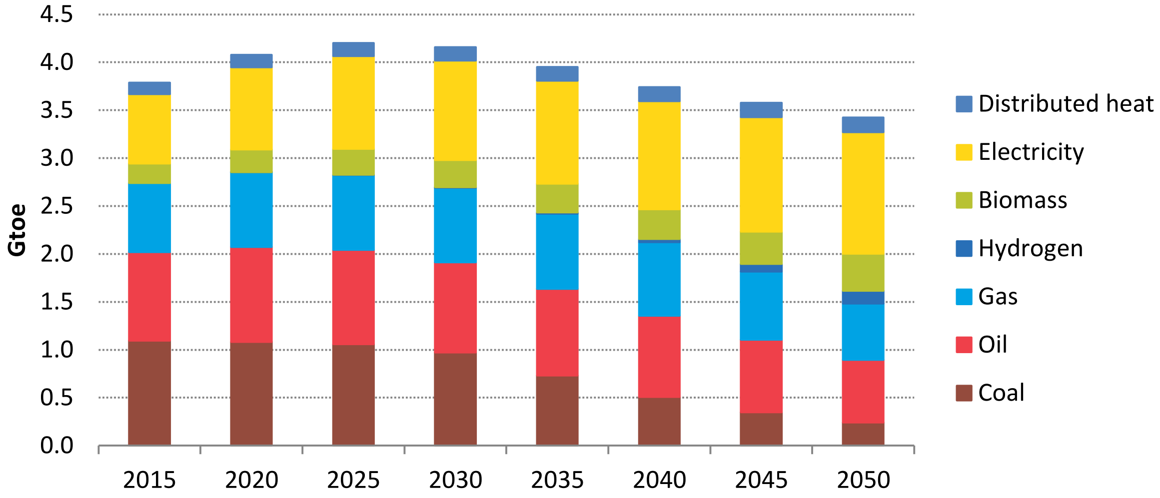
Increased energy efficiency would be the chief mitigation option in the industrial sector. This would involve further R&D in enhancing currently existing processes but also the wider adoption of already existing best available technologies. This mitigation option's effects can be maximised by accelerating the renewal of stock, fostering innovation and cross-border cooperation with the exchange of new technologies.

Large energy efficiency potential is also the creation of synergies by using the waste heat from one industry as input into another industry's processes. Also, combined heat and power (CHP) is being used more and more by industries for onsite power generation and simultaneously satisfy the demand from both high-temperature processes and electric processes.

Finally, structural changes in industrial production could also indirectly result in energy efficiency gains, brought about by regional or global demand for consumer products and by domestic industrial policy. The mix of energy-intensive industries versus non-energy-intensive industries in a country would determine energy consumption and GHG emissions.

In the central 2°C scenario, climate policies would spur a significant reduction of the consumption of energy for heat uses in industry, through increased energy efficiency and fuel substitution. Gas consumption would continue to grow until the mid-2030s, and would then slightly decrease, partially substituted by hydrogen. Coal consumption already peaked in 2014; its consumption would be drastically reduced sixfold by 2050. On the other hand, oil consumption would grow at a moderate pace until 2030 and would decrease beyond that point (Figure 37).

Figure 37. Industry final demand energy mix, central 2°C scenario, World



Source: POLES-JRC 2018.

4.3.2 Industrial heat electrification

Heat is mainly demanded for industrial processes (and to a lesser extent for space heating in buildings); historically it accounts for 80% of the total final energy consumption in industry. Heat is often generated onsite with boilers to generate steam or hot water for thermochemical final and/or intermediate manufacturing processes. Electricity is used for operating industrial motors and machinery and ventilation, as well as for lighting, office equipment, and office space heating and cooling.

In some industrial processes, electricity can come in direct competition with heat, either in low-enthalpy (20) processes (it is possible to provide that energy with highly efficient electric heat pumps) or by changing the nature of the process altogether (e.g. primary iron ore blast furnace versus secondary steel smelting).

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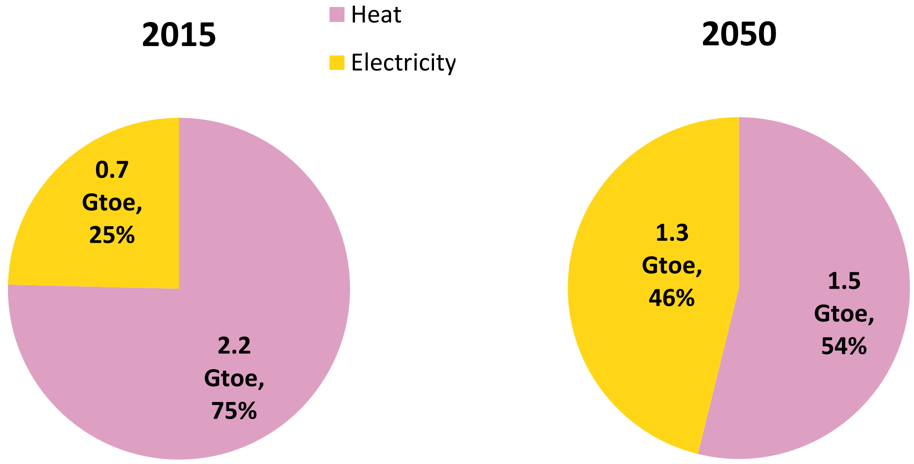
(20) Chemical processes below 100°C.

Figure 38. Distribution of energy end-uses in the industrial sector, central 2°C scenario, World



Note: Electricity uses can include uses for low-temperature industrial processes.

Source: POLES-JRC 2018.

Where possible, the electrification of industrial processes would thus be a main driver for mitigating emissions, thanks to the deep decarbonisation of the global power mix. In the 2°C scenario, electricity would cover 46% of the total energy consumption for energy uses in industry in 2050 compared to 25% in 2015 (Figure 38).

4.3.3 Non-CO_2 emissions

Depending on the type of GHG gas considered, a number of technological options exist to limit non-CO_2 GHG emissions. In the case of methane, particular attention has to be paid to leak and fugitive emissions from suboptimal processes. Nitrous oxide is released in several chemical processes related to fertiliser production. Fluorinated gases (F-gases), which include as a main group of gases hydrofluorocarbons (HFCs), can be abated either by chemical capturing or by substituting them with alternative chemical species. Given the high global warming potential of these gases, the implementation of these mitigation measures would be a relatively low-hanging fruit in terms of costs.

International policies for pollution arising from such species are already in place as a continuation of international agreements that were created to deal with ozone depletion. In our central 2°C scenario projections, the industrial sector includes policies globally to reduce emissions from HFCs, which are subject to the Kigali Agreement of the Montreal Protocol ([21]); HFCs were responsible for nearly two thirds of global warming potential (GWP) weighted non-CO_2 emissions from industry in 2015.

F-gases have become the fourth chemical species by relevance in terms of global warming impact. Contrary to the CO_2, CH_4 and N_2O, F-gases have relatively complex molecules that are entirely produced and used by man in many industrial procedures. Most of them have come to gain relevance in atmospheric chemical processes as substitutes to ozone-depleting chlorofluorcarbon gases (CFC). There are three groups of F-gases, namely HFCs, perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). From those, HFCs are the most important ones in terms of climate impact. In 2016, an internationally-agreed amendment to the 1987 Montreal Protocol (the Kigali Amendment) included HFCs to the list of controlled substances. These agreements aim at phasing-

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([21]) F-gas policy is implemented in the Reference scenario in the EU, as it has been ratified. https://ec.europa.eu/clima/news/eu-ratifies-kigali-amendment-montreal-protocol_en down HFCs and abate around 80 $GtCO_2$-eq until 2050, given the well-proven existence of techno-economically suitable alternatives to most F-gases.

In the central 2°C scenario, most of the technological options to mitigate non-CO_2 GHG emissions will be put into place by 2030. Despite their implementation, some amount of emissions would remain in the years beyond. Non-CO_2 emissions decrease from about 1.1 $GtCO_2e$ in 2015 to 0.3 $GtCO_2e$ in 2050 (with most of the residual still being HFCs).

4.3.4 New fuels: Biomass and hydrogen

Several energy-intensive industries need high-enthalpy heat, which cannot be easily provided by electricity-based processes; for such industries, decarbonisation options would require either structural changes (i.e. physical production decrease based on product substitution), enhanced technological efficiency and/or fuel substitution with solid biomass or synthetic gases.

In the central 2°C scenario, contrary to fossil fuels, solid biomass consumption would increase by a factor of two over 2015–2050; and hydrogen as a combustion fuel is expected to cover one fifth of overall gaseous fuels consumption by 2050 (this would only represent 3% of total industry energy consumption).

4.3.5 Carbon capture, storage and re-use

CCS for industrial emissions could become a feasible and affordable mitigation option, in particular for energy-intensive processes that require high-enthalpy heat, and are more difficult to decarbonise.

In the central 2°C scenario, CCS would first be adopted in the power sector starting from the 2030s. Adoption in the industrial sector would prove more challenging, with industrial installations being more diffuse; a small amount of industrial emissions would be captured by 2050 (<1%).

Carbon capture and use (CCU) would be another way to mitigate emissions, by putting a cost cap on CO_2 above the carbon pricing imposed by policy. Depending on the type of use, CCU could result in near-net-zero emissions, if the CO_2 is transformed into a form that can be chemically stored in solid finished products, at the expense, however, of additional energy consumed. In spite of these technological developments, it has been estimated that the potential of CCU for solid finished products is relatively low compared to the volumes of CO_2 emissions that need to be mitigated (Naims, 2016).

A different type of CCU would be to re-cycle the carbon and re-use it as an energy fuel, if the CO_2 is used as raw input together with hydrogen in the production of synthetic methane, also with the input of additional energy. The use of synthetic methane would be preferable to that of hydrogen as it would remove the barriers associated with hydrogen storage and distribution; however, it would be limited by the energy-intensive nature of its production process and its overall carbon footprint ([22]).

In the central 2°C scenario, carbon capture motivated by the production of synthetic methane would emerge in the 2040s and would absorb as much as 300 $MtCO_2$ by 2050.

4.3.6 Process emissions

Process-related CO_2 emissions are projected to be mitigated along with the energy-related emissions, although they are structurally more difficult to abate. Residual industrial process-related emissions after mitigation in 2050 would still amount to 2.3 $GtCO_2$/year in 2050, compared to 3.0 $GtCO_2$/year in 2015. Further mitigation could be possible with additional structural changes of the industrial sector and the adoption of

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([22]) Synthetic fuels (methane, hydrogen) are accounted in the final energy demand; the energy consumption to produce these fuels is accounted in the energy transformation sector.

CCS associated with these emissions (which would, however, reduce the energy efficiency of these processes).

Box 11. Circular economy: Effects on industry organisation and energy consumption

Circular economy (CE) is defined as an economy "where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste is minimised" (European Commission, 2015). To this end, the CE moves away from the concept of the linear economy, and focusses on the concepts of "reuse, reduce, recycle and recovery" (European Commission, 2014). CE is based on the design of industrial processes that facilitate the disassembly and reuse of finished products, eliminating the concept of waste: waste can be designed for continuous recovery and reutilisation as a feedstock for other processes or uses. CE aims to reproduce "biological metabolism" as a model for developing a "technical metabolism" (Braungart, 1998) where the products and materials are designed with life cycles that are safe for human health and the environment and that can be reused perpetually, striving for a closed cycle. Higher and sustained improvements of resource efficiency performance are within reach and can bring major economic benefits (Wyns, et al., 2018).

The so-called "economy in loops" would also have a large impact on job creation, economic competitiveness, resource savings, and waste prevention. In the transition to a low-carbon economy, a CE would enable new business models. In the industrial sector, nine types of business models have been identified. These are industrial symbiosis (e.g. valorisation of waste heat and materials waste streams), Product Management Service (PMS), Cradle to Cradle (C2C), Green Supply Chain Management (GSCM), circular supplies business model, Product Life Extension (PLE), lean manufacturing, closed loop production, and Take Back Management (TBM).

These new and emerging business models hold the potential to generate higher levels of employment. However, skills development will be a particularly important challenge[23.]In doing so, it brings about benefits to a wide range of fields such as climate change, resources scarcity, environmental protection, effective waste management, and R&D and innovation. Regarding CE's CO_2 mitigation potential, a recent study (Enkvist & Klevnäs, 2018) estimated that the CO_2 emissions of EU heavy industries (steel, plastics, aluminium and cement) could be more than halved in a scenario that assumes an ambitious implementation of CE. In the central 2°C scenario presented in this report, recycled secondary steel would provide two thirds of total annual steel needs globally, compared to just a quarter in 2015, reducing the need for the emissions-intensive thermal processing of primary steel.

CO_2 emissions themselves can be captured and used as a raw material in certain chemicals and materials industries (CCU). CO_2 can also be used for the production of synthetic methane with an important energy premium: in the 2°C scenario, 240 $MtCO_2$/year are thus re-used in 2050. However, the annual amount of CO_2 that can be re-used is estimated to be relatively low (0.2 to 2.3 $GtCO_2$/year according to (Naims, 2016) compared to about 50 $GtCO_2$-eq/year emissions that need to be mitigated from a Reference to a below 2°C scenario (Kitous, et al., 2017).

The EU is supporting the implementation of CE through a number of measures, and in early 2018 adopted a set of measures to implement its Circular Economy Action Plan (European Commission, 2018).

The adoption of legislation related to CE is pursued outside of the EU as well. For example, China has gradually included the CE in its strategy since 2002, not as improved environment management but as a new development model to help China leapfrog into a more sustainable economic structure. The successful enforcement of a CE can be seen as a way for China to tackle its urgent problem of environmental degradation and source scarcity. The "3R principles" (Reduction, Reuse, and Recycle) have been included in the flows of materials and energy in production, distribution and consumption; CE policies also extend to land use and water management (Su, et al., 2013).

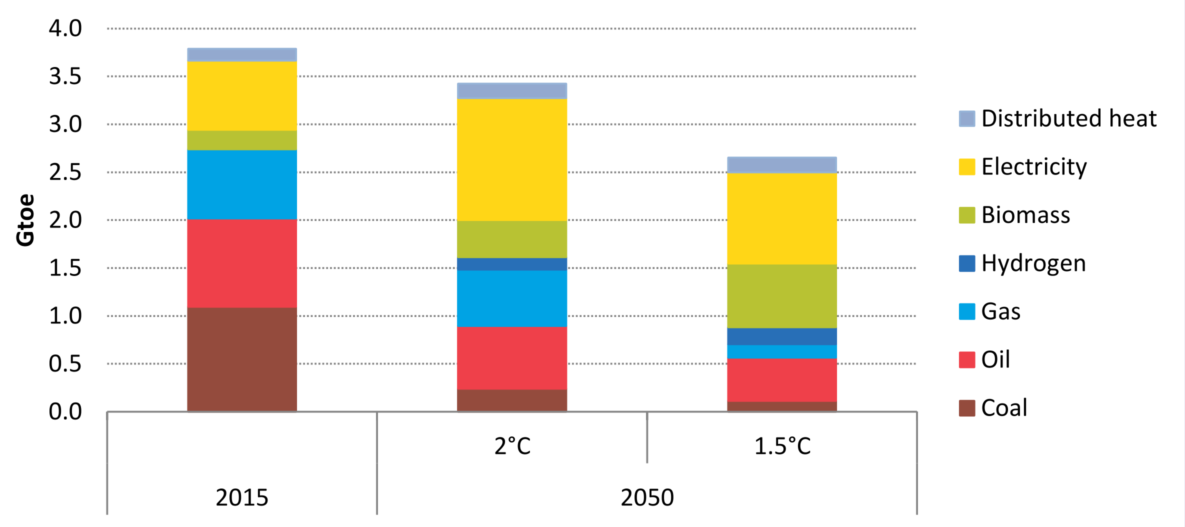
Box 12. The industrial sector in the 1.5°C scenario

In the 1.5°C scenario, further energy efficiency and a wider use of alternative fuels would drive the additional decarbonisation of the industrial sector by 2050.

CO_2 emissions from energy uses would drop from 6.1 $GtCO_2$ in 2015 to 0.3 $GtCO_2$ by 2050; CO_2 emissions from processes would be mitigated only slightly further.

Energy consumption for energy uses would drop to 2.0 Gtoe in 2050 (compared to 2.7 Gtoe in the central 2°C scenario). Electricity and solid biomass would provide 46% and 32% of industry's energy uses, while hydrogen would make up 77% of gaseous fuels in 2050 (these figures would be 46%, 14% and 22% in the central 2°C scenario, respectively). Nearly all fossil fuel consumption in industry would be for non-energy uses (Figure 39).

Figure 39. Industry final demand energy mix in 2050, central 2°C and 1.5°C scenarios



Source: POLES-JRC 2018.

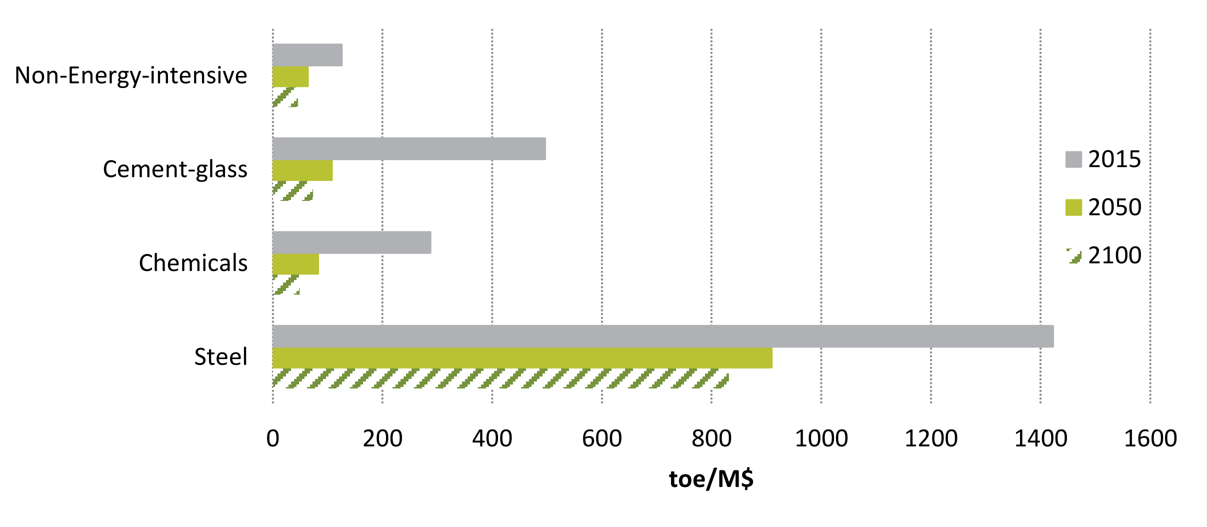
The extent of these changes, in particular in energy efficiency, appear extremely challenging and raise important questions as to the technical solutions to decarbonise industry further, as well as to the nature of policies to be implemented to achieve it.

Box 13. The industrial sector in 2100

Projecting the industrial sector beyond 2050 is a complex and sensitive issue, as it would be highly dependent on the nature of the goods that would be consumed, and on potentially disruptive technologies for industrial processes that have not yet been developed. As a result, the existing correlations between industrial value added (derived from economic growth) and energy needs might not hold in the long term.

In our projections, energy efficiency improvements and electrification would continue to shape the industrial sector. The evolution of the energy intensity per unit of value added for four industrial branches are presented in Figure 40.

Figure 40. Evolution of energy intensity per unit of economic output by industrial sector, central 2°C scenario World



Source: POLES-JRC 2018.

Between 2050 and 2100, the energy uses consumption of the industrial sector would be stable while industry value added would grow by a factor of 1.6. Electricity would provide 61% of the sector's energy use and solid biomass a further 19%. Energy-related CO_2 emissions would drop to zero with the expansion of CCS (including carbon-negative BECCS, absorbing 0.8 $GtCO_2$ annually by 2100); some CO_2-process and non-CO_2 emissions would still remain, at 0.8 and 0.1 $GtCO_2$-eq, respectively.

4.3.7 Air pollutants emissions in industry

Industrial activity has a significant contribution to air pollution for most of the categories of substances covered in this study. The causes of air pollution from industry are both energy-related (combustion of fossil fuels and biomass to provide energy to industrial processes) and process-related (transformation and manufacturing processes). The shares of industry-related emissions per pollutant in the central 2°C scenario are presented in Table 7.

Table 7. Air pollutants emissions from industry in the central 2°C scenario, volumes and shares of total, World

	2010		2030		2050	
	Emissions (Mt)	Share of total	Emissions (Mt)	Share of total	Emissions (Mt)	Share of total
SO_2	34	37%	34	54%	11	57%
NO_x	18	16%	15	18%	6	16%
$PM_{2.5}$	11	28%	12	30%	5	27%
CO	79	17%	78	19%	27	14%
VOC	5	5%	5	5%	3	5%

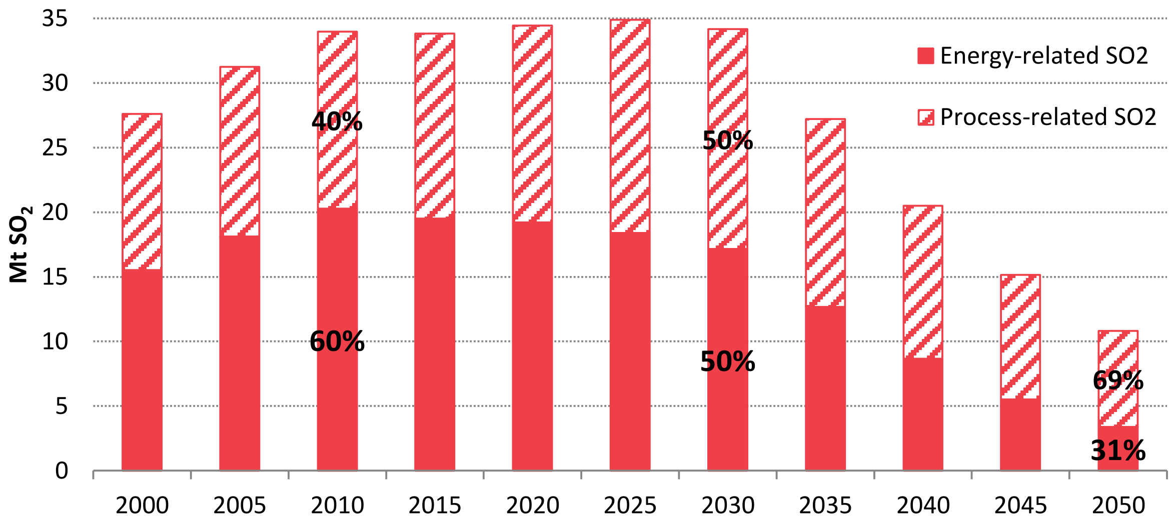
Source: POLES-JRC 2018

Industry emissions would represent the highest proportion of total SO_2 emissions (respectively 34, 34 and 11 Mt in 2010, 2030 and 2050); the increasing share, due to substantial abatements achieved in the power sector, would make industry the main SO_2 emitter in 2050 in the central 2°C scenario.

NO_x, CO and $PM_{2.5}$ from industry would represent rather stable 14–20% (NO_x and CO) and 27–30% ($PM_{2.5}$) shares of total emissions throughout the studied period, meaning that their abatement path would follow the total trend for each pollutant. As the regulation described through the emissions intensity factors gradually enforces the use of maximum technically feasible reductions in the industrial sector, the emissions intensities of the main categories of pollutants are expected to drop over time. On the other hand, industrial activity would keep growing, which would reinforce the need for the technological improvement of industrial processes. In addition, energy efficiency and fuel switching are expected to reduce energy-related emissions – this is the main area of the co-benefits of climate policies with air pollution.

These dynamics are well illustrated by examining the case of SO_2 emissions. Figure 41 shows the split of emissions between energy and non-energy-related emissions. In recent history, energy-related emissions represented the majority (60% in 2010) of emissions: as total emissions would be initially stable and would then fall sharply, the share of energy-related emissions would drop to 31% in 2050, indicating a faster decoupling with activity levels compared to process emissions.

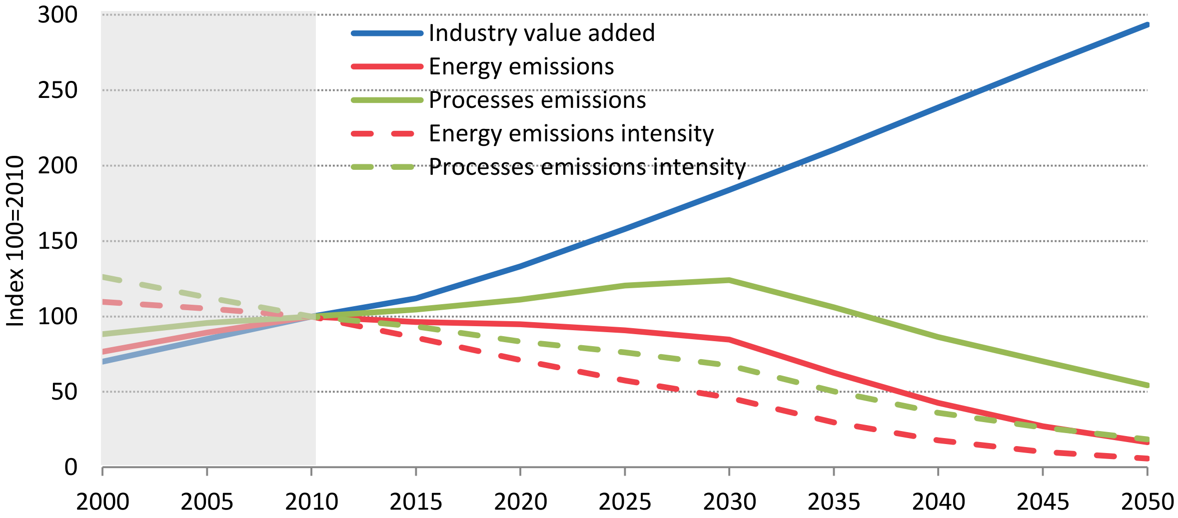
Figure 41. Breakdown of SO_2 emissions in industry, central 2°C scenario



Source: POLES-JRC 2018.

Figure 42 shows the decomposition of these emissions according to activity (industry value added) and emissions intensities (emissions per unit of activity). While changes in the energy system would induce a significant drop in emissions intensity of energy use, the reduction of process-related intensity would be slower. Hence, energy-related emissions would be reduced between 2010 and 2030, while process emissions would be sustained by the growth of economic activity. However, after 2030, both emissions intensities would keep falling at a pace high enough to compensate for the growth of industrial output.

Figure 42. Drivers of industry SO_2 emissions, central 2°C scenario



Source: POLES-JRC 2018.

4.4 Mitigation options for the Transport sector

The transport sector (24) accounted for 29% of total energy consumption and was responsible for approximately 24% of total CO_2 emissions (16% of total GHG emissions) in 2015. GHG emissions primarily involve fossil fuels burned for road, rail, air, and maritime transportation. Currently, almost all of the world's transportation energy comes from petroleum-based fuels, largely gasoline and diesel (95% in 2015).

Table 8. Summary of the transport sector, central 2°C scenario

Transport in transition	**2015**	**2050**
Passenger mobility: private cars, public transport (bus, rail) and air (Tpkm)	33, 17, 6	55, 42, 17
Freight traffic:road, rail, aviation, maritime (Ttkm)	27, 8, 0.2, 87	61, 15, 0.4, 147
Total transport energy use (Gtoe) % of total energy use)	2.7 29%	2.3 28%
CO_2 emissions ($GtCO_2$) % of total CO_2	7.9 24%	4 33%
Electrification (% of energy use)	1%	14%
Direct renewable participation (% of energy use)	3%	16%
Plug-in hybrid and full electric share in sales (%), private vehicles	0.2%	60%
Gas and hydrogen share in sales (%), private vehicles	0.2%	31.5%
Synthetic methane in gas use (%)	0.0%	53.3%

Note: Figures include energy consumption and emissions of international aviation and maritime bunkers. Direct renewable participation refers to liquid biofuels.

Source: POLES-JRC 2018.

The challenges faced by the transport sector to reduce its GHG emissions are related to this sector's diffuse emission sources, to the carbon intensity of the fuels used and to the continuing growth in passenger and freight activity that is expected in the coming decades. Traffic growth could outpace mitigation measures, unless emissions can be strongly decoupled from economic growth and the increase in private car ownership rates. Reducing the carbon intensity of fuels for transport will only be possible by substituting oil-based products with liquid biofuels, natural gas, electricity or synthetic gases (hydrogen, synthetic methane) produced from low-emissions sources (25).

In the central 2°C scenario, total transport energy consumption is projected to grow until 2020 with a stable growth ratio since 1990 of 2.0%/year as a world average. After 2020 it would decrease at 1.0%/year rate over 2020–2050, reaching the levels of 2005 in 2050, at around 2,300 Mtoe (Figure 43). Despite an increase in the consumption of international aviation and maritime bunkers, most of the energy consumption will still be due to road transport throughout the projection period.

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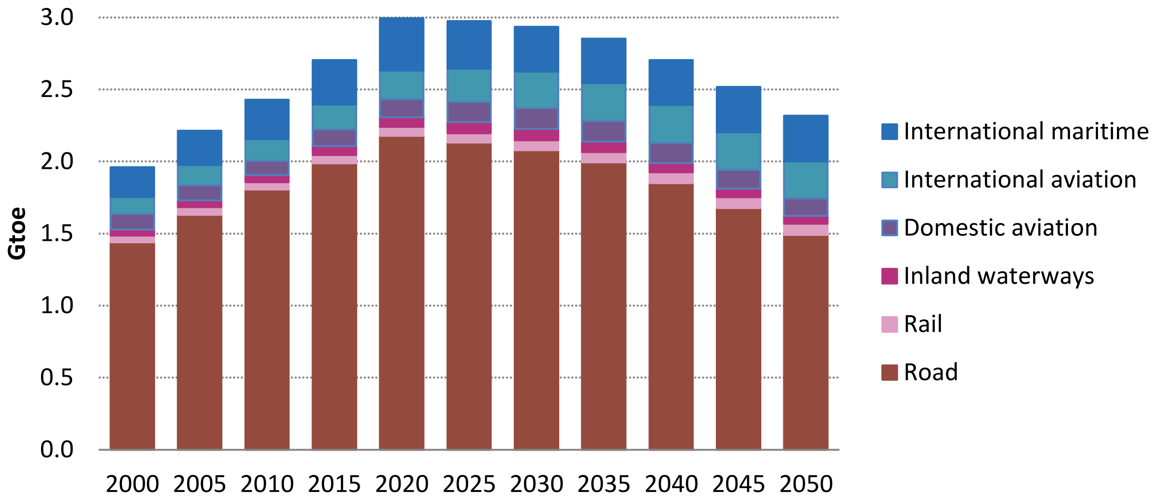
(24) Figures on energy and emissions of transport throughout this report refer to the final energy demand of transport activities (road, rail, inland waterways, domestic aviation) as well as international aviation and international maritime bunkers.

(25) In this report, oil products in transport and other final demand sectors include a small amount of synthetic liquids (<1%, from coal and gas liquefaction, Figure 87). Total gas refers to methane of natural or synthetic origin; synthetic methane (produced from combining hydrogen and CO_2) is consumed only in road transport. Liquid biofuels are consumed in transport (including the international aviation and maritime sectors). Hydrogen in transport is consumed in road transport and international maritime bunkers.

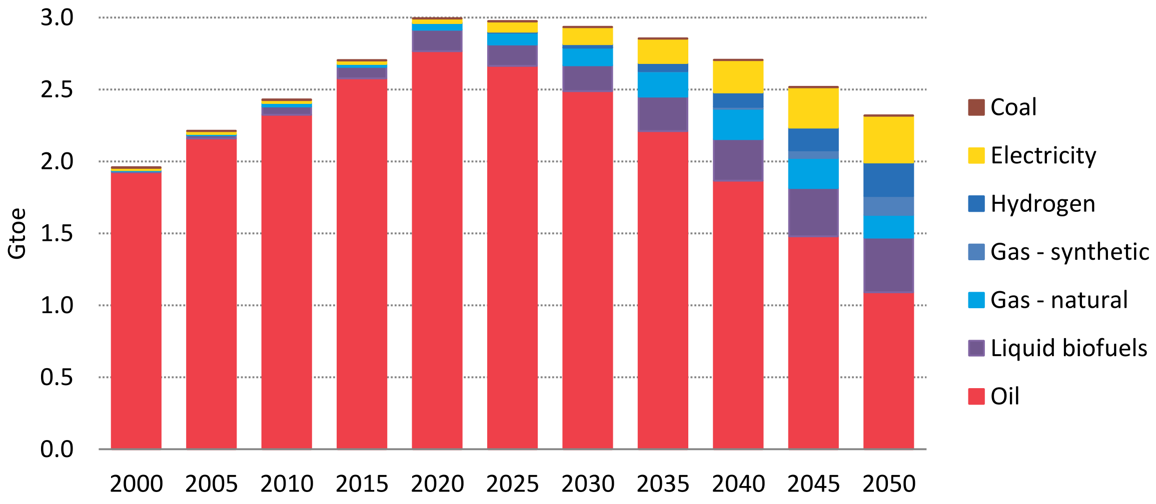
Figure 43. Transport energy consumption by mode, World, central 2°C scenario



Source: POLES-JRC 2018.

While oil products are currently the main fuel used in the global transport sector, making up nearly all of road, air and maritime consumption, the fuel mix is projected to diversify, notably with the expansion of liquid biofuels and electricity. By 2050 oil products are projected to satisfy just 47% of world transport's energy needs (Figure 44). The energy mix of transport is projected to become more diversified. By 2050, nearly half of the methane gas used in the transport sector overall would be synthetic (produced by combining hydrogen with captured CO_2) and used in road transport.

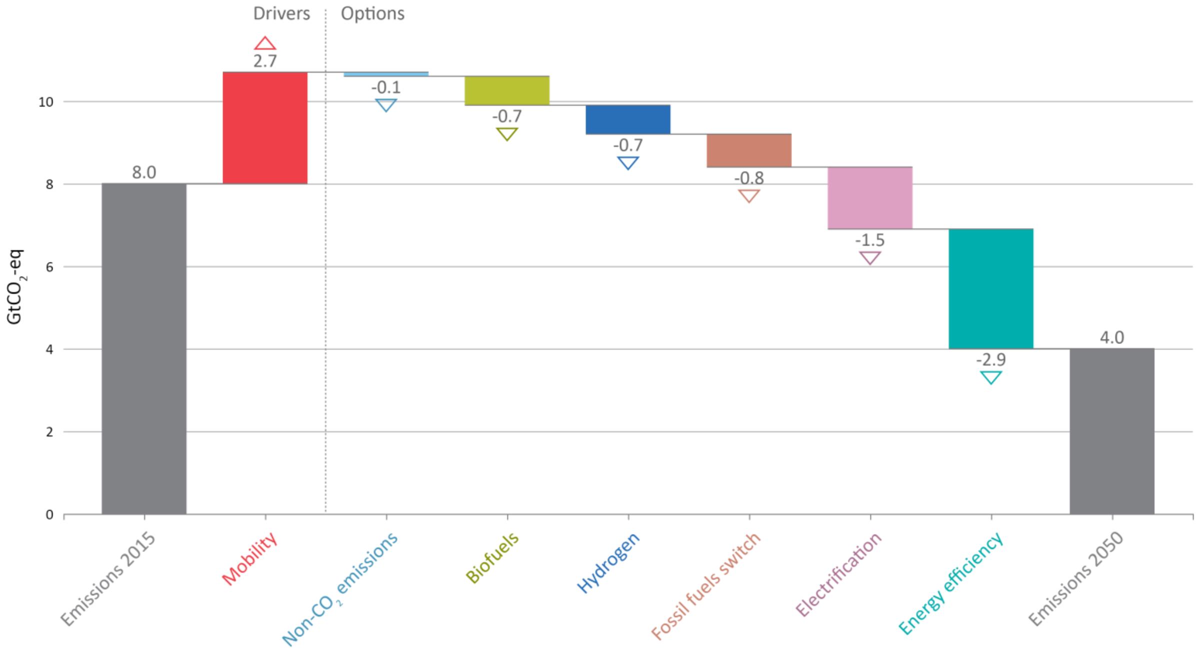
Figure 44. Transport energy consumption by fuel, central 2°C scenario, World



Source: POLES-JRC 2018.

The GHG emissions mitigations options adopted by the transport sector in the central 2°C scenario are presented in Figure 45.

Figure 45. Transport GHG mitigation options from 2015 to 2050, central 2°C scenario, World



Notes: "Mobility": emissions growth due to the growth of population and the economy (passenger and freight traffic). "Hydrogen", "Biofuels", "Electrification": emissions prevented by the use of these fuels (emissions for their production accounted elsewhere). "Fossil fuels switch": substitution of oil with natural gas and synthetic methane. Includes international aviation and maritime bunkers.

Source: POLES-JRC 2018.

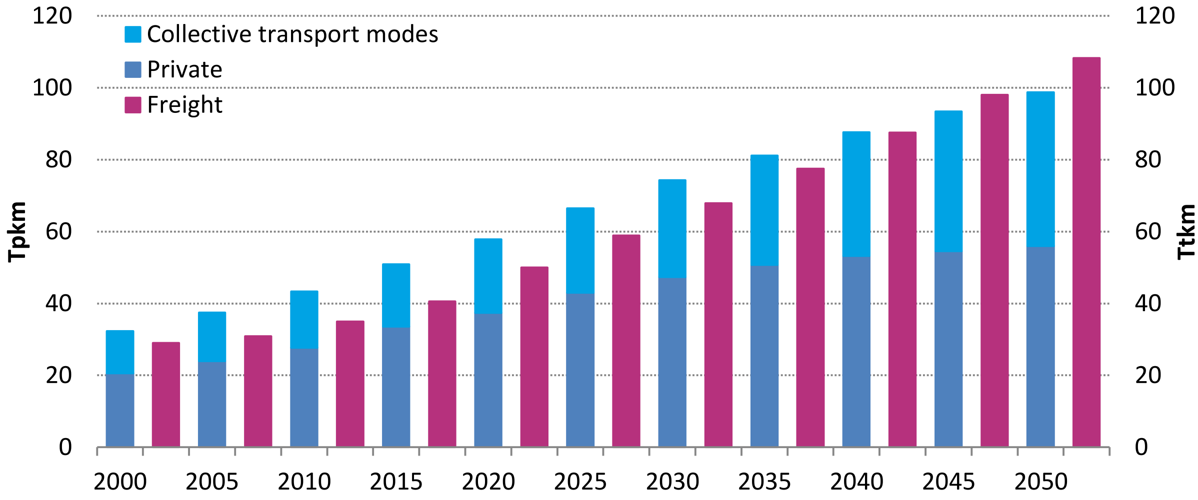
The following sections examine the mitigation options for each transport mode and the drivers behind the evolution of each mode's energy use.

4.4.1 Land transport trends

Road transport is a sector where the underlying activities – passenger and freight traffic – are expected to grow significantly in the future. However, many expectations of an easy and fast decarbonisation have risen thanks to the decreasing costs of electric batteries.

More than half of the total energy consumption in road transport currently (2015) is due to private cars. Total passenger traffic in road transport is expected to double over 2015–2050, with an increasing share of trips taking place by collective transport modes (i.e. buses and coaches) in the central 2°C scenario, a modal shift motivated in part by climate policies (Figure 46). The high growth in road passenger transport activity is driven by economic growth and increasing car ownership, in particular in developing economies where the car ownership ratio is still significantly lower compared to developed economies: six times as high in OECD compared to non-OECD regions in 2015, a gap that decreases to just twice as high by 2050. The number of cars on the road worldwide is projected to more than double, from about 1.1 billion vehicles in 2015 to 3.0 billion vehicles in 2050. However, in terms of passenger-kilometres, cars' activity is projected to increase less (by 70% only), due to lower kilometres travelled per car over time and a shift towards collective transport modes (motivated in part by climate-related policies).

Figure 46. Evolution of passenger and freight traffic in road transport, private and collective transport modes, central 2°C scenario, World



Source: POLES-JRC 2018.

Freight transport is currently (2015) responsible for about 36% of road transport's energy consumption. With the expected economic growth trend, the transport of goods over land is projected to more than double over 2015–2050, for both road and rail modes (Figure 46) in the central 2°C scenario.

4.4.2 Efficiency

In order to satisfy these mobility needs and decarbonise its energy use, in the central 2°C scenario the road transport sector will have to reduce the carbon intensity of its fuel use, either via a more efficient use of oil products or by changing to an engine type that uses different fuels.

Cars with internal combustion engines (ICE) are expected to continue to improve their performance; this could be the result of different improvements such as pure powertrain efficiency gains, regenerative breaking, plug-in hybridisation and range extension, but also due to changes in the design and manufacturing of the body (size, materials used). New ICE cars' fuel efficiency is projected to increase considerably in OECD countries, with a reduction of energy use per kilometre travelled of 31% over 2015–2050 (to be compared with the corresponding 21% decrease over 1990–2015). The adoption of such cars by OECD markets, or any market worldwide large enough to drive innovation, will then diffuse and be adopted by the rest of the world. For instance, China's fuel efficiency standards have followed Euro standards with ever shorter time delay (Crippa, et al., 2016). Two main reasons explain this fast adoption of OECD standards: on the one hand, the willingness to guarantee clean air of similar quality as in large Western cities and (possibly more importantly) the willingness to export cars to OECD markets. For these reasons, ICE new cars' energy use per kilometre travelled in non-OECD countries is projected to decrease by 60% over 2015–2050.

4.4.3 Biofuels

Concerning the energy consumed in ICE vehicles, further decarbonisation can be achieved with liquid biofuels, which have a lower carbon intensity (26) than liquids of fossil origin. Most of the gasoline and diesel cars currently sold do not support high blends of bioethanol; however, this can change in the future in a relatively short time, as the Brazilian experience has shown (flexi-fuel cars went from zero to 95% of total new car registrations within 10 years following the commercialisation of the first flexi-fuel model (ANFAVEA, 2013).

In the central 2°C scenario, bioethanol and biodiesel consumption in various blends is expected to increase over time and would account for 18% of total liquids in road transport in 2050, compared to 4% in 2015. Higher blends could be reached with targeted policies to support biofuels uptake and an accelerated turnover of the car fleet. However, liquid biofuels production is in competition with other uses of biomass that might offer higher emissions reductions (section 5.4).

4.4.4 Powertrain electrification

The main drivers for the electrification of road vehicles are regulations and technological developments. In Europe, several countries envisage phasing out ICEVs entirely: the UK and France from 2040, Norway potentially from 2025 and Germany from 2030–2040. Discussions on a ban on diesel from inner cities put further pressure on car manufacturers to shift their production capacities towards the manufacturing of EVs. In addition, certain countries provide financial incentives for the purchase of electric cars (e.g. Germany supports buying a full EV with €4,000 and a plug-in-hybrid with €3,000) (27). China set a new-energy vehicle quota of 10% for 2019 and 12% for 2020; it is expected to be between 20–25% in 2025 (28).

In parallel to political support and regulations, technological developments have significantly reduced electric battery costs (Box 14).

On a global scale the market share of EV in new sales reached 1% or 1.2 million vehicles in 2017. China is leading the market with a 48% market share followed by Europe with 26% (29). As of the end of 2017, 165 models of EV were available to be sold commercially and several major car manufacturers have announced (30) a widening of

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(26) Carbon intensity refers in this report to the direct emissions from biofuels production. The emissions are the result of agriculture and processes and can give a wide range depending of the carbon intensity of the energy needs for the conversion processes as well as factors such a fertiliser application rate. This results in a carbon intensity for bioethanol that can be between 8 times smaller (in the case of Brazilian sugarcane) to levels only two times smaller than gasoline (for corn ethanol production). The biodiesel carbon intensity range is in average 4 times smaller than diesel and can even reach 8 times smaller; it depends on the biofuel production process and the substitution of the fossil energy needs with biomass self-consumption (https://ww2.arb.ca.gov/homepage). Carbon contents used in this report range from as much as oil products to three times smaller, depending on the biofuel type considered and substitution with biomass self-consumption; indirect land use change emissions are accounted in land use in 4.6. The use of liquid biofuels in final consumption is then considered to have zero emissions.

(27) BMWI (Federal Ministries for Economic Affairs and Energy) 2018, https://www.bmwi.de/https://www.bmwi.de/Redaktion/EN/Dossier/electric-mobility.html, https://www.bmwi.de/Redaktion/EN/Artikel/Industry/regulatory-environment-and-incentives-for-using-electric-vehicles.html

(28) http://english.gov.cn/state_council/ministries/2017/09/29/content_281475892901486.htm

(29) https://go.frost.com/EU_PR_KMenzefricke_MDAB_ElectricVehicle_May18

(30) Volkswagen announced plans to build up to three million electric vehicles annually by 2025 and market 80 new electric Group models (https://www.volkswagenag.com/en/news/2018/03/VolkswagenGroup_expand_production.html) Toyota is aiming to launch 10 new BEVs worldwide by “the early 2020s” and it wants to have electric options throughout its entire lineup of cars by 2025 (https://electrek.co/2017/12/18/toyota-electric-car-plans/). General Motors plans to launch a new family of electric vehicles in 2021 (https://www.reuters.com/article/us-gm-ceo/gm-challenges-tesla-with-promise-of-profitable-electric-cars-idUSKBN1DF272). Further plans were announced by Renault, Ford, Daimler, BMW, Fiat, Volvo and others

their portfolio of electric models, pointing towards an acceleration of the uptake of becoming fully EV in the coming decades.

In the central 2°C scenario, new registrations of electric private cars increase from less than 1% globally in 2015 to 44% in 2050. This uptake is faster in OECD countries: 55% of new registrations in OECD vs 41% in non-OECD in 2050. Indeed, oil products are taxed higher in OECD countries than in non-OECD countries and public support for recharging infrastructure already exists or is expected to be quickly developed. As a result, battery EVs would represent a substantial 36% of the world vehicle stock in 2050. To this should be added the plug-in hybrid vehicles, which would make up 16% of the world vehicle stock by the same date.

Uptake in trucks is projected to be much slower mainly due to technical reasons. Whereas ICEs gain thermal efficiency with size, therefore inducing economies of scale for large (mainly diesel) motorisations, electric power is additive and proportional without offering any competitive advantage in scaling up. In addition, the need for large battery stacks, and the use of these vehicles for long-distance trips would induce higher costs for battery electric trucks. Within this market segment, hydrogen trucks could, however, become cost-competitive in the central 2°C scenario, as the energy mass density of hydrogen gives an advantage to long-distance travelling. However, this picture might be different for buses that are used in urban areas, where predefined routes and planned recharging times would make it possible to limit battery size.

As a consequence of these trends, electric battery and plug-in hybrid vehicles would come to represent only 5% each of the global stock of coaches and trucks by 2050. Conversely, coaches and trucks powered by alternative combustion fuels would show higher penetration rates (17% of vehicles with gas, both natural and synthetic methane in compressed gas vehicles and in gas fuel cells; and another 13% with hydrogen).

Finally, without thermal losses, a vehicle with an electric engine and powertrain is approximately three times as more energy-efficient as an oil-fuelled vehicle. This would contribute significantly to the overall decrease of road transport’s energy consumption.

The above-discussed developments in terms of efficiency, biofuel blending and EVs deployment, a limited expansion of compressed natural gas vehicles (7% and 13% of total private cars and trucks stock in 2050, respectively), the use of synthetic methane instead of natural gas (35% of total gas in road transport would be synthetic by 2050) and a relatively limited expansion of hydrogen-fuelled vehicles (10% and 14% of total private cars and trucks stock in 2050, respectively) would all contribute to the reduction of oil use in the road transport sector from 1.9 Gtoe in 2015 to 0.7 Gtoe in 2050, a 65% decrease in the central 2°C scenario (31).

(https://www.reuters.com/article/us-autos-electric-factbox/factbox-automakers-get-serious-about-electric-cars-idUSKBN1DH28A, Business News)

(31) Synthetic methane (produced from combining hydrogen and CO_2) is consumed only in road transport and represents a share of total gas consumed; it can be used in compressed gas vehicles or in vehicles with gas fuel cells. Hydrogen is accounted separately from total gas; it is consumed in vehicles with fuel cells.

Box 14. Batteries and the emergence of massive electric mobility

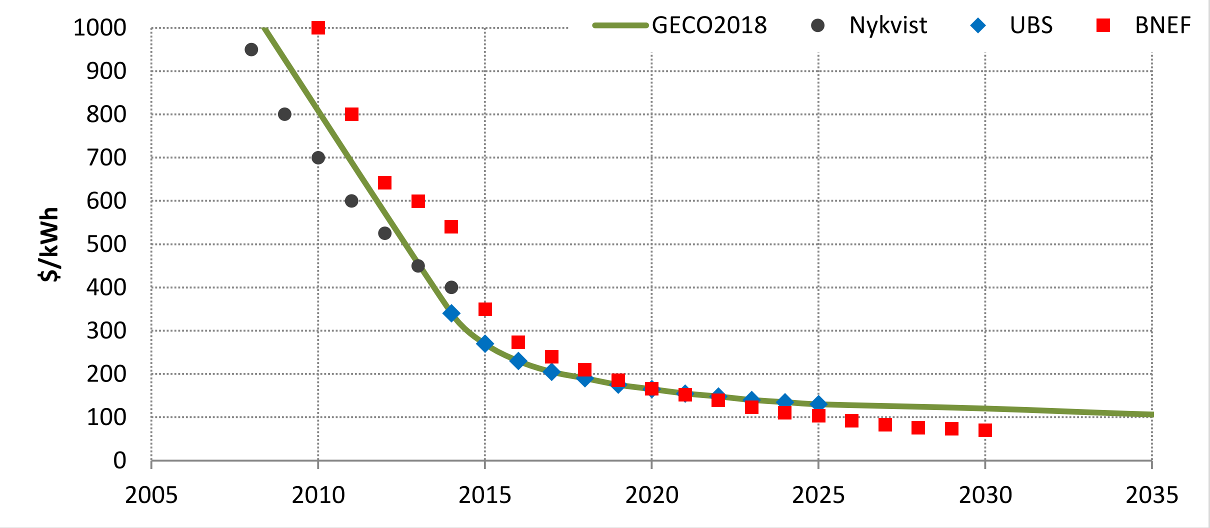
Electrochemical power storage has evolved significantly since Alessandro Volta conceived the first copper-zinc battery in 1800. Technological progress has led to batteries with larger availability of sizes, use formats and purposes, both for primary (single-discharge) and, more importantly and growing, secondary use (rechargeable). The automotive industry has witnessed in the previous 10–15 years a remarkable technological improvement in lithium-ion (Li-ion) battery production costs and economies of scale of batteries assembly and production, thus boosting the expectations for a massive deployment of road electro-mobility.

Electric vehicle battery cost

EVs powered with Li-ion were first introduced on a market scale around 2010, and their battery packs costed over 1,000 $/kWh. Today, EVs battery pack costs are around 200 $/kWh, and some companies like Tesla claim to be below $190/kWh since early 2016, consolidating a 70% cost decline in an extremely short time period. The price of Li-ion batteries has dropped at an unprecedented rate as manufacturers have developed more cost-effective designs and as production methods and scales have accelerated the technology learning rate. Bloomberg New Energy Finance foresees the price of a lithium-ion battery pack dropping to as low as 73 $/kWh by 2030.

Technology consolidation has also conveyed a reassurance to the market of the durability and reliability of batteries that are now often sold with a guarantee of 5–8 years of operation and/or above 150,000 km of kilometres travelled.

Figure 47. Battery cost projection in the central 2°C scenario



Source: Nykvist (Nykvist & Nilsson, 2015) (March 2015), UBS (May 2017) (32), BNEF (July 2017) (33)

These costs might have to be revised as the penetration of EVs increases and new uses are found for their batteries: vehicle-to-grid (V2G) applications would increase the number of cycles, thus shortening the lifetime of the battery; a battery designed for a longer number of cycles and faster charge/discharge would be different from the ones in current car models, which are more geared towards a longer autonomy, and would increase the cost (Speidel & Bräunl, 2014).

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(32) https://neo.ubs.com/shared/d1wkuDlEbYPjF/
(33) https://about.bnef.com/blog/lithium-ion-battery-costs-squeezed-margins-new-business-models/

Running costs of an EV

In many world markets such as the EU, EVs are already close to matching the running costs of traditional ICE vehicles. In terms of fuel costs, present EVs operate with an efficiency ranging between 12 kWh/100km (small ones – Renault Zoe) to 25 kWh/100km (large ones – Tesla), i.e. yielding fuel-related operation costs ranging between 0.018 €/km and 0.0375 €/km (assuming an electricity retail price of 0.15 €/kWh). Fuel costs for ICEVs (assuming a gasoline/gasoil price of 1.5 €/l and specific consumption between 4 l/100km and 8 l/100km) would range between 0.06 €/km and 0.12 €/km. Maintenance costs are also expected to be much lower for EVs than for ICEs (around half the cost, even though a range extender could raise the maintenance costs of EVs up to the level of ICEs (IFP Energies Nouvelles, 2018)). For EV and PHEV charging, the existence of some subsidies to the EV purchase, the stability and planning benefits of household electricity rates and the regulatory advantages offered by many administrations in terms of parking use, toll exemption and avoidance of congestion charges offer an attractive alternative compared to traditional petroleum-based transportation. Therefore it would seem that, without considering autonomy constraints, the economics of the full chain of EVs is expected to become commercial in the close future ([34]).

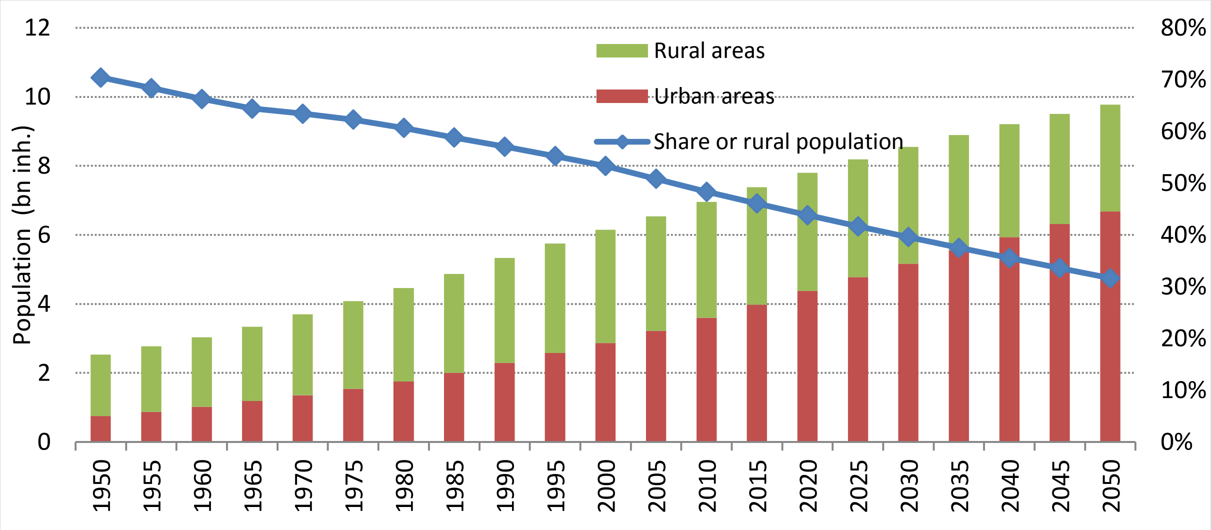
Box 15. New mobility patterns and urbanisation

The road transport sector is undergoing several structural changes:

- **Electrification** is increasingly supported by governments and is gaining acceptance in societies. Tougher regulations of CO_2 emissions and fuel consumption could lead to a significant electrification of powertrains. Technical progress on batteries would lead to a reduction of costs and an improvement in the technical features of EVs, like the driving range.
- At the same time **autonomous driving** through the application of a wide range of sensors has appeared. While autonomous driving, like driving assistance (level 1), is already implemented in many cars, cars with full self-autonomous driving features (level 5) are currently in the test phase.
- **Car-sharing** concepts like ride hailing have already emerged (Uber) and several market players have agreed on co-operations to establish further car-sharing concepts (e.g. DriveNow & Car2go by Daimler & BMW). The rise of car-sharing could reduce costs and shorten investment paybacks through higher utilisation rates.
- In addition, key drivers for new mobility are **urbanisation** and the **ageing** society. Globally, a strong push towards more urbanisation is taking place. While in the 1950s around two thirds of the population lived in rural areas and only one third in urban ones, the relation between the two levelled out in 2008. According to the UN it is assumed that urbanisation will continue to increase resulting in an urban population that is twice as high compared to the rural population in 2050.

([34]) Data sources: JRC own estimates based on (INL, 2014) and (BNEF, 2018)

Figure 48. World urban and rural populations, 1950-2050



Sources: UN, World Urbanisation Prospects 2018.

Higher urbanisation and population growth is putting more pressure on existing infrastructure leading to more congestion, higher local air pollutant emissions and difficulties regarding parking space. In addition, the ageing society might foster new mobility patterns. Car-sharing is often linked to the "sharing economy", and is more popular amongst the millennials generation. Autonomous driving might also enable the elderly to maintain their mobility levels.

While urbanisation and the ageing society support new mobility patterns, there are also several risks and barriers. If major developments on the battery side (costs, energy density, shorter charging times) are not delivered, the rollout of EVs could be hampered. Raw materials and low consumer acceptance could hinder the advance of new mobility patterns and/or the uptake of EVs.

New mobility patterns may lead to new ways of looking at transport, focussing on the usage of vehicles and less on their ownership. While currently emotions and prestige dominate vehicle choice, values might change in the future. In addition, the shift to electric transportation might also have a significant impact on settlements, as passengers in driverless vehicles could make use of the commuting time productively – thus, enabling commuters to live further from city centres.

4.4.5 Air transport

Both passenger and freight air transport activity is projected to more than double over the period 2015–2050 in the central 2°C scenario. While growth would be less pronounced for OECD countries, non-OECD countries would experience an even stronger growth: passenger transport in particular is projected to increase by a factor of 2.7 over that period. Passenger transport activity for international flights (a 2.9-fold increase in 2015–2050) is expected to grow at a faster pace than domestic flights (a 2.4-fold increase in the same period), reflecting increasing globalisation and the increasing availability of discretionary spending.

Efficiency gains, both in terms of fuel efficiency and non-engine-related efficiency measures, are the main drivers behind reducing emissions in this sector. These measures include better air traffic management, deployment of next generation aircrafts with more fuel-efficient engines, re-engining (35) and technically improved flight patterns

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(35) https://www.iata.org/publications/economics/Reports/not-published/IATA-CO2-abatement-modelling-report-July-2013.pdf

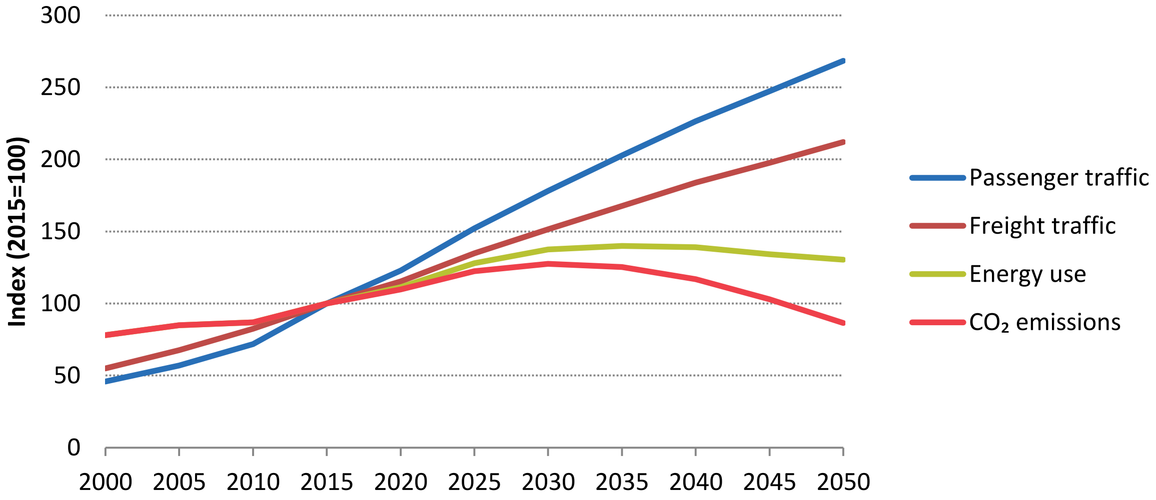
(Dahlmann, et al., 2016). Mobilising this wide range of options, new airplanes are projected to consume 70% less fuel on average in 2050 compared to 2015.

The second option is a fuel switch. Biofuel blends currently appear to be the most economic option. In the central 2°C scenario, they are projected to represent a third of total fuel use by 2050, thereby displacing 130 Mtoe of oil products. Other synthetic liquids could be an option that is, as yet, still in the early stages of development ([36]).

Electric engines and hydrogen engines are other solutions that are presently too embryonic and were not considered in this study. However, electric engines could develop and may satisfy a share of relatively short-distance flights, such as domestic or intra-EU flights ([37]).

Key indicators of air transport projections in the central 2°C scenario are presented in Figure 49.

Figure 49. Key projections in air transport, central 2°C scenario, World



Source: POLES-JRC 2018.

Total aviation energy consumption is thus projected to increase and then stabilise, from 290 to 379 Mtoe over 2015–2050. Of the total fuel use, the largest share is expected to come from the international aviation sector (60% in 2015, 67% in 2050). On the other hand, the corresponding emissions are projected to increase only up to 2030 and decrease thereafter, going from 850 in 2015 to 1085 in 2030 to 740 $MtCO_2$ by 2050.

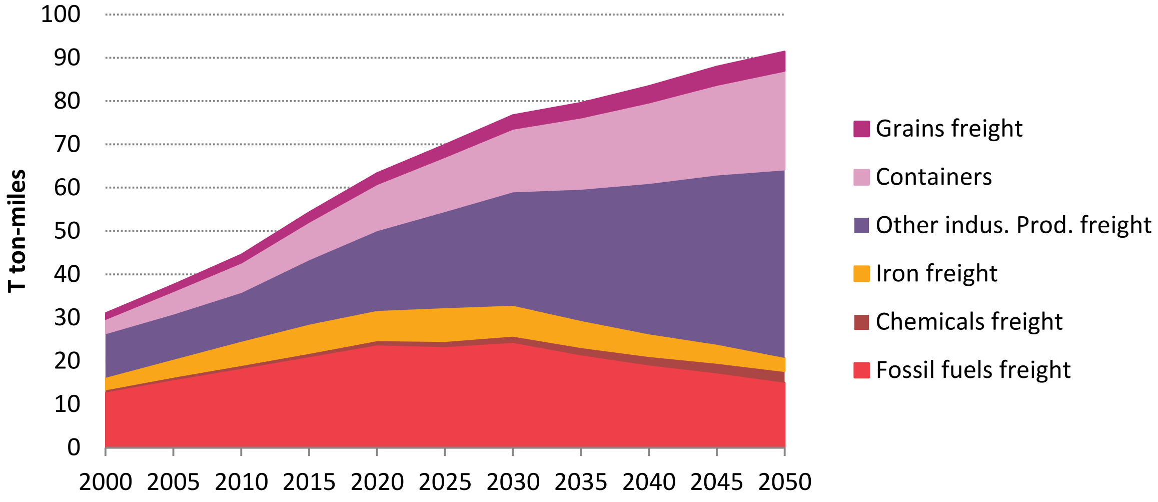
4.4.6 Maritime transport

With increasing global trade, international maritime transport is projected to grow strongly in the future. However, due to the climate policies implemented in the central 2°C scenario, the combined international trade of oil, gas and coal is expected to plateau throughout 2030 and decrease thereafter (despite a growing use of Liquefied Natural Gas (LNG)); while traffic for some other goods types is expected to increase significantly. As a consequence, total maritime activity would increase from about 54,000 billion ton-miles in 2015 to over 90,000 billion ton-miles in 2050, a 68% increase over the considered period (Figure 50).

([36]) Synthetic methane is included in road transport. This report does not consider synthetic liquids produced by combining hydrogen with CO_2 ("Power-to-liquids").

([37]) https://www.airbus.com/newsroom/press-releases/en/2017/11/airbus--rolls-royce--and-siemens-team-up-for-electric-future-par.html; https://www.telegraph.co.uk/business/2017/11/28/electric-aircraft-near-take-off-rolls-royce-airbus-siemens-team/

Figure 50. Projections of maritime traffic per type of traded product, central 2°C scenario, World



Source: POLES-JRC 2018.

Efficiency improvements represent a very important driver for the foreseen emissions mitigation in the maritime freight sector. It is achieved through a wide range of options: propulsion engines, propeller optimisation, enhanced hull coating and speed reduction (IMO, 2014) (DNV GL, 2017). These measures are applicable not only to newly built cargo ships, but also to the existing fleet retrofitted; over the 2015–2050 period, these technological improvements would result in a decrease of energy use per ton-kilometre travelled by 24% for existing ships and by 50% for new ships. These factors result in a fleet in 2050 that is 44% more efficient compared to 2015.

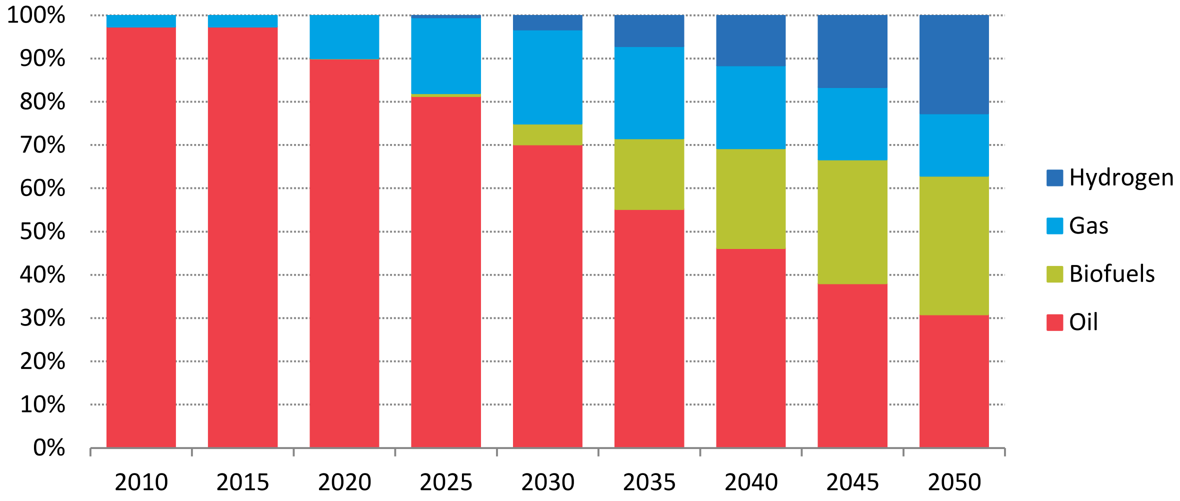
Emissions can be further mitigated through a switch towards less carbon-intensive energy carriers than oil (Figure 51).

- In the central 2°C scenario, liquid biofuels, either blended in existing fuel oil ships, or in new ships that can accommodate 100% blends, would come to represent 51% of liquids consumed in this sector in 2050.
- The use of gas as a fuel in ships can be expanded to more than LNG tankers. Currently, LNG is seen as a solution to reduce the SO_x and NO_x emissions and to fulfil the International Convention for the Prevention of Pollution from ships (MARPOL) regulations ([38]). The increased use of LNG requires the setup of the necessary distribution and refuelling infrastructure in ports. In 2017, LNG liquefaction capacity reached around 340 Mt/year, while another 115 Mt/year were under construction (International Gas Union, 2017). These figures illustrate the growing importance of LNG, driven by enhanced gas supply capacity from the USA and other gas-exporting countries thanks to the ongoing deployment of a broad number of liquefaction and regasification terminals.
- Hydrogen presents similar infrastructure issues and a high production cost (and hydrogen for use in on-board fuel cells would present even higher costs). With appropriate support, gas and hydrogen are projected to represent 23% and 14% of total maritime fuel use by 2050, respectively.

([38]) http://www.imo.org/en/about/conventions/listofconventions/pages/international-convention-for-the-prevention-of-pollution-from-ships-(marpol).aspx

- Electric propulsion is also discussed as a solution for removing air pollutants emissions entirely, and is being implemented in Norway for short domestic journeys ([39]).

Figure 51. Shares of fuels used in maritime, central 2°C scenario, World



Source: POLES-JRC 2018.

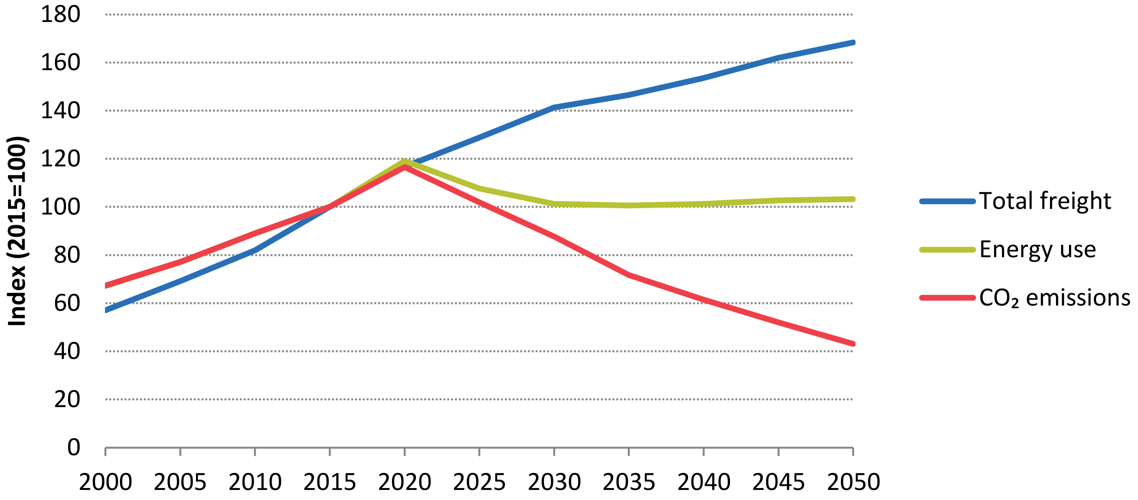
The efficiency gains and the uptake of alternative fuels described in the central 2°C scenario would be made possible thanks to an acceleration of the replacement of the ship fleet. Action would have to be undertaken on a global level, for example by internationally-coordinated agreements to review the international bunkers' environmental standards.

Looking to the aggregated impact of these measures, they would yield a total energy consumption that would plateau over the next decade and decrease thereafter, evolving from approximately 310 Mtoe in 2015 to 320 Mtoe in 2050. Maritime emissions would stabilise quickly and then decline, from approximately 970 $MtCO_2$ in 2015 to 420 $MtCO_2$ in 2050.

Key indicators of maritime transport projections in the central 2°C scenario are presented in Figure 52.

([39]) https://www.bbc.com/news/business-39478856

Figure 52. Key projections in maritime, central 2°C scenario, World



Source: POLES-JRC 2018.

This evolution would be in line with the objective of the International Maritime Organisation (IMO) announced in 2018, of cutting maritime emissions by half compared to 2008 by 2050 ([40]).

Box 16. Transport in the 1.5°C scenario

Transport emissions in the 1.5°C scenario in 2050 would be 1.6 $GtCO_2$-eq, significantly lower (59%) than those of the central 2°C scenario. The main emissions cuts would come from road transport (73% less) and international aviation (52% less).

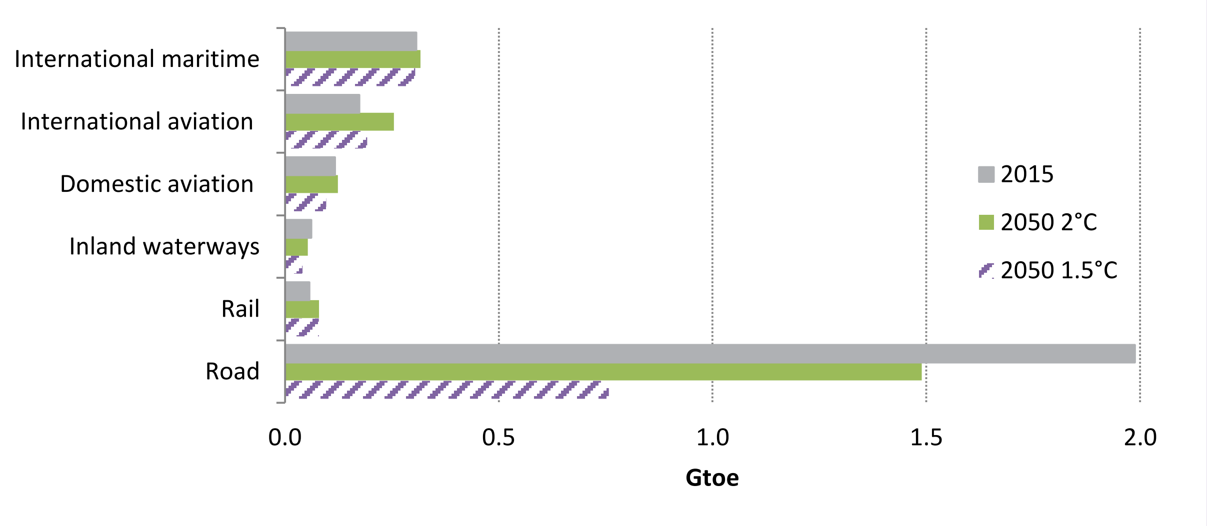
In road transport, the emissions reductions would be achieved thanks to further efficiency gains in liquid fuels engines across all modes (70% increase in efficiency of ICE cars over 2015–2050 vs 60% in 2°C), further substitution of oil products with biofuels (50% of liquids in 2050 vs 18% in 2°C), and further penetration of EV (61% of the car fleet would be made of battery electric and plug-in hybrids in 2050 vs 52% in 2°C).

Behaviour change would also have a significant impact in limiting the increase of passenger traffic, notably of land traffic. Land passenger traffic would increase by 82% over 2015–2050 vs 94% in 2°C; this would also be accompanied by a modal shift towards collective means of land transport (buses, rail), with these modes covering 57% of mobility in 2050 in 1.5°C vs 43% in 2°C. Oil products would represent just 28% of transport's total energy consumption in 2050 (vs 47% in the 2°C).

The combined effect of the trends per mode is summarised in Figure 53 and Figure 54.

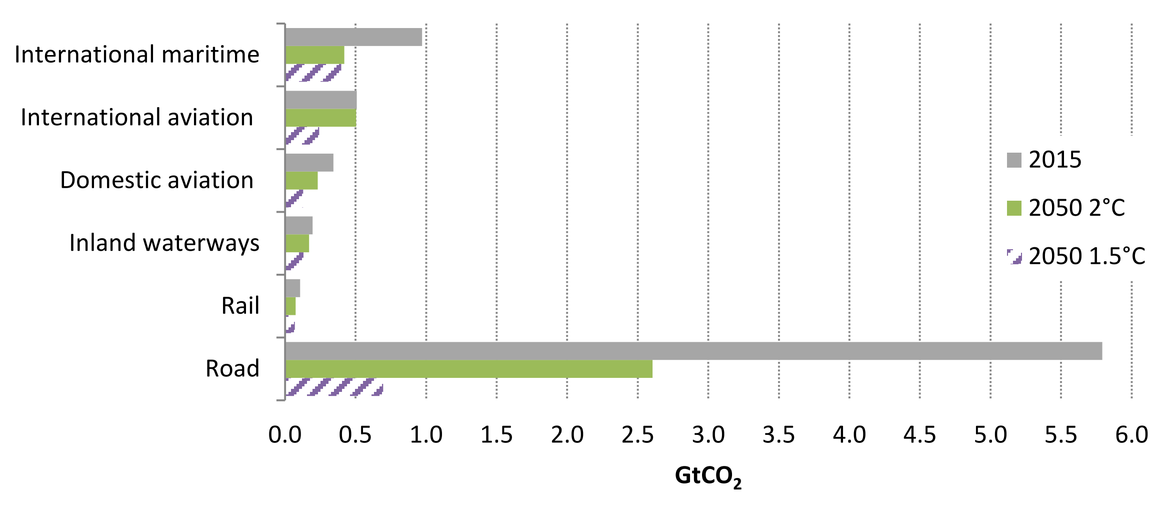
([40]) http://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx

Figure 53. Energy consumption per mode in transport, 2015 and 2050, 1.5°scenario, World



Source: POLES-JRC 2018.

Figure 54. CO_2 emissions per mode in transport, 2015 and 2050, 1.5°C scenario, World



Source: POLES-JRC 2018.

All aspects of this additional mitigation appear highly challenging. With the appropriate support policies to accompany electrification, decarbonisation of the light vehicles fleet would appear to be a relatively easier goal, the efficiency improvements in heavy road vehicles and other modes of transport would require significant investments in research and fast deployment. In addition, deep behavioural changes across all world regions at the relatively short timescale of three decades would pose novel challenges as to what would be the appropriate policy to support them.

Box 17. Transport energy use in 2100

Given the unknown long-term evolution of technology and the unpredictability of innovation related to consumer goods, it is difficult to project transport's energy use to the end of the century. Values mentioned here can be considered merely exploratory under many aspects.

By 2100 in the central 2°C scenario, road transport would have significantly shifted to zero-carbon fuels, however, with different fuel mixes for cars and for heavier vehicles. Cars would mainly run on alternative fuels (42% of kilometres travelled using electricity, 18% hydrogen, 7% biofuels, 9% synthetic methane, 76% total alternative fuels). Heavier vehicles such as buses, coaches and trucks would offer lower but nevertheless highly decarbonised figures (17% of kilometres travelled with electricity, 35% hydrogen, 11% biofuels, 8% synthetic methane, for a total of 71% of alternative fuels).

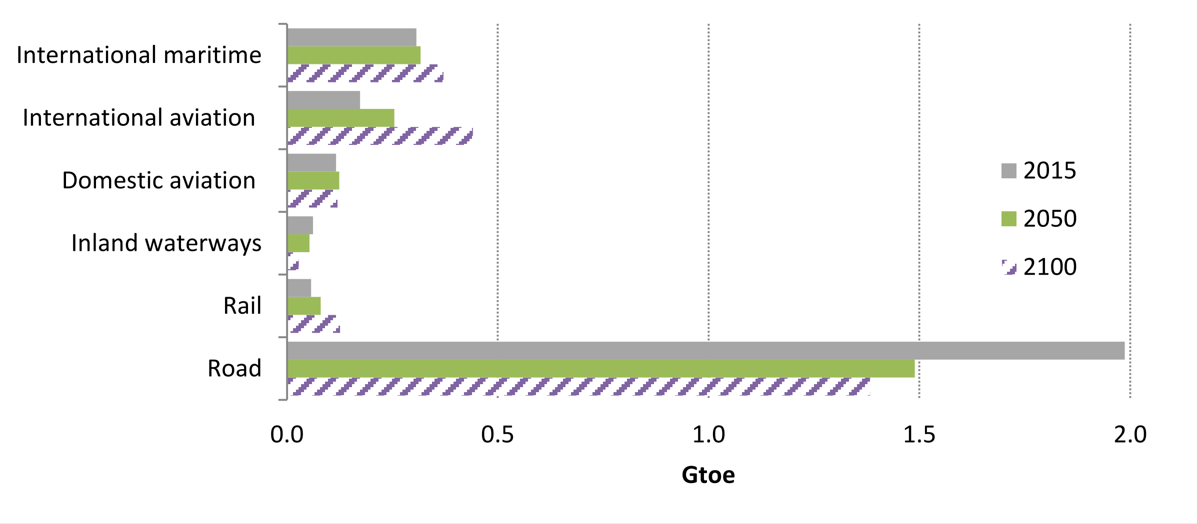
Synthetic methane, produced by combining CO_2 from CCS activities with hydrogen (itself produced with low-carbon energy sources), could become a lower-carbon alternative to natural gas which could help the further decarbonisation of road transport ([41]) ([42]). Given the climate policy constraints of a central 2°C objective, it could be a technology that would start being deployed before 2050; it would represent most of the gaseous fuels consumed in transport by 2100.

Growing passenger and freight air transport activity would push up energy demand from this transport mode beyond 2050, despite additional efficiency improvements. However, the carbon footprint would significantly improve, as most of it would come from biofuels (three quarters of energy use by 2100).

Biofuels and hydrogen would make up most of the maritime bunkers' energy use beyond 2050, each contributing a third of their energy consumption in 2100.

Total energy consumption per mode is presented in Figure 55.

Figure 55. Energy consumption per mode in transport, 2015, 2050 and 2100, central 2°C scenario, World



Source: POLES-JRC 2018.

([41]) Synthetic fuels (methane from hydrogen and CO_2, hydrogen) are accounted in final energy demand; the energy consumption to produce these fuels is accounted in the energy transformation sector.

([42]) Synthetic liquids from hydrogen and CO_2 have not been considered in this report; however they could also become an option.

4.4.7 Air pollutants emissions in transport

Transport is the main source of NO_x emissions worldwide (Table 9), essentially due to international maritime shipping and road transport exhaust emissions. In 2010, they represented 64 Mt out of 116 Mt of NO_x emitted in the world, although regulations have been enforced throughout the world to diminish their emissions.

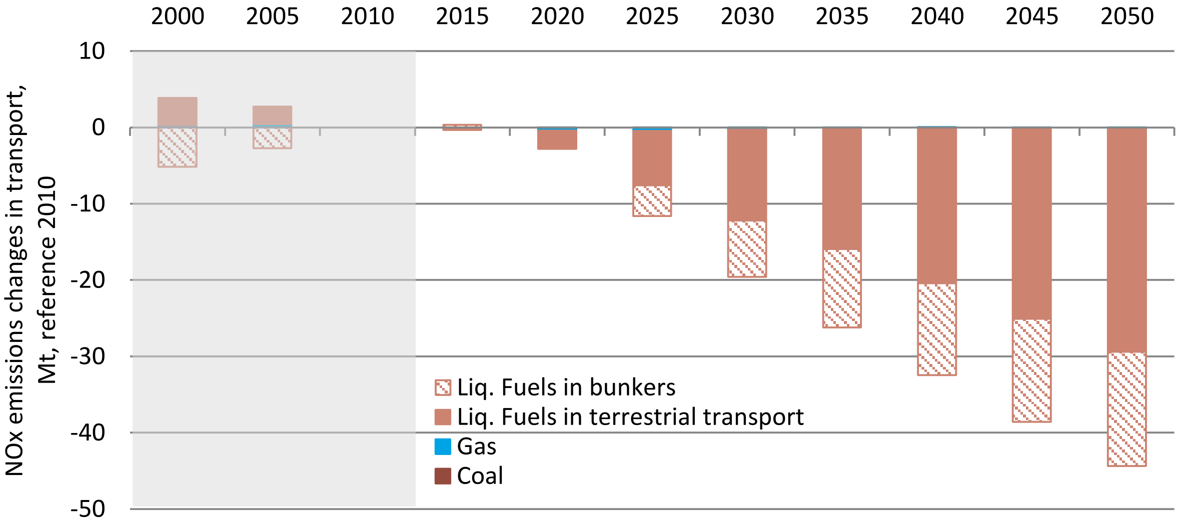
Table 9. Air pollutants emissions from transport in the central 2°C scenario, volumes and shares of total, World

	2010		**2030**		**2050**	
	Emissions (Mt)	Share of total	Emissions (Mt)	Share of total	Emissions (Mt)	Share of total
SO_2	13	14%	3	5%	1	6%
NO_x	64	55%	44	52%	19	53%
$PM_{2.5}$	4	10%	3	8%	1	6%
CO	150	32%	104	25%	38	20%
VOC	23	21%	13	13%	4	8%

Source: POLES-JRC 2018.

In the central 2°C scenario, tightened emissions standards in both road and maritime[43] modes and the diversification of road vehicle fleets would drive NO_x transport emissions of transport down (Figure 56). This would essentially be achieved by reducing the use of liquid fuels, which are the main source of NO_x emissions within the sector, either due to efficiency improvements or due to fuel substitution with gaseous fuels and electricity (if oil products were substituted with biofuels, NO_x emissions would be similar or slightly higher ([44]).

Figure 56. NO_x emissions changes by source, transport, central 2°C scenario, World



Source: POLES-JRC 2018.

([43]) MARPOL Regulation 13: http://www.marpoltraining.com/MMSKOREAN/MARPOL/Annex_VI/r13.htm

([44]) https://uk-air.defra.gov.uk/assets/documents/reports/cat15/0901151441_NAEI_Road_Transport_Biofuels_report_2008_v1.pdf

These changes are expected to happen in both road transport and maritime bunkers, although at different paces: road transport would achieve higher reductions, in line with recent trends and associated with the deployment of stronger emissions standards across world regions, while changes in maritime transport would first have to curb the increasing trend of energy use before decoupling NO_x emissions from bunkers' activity.

4.5 Mitigation options for the Power generation sector

The power sector is an essential piece of the global decarbonisation puzzle. The main reason lies in the extraordinary technological diversity within the sector: since the first electrification wave of the advanced economies some 150 years ago, the technological options to generate electricity at different scales has become more and more diversified and now offers the most widespread portfolio. The following paragraphs present how this technology diversity would be deployed to trigger its full climate change mitigation potential.

Table 10. Summary of the power generation sector, central 2°C scenario, World

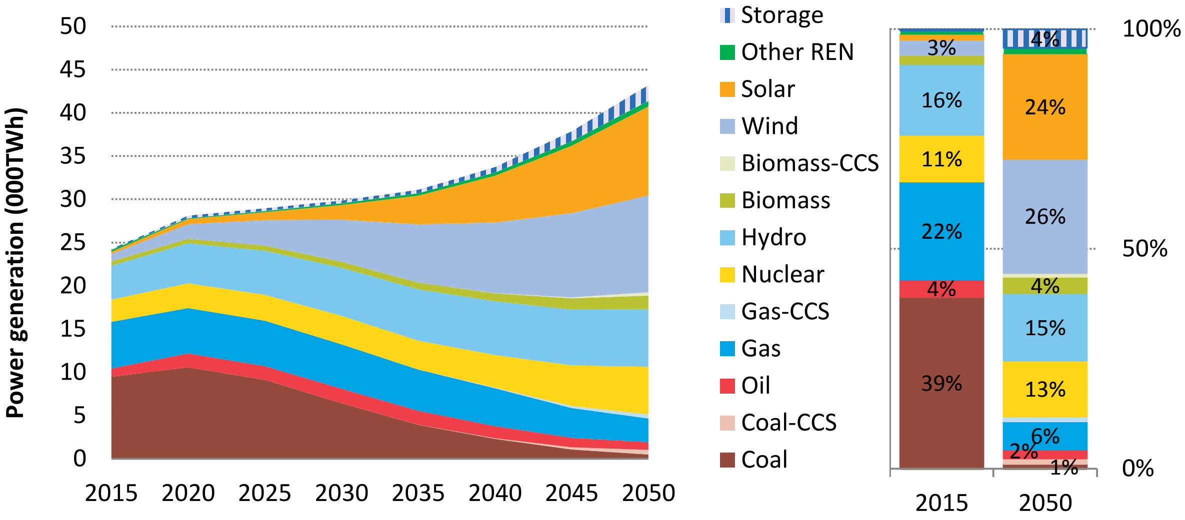
Power generation in transition	**2015**	**2050**
Total power production (TWh)	24000	43000
Primary energy inputs (Gtoe)	4.4	4.4
CO_2 emissions ($GtCO_2$) % of total CO_2	12.2 37%	1.9 16%
Renewables generation (%) of which variable (wind and solar)	23% 5%	71% 50%
Generation with CCS (%) of which BECCS	0% 0%	3% 0%
Average investment in low-carbon energy (bn$/year); share of total power investments (%/year)	320, 54%	839, 83%

Source: POLES-JRC 2018.

Another reason for the power sector to play a crucial role in achieving substantial GHG mitigation is its strong and relatively quick reaction to climate policies. The level of technology substitution that this sector can exhibit results in among the fastest and cheapest decarbonisation options across human activities.

GHG emissions of the power sector would drop from 24% of the total in 2015 to 11% in 2050. This is made possible by the easy substitution of fuels to produce electricity, coupled with the high potential of renewable energy sources, as detailed below. The development of renewable energy sources is vast, completely changing the picture for power generation in the coming decades (see also Figure 24).

Figure 57. Power generation mix, central 2°C scenario, World



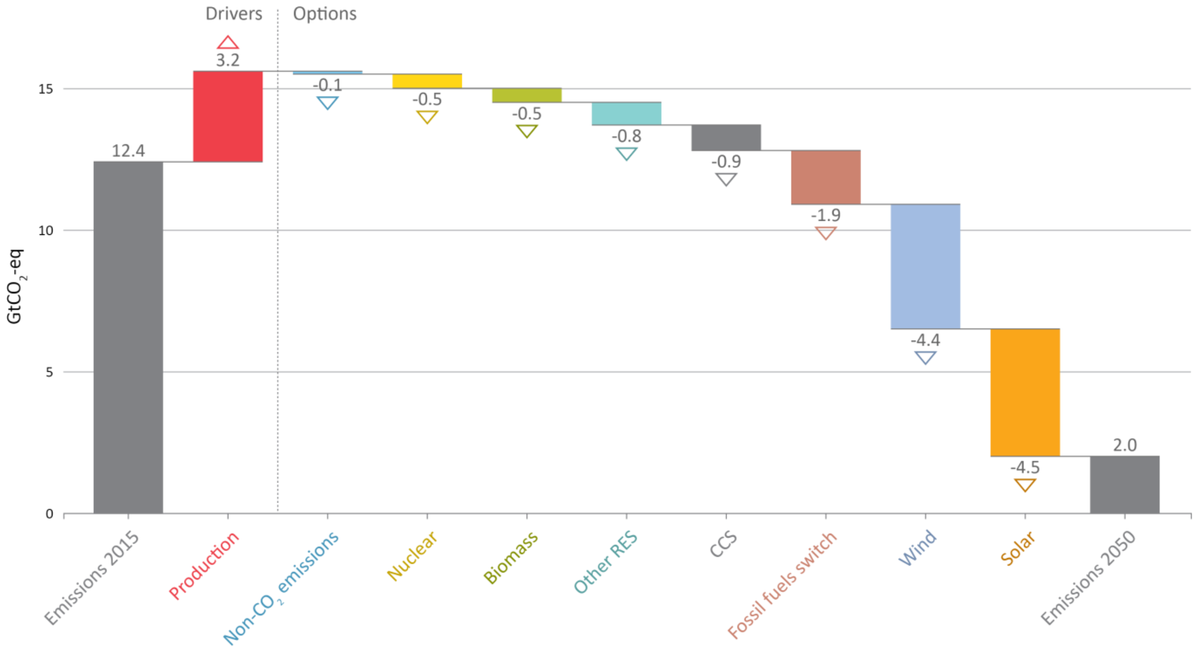
Source: POLES-JRC 2018.

The power generation mix in the central 2°C scenario is presented in Figure 57. Some key figures illustrating the depth of changes follow:

- almost a quarter of electricity was renewable in 2015 (23%); above a quarter would be non-renewable in 2050 (29%);
- fossil fuel share (without CCS) in power generation would drop from 61% in 2015 to 7% in 2050;
- coal power generation would decrease by a factor of 9 over 2015–2050.

The GHG emissions mitigations options adopted by the power sector in the 2°C scenario are presented in Figure 58.

Figure 58. Mitigation options in the power sector, central 2°C scenario, World



Notes: "Production": emissions growth due to the increase of electricity demand in final demand sectors. "CCS": emissions prevented by carbon capture and storage. "Other RES": other renewable technologies (hydro, geothermal, ocean). "Fossil fuels switch": refers to shifts from high-carbon content towards lower-carbon content within the fossil fuel mix (generally from coal and oil to natural gas).

Source: POLES-JRC 2018.

4.5.1 Electrification of final energy demand

Given the relative flexibility with which the power sector can get decarbonised, a deeper electrification would become a key instrument for decarbonising other sectors, by increasing their electricity share in the corresponding final energy mix instead of using fossil fuels to avoid direct GHG emissions. In the 2°C scenario, electricity would grow from 18% of total final energy in 2015 to 34% in 2050 (Figure 24).

Interestingly, for buildings, the evolution of electricity demand shows a break in the 2020 trend due to efficiency gains in appliances, and from 2030 followed by a strong rise due to the predominant electrification of heat and cooling (see section 4.2).

Transmission and distribution losses would remain in the range of 8–9% of total power produced; auto-consumption of gross electricity produced would, however, drop from about 9% to 7% and decreasing, due to the changing power technologies in the mix.

Furthermore, the uptake of EVs would increase electricity consumption in the transport sector, and offer an opportunity to optimise utilisation of the grid. This could be accomplished if recharging technology, together with proper pricing and smart and flexible charging, are deployed – e.g. car owners charge their EVs at times when grid utilisation is low (at night) or when supply is very high (windy and sunny afternoons, when renewables are highly productive). In addition, vehicle-to-home/vehicle-to-grid (V2G) technology could be an enabler – where electricity of the batteries can be injected back to the home or grid.

4.5.2 Contraction and decline of fossil fuels

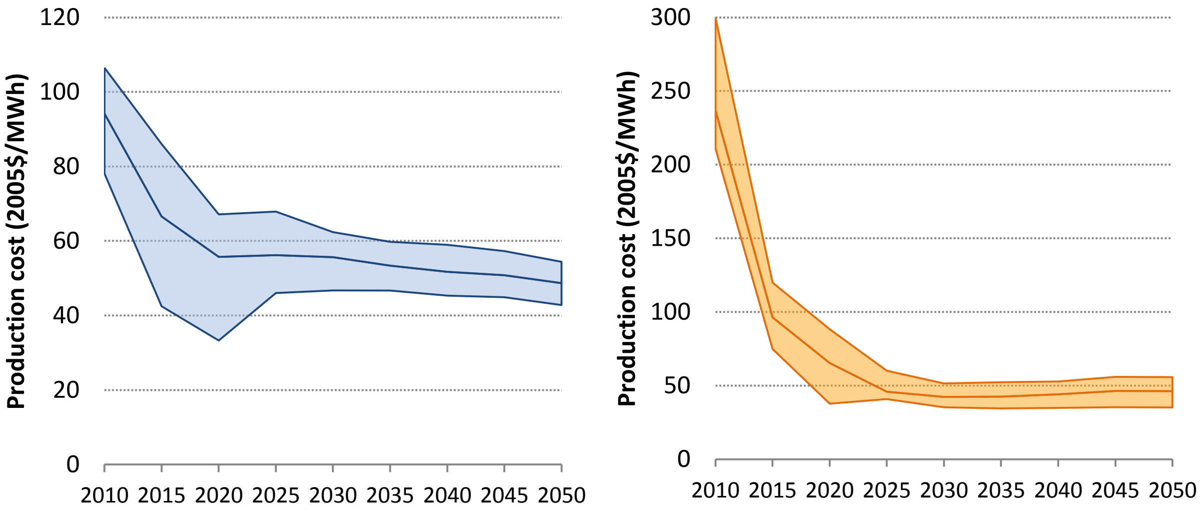
Emissions from coal-, gas- and oil-fired power plants would be divided by more than six between 2015 and 2050. In particular, coal installed capacities would be divided by six over that period. The running costs of fossil-fuelled plants would also increase as a consequence of steadily increasing carbon values ([45]). Load factors for installed coal-fired power plants (excluding CCS capacities) would be divided by three, pointing to the reduced exploitation margins of existing plants. Gas would follow a similar path, but it would be much less pronounced. Gas-fired installed capacities (excluding CCS capacities) would decrease by a third, gas load factors would decrease by 20%, shifting the role of these plants from semi-baseload more towards peak load. Electricity production from oil would remain marginal.

4.5.3 Wind and solar development

Several factors have interacted to create a great incentive to invest in wind and solar technologies. The significant decrease in their costs has already substantially materialised and is projected to continue in the future (Figure 59). The modularity of these technologies is an advantage for the sizing of wind and solar projects, as each individual investment plan can be adjusted to the investor’s capacity, making them attractive for a wide range and type of actor.

In the central 2°C scenario, wind and solar would cover almost half of global electricity production by themselves, compensating the fossil fuel decrease.

Figure 59. Onshore wind (left) and utility-scale PV (right) electricity production costs, central 2°C scenario



Note: Feed-in tariffs and other support policies are not included. Areas show values for the 2nd and 3rd quartiles of modelled regions.

Source: POLES-JRC 2018.

([45]) Either under the Pigouvian tax format or as an emissions permit price.

4.5.4 Other renewables: Biomass, hydro, geothermal, ocean

Electricity production using biomass would also contribute to the decarbonisation of the power sector. This technology is expected to increase its market share from 2% to 5% of total power production between 2015 and 2050. Being a relatively flexible technology, it would support the system for load-tracking purposes, and contribute to accommodating the large quantities of non-dispatchable wind and solar production into the system. Biomass with CCS (BECCS) would develop only marginally at the time horizon of 2050, with about 60 GW installed worldwide (compared to about 340 GW of total biomass capacities).

Hydropower is also expected to grow in absolute terms, in particular hydro from dams, however its contribution to total generation would stay relatively constant at around 17%. The advantages of this technology include its strategic role for peak generation and load-tracking, and its low-carbon footprint.

Still marginal technologies as of today, geothermal and oceanic power generation would both expand, but they would only contribute a limited amount of total power production by 2050 (1.3% and 0.2%, respectively).

4.5.5 Nuclear

The contribution of nuclear energy would increase to 13% of total power production after 2040, compared to a stable contribution of 11% over 2010–2040. The current market trends show signs of slowing due to post-Fukushima increased building costs and security measures, and a phase-out in some countries like Germany. This highlights the difficulty of overturning the situation and launching the necessary investments to increase the role of nuclear again. Nevertheless, nuclear is expected to be very relevant in many countries, most of them in Asia, and more importantly in China.

4.5.6 Carbon Capture and Sequestration

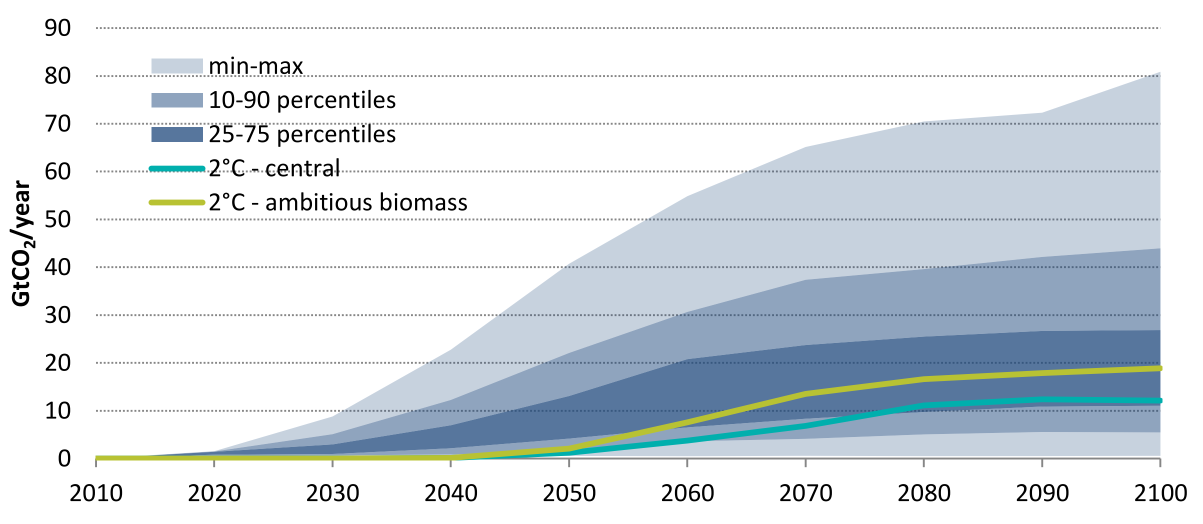
In the central 2°C scenario, some thermal power generation technologies coupled with CCS would develop starting in 2030, but they would remain at a very limited deployment before 2050 (210 GW and 3% of 2050 global electricity production in 2050). About one third of the CO_2 captured in power generation would come from coal power generation coupled with CCS. Despite this development, this would not prevent the decrease of coal power generation, either without or combined with CCS.

Box 18. Carbon Capture and Sequestration technologies, CCS, BECCS and DAC

A full decarbonisation of the economy would need to make use of all options technically available and economically affordable for such an ambitious purpose. CCS technologies would become a major element of the mitigation effort, in particular in the second half of this century. The potential for CCS is anticipated to be the largest in the power sector, but it can also play a role in the industrial sector.

The GECO 2018 scenarios present, compared to the existing literature, rather conservative assumptions regarding the deployment of CCS technologies by 2100 (Figure 60)

Figure 60. CO_2 captured in the GECO 2018 scenarios, compared to existing literature



Sources: CD-Links project & POLES-JRC 2018.

According to data from the Global CCS Institute (46), 18 operational large-scale CCS facilities currently exist in the world, integrating the capture, transport and storage process phases. Most of them (12 out of 18) are developed in North America. The natural gas processing industry is leading the deployment for industrial CO_2 separation processes (9 out of 18), followed by power generation plants (2), hydrogen (2), fertiliser (2) and ethanol (1) production facilities. The most common use for the CO_2 is enhanced oil recovery (EOR): the practice of injecting into producing oil fields to partially recover their declining productivity has been in use for decades. Not all CO_2 is stored immediately, as more than half of the injected CO_2 returns to the atmosphere with the oil produced (47). Long-term underground CO_2 storage for climate protection purposes, and thus not economically motivated by hydrocarbons production, is currently still under development.

Technically, integrated CCS facilities remove (partially) the wasted CO_2, and transport it into a long-term storage site. There is a wide variety of CCS technologies at various states of technical and commercial readiness, depending on the type of CO_2 generating plant and fuel used. In order for CCS technologies to expand beyond first-of-a-kind projects and be scaled to form an industry capable of transporting several billion tonnes of CO_2 every year, a number of significant deployment barriers need to be addressed:

- high energy consumption for the CCS processes;
- CO_2 transport and storage infrastructure costs;
- uncertainty over storage capacity;
- uncertainty of the long-term management of storage, with potential environmental concerns in case of leakages;
- general public acceptance.

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(46) https://www.globalccsinstitute.com/projects/large-scale-ccs-projects

(47) 50–70% of carbon dioxide returns with the oil; however, this can be separated and re-injected into the hydrocarbon reservoir to minimise operational costs. The remaining carbon dioxide is trapped in the reservoir formation and may be considered as permanently stored.

CCS is an energy-intensive process. Energy consumed per tonne of CO_2 stored is a major concern related to the future commercialisation of CCS projects. **Capturing and compressing CO_2** may increase the energy needs of a coal-fired CCS plant, resulting in an efficiency penalty of up to 10 points for post-combustion technologies. This penalty is expected to decrease in the future with new post-combustion technologies, such as gasification (Koornneef, et al., 2012).The increase in energy consumption can push up the marginal cost to produce each new unit of energy, reaching a point where economic gains will be reduced. Assuming a capture rate up to 90%, the capture process would result in an energy penalty (additional energy spent) of about 2–3 GJ/tCO_2 captured. A particular consideration is the possibility of retrofitting existing coal thermal power plants with CCS technologies: the most likely possibility would be post-combustion technologies, where a trade-off between expenditure efficiency and CO_2 reduction (CO_2 value) must be assessed.

CO_2 transport can possibly benefit from the existing oil and gas pipelines network. The bulk transport of CO_2 by ship already exists, though on a relatively minor scale ([48]). Transport by truck and rail is also possible for small quantities of CO_2, but is unlikely to be significant in large CCS projects because of the lack of economies of scale when it comes to capturing very large amounts of CO_2 (IPCC, 2005).

The stability of the large CO_2 long-term **stored volumes** is key not only for climate protection purposes but also in terms of human health. A sudden release of CO_2 in highly populated areas could have very dramatic consequences for the population at risk. Geological storage is being discussed, making use of depleted oil/gas reservoirs and saline aquifers, where CO_2 will be injected underground ([49]). Global estimates vary extensively, between 1,700 $GtCO_2$ and 10 times that figure ([50]). However, the geographical location of these storage sites might be remote compared to where the CO_2 is captured. Storage capacity varies greatly across countries, raising the need for industrial-scale cross-border CO_2 transport.

Bioenergy with carbon capture and sequestration (BECCS), currently only in the development phase, opens the potential for negative CO_2 emissions. Therefore BECCS technologies are one of the most prospective large-scale options required to reduce the atmospheric concentration of CO_2. Currently, there are only two large-scale BECCS facilities planned and in operation worldwide ([51]). Biomass firing plants are typically of a smaller size and a lower electrical efficiency, compared to coal power plants (30-35% using dry biomass, and 22% for municipal solid waste). The energy demand for CO_2 capture results in an efficiency penalty of up to 10%, making this solution not attractive from a pure thermodynamic point of view. However, in the long run, the Biomass Integrated Gasification in Combined Cycle (BIGCC) with CCS has the lowest energy costs with efficiency penalties of around 4% in 2050 (Koornneef, et al., 2012). As a consequence, in a world where an ambitious climate-protection objective is pursued, the attractiveness of BECCS power plants could come more from its net-negative carbon emissions rather than from its electricity production and sale (Klein, et al., 2014). This undoubtedly raises some questions as to the business model and electricity market operation of such a power plant, in particular in the context of adequately valuing the positive externalities generated.

([48]) This occurs in insulated containers at temperatures well below ambient, and much lower pressures than pipeline transport.

([49]) https://www.naturalgasworld.com/shell-says-industry-needs-to-push-for-ccs-co2-tax-36043

([50]) IEA Carbon capture and storage roadmap, 2010

([51]) https://www.globalccsinstitute.com/news/institute-updates/are-beccs-projects-are-being-deployed-sufficient-scale-globally

Direct air capture (DACCS) is the most innovative CCS technology, with even fewer prototype plants at the time of writing. Studies estimate total DAC cost would be on the order of 600–1000$ per ton of CO_2 (House, et al., 2011) (Socolow, et al., 2011) with considerable uncertainty ([52]). DAC is an energy-intensive process and a large part of the costs would be energy (for ventilation, compressors, heat for chemical absorption), resulting in about 8 GJ/tCO_2 captured.

In the central 2°C scenario, the first operational CCS facilities would appear in the 2030s, however, their expansion is expected to be gradual. CCS facilities would capture about 1.2 $GtCO_2$ by 2050, mostly using biomass (39%) and coal (37%) sources. CCS would expand significantly in the decades after 2050, used in power plants, hydrogen and liquid biofuel production plants, and DAC. Total CCS would reach up to 12 $GtCO_2$ annually by 2100, mostly associated with biomass (61%) and DAC (29%) technologies, with the cumulated CO_2 stored exceeding 400 $GtCO_2$.

4.5.7 Development of power dispatch flexibility options

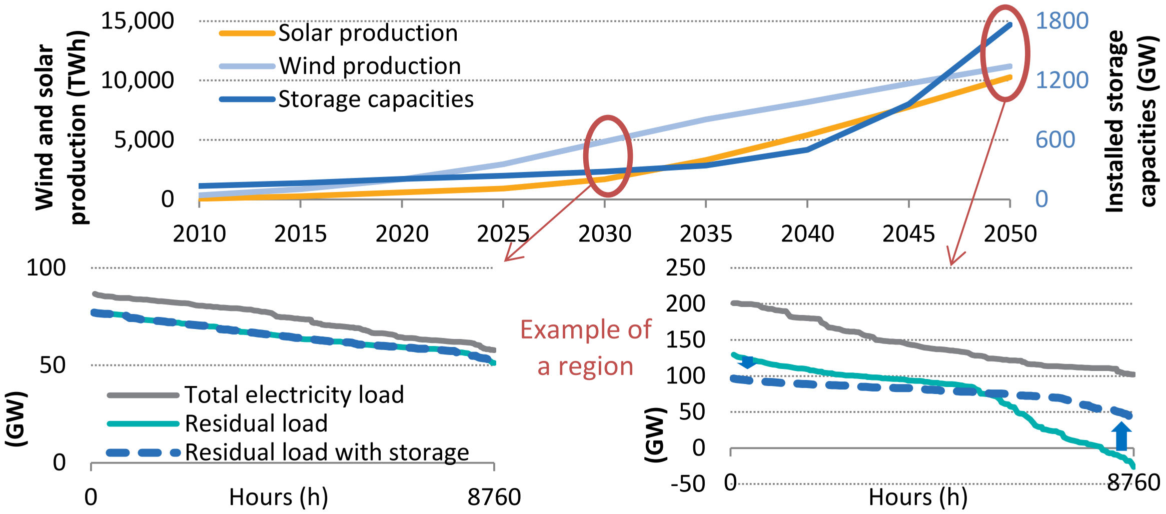
As wind and solar deployment expands, the issue of grid stability becomes more central: the non-dispatchable production of wind and solar would not necessarily match the electricity demand. Although other non-dispatchable productions (mainly run-of-river hydro, but also small hydro plants or ocean energy) would also have to be accommodated by the system, the dominant role of wind and solar highlights their special impact on the residual production to be covered by dispatchable capacities.

In order to mitigate the need for installing new fossil-fuelled peaking and load-tracking plants, which are a source of emissions, some new flexibility options would develop: namely electricity storage technologies, either stationary or in the form of EV, and demand-side management. Increased electricity trade thanks to enhanced cross-boundary electricity transport interconnections is undoubtedly another option to better manage this residual load across neighbouring countries (not captured in this study).

In the central 2°C scenario, electricity storage would develop strongly starting from 2035 (Figure 61).

([52]) https://www.cell.com/joule/fulltext/S2542-4351(18)30225-3

Figure 61. Global wind, solar and storage development, and illustration of load curve development in one country, central 2°C scenario

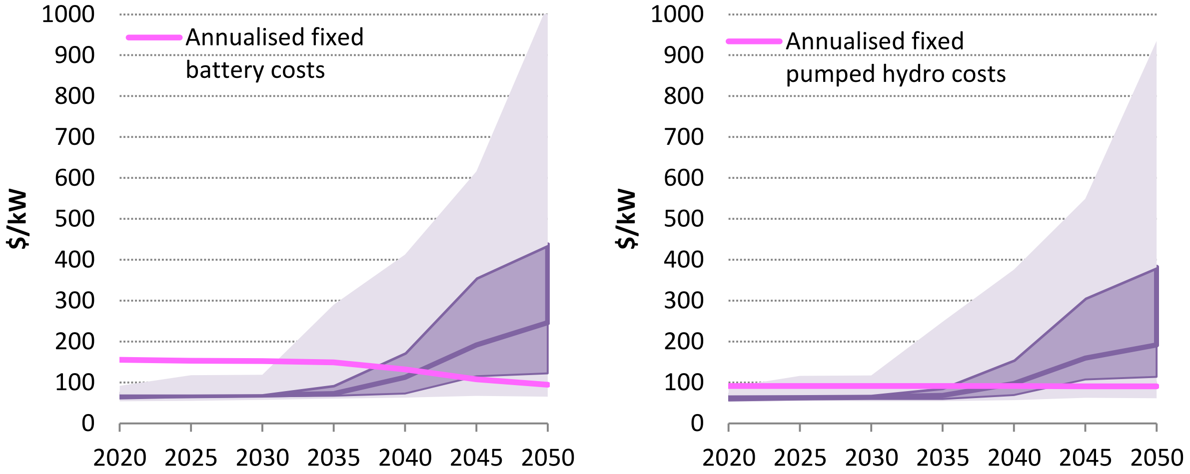


Note: Residual load refers to the total load net of non-dispatchable production (wind, solar, small hydro, run-of-river hydro and ocean).

Source: POLES-JRC 2018.

Indeed, the economic value of storage is quantified based on its contribution to balancing and grid services, capacity value and arbitrage in power markets. With suitable market regulation schemes in place, this last component would become predominant after 2035, triggering investments thanks to the foreseen revenues (Figure 62). In addition, battery investment costs for both stationary and vehicle batteries are to become more and more competitive with cumulated production and installation according to learning processes (also Box 14).

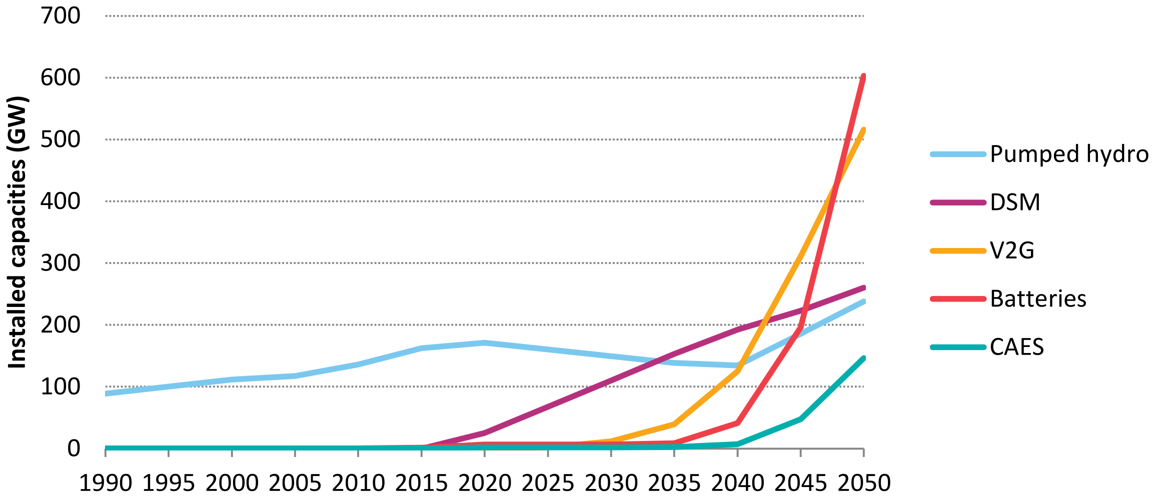
Figure 62. Stationary battery and pumped hydro costs (lines) compared to their economic value (areas, quartiles of all modelled regions), central 2°C scenario



Source: POLES-JRC 2018.

Historically, pumped hydro storage has been a predominant form of electricity storage. Various new storage options are now emerging and would develop in the future to facilitate the instantaneous supply-demand matching (Figure 63). Flexibility instruments for demand-side management (DSM) would develop strongly at first, in industry and buildings; they would be followed by a progressive adoption of decentralised vehicle-to-grid (V2G) options, which would take off in the 2030s, following the deployment of EV starting from the 2020s. In the 2040s, large-scale supply-side options would develop, such as large stationary battery storage and compressed air energy storage (CAES). Their development would react to the higher economic value that they can provide based on their system utility, meeting the sharply increasing need for storage, particularly linked to larger and larger shares of solar electricity in the global power mix.

Figure 63. Development of storage technologies, central 2° scenario



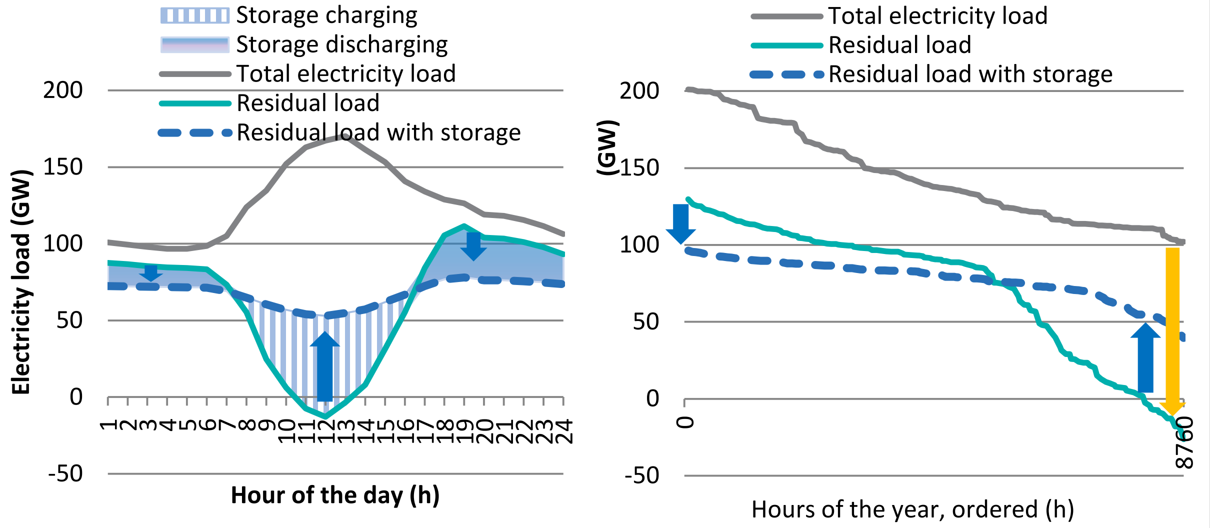
Source: POLES-JRC 2018.

These new power storage technologies would respond to the foreseeable new business models that would be created within the power generation sector as the global energy transition develops during the 21st century. An appropriate regulatory environment would need to accompany their emergence, putting in place the necessary remuneration mechanisms for the new services provided by the different economic actors within the power sector.

Box 19. Storage in the future power sector

Electricity storage at daily timescales becomes a natural partner of solar, displacing its abundant power from mid-day to night. In the days with the highest in-feed of non-dispatchable power, some renewable power has to be curtailed.

Figure 64. Example of the operation and planning as impacted by electricity storage, central 2°C scenario



Note. Residual load refers to the total load net of non-dispatchable production (wind, solar, small hydro, run-of-river hydro and ocean).

Source: POLES-JRC 2018.

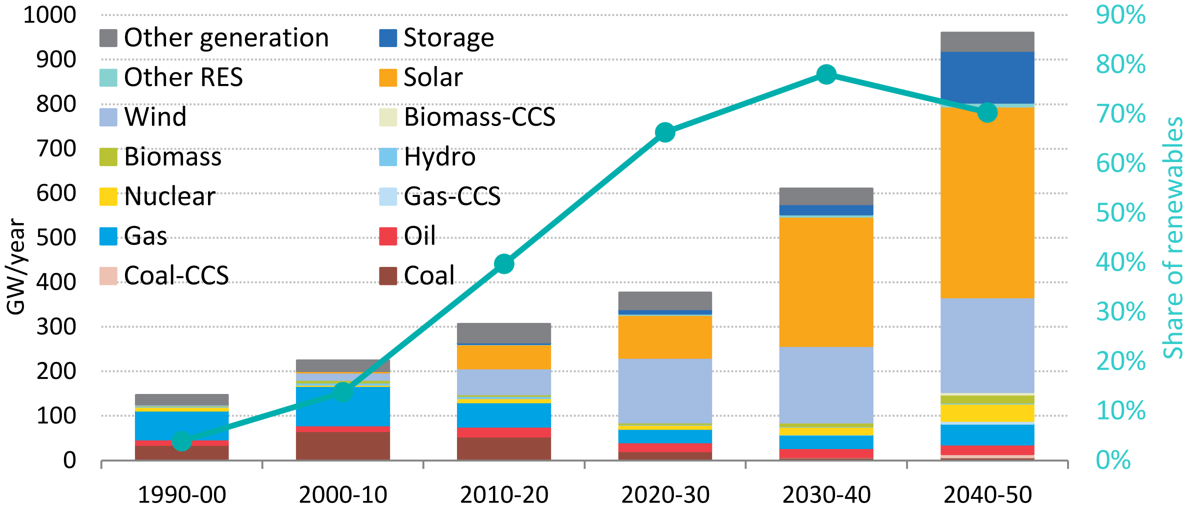
In Figure 64, the orange arrow shows the strong impact of solar in some regions of the world. It digs deeply into the residual load and is mostly concentrated in a portion of the year. The purple arrows show the effect of storage: upward arrows correspond to storage charging, in particular for absorbing the solar production surplus that flexible load could not accommodate, while downward arrows indicate storage discharging, thus reducing the need for peaking power plants. As a result of storage, the residual load is much smoother and thus easier to tackle by dispatchable plants.

4.5.8 Investment opportunities

The global increasing electrification trend will have consequences in terms of capital equipment demand. Total installed power generation capacity is projected to increase from 6.5 TW globally in 2015 to about 9.7 TW in 2030 and 17.8 TW in 2050 (a more than twofold increase versus current capacity). Renewable technologies would represent the largest bulk of these new installations, as they would exceed 80% of the total installed capacity by 2050 in the 2°C scenario (Figure 65).

New generation capacities would need to be deployed quickly to cover for the rapidly increasing demand (in developing economies in particular), as well as to substitute for decommissioned power plants (both in developed and developing countries). While new annual capacities totalling almost 160 GW/year were built over the 1990–2010 period, they would rise to almost 350 GW/year over 2010–2030 and to 800 GW/year over 2030–2050 on a global level – with a very different investment pattern across world regions.

Figure 65. Annual average new electrical capacity additions per decade, central 2°c scenario.



Source: POLES-JRC 2018.

In the central 2°C scenario, new installations of coal technologies without CCS would decrease from 50 GW/year in 1990–2010, to just 7 GW/year in 2030–2050. In contrast, nuclear would increase its installation rate fivefold, from 6 GW/year in 2010–1990 to 28 GW/year in 2030–2050. Gas and hydro would roughly halve their installations rate compared to the 1990–2010 period, while solar would reach an installation rate of almost 360 GW/year, and wind of 190 GW/year in 2030–2050. Finally, storage technologies would emerge with 70 GW/year in 2030–2050.

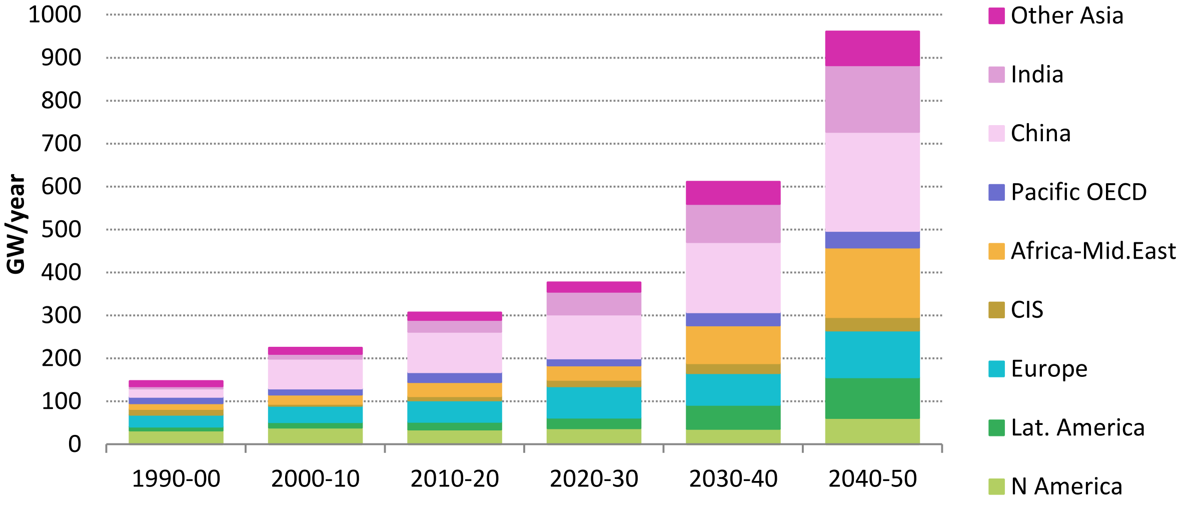
4.5.9 Regional trends

All regions are expected to diversify their power mix towards low-emission sources, although at different speeds depending on each region’s domestic potential, market conditions and policy momentum.

China and India are projected to be the new giant markets for power plants, already in the next decade. After 2030, Africa would emerge as a huge attractor for new generation capacities, driven by decentralised solar, but also wind and electricity storage technologies. Latin America would also become very dynamic in decentralised solar and in wind, but would need less storage thanks in particular to the high flexibility brought by its large hydroelectric plants.

In comparison with Asia and Africa, the new installation levels in the central 2°C scenario in Europe and North America are much more in line with the historical markets; most of the new capacities – and thus of the investments – would occur in the developing world (Figure 66).

Figure 66. New electrical capacity installed by region, annual average per decade, central 2°C scenario



Source: POLES-JRC 2018.

Table 11. Cumulated installations of capacities by world region (GW)

Additions 2015–2050	All	Solar	Wind	Storage	Hydro	Nuclear	CCS
N America	1540	390	610	40	160	80	10
Lat. America	1840	840	410	190	190	50	20
Europe	2820	1220	800	140	180	70	30
CIS	750	320	110	60	120	40	0
Africa-Mid.East	2940	1400	520	350	150	60	60
Pacific OECD	990	410	280	60	40	40	10
China	5330	2010	1830	250	300	270	40
India	3110	1220	840	410	130	70	0
Other Asia	1580	700	230	200	260	30	10
Total	20900	8510	5650	1690	1530	710	210

Source: POLES-JRC 2018.

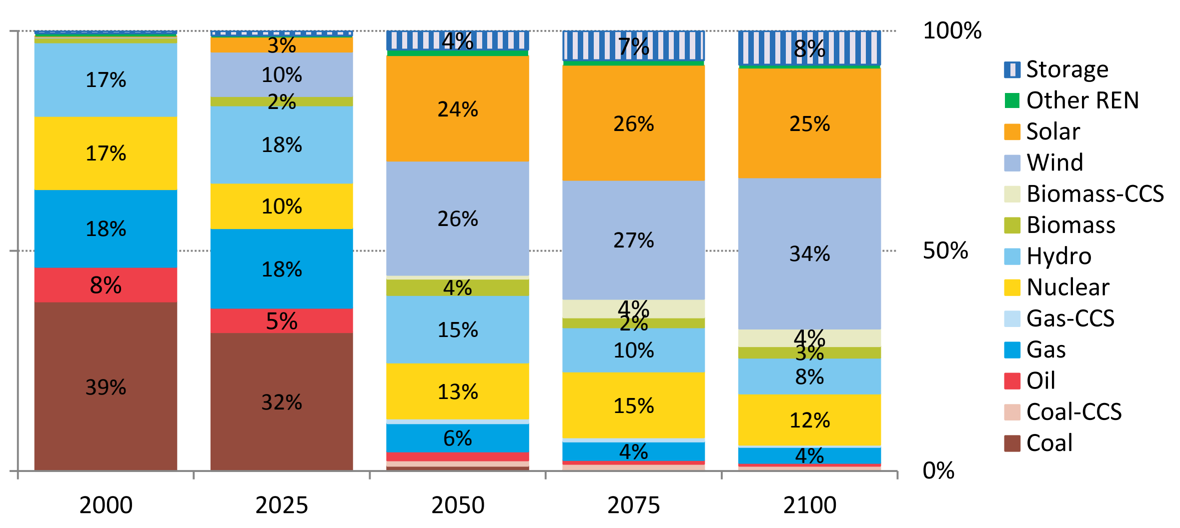
Box 20. The power system in 2100

The power sector is expected to be a main contributor to negative emissions at the end of the century, storing 3.0 $GtCO_2$ annually by 2100 with BECCS. Only the LULUCF sector would cumulatively extract more CO_2 from the atmosphere (see section 4.6).

Demographic and economic growth projections, as well as the anticipated large increase in the electricity share in final energy consumption, namely from 34% in 2050 to 58% in 2100, would lead to a doubling of electricity production (from 43,000 TWh in 2050 to 99,000 TWh in 2100), along with a doubling of power sector primary energy use (from 4.4 Gtoe to 9.2 Gtoe).

As shown in Figure 67, the electricity mix would remain relatively similar to 2050: most of the power sector transition to decarbonisation would have to happen in the coming 30 years to respect the 2°C objective.

Figure 67. World power mix across the century, central 2°C scenario



Source: POLES-JRC 2018.

The power mix would show two noteworthy evolutions:

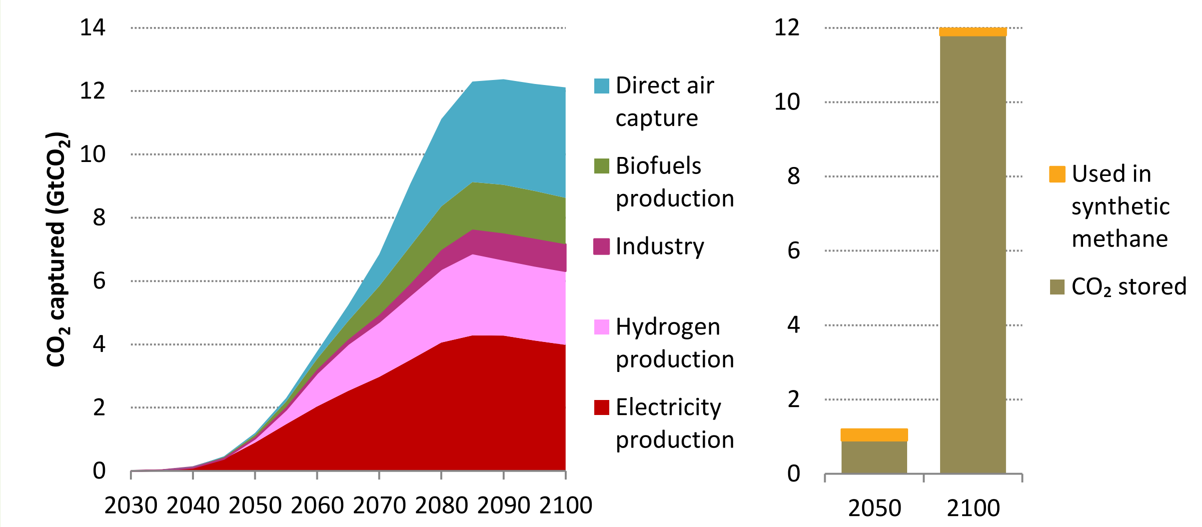
-Wind would increase to a third of power generation, compensating for a decreased contribution (in the share) of hydro and gas production, and would be linked to a strong increase in electricity storage capacities.

- CCS technologies would emerge, covering 5% of electricity generation by the end of the century (compared to less than 3% in 2050). Three quarters of this CCS would be associated with biomass technologies (BECCS), the rest being mainly coal technologies.

It is worth underlining that this type of very long-term scenario on such a time horizon is mostly relevant for studying the overall transformation of the system as it relates to climate change, and not the specificities of the results. In particular, new technologies could emerge and develop progressively. However, the intrinsic long time horizon of the energy sector makes it relatively unlikely that a technology without any pre-commercial demonstrator could be developed and to make a significant share of the power mix by 2050. CCS (only after 2030) and new nuclear designs (after 2050) are the main new technologies with high potential represented here; they would reach 5% and 12% of the global power mix in 2100, respectively.

In particular, CCS would develop to store (in the ground, the sea or in synthetic methane) a total of 12 $GtCO_2$ annually by 2100 (Figure 68), with cumulated stored CO_2 amounting to some 400 $GtCO_2$ by 2100. Of that amount, a small share (about 300 $MtCO_2$ annually in the second half of the century) would be combined with hydrogen to produce synthetic methane for sectors that would be difficult to fully decarbonise, namely transport (Box 3). Overall, total BECCS (from power generation and other sectors) would amount to 7.4 $GtCO_2$ annually by 2100, while DACCS would rise to 3.5 $GtCO_2$ annually by 2100.

Figure 68. Evolution of CO_2 capture (left) and storage (right), central 2°C scenario



Source: POLES-JRC 2018.

This would represent an industry comparable to the size of the current fossil fuel extraction industry (11 Gtoe of fossils extracted in 2015, which correspond to an equivalent 36 $GtCO_2$ of emissions were they all combusted; this would drop to an equivalent 15 $GtCO_2$ in 2050). This high development of CCS is made necessary to reach the 2°C objective, but would have to rely heavily on the support of some fiscal policy (tax or subsidies). The political and social consensus would therefore need to be strong and well established to allow for a stable scheme incentivising CO_2 capture.

Box 21. The power system in a 1.5°C scenario

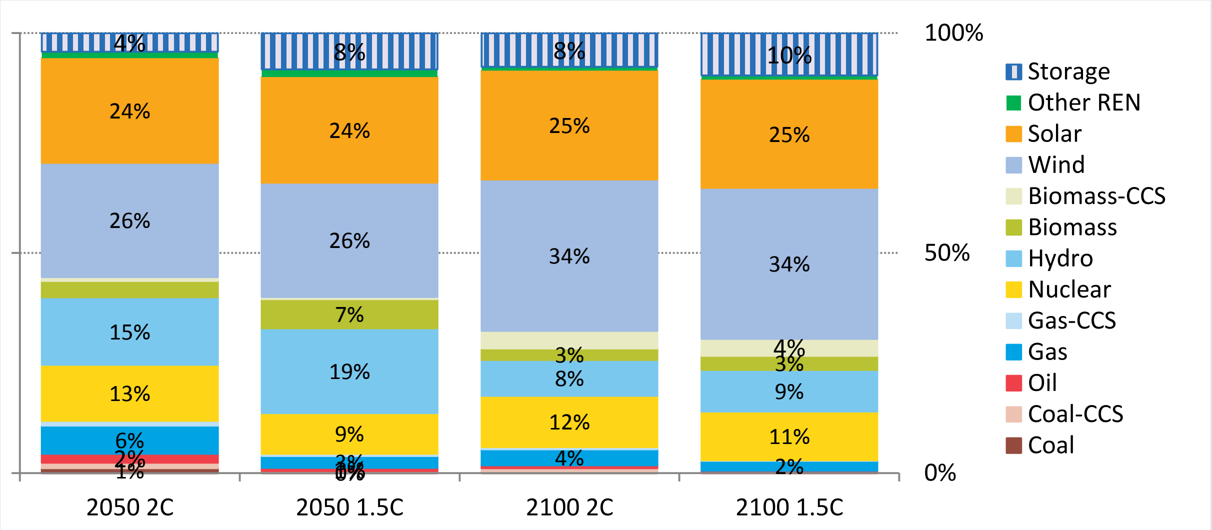
In a 1.5°C scenario, the much stronger reduction of global final energy consumption would result in electricity consumption that would be 10% lower (38,000 TWh) than in the central 2°C scenario in 2050, however with the power mixes it would be relatively similar. Electrification as a share of final energy demand would reach higher rates (37% in 2050, vs 34% in the 2°C scenario) due to further substitution of other thermal carriers, especially in the residential sector. The transition towards the decarbonisation of the 1.5°C scenario would be even faster in the coming 30 years than in the central 2°C scenario, although the patterns would be more pronounced (78% of renewables in 2050 vs 71% in the 2°C scenario), thus making the challenge of the 1.5°C objective more challenging as the 2°C objective for the power sector.

The share of fossil fuels (without CCS) in electricity generation would decrease more, and faster (4% of global electricity production in 2050, compared to 10% in the 2°C scenario).

Pumped storage and other forms of electricity storage would develop at some speed from the 2040s, similar to the central 2°C scenario. Storage technologies would develop slightly faster (mostly batteries and compressed air), although their longer term market niches would not be modified.

Hydrogen as storage (to feed stationary fuel cells) would emerge by 2050 in the 1.5°C case; it would mainly be used in industry. Hydrogen production would mainly be based on electrolysis from wind power (three quarters of total hydrogen production in 2050). As a total, hydrogen as a direct fuel and a storage solution would develop strongly (960 Mtoe in 2050, including hydrogen used in maritime bunkers, 29% higher in the 1.5°C scenario compared to the 2°C scenario).

Figure 69. Power mix in 2050 and 2100, central 2°C scenario and 1.5°C scenario



Source: POLES-JRC 2018.

The differences in other production sources would be less pronounced. Biomass would partly benefit from the stronger decline of fossil fuels. The role of CCS would remain in the range of a few percent of power production (1% in 2050, 4% in 2100). Nuclear generation would not develop as much as in the central 2°C scenario and would stay limited to 9% of the 2050 electricity mix (vs 13% in the 2°C scenario).

The differences in the second half of the century would be much less pronounced, except for this more important role of long-term hydrogen storage. Regarding CCS technologies, it would not be needed to store more CO_2 throughout the rest of the century, given the additional overall efficiency improvements; biofuel and power technologies equipped with CCS would be less solicited, while hydrogen production with CCS and DACCS (4.1 $GtCO_2$ annually in 2100) would be more developed.

4.5.10 Air pollutants emissions in the power sector: SO_2 and NO_x

The power generation sector was historically a major emitter of SO_2 and NO_x. Reducing these emissions has been a concern in recent decades, since sulphur and nitrogen oxides have been identified as the main cause of acid deposition (through rain), leading to damages in soil, water, ecosystems and human health. Health impacts consist mainly of respiratory diseases (EEA, 2006). Therefore, measures have been taken since the 1980s to reduce emissions from conventional thermal power plants. For example, in Europe, EU directives were implemented in 1988 and 2001 to limit emissions from large conventional plants; in the United States, the Clean Air Act of 1970/1977 and its 1990 amendments included tightening regulations with respect to air pollutants (EPA, 2018).

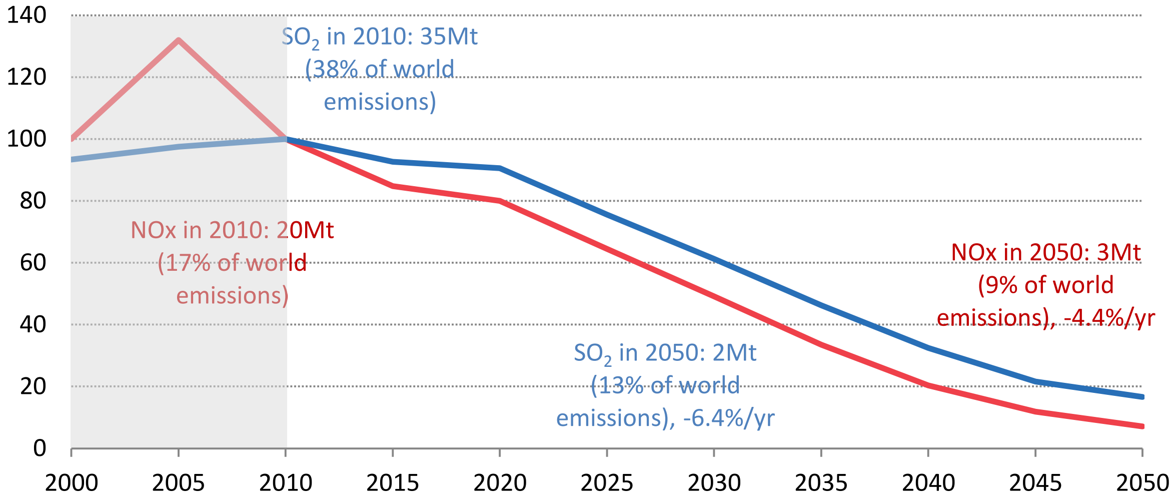
Table 12. Air pollutants emissions from power generation in the central 2°C scenario, volumes and shares of total, World

	2010		2030		2050	
	Emissions (Mt)	Share of total	Emissions (Mt)	Share of total	Emissions (Mt)	Share of total
SO_2	35	38%	17	27%	2	13%
NO_x	20	17%	12	15%	3	9%
$PM_{2.5}$	0.2	1%	1	1%	0.1	1%
CO	4	1%	4	1%	2	1%
VOC	1	1%	1	1%	1	1%

Source: POLES-JRC 2018.

Recently, coal power plants have represented the majority of SO_2 emissions from the power sector (82% in 2010); therefore, they should still be the main target for reductions. In 2010 (Figure 70), SO_2 emissions from coal power plants were estimated to represent 38% of the total SO_2 emissions worldwide (35 Mt), while NO_x emissions were estimated to account for 17% of the world total (20 Mt). In the central 2°C scenario, SO_2 and NO_x emissions from power generation would drop at a high pace (-6.4%/year for SO_2 and -4.4%/year for NO_x), and reach 2 Mt and 3 Mt in 2050, respectively.

Figure 70. World SO_2 and NO_x emissions in power generation, historical and projection in the central 2°C scenario



Source: POLES-JRC 2018.

Several factors would explain this improvement over the projection period:

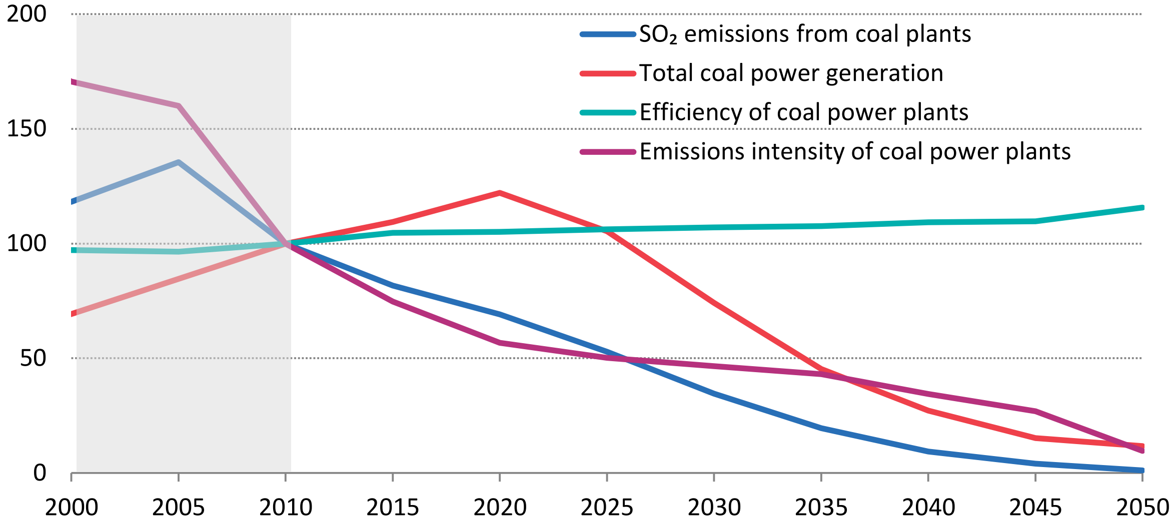
- Changes in the fuel mix: coal is the fuel with the largest emission factors. Substitutions by other fuels in the conventional thermal generation mix reduce air pollution.
- Improved efficiency of power plants: reducing the fuel consumption for each MWh produced would also reduce the associated emissions.
- Technological improvements to lower the emissions intensities of power plants. These aggregates would include:
  - The deployment of abatement techniques (Figure 71) as well as their improvement over time. Low NO_x combustion boilers technologies and flue gas treatment systems are used. SO_2 emissions can be controlled by flue

gas desulphurisation (limestone scrubbing, etc.) or dry sorbent injection (EIA, 2017).

- Regulation of fuel specification, to enforce the use of cleaner fuels for the input at power plants (in particular banning sulphur-rich coal).

Focussing on SO_2 air pollution by coal power plants, the drop in emissions can be explained by a combination of factors: the above-mentioned technology and substitution effects, combined with a strong activity contraction effect. Coal-based power generation would be decreasing as a consequence of specific policies and increasing power plant efficiency would reduce coal input requirements.

Figure 71. SO_2 emissions of coal power plants and related indicators (Index, 2010=100), central 2°C scenario



Source: POLES-JRC 2018.

In the central 2°C scenario, the reduction in emissions between 2010 and 2030 would be achieved mainly by reductions in emissions intensity, since this indicator would drop faster than the activity-related variables. After 2030, although emission intensities would continue falling, reductions in emissions would be more driven by stronger decreases in conventional thermal power generation.

4.6 Mitigation options for Agriculture, Forestry and Other Land Use

Agriculture, Forestry and Other Land Use (AFOLU) is a GHG inventory category that encompasses emissions due to human-induced land use such as agriculture, livestock settlements and other land commercial uses, land-use changes from natural land and between managed uses, and forestry activities.

Table 13. Summary for land use, central 2°C scenario

Land use in transition	2015	2050
Total food production (Pcal), of which livestock (%)	21, 17%	31, 17%
Total roundwood production (Gm3)	3.2	6.6
CO_2 emissions of LULUCF ($GtCO_2$)	1.4	-3.4
Non-CO_2 emissions of agriculture ($GtCO_2$-eq) % of total GHG	6.1 12%	4.1 23%
Agricultural surfaces, of which gen.1 biofuels (Mha)	4800, 40	4000, 70
Forest surfaces (Mha)	3800	4100

Source: POLES-JRC 2018

Agricultural land has expanded significantly in previous decades in order to supply with a growing world population with food. However, recent years have shown a relative decoupling of agricultural land area and food production (an annual decrease of 1% of agricultural surfaces versus a +36% total supply of crops in calories over 1995–2013 ([53]). Efficiency improvements are expected to drive the agriculture sector along this pathway in the future, in the form of increased crop yields per hectare and the improved management of livestock in developing countries. Beyond GHG emissions, the agriculture sector faces enormous challenges in other environmental areas, such as soil erosion, nutrient depletion, nitrogen and phosphorus runoff, and water use.

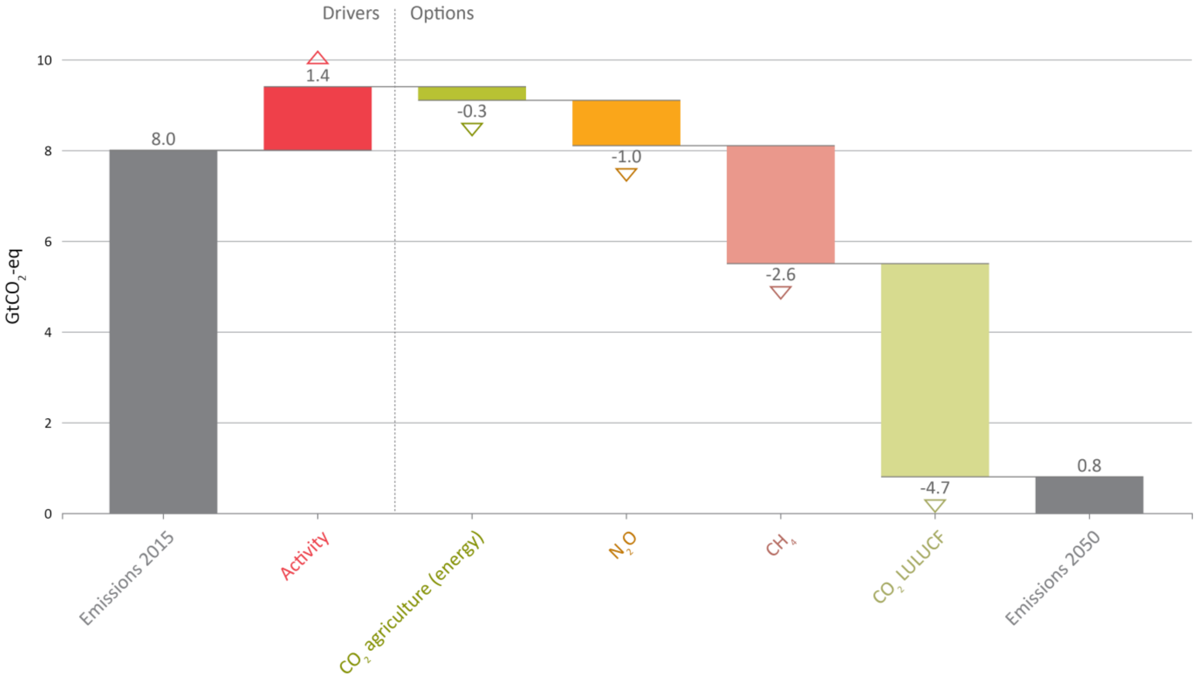
The energy sector interacts with other uses of land in the form of biomass inputs in the energy sector, either as input to synthetic liquid fuels or in direct use as a combustion fuel. The expansion of these uses of biomass would increase the demand for lignocellulosic biomass products and might put energy uses of biomass in direct competition with other uses such as timber. Other agricultural non-woody wastes can also play a role as input to the energy sector. Expectations related to the growth of biomass use endanger the further decrease of natural forests surfaces, unless proper management practices are put into place.

GHG emissions mitigation by the agriculture and land sectors in the central 2°C scenario are presented in Figure 72 ([54]).

([53]) http://www.fao.org/faostat/

([54]) The projections for agriculture and land use metrics in this report were made by soft-linking the specialised model GLOBIOM (IIASA, 2017) with the energy system model POLES-JRC. Food production, land uses and supply cost curves for several types of solid biomass resources and associated GHG emissions were derived from GLOBIOM under different levels of biomass energy supply and carbon prices. Biomass energy demand was derived from POLES-JRC.

Figure 72. Agriculture and land GHG mitigation options from 2015 to 2050, central 2°C scenario, World



Note: "CO_2 agriculture (energy)" refers to emissions reductions from the energy consumption of the agriculture sector. Other emissions in this figure refer to land use-related emissions.

Source: POLES-JRC 2018.

The agriculture sector is the source of a significant amount of two important non-CO_2 GHG emissions: about half of the world's methane emissions and about three quarters of the world's nitrous oxide, in 2015.

4.6.1 Methane emissions

Compared to CO_2, methane is a relatively short-lived species in the atmosphere, having an atmospheric lifetime of 12 years. Natural sinks for methane exist but, given its high global warming potential ([55]), its role is very important in the global warming process. In recent decades, methane emissions have been growing, but at a slower pace than CO_2; according to the WGIII contribution to the fifth Assessment Report (IPCC, 2014), global methane emissions in 1980 amounted to more than 200 $MtCH_4$, and rose to about 313 $MtCH_4$ in 2010 (about 16% of total GHG emissions).

Atmospheric methane sources include anthropogenic emissions and natural emissions. Natural emissions would account for about 42% of the total for the decade of 2000–2009 ([56]), with the main ones being wetlands and marshes; the rest are currently not very well understood (e.g. geological processes, lakes, rivers, termites). Anthropogenic emissions would account for the rest, with the main sources within anthropogenic emissions being agriculture and biomass burning (44%), fossil fuel production and use (37%) and waste (19%) in 2015.

Options to mitigate anthropogenic methane emissions exist, however, reducing methane emissions from the agriculture sector might prove more difficult than for methane emissions in the energy sector and waste. There is room for the dissemination of best

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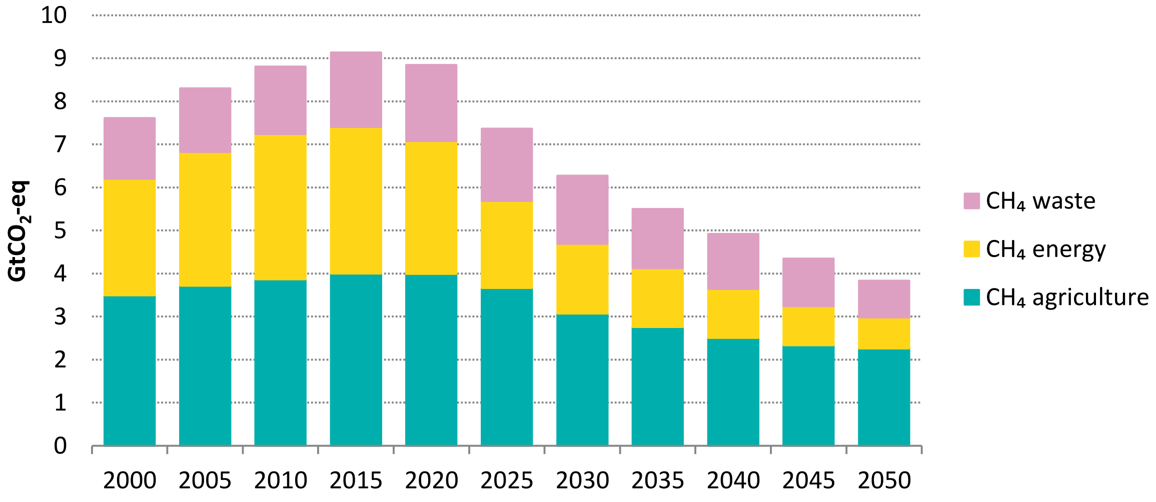
([55]) The IPCC's recommended value for the methane global warming potential over 100 years relative to CO_2 is 25 (IPCC, 2013); this value has been used in this report.

([56]) http://www.globalcarbonproject.org/methanebudget/13/hl-compact.htm agricultural practices, i.e. the intensification of widespread pasture-based livestock production systems and the substitution by existing and more productive systems. Methane emissions from livestock and rice paddies are seemingly harder to mitigate. On-going research on cattle indicates that changes in feed composition, the development of methane inhibitors and the identification of low-methane-producing cattle breeds are promising technologies, although not available in the short term commercially and less so in developing countries. These technologies can simultaneously improve milk and meat productivity and reduce methane emissions from ruminant digestion (Government of Western Australia, 2018). Methane emissions from rice paddies can be substantially lowered if appropriate management techniques are implemented, offering at the same time higher productivity and a better use of water resources (Searchinger, et al., 2014).

In the central 2°C scenario, total anthropogenic methane emissions decrease by nearly 58% over 2015–2050 (Figure 73). A large part of the reduction is from the energy sector, associated with the production and use of fossil fuels, assuming the link to a progressively decarbonised energy sector. The decrease in agricultural emissions is more moderate (-43%); the share of agriculture in total methane emissions thus increases to 60% by 2050.

Figure 73. Anthropogenic methane emissions sources, central 2°C scenario, World



Source: POLES-JRC 2018.

A further decrease of methane emissions could be achieved with changes in the demand of products that result in these emissions: dietary change towards a lower consumption of meat, in particular beef and lamb, would significantly reduce methane emissions as well as a number of chemical pollutants of water. This was not explored in the central 2°C scenario where livestock grows in total but livestock consumption remain roughly constant in terms of calories per capita (17% of total calories consumed as a world average; 27% and 15% for OECD and non-OECD countries, respectively).

4.6.2 Nitrous oxide emissions

Nitrous oxide (N_2O) is the third largest GHG in terms of global warming potential-adjusted emissions (^{57}), with an atmospheric lifetime of about 120 years. It is emitted predominantly by biological sources in soil and water. Direct anthropogenic emissions accounted for 40% of total emissions, with cultivated soils (20% of total), industrial

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(^{57}) This report uses the IPCC's Fourth Assessment Report (IPCC, 2014) values for global warming potentials relative to CO_2; this value is 298 for nitrous oxide.

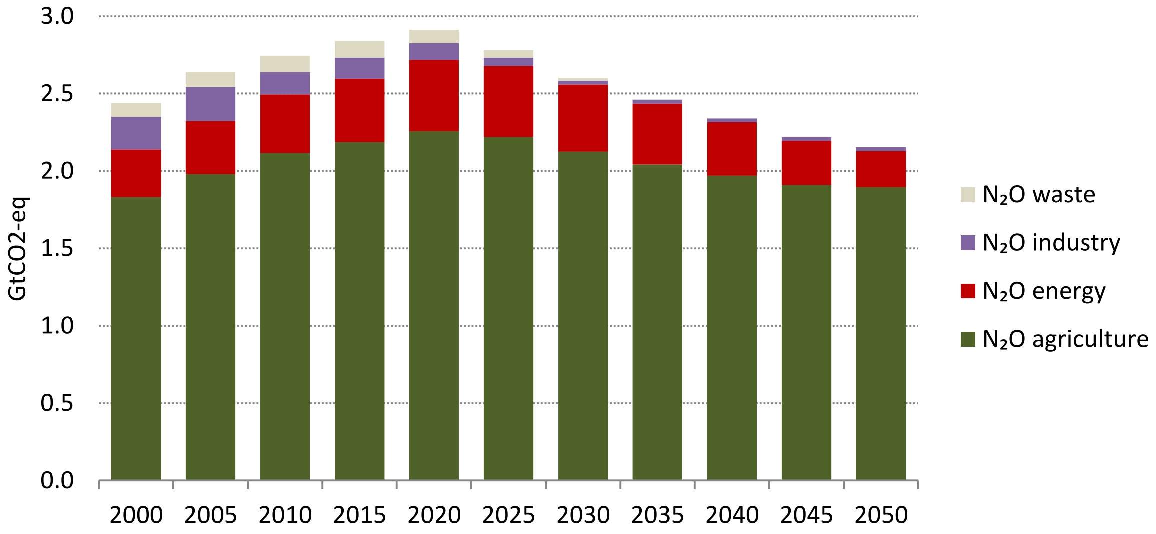
sources (8% of total), biomass burning (3.5% of total) and cattle and feedstock (2.5% of the total) as main chapters (Tian, et al., 2015).

N_2O mitigation would focus on the agriculture sector and the fertiliser producing industry. In the past, N_2O emissions from synthetic nitrogenous fertilisers decreased over 1985-2000 due to a shift towards organic soil cultivation in combination with more efficient agricultural methods and fertiliser use (Prokopiou, et al., 2017). However, given the dispersion of sources and lack of stringent measures related to this GHG, emissions have again increased since 2000. Reducing them in the future would prove to be challenging, given projections for food demand increase, and would require targeted policies and measures within the agriculture sector and the fertiliser-producing industry.

Technical mitigation opportunities to reduce nitrous oxide emissions from these sectors have recently been reviewed by (Winiwarter, et al., 2018). Low-cost abatement options are available in industry, wastewater and agriculture (large farms). The largest abatement potential at higher marginal costs is from agricultural soils, by employing precision fertilisation and using the so-called nitrification inhibitors.

In the central 2°C scenario, total anthropogenic nitrous oxide emissions decrease by 24% over 2015–2050 (Figure 74). The largest part of the reductions in volume would be from the agriculture sector. N_2O from industry and waste in particular would be mitigated nearly completely. As a result, the share of agriculture in total nitrous oxide emissions would increase to 88% by 2050.

Figure 74. Anthropogenic nitrous oxide emissions sources, central 2°C scenario, World



Source: POLES-JRC 2018.

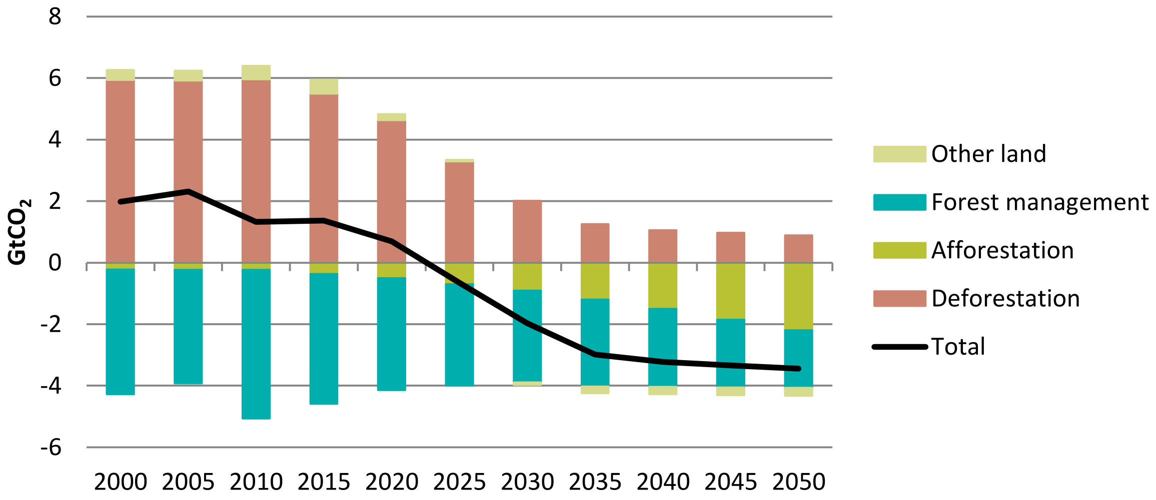
Nitrous oxide also plays a crucial role as the primary originator of other oxides of nitrogen NO_x that are formed in the stratosphere, which determines the concentration and distribution of stratospheric ozone.

4.6.3 CO_2 AFOLU emissions

Land use faces the challenge of mobilising soil and forests' capacity to act as carbon sinks, while also increasing the production of biomass to supply the energy sector and other uses of biomass (timber, construction material, pulp and paper). Land use would also have to develop while respecting biodiversity and minimising wildlife habitat loss (see section 5.4).

The predominant part of CO_2 emissions from AFOLU come from LULUCF. This category of emissions can become a net sink of CO_2 emissions, globally, within the next decade, if the proper land and forest management policies are put into place. In the central 2°C scenario, total net CO_2 emissions from LULUCF would decrease from their 2010 level of about 1.3 $GtCO_2$ ([58]) to an annual sink of about 3 $GtCO_2$ in 2035; the sink would continue to grow much more marginally beyond that (Figure 75). This would mainly be achieved through a drastic reduction of deforestation and an increased effort in afforestation. In addition, forest management activities would continue to act as a sink, as new forest surfaces are planted and grow in anticipation of increased harvest for bioenergy uses.

Figure 75. Components of CO_2 LULUCF emissions, central 2°C scenario, World

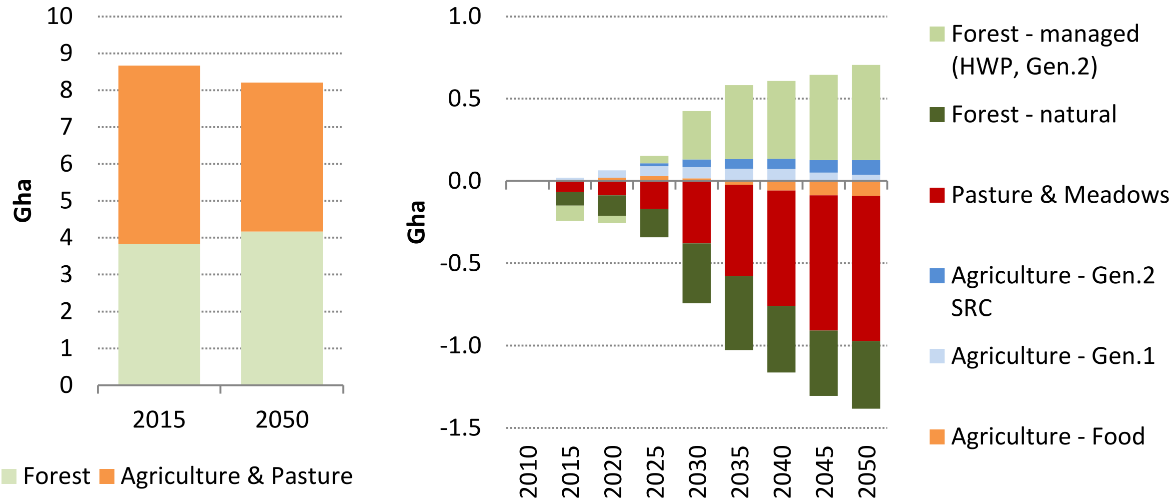


Source: POLES-JRC 2018.

This double pressure of biomass market expansion and the mobilisation of forests as a net sink can be seen in the land surface use changes over time (Figure 76). The net effect of changes in deforestation, afforestation and managed forests would be an increase in total forest area of 300 Mha (over a total forest surface in 2015 of 3,800 Mha), however, with a shift towards more managed forests (from about 14% to 29% of total forest area). Total land surface used by human activities would marginally decrease, from about 5,400 Mha in 2015 to less than 5,300 Mha in 2050, in large part thanks to the decrease of agricultural and pasture land surfaces (due to crop yield gains and a concentration of livestock activities). Surfaces used for first generation biofuels would increase, from 45 to 70 Mha over 2015–2050, but this would be limited, as second generation biofuels would expand.

([58]) Considerable differences exist between estimates of historical LULUCF emissions. Notably, a gap of about 4 $GtCO_2$/year has been identified between countries' inventories and data used in IPCC reports for the period 2005–2014, most of which can be attributed to methodological and perimeter differences in establishing emissions and sinks estimates (Grassi, et al., 2018). Emissions presented here are derived from the GLOBIOM model, for both historical levels and projections.

Figure 76. Land surface use and changes versus 2010, central 2°C scenario, World



Notes: Managed forest include surfaces that produce wood products for the energy sector (direct solid biomass use, inputs to 2nd generation biofuels) but also other industries. HWP: Harvested Wood Products (sawnwood, plywood, particleboard, paper, packaging material, etc.); SRC: short rotation coppices.

Source: POLES-JRC 2018.

Box 22. Agriculture and land use in 2100

The mitigation potential of the agriculture sector would be significantly mobilised by 2050. However, no net sink or negative emissions option exists for the residual emissions. With over 3 $GtCO_2$-eq of GHG emissions in 2100, agriculture would be one of the main remaining sectors with residual emissions. The global average GHG emissions from agriculture per capita would decrease from 0.84 tCO_2-eq /cap in 2015 to 0.44 tCO_2-eq/cap in 2050, and to 0.35 tCO_2-eq/cap in 2100, while food consumption would stabilise at 3,300 kcal/cap from 2030 onwards (compared to 2,900 kcal/cap in 2015).

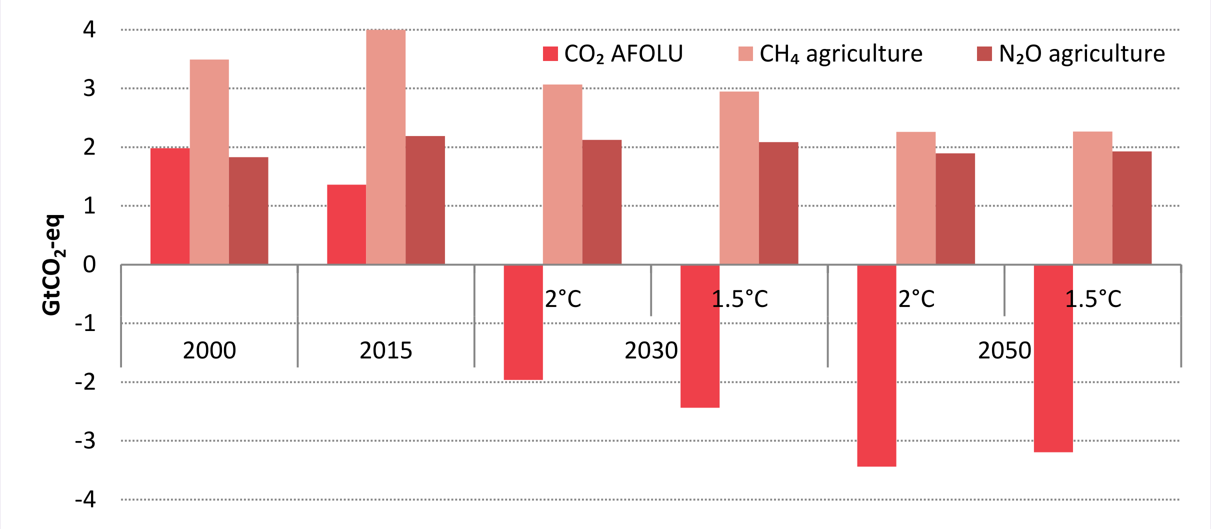
On the other hand, LULUCF would become carbon-neutral relatively early and would continue to be a net sink by the end of the century. By 2100, it would remove about 5 $GtCO_2$ from the atmosphere annually, with the additional sink compared to 2050 mainly due to additional afforestation. Over the long term, the net sink offered by forest management activities would stabilise to zero, as these forests would reach maturity and harvests would coincide with growth.

Box 23. Agriculture and land in the 1.5°C scenario

With the same constraint to provide sufficient food for the world's population, the same mitigation measures would be adopted in agriculture; emissions would be similar in the 2°C and 1.5°C scenarios, ranging around 4.1 $GtCO_2$-eq in 2050.

Similarly, most mitigation in LULUCF would take place over the next two decades, with LULUCF becoming a net sink globally in the 2020s, and reaching a sink of 3.2 $GtCO_2$-eq in 2050. This sink in the 1.5°C scenario would be slightly less than in the 2°C scenario, due to the more important forest management emissions related to a higher use of biomass in the energy sector (130 EJ/year versus 110 EJ/year in 2050).

Figure 77. Agriculture and land use emissions in the 2°C and 1.5°C scenarios



Source: POLES-JRC 2018.

5 Historical trends and projections for energy

This section provides additional details on the foreseen impact of the 2°C policies on the final and primary energy demand, and the interaction of socio-economic growth with decarbonisation constrains. This section includes a specific focus on biomass supply and demand.

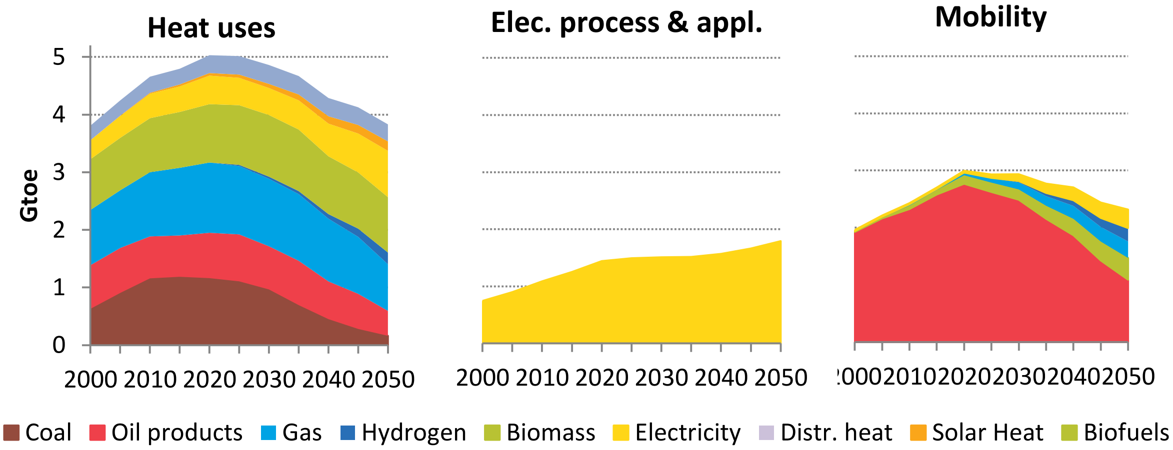
5.1 Uses of energy

World energy uses is the largest contributor to GHG. While in the past decade the electricity sector has been the main focus of low-carbon policies, the drop in renewable electricity generation costs implies that decarbonisation efforts will also need to build momentum in the other energy uses, heat and mobility.

In recent years, final energy demand (including non-energy uses in industry and energy consumption of international aviation and maritime bunkers) has kept rising, despite the world economic slowdown. In 2016 global final energy demand reached 9.8 Gtoe, 1.9% higher than 2015, to be compared with 1.4%/year on average over the previous five years.

However, in the central 2°C scenario ambitious climate policies and energy efficiency efforts would result in a decelerating growth of final energy demand beyond 2020. After a decade with a high annual growth (2000-2010, 2.3%/year) and a notable deceleration in recent years due to the global economic slowdown (2010-2015, 1.4%/year), total final energy demand is projected to peak in 2020, at around 10.3 Gtoe, and then stabilise around 8.6 Gtoe in 2050, decreasing progressively every decade after 2020 by -0.2%/year, -0.8%/year and -0.8%/year respectively.

Figure 78. World final energy demand by end-use, by fuel



Note: Figures include the energy consumption of international aviation and maritime bunkers.

Source: POLES-JRC 2018.

In terms of demand by end-use, see Figure 79, energy efficiency and the carbon intensity of the fuel mix are the driving forces behind the evolution of final demand.

Heat generation is currently the largest energy end-use in the world. It covers more than half of final energy demand, 50% in 2015, of which 64% comes from unabated fossil fuels, mostly gas in OECD countries but also coal in China, CIS and Eastern Europe, and oil mainly in the USA and China. By 2050 heat uses would still represent the bulk of final fuel consumption, at 44%, but with a higher participation of electricity and biomass.

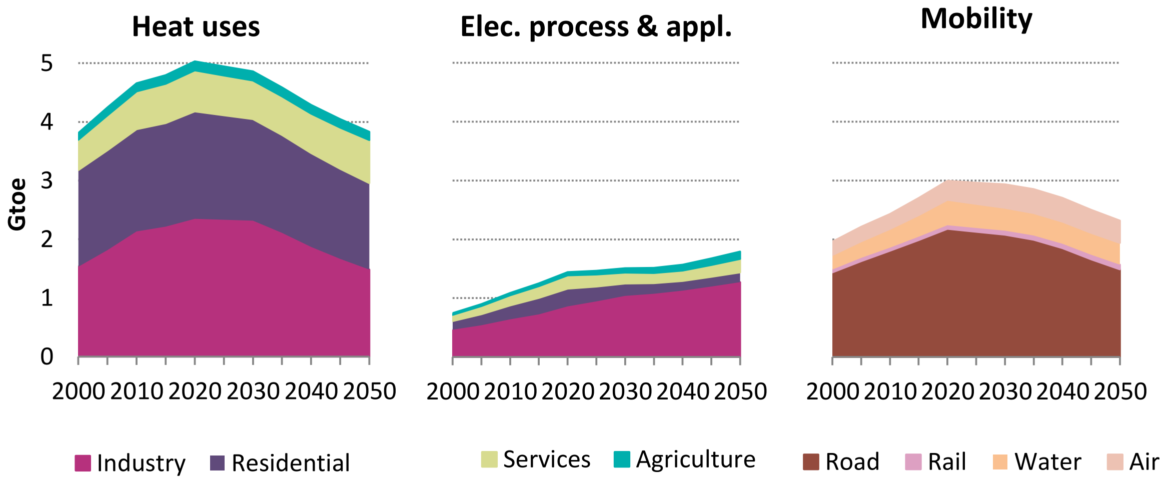
Coal would reduce its participation to 4% while gas would stay stable at 21% (Figure 78).

The **mobility** sector would still remain reliant to a significant degree on liquid fuels throughout 2050, albeit to a reduced extent. Oil products supplied 95% of the total energy demand for mobility end-uses in 2015, but would only represent 47% by 2050. The gap would be filled by liquid biofuels (16%), electricity (14%), gas (12%) and hydrogen (10%). This shift towards decarbonisation in the mobility sector would in addition be driven by more energy-efficient vehicles, vessels and aircraft and other operational improvements, leading to a decline in CO_2 emissions from 2020 onwards (Figure 78).

Electrification of end-uses can dramatically change the shape of the load faced by the power supply sector, due to increasing equipment rates for appliances but also particularly due to the increased adoption of electric batteries for mobility and electric heat pumps for space and water heating needs.

The distribution of energy demand by sector (Figure 79) would remain fairly stable in the future – at roughly one third for industry, buildings and transport.

Figure 79. World final energy demand by end-use, by sector



Notes: Electricity demand is found in "Mobility", "Electrical processes" and "Heat uses". "Electrical processes" include electrical appliances. Note: Figures for air include international aviation and for water include maritime bunkers.

Source: POLES-JRC 2018.

5.2 Global primary energy demand by fuel

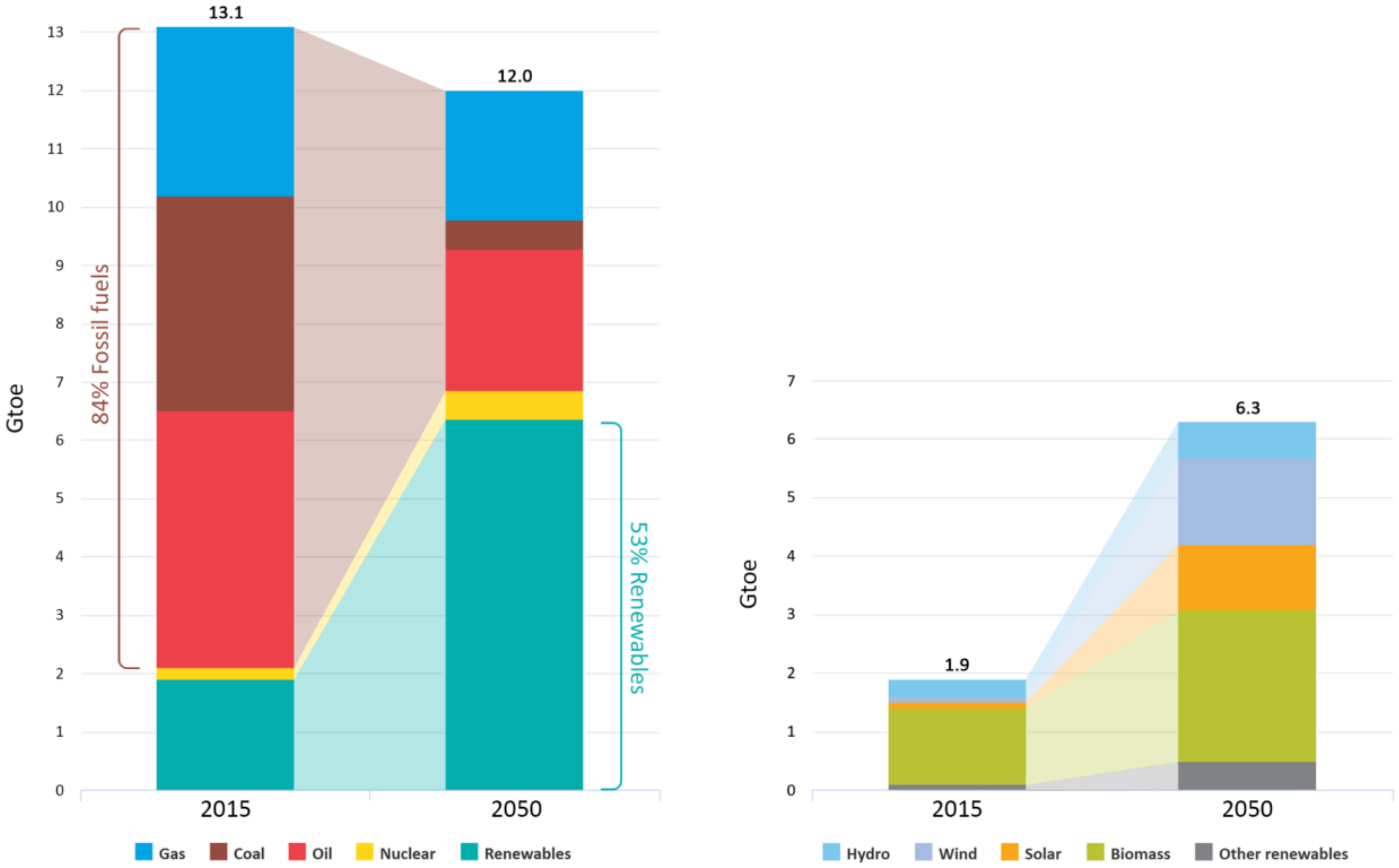
Total primary energy demand is the sum of final energy demand and the energy used in the transformation into final fuels (power generation, synthetic liquids and gases ([59])) and losses. World primary energy demand grew at an annual rate of 2.2%/year from 2000 up to 2015. In the central 2°C scenario, it would peak in 2020 and decrease at an average global annual rate of 0.5%/year throughout 2050, as a consequence of the climate policies and sectoral mitigation strategies described above.

In 2016, total primary energy demand worldwide reached 13.4 Gtoe. More than three quarters (84%) of global energy demand was still being met by fossil fuels, despite the significant growth of renewable energy over the previous decade. The participation of renewables in 2016 reached 14%, more than half of it being traditional biomass.

Crucially, the implementation of climate policies across countries and the growing role of new technologies would determine the future fuel mix evolution. In the central 2°C scenario, all fuels except renewable and nuclear would decrease their share in the primary energy mix throughout 2050 (Figure 80). Non-GHG-emitting sources, consisting of renewables, nuclear and fossil fuels associated with CCS, would rise to 58% of the total energy mix.

([59]) Synthetic liquids include liquids from biomass, coal and gas liquefaction; synthetic gases include hydrogen and synthetic methane (produced from combining hydrogen and CO_2). All these synthetic fuels are accounted in final demand (and in the international aviation and maritime sectors); the energy inputs to produce them are accounted in the energy transformation sector.

Figure 80. Primary energy supply by fuel 2015–2050, central 2°C scenario, World



Note: Nuclear is accounted as primary electricity.

Source: POLES-JRC 2018.

Renewable energy sources (hydro, biomass, solar, wind, geothermal and ocean) would be the fastest growing source of energy, with its share in primary energy demand increasing to 53% by 2050, vs. 14% in 2015. This growth would mainly be through the increased contribution of biomass (22%) and two key primary renewable sources: wind (13%) and solar (9%). Supported by climate policies, when combined, renewables could become larger than any of the three fossil fuels as early as 2033.

The renewables expansion is followed by **nuclear**. World nuclear supply is projected to grow in the coming decades, increasing twofold over 2015–2050 in the central 2°C scenario up to 4% in 2050 of total primary energy vs. 2% in 2015. This would be mainly due to the expansion of nuclear power in non-OECD countries (mostly concentrated in China, India, South-East Asia, Central Asia and Russia), which would account for two thirds of the world nuclear power generation in 2050. In OECD countries, the growth would be smaller and new installations would mostly replace decommissioned plants.

These changes would mainly be at the expense of **fossil fuels**, and more specifically of coal. Fossil fuels' combined demand would peak in 2020.

- The share of **oil** would progressively decline, in line with a longer trend observed since the 1970s. Oil demand would peak in 2020, and start decreasing progressively with a rate of -1.7%/year over 2015–2050. By 2040 it would reach its 2000 level.
- The share of **gas** would decrease, however its absolute demand would not peak before 2030. It would progressively decrease beyond that with a rate of -1.8%/year between 2030–2050. By 2060 it would reach its 2000 level.
- **Coal** demand would be most strongly and quickly impacted by stringent climate policies. Coal demand would peak in 2020 and decline at -5.4%/year over 2015–2050, and would be completely phased out from some of its uses (e.g. as a cooking fuel in the residential sector). It would reach its 2000 level in the early 2030s. By 2050 it would only represent 4% of total primary energy demand, the lowest share it has had since the industrial revolution. This trend would occur despite the gradual deployment of CCS technologies in the 2030–2050 decades (by 2050, only about a quarter of total coal use would be associated with CCS).

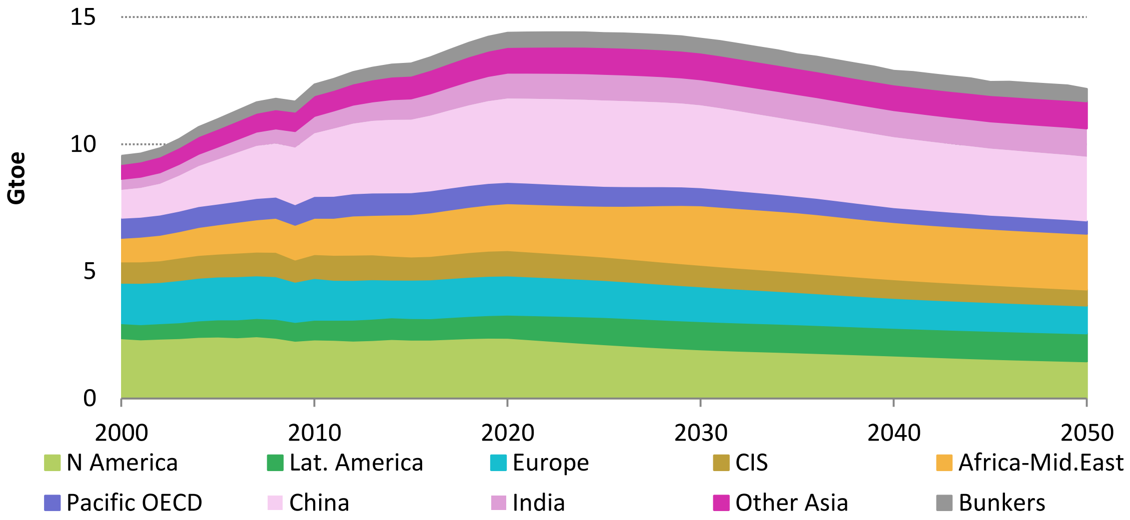
5.3 Global primary energy demand by region

An ambitious objective for limiting climate change will trigger deep changes in the energy system through accelerated fuel substitution, strengthened energy efficiency, and also changes in the type of energy that is consumed based on the relative mitigation costs of decarbonising each sector and each energy carrier. Specifically, the electrification of final demand coupled with the power sector decarbonisation is expected to play a crucial role in the overall process, as has already been underlined in the previous sections.

In the central 2°C scenario, from a global perspective, primary energy demand would peak in 2020.

Figure 81 shows the world primary energy demand by region in the central 2°C scenario. It would peak at around 14.4 Gtoe in 2020, and from there it would fall to 12.0 Gtoe in 2050, the lowest level since 2010. Asian countries are projected to almost stabilise their share in the world energy demand, getting close to 39% by 2050 compared to 35% in 2015, although socioeconomic assumptions describe a growing population and a quickly expanding economy. OECD countries would still account for 30% in 2030, compared to 37% in 2015, with their demand per capita being significantly higher than in non-OECD countries.

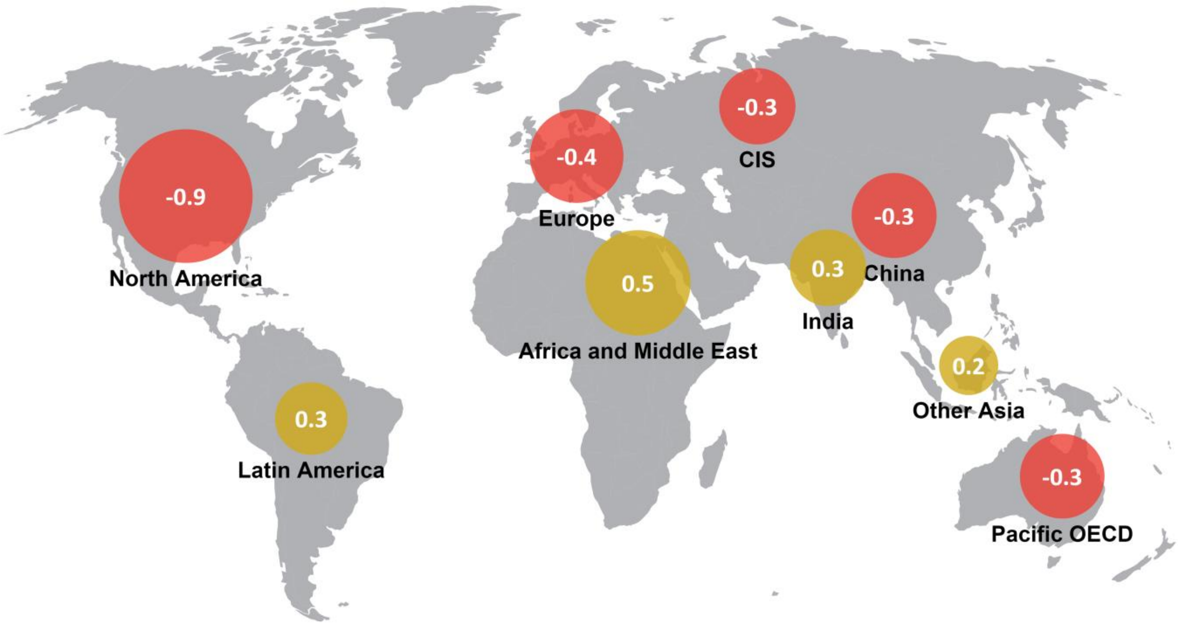
Figure 81. Primary energy demand by regions, central 2°C scenario, World



Source: POLES-JRC 2018.

Despite the strong climate policies implemented, primary energy consumption would continue to increase in growing emerging economies such as Latin America, Asia and Africa (Figure 82).

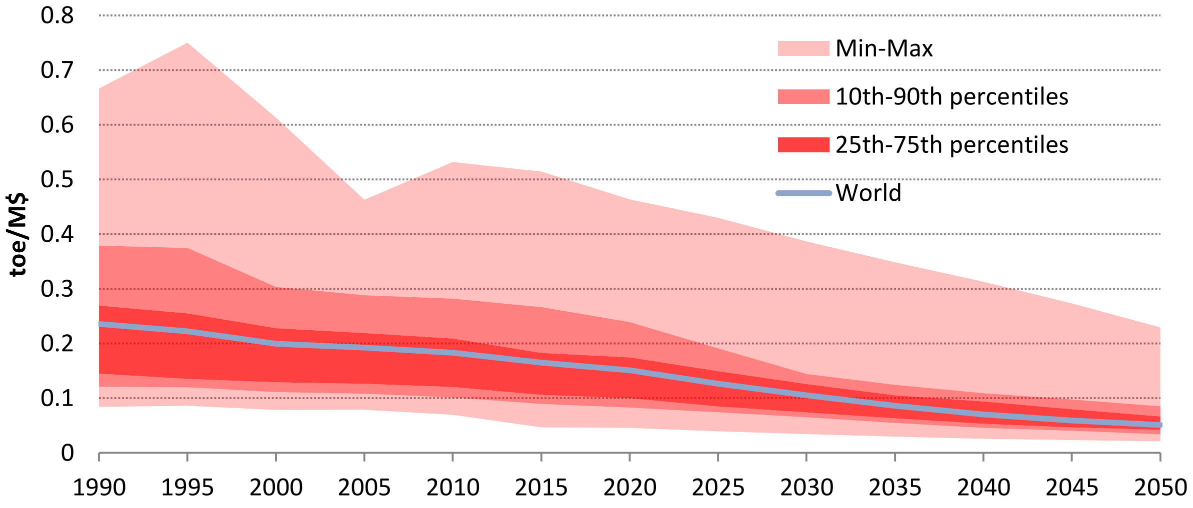
Figure 82. Change in primary energy demand by region 2015–2050, central 2°C scenario



Source: POLES-JRC 2018.

The convergence of primary energy use per GDP unit in the different world regions in the central 2°C scenario is the result of the decoupling of economic growth from energy consumption (Figure 83).

Figure 83. Average world primary energy per GDP, historical data 1990–2015, central 2°C scenario projection 2015–2050



Source: POLES-JRC 2018.

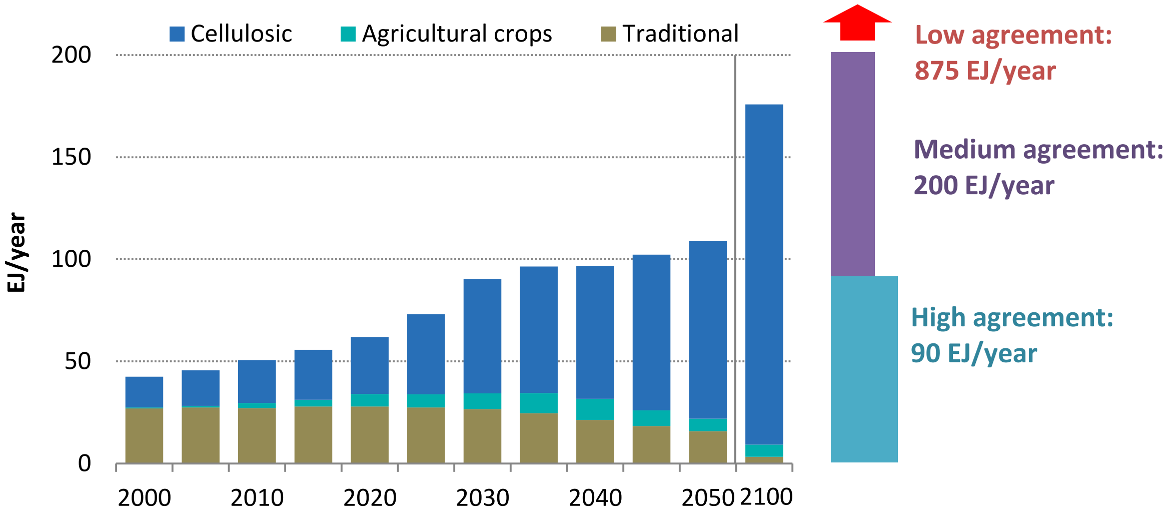
5.4 A closer look at biomass markets

Agricultural and forestry products provide food, textile, construction materials, as well as various forms of biomass as input to the energy system. Future biomass uses for energy are projected to expand with climate policies, mainly as an alternative to fossil fuels for direct combustion and as a feedstock for the production of synthetic liquid fuels.

Bioenergy coupled with CCS technology can result in net negative CO_2 emissions. The emissions mitigation potential of bioenergy together with CCS will have to be mobilised with due care for the wider impacts of increasing biomass-for-energy use: in particular, environmental side-effects such as land erosion, loss of habitat of wild species and biodiversity loss (see SDG15: Life on land) ([60]). Biomass use also interacts with other sustainability criteria; most notably food security and water use (see 4.6).

Figure 84 right axis, plots long-term biomass-to-energy potentials estimates ([61]) across several biomass source types, from a comparative study (Creutzig, et al., 2015); estimates vary on a multitude of criteria such as social, political and economic factors plus the stringency of sustainability criteria. There appears to be a moderate agreement in the literature for the potential of biomass for energy use of about 200 EJ/year, and a higher level of agreement for the more conventional figure of 90 EJ/year. With these constraints in mind, the central 2°C scenario was designed so as to keep biomass-for-energy use below a relatively conservative ceiling of 180 EJ/year throughout the century ([62]).

Figure 84. Biomass for energy and sustainable potential estimates, central 2°C scenario



Source: POLES-JRC 2018.

Current biomass inputs to the energy system exceed 50 EJ/year. By 2050 they would increase to as much as 108 EJ/year (and remain below 180 EJ/year throughout the rest of the century), with a growth rate of 2% between 2015 and 2050.

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[60] SDG 15: Life on land: Protect, restore and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

[61] Accessible potentials regardless of the time horizon considered

[62] The way this potential is used takes into account the future development of yields and an increasing cost of production as more of the potential is being used, using information from the GLOBIOM model, see (IIASA, 2017).

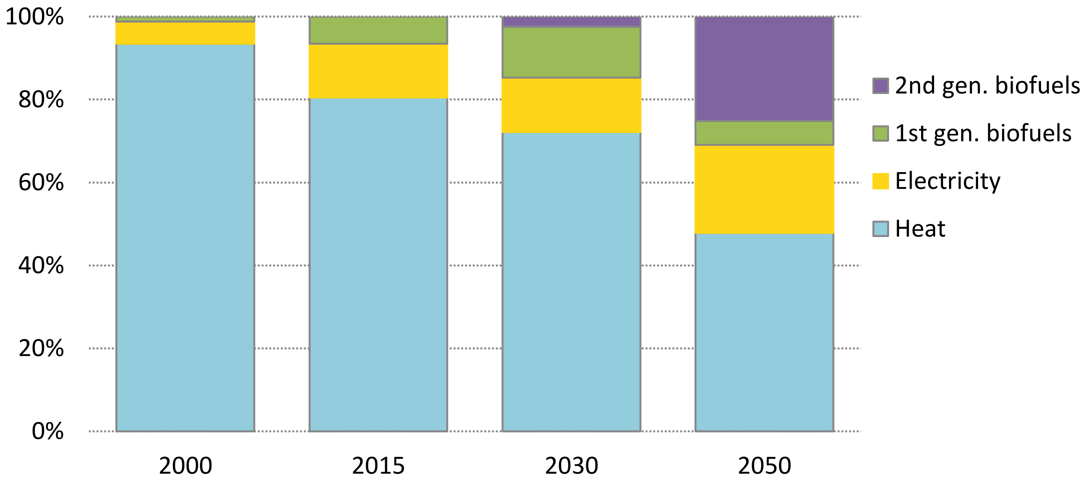
Half of bioenergy currently (2015) comes from traditional biomass ([63]), in the form of hand-collected wood and animal waste. This is projected to decrease in the future as economies grow and replace it with modern fuels (see section 4.2).

Most of the modern biomass-for-energy supply would come from lignocellulosic resources (forestry residues and dedicated short rotation coppices for biomass-to-energy conversion), either for direct use in combustion or for second generation biofuels.

Dedicated agricultural crops for first generation biofuels made up 6% of total biomass supply in energy terms in 2015. They would grow till 2030 and beyond that would progressively be displaced by cellulosic plantations for second generation liquid biofuels, decreasing back to 4% of the total in 2050.

Around 2015, most of the biomass consumption was dedicated to combustion for heat uses (about 93% in 2015), with approximately 1% being consumed in the form of liquid biofuels (first generation) and the rest in power generation (Figure 85). In contrast, future demand growth would be driven by power production and second generation biofuels. By 2050 biomass in power production would reach 21% of total biomass use, while biomass for heat would drop to 48%. Second generation biofuels would emerge progressively in the 2020s and expand significantly in the 2030s, accounting for the remaining 25% of biomass uses.

Figure 85. Primary bio-energy demand by use, share, central 2°C scenario

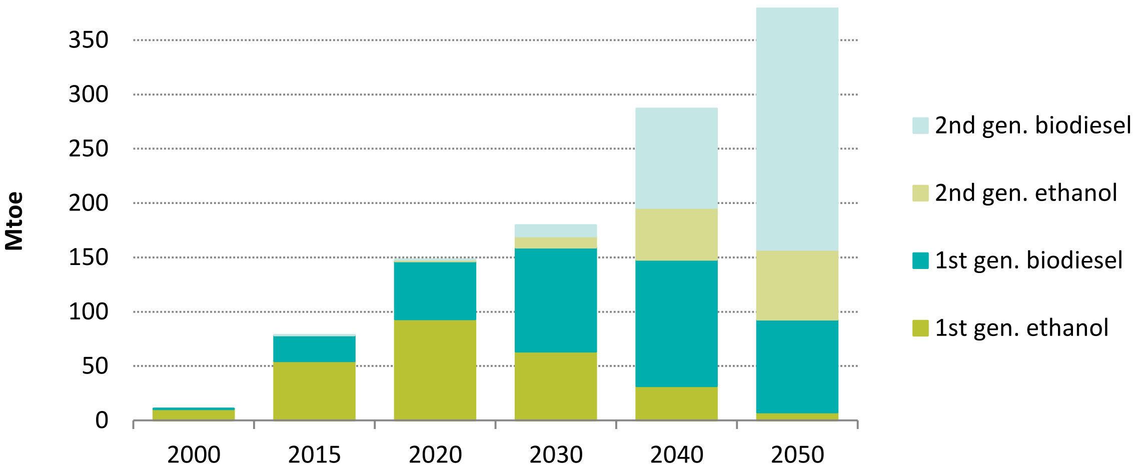


Source: POLES-JRC 2018.

Liquid biofuels demand is projected to grow (Figure 86) as a way of decarbonising transport, but also as products that are in direct cost-competition with oil products. Their expansion in road transport is relatively limited by increases in ICE efficiency, and by substitution with other technologies (most notably electric engines). However, their use grows not only in road transport but also in aviation and maritime transport, which would consume most of the biodiesel produced. By 2050, biofuels would account for 18% of total liquids in road transport energy demand as a world average, 34% in world air transport energy demand, and 32% in international maritime energy demand.

([63]) Modern biomass: pellets, bricks, processed agricultural waste, etc. Traditional biomass: solid biomass (non-marketed wood, agricultural residues, animal dung) used mostly for cooking but also space heating, with pre-modern techniques (stone oven, indoor open-fire pit) that result in low efficiency (about 20%) and high air pollution.

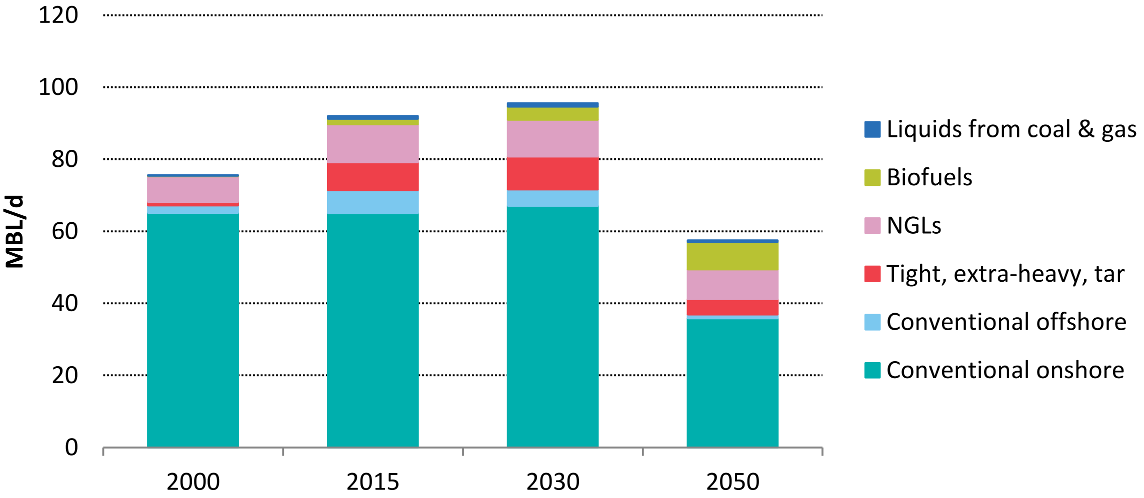
Figure 86. Liquid biofuels production, central 2°C scenario, World



Source: POLES-JRC 2018.

First generation biofuels use dedicated agriculture crops, which can come into competition with food over land use; their share is expected to decrease over time with the development of second generation biofuels. In 2011 the production of synthetic liquid fuels consumed 4% of all crops production ([64]) (Morrison & Golden, 2015), while its contribution in the world energy system has been small: in 2015, biofuels were 2% of total liquids demand and 4% of liquids demand in road transport (Figure 87) ([65]).

Figure 87. Crude oil and liquids supply by source, central 2°C scenario, World



Source: POLES-JRC 2018

Biomass use in the power sector would also grow, either in direct combustion or in a gasification process. Biomass power plant capacities globally would increase from about 100 GW in 2015 340 GW in 2050 (of which, about 60 GW would be coupled with CCS).

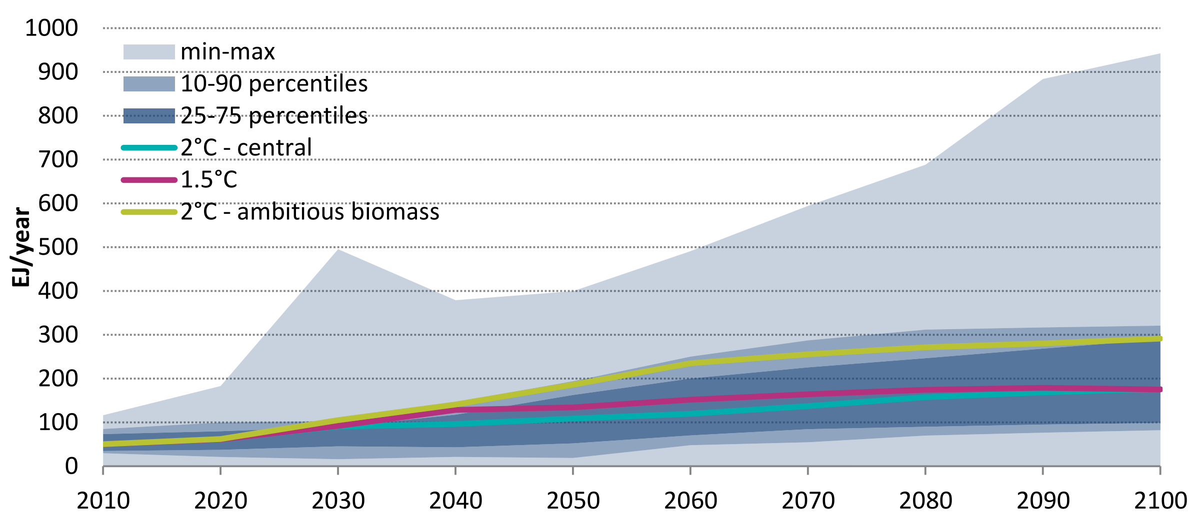
([64]) In tonnage of all cereals, roots, fruits and vegetables; not including roundwood forestry.

([65]) Oil products in transport and other final demand sectors include a small amount of synthetic liquids (<1%, from coal and gas liquefaction, Figure 87). Gas refers to methane of natural or synthetic origin; synthetic methane (produced from combining hydrogen and CO_2) is consumed only in road transport. Liquid biofuels are consumed in transport (including the international aviation and maritime sectors). Hydrogen is consumed in several final demand sectors (iron reduction, stationary fuel cells, fuel cells in transport).

Box 24. Anticipating different futures: Ambitious biomass availability

The central 2°C scenario has a conservative contribution of biomass in the energy system, mainly due to the increasing concerns about the impact of increasing biomass use on biodiversity and the potential competition with food production. However, the interaction of biomass use with sustainability criteria is still a matter of intense research; in addition, the constraints of a fast and deep decarbonisation of human activities might push for a wider use of biomass. For this reason, an alternative scenario with higher biomass use compared to the central 2°C scenario, is analysed below. This ambitious biomass scenario uses a long-term biomass supply potential of 300 EJ/year, compared to 180 EJ/year for the central 2°C scenario. Compared to existing projects and literature including multi-models comparisons, both the conservative and ambitious biomass scenarios are within acceptable ranges (Figure 88).

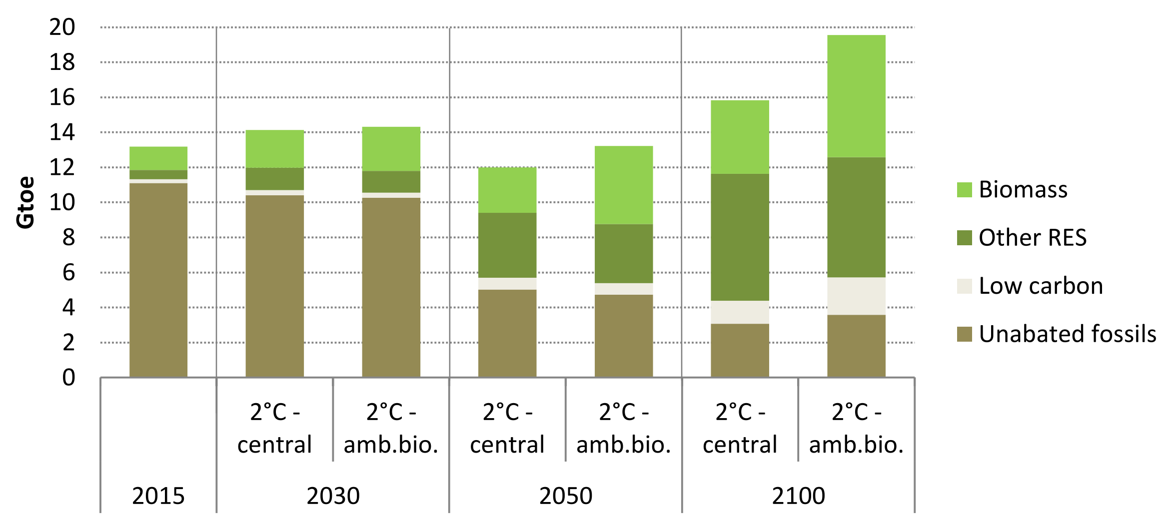
Figure 88. Biomass primary energy demand in the GECO 2018 scenarios, compared to the existing literature



Sources: CD-Links project & POLES-JRC 2018

Figure 89 illustrates the primary energy demand in these two scenarios and the contribution of biomass to the energy system. Biomass energy supply is projected to be 17% higher in the ambitious biomass scenario compared to the central 2°C scenario already in 2030; and around 70% higher in 2050 and in 2100. Biomass would remain the single largest contributor to the renewables energy supply in 2050 (57% of total renewables in the ambitious biomass scenario compared to 41% in the central 2°C scenario, down from 71% in 2015).

Figure 89. World primary energy demand for the central 2°C and the ambitious biomass scenarios



Source: POLES-JRC 2018

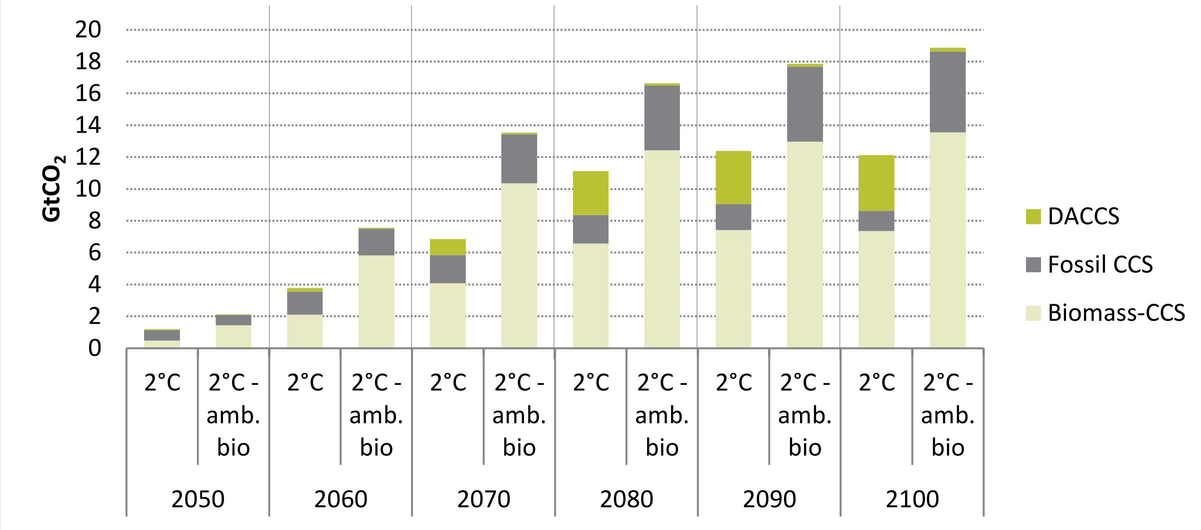
The wider availability of a low-carbon energy source decreases the level of stress on the energy system to decarbonise. As a result, in the ambitious biomass scenario fewer energy efficiency efforts are undertaken and total primary energy demand is projected to be higher (10% higher in 2050). In order to maintain the 2°C warming objective, the contribution of renewables and low-carbon energies is projected to be higher (64% in 2050 compared to 58% in the central 2°C scenario) while the volume of fossil energies is relatively similar (4.7 and 5.0 Gtoe in 2050 in the ambitious biomass and central 2°C scenarios, respectively).

The higher availability of biomass in the power sector would put it in more competition with other renewable technologies. Wind in particular would be impacted in this scenario (20% less production in 2050 compared to the central 2°C scenario). Investment decisions would be dependent on rules of operation of the market and how BECCS, as a negative emissions technology, would be remunerated.

The expansion of CCS technologies in the second half of the century allows a higher use of BECCS in the ambitious biomass scenario: up to 14 $GtCO_2$ annually by 2100 compared to 7 $GtCO_2$ in the central 2°C scenario. This higher mobilisation of a net negative emissions technology allows for less energy efficiency and a relatively higher use of fossil fuels (4.8 Gtoe in 2100 compared to 3.4 Gtoe in the central 2°C scenario, including CCS). In addition, CCS with fossil fuels would be more competitive (fugitive emissions would penalise them in the central 2°C scenario) and as a result of a cheaper decarbonisation the deployment of direct DACCS would be greatly diminished (Figure 90).

For the 1.5°C ambitious biomass scenario, annual decarbonisation rates are projected to reach 9%/year as a global average over 2015–2050. GHG emissions reductions in 2050 compared to 1990 would reach 83%.

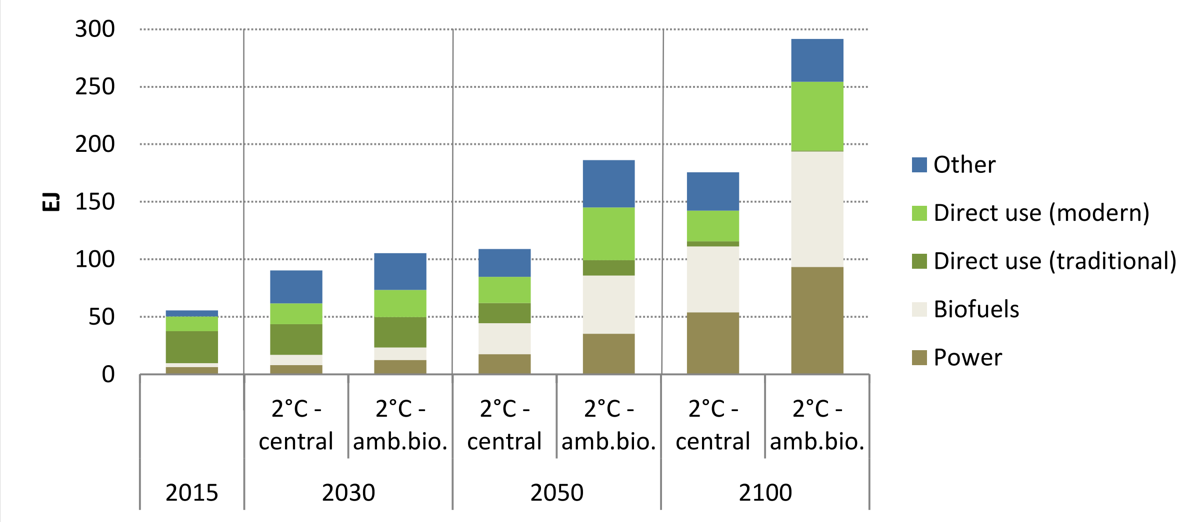
Figure 90. Annual CO_2 capture, World, central 2°C and ambitious biomass scenarios



Source: POLES-JRC 2018

However, biomass would increase in other uses as well, making decarbonisation easier for certain sectors (Figure 91). Biomass use in liquid biofuels for transport and in direct use as a combustion fuel (notably in energy-intensive industries) would be double compared to the central 2°C scenario.

Figure 91. Uses of bioenergy, World, 2°C central and ambitious biomass scenarios

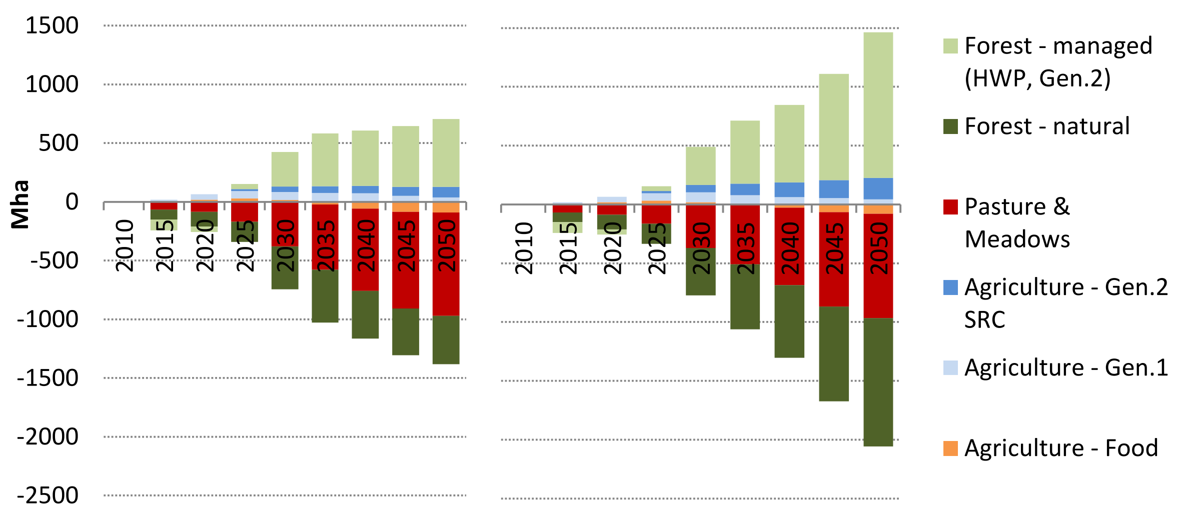


Note: Biofuels refers to solid inputs in liquid biofuels production.

Source: POLES-JRC 2018.

As a consequence of this higher use of biomass resources, significantly more surfaces would need to be mobilised to produce bioenergy (Figure 92, as compared to Figure 76). In particular, managed forests (1240 Mha increased use over 2010–2050 compared to 580 Mha in the central 2°C scenario) and short rotation coppices surfaces (180 Mha compared to 90 Mha) would increase while natural forests would shrink (decrease of 1,090 Mha compared to 410 Mha); surfaces for pasture remain essentially unchanged. This might have significant consequences for wildlife and biodiversity.

Figure 92. Land surface use changes versus 2010, central 2°C (left) and 2°C – ambitious biomass scenario (right), World



Notes: Managed forest include surfaces that produce wood products for the energy sector (direct solid biomass use, inputs to 2nd generation biofuels) but also other industries. HWP: Harvested Wood Products (sawnwood, plywood, particleboard, paper, packaging material, etc.); SRC: short rotation coppices.

Sources: POLES-JRC 2018.

6 Historical trends and projections for air pollutants emissions

The largest share of major air pollutants emissions are driven by human activity and actually originate, if we do not consider those related to non-steady natural single events (volcanic eruptions, etc), from the same source as GHG emissions, namely fuel combustion for energy supply purposes. Actual emissions depend on the type of activity, the fuel type and the technology used, which can evolve with air quality policies and standards. Thus, by reducing energy fuel consumption, energy and climate policies can bring about significant co-benefits on the emissions of pollutants and air quality. The main impact of those emissions is crucially associated with human and livestock health, as well as vegetal cover fitness and resilience. Many air pollution chemical species also have, some interaction with the climate, and notably certain air pollutants have an effect on the temperature that is mostly an atmosphere-cooling effect.

Previous work (Vandyck, et al., 2018) has studied the air quality co-benefits of climate policy for agriculture and human health in the context of the Paris Agreement. In that paper, simulations of projected GHG and air pollutant emissions up to 2050 for three climate policy trajectories were studied: a Reference scenario with only current policies, a NDC (Nationally Determined Contributions) scenario, and a 2°C-consistent pathway. The co-benefits for avoided premature mortality due to air pollution were found to be particularly large in India and China, thanks to this positive mechanism, they could roughly offset the cost of mitigating climate change on a global level. The ancillary intensity of the benefits of climate policies depends on the levels of air pollution or the stringency of controls already in place. They can be significant and can bring about pollutant emissions reductions that would be comparable to end-of-pipe measures in the absence of climate policies. Importantly, air quality benefits occur in the short run and are mostly felt in the regions close to where measures are being implemented.

As above-stated, only a fraction of pollutants emissions are anthropogenic (including non-energy processes, such as agricultural waste burning, forest fires, peat fires). Other sources of pollutants of natural origin (atmospheric dust spreading, sea salt spreading, emissions from volcanoes, etc.) are not addressed here Only anthropogenic emissions excluding fires are presented in this report.

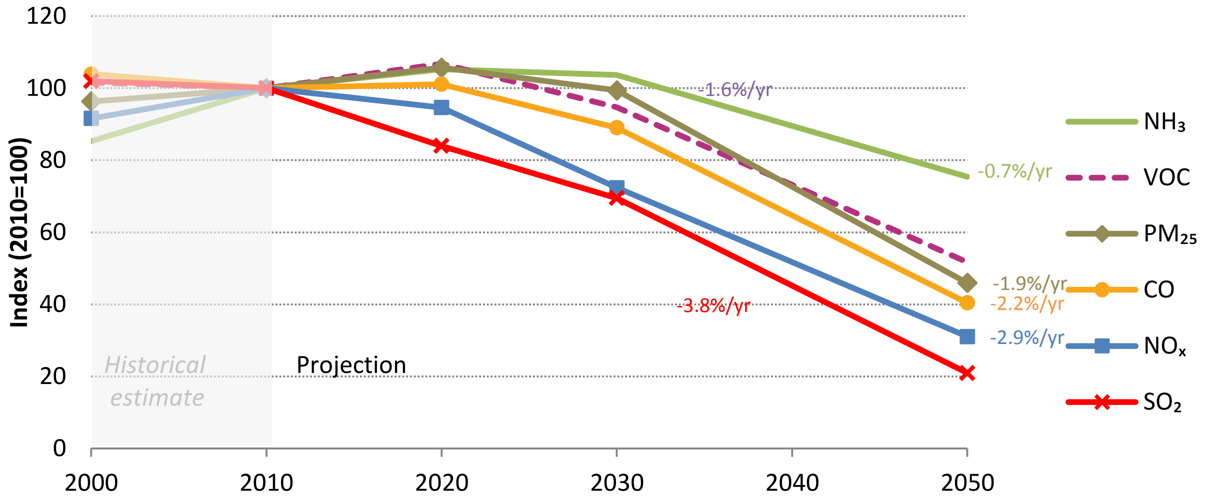
In addition to the socio-economic, the technological and the energy use pathway described by the central 2°C scenario, air pollutants emissions are characterised by emission intensity factors for each of the pollutant sources. These factors are set to describe a progressive "middle-of-the-road" trajectory of emission intensity factors, between a no-improvement (frozen policy) case and the maximum technically feasible reductions, described in more detail in Annex 5.

To start with, an overview of all major air pollutants is presented. Subsequent sections go into more detail for each of the species considered. A breakdown by sector can be found in the corresponding sections of chapter 4.

6.1 Global emissions trends

In the context of the central 2°C scenario, climate-protecting policies complemented by a moderate diffusion of air quality policies would bring about a very considerable decrease in sulphur dioxide (SO_2) and nitrogen oxides (NO_x emissions – with abatement levels of, respectively, -79% and -69%, or CAGRs of -3.8% and -2.9% per year over the period 2010–2050. Carbon monoxide (CO) and particulate matter ($PM_{2.5}$) emissions would also fall strongly (-60% and -54% between 2010 and 2050, which correspond to annual growth rates of -2.2%/year and -1.9%/year), although at lower paces than SO_2 and NO_x. Other atmospheric pollutants show significantly different behaviours. Ammonia (NH_3) emissions would remain stable until 2030 and would then decrease (-25% and -0.7%/year). Volatile organic compounds (VOC) emissions would grow until 2020 and then drop at a pace similar to other pollutants such as SO_2 (-48% and -1.6%/year), (Figure 93).

Figure 93. Evolution of pollutants emissions, central 2°C scenario, World



Note. Excludes emissions from fires and natural PM.

Source: POLES-JRC 2018.

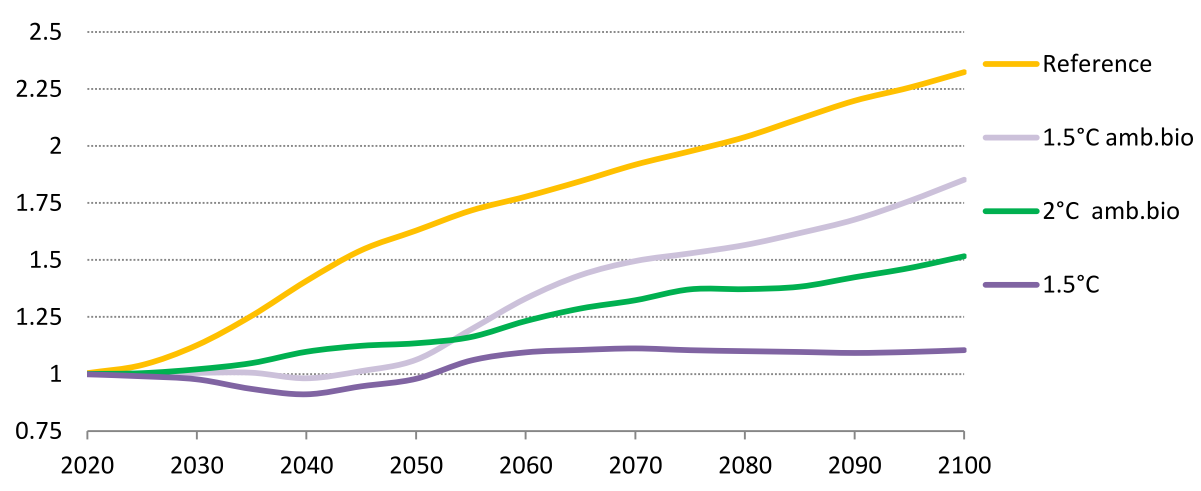
These global dynamics highlight some major trends of the potential co-benefits of mitigating GHG emissions with air pollution concerns. The main sources of SO_2 and NO_X are fossil fuels; therefore, the shift away from fossils in the 2°C scenario would induce a large decrease of these air pollutants. Particulates and carbon monoxide emissions are historically less fossil-fuel related; it follows that their abatement levels would be lower over the projection period to 2050. As will be shown below, these changes in the energy system would imply the penetration of fewer emitting energy sources/services options. NH_3 and VOCs are special cases: the former is not related to fossil fuels – agriculture being the main source; the latter relates essentially to industrial output (solvents), so that the evolution of economic activity itself, along with the implementation of specific regulations, would drive the drop in VOCs emissions.

The sectoral decompositions of the pollutant emissions as well as the co-benefits of the climate policies are explored in the following section.

Box 25. Sensitivity of air pollution to climate policies

Some of the key drivers behind climate change, particularly fossil fuel combustion, also cause local air pollution. As a result, climate action can bring synergies for air quality. Figure 94 highlights that the current climate and energy policies (Reference) would imply emissions of fine particulate matter that are approximately twice as high as in the 2°C scenario from the year 2070 onwards. In addition, the technologies and mitigation options chosen can play an important role. An alternative 2°C scenario with more biomass availability (2°C ambitious biomass scenario) lowers the ($PM_{2.5}$) air quality co-benefits compared to the central 2°C scenario. Pursuing the more ambitious 1.5°C scenario brings additional reductions of $PM_{2.5}$ emissions in the medium run, but the increasing use of biomass with CCS as a negative emission option raises the levels of $PM_{2.5}$ above those in the 2°C scenario post-2050, particularly when assuming higher biomass availability (1.5°C ambitious biomass scenario). Research by (Bertram, et al., 2018), however, shows that most of the sustainability risks of a 1.5°C pathway can be offset by targeted sector policies, early action and lifestyle changes. Their results show an improvement in air quality in the 1.5°C compared to the 2°C scenario, however, the air quality indicator only covers SO_2 emissions.

Figure 94. Evolution of fine particulate matter emissions in various scenarios, indexed to the central 2°C scenario



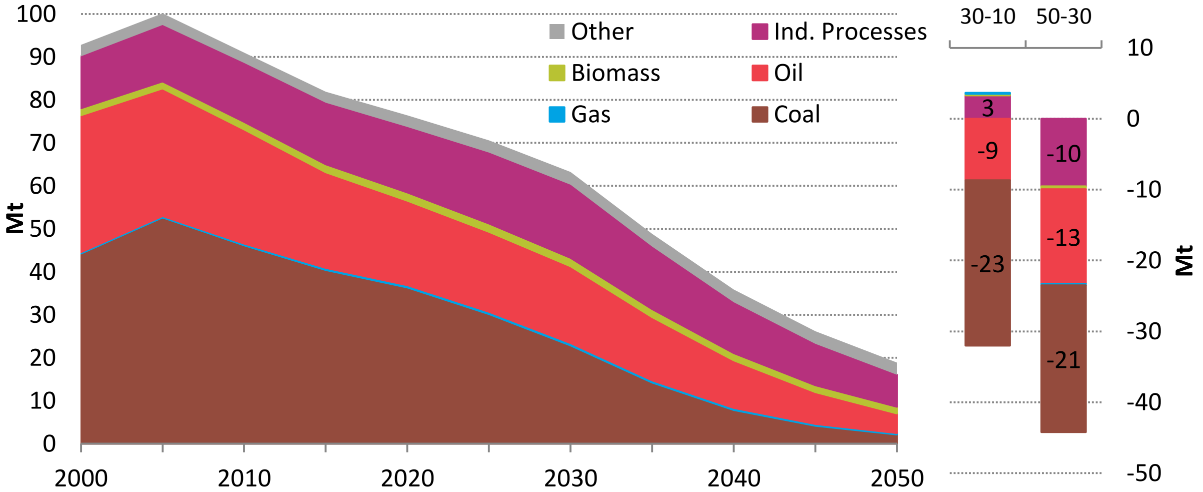
Source: POLES-JRC 2018.

6.2 SO_2 emissions

In OECD countries, SO_2 emissions, one of the main causes of acid rain, have been the subject of strict policies since the 1970s and 1980s. Correspondingly, emissions have decreased significantly since the 1990s. In non-OECD countries, strong economic growth has led to a sharp rise in SO_2 emissions which has triggered the development of air quality policies in many countries over the past decade. Strong air quality control policies in Asia have succeeded in decreasing emissions. In China, SO_2 emissions in 2015 were 28% lower than in the peak year of 2006 ([66]). This trend is expected to continue as more stringent air quality policies are implemented and flue gas desulfurisation is applied to more and more existing and future coal- and oil-fired power plants, which are the main emission sources, in China and elsewhere ([67]).

In this context and within the central 2°C scenario, global SO_2 emissions are projected to drop by 31% and 79% compared to 2010 by 2030 and 2050, respectively (Figure 95). In terms of pollutant sources, coal and oil play a major role in SO_2 emissions; hence they represent the bulk of the abatement potential, followed by industrial processes. Biomass, gas and other sources would have minor contributions. The massive reduction in coal- and oil-related emissions would make industrial processes the major emitter by 2050, with a share rising from 13% to 36%.

Figure 95. SO_2 emissions by sources, World, in the 2°C scenario, and contributions to reductions 2010–2030 and 2030–2050



Note: Other includes solvents, agriculture, and waste. Fires are not included.

Source: POLES-JRC 2018.

Combining more strict air pollution controls with climate policies compatible with remaining below a 2°C temperature rise brings strong reductions of SO_2 emissions over time. Decarbonising the power sector leads to important SO_2 reductions already in the short run, with continued emission cuts almost linearly over four decades (-17 Mt between 2010 and 2030, -17 Mt between 2030 and 2050 (Figure 96). The second most contributing sector, industry, would have stable emissions between 2010 and 2030 (+1 Mt), but becomes the main source of emission reductions between 2030 and 2050 (-23 Mt). Transport would show a different pattern, since most of the reductions would be

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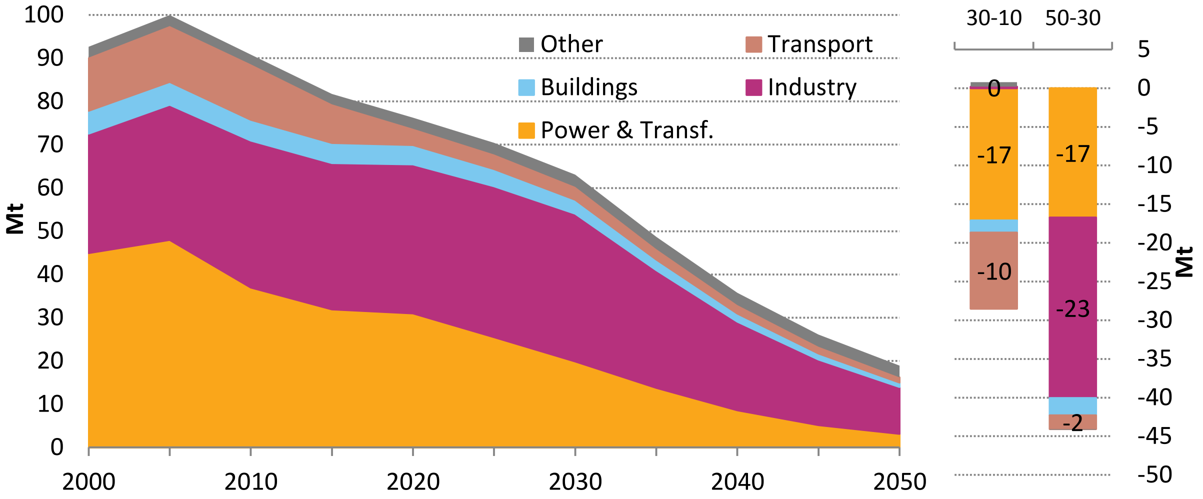
([66]) Sources: State of the Environment in China reports, China Statistical Yearbooks

([67]) The removed SO_2 can then be used in the sulphuric acid production industry, e.g. as an input in fertiliser and other chemicals production.

achieved by 2030 (-10 Mt), essentially due to fuel switching and fuel sulphur content regulations in the maritime sector ([68]).

Figure 96. SO_2 emissions by sectors, World, in the 2°C scenario, and contributions to reductions 2010–2030 and 2030–2050



Source: POLES-JRC 2018.

More precisely, coal (power generation) and oil (maritime bunkers: substitution of oil with gas due to climate policies and regulation of sulphur content) would be the main emissions reduction levers between 2010 and 2030. By 2050, the use of coal would be further reduced in industry, similar to power generation. Oil-related SO_2 emissions would drop in all sectors, while reductions in industry would principally be due to the manufacturing processes.

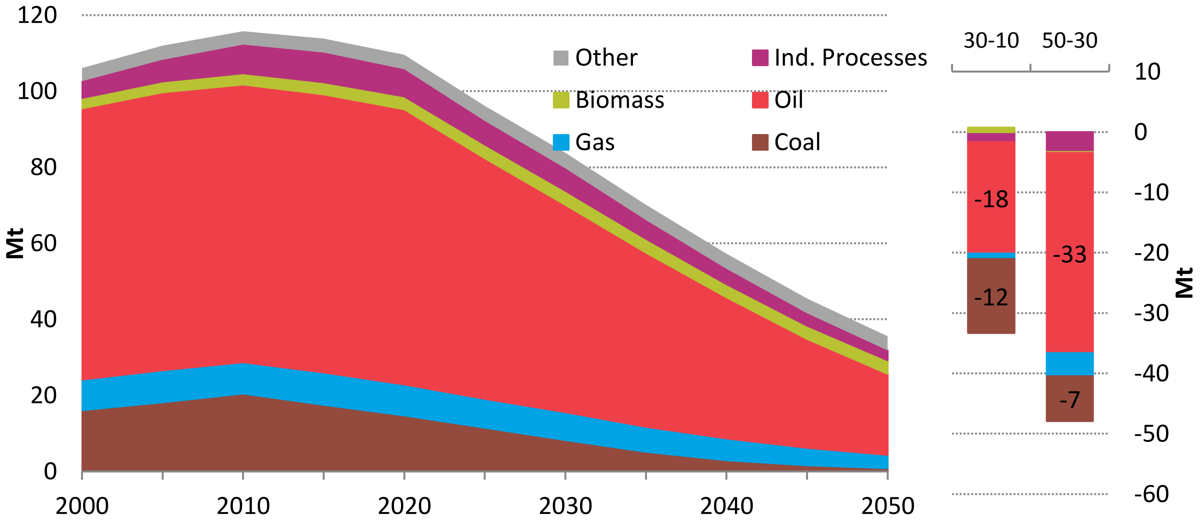
([68]) MARPOL Regulation 14 (International Convention for the Prevention of Pollution from Ships, International Maritime Organization).

6.3 NO_x emissions

NO_x emissions have been subject to numerous governmental regulations due to their severely negative health effects (particularly with road traffic exposure in dense urban centres), as well as because of acid rain. Notably, since the 1980s, the spread of catalytic converters to treat road vehicles exhaust gases has helped reduce these emissions. Nevertheless, half of current NO_x emissions still come from oil combustion in road transport vehicles and international maritime bunkers.

The introduction of stricter vehicle emissions regulations and maritime fuel regulations, combined with ambitious climate policies, would result in a 34% decrease of total NO_x emissions worldwide compared to its maximum level (131Mt) of the years around 2010, despite increasing mobility needs particularly in emerging economies (Figure 97).

Figure 97. NOx emissions by sources, World, in the 2°C scenario, and contributions to reductions 2010–2030 and 2030–2050



Note: Other includes solvents, agriculture, and waste. Fires are not included.

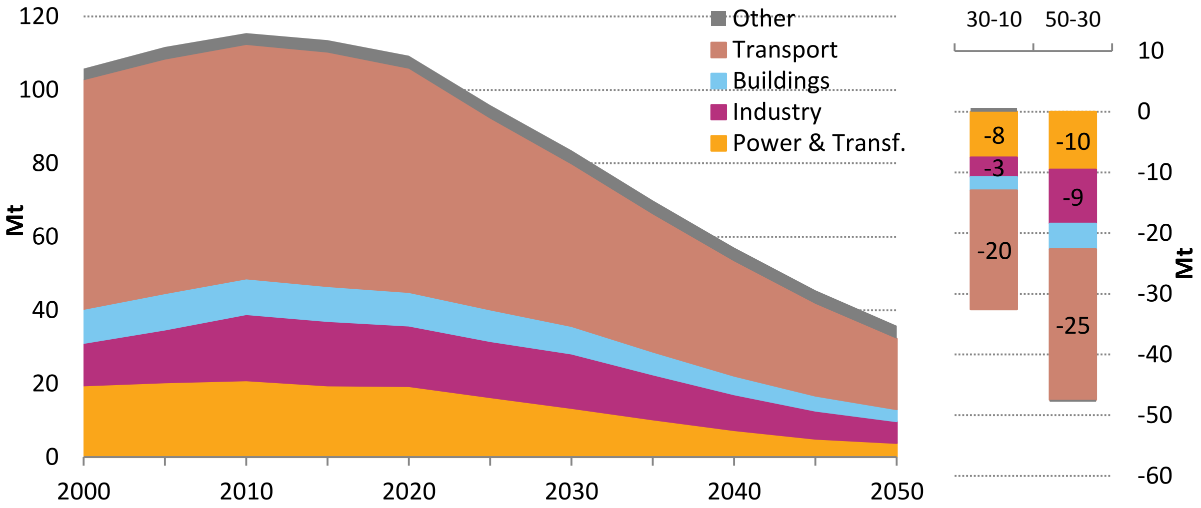
Source: POLES-JRC 2018

These reductions would be achieved due to a decrease of coal use (power plants) and of total liquid fuels (including biofuels) use especially in road transport (ICE efficiency, EV) and maritime (along with targeted policies ([69])). A shift towards large-scale biomass power generation would result in a relatively small additional amount of NO_x emissions from biomass by 2030, , followed by stabilisation. NO_x emissions could decrease by up to 65% compared to the 2010 level by 2050 combined with the climate policies in place in the central 2°C scenario.

The sectoral split of NO_x emissions further clarifies further the major role played by transport (Figure 98), along with the effort of all sectors to reduce emissions further between 2030 and 2050, compared to the 2010–2030 period.

([69]) MARPOL Regulation 13

Figure 98. NOx emissions by sector, World, in the 2°C scenario, and contributions to reductions 2010–2030 and 2030–2050



Source: POLES-JRC 2018.

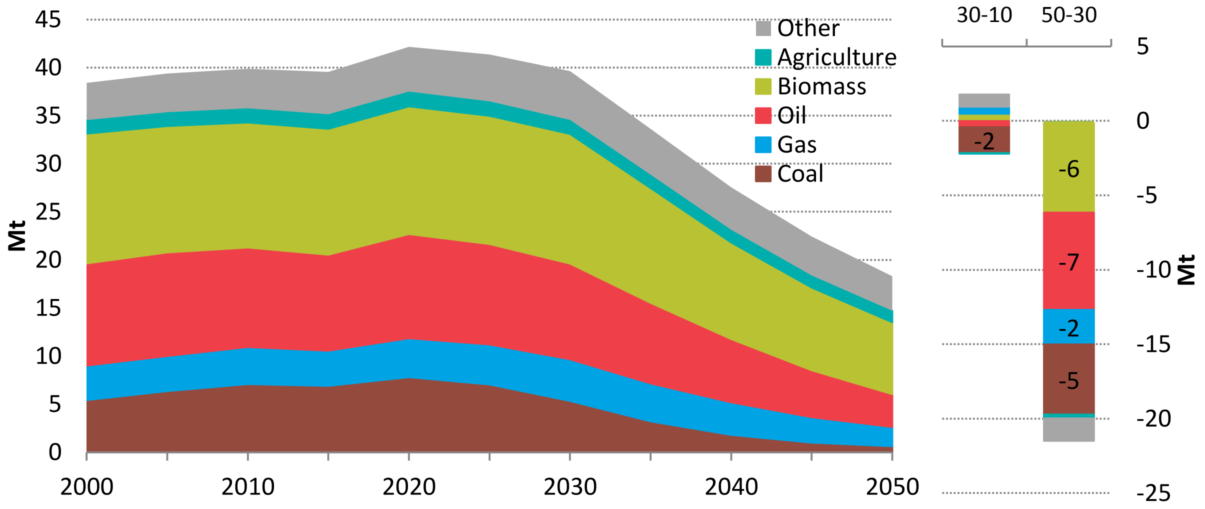
6.4 $PM_{2.5}$ emissions

Fine particulate matter (PM) emissions have significant health impacts; as such, they are the subject of increasingly rigorous air quality control policies, for example with fuel quality standards for road transport fuels. Certain PMs, such as black carbon, also have a climate impact, even though they are generally a short-lived species. Focus is put on particulate matter with a diameter smaller than 2.5µm ($PM_{2.5}$), as their long-term health effects are more significant than larger particles ([70]).

With certain $PM_{2.5}$ emissions excluded (such as natural sources and fires), the combustion of energy fuels is a key source of PM emissions. In particular, biomass use in households, oil use in road transport and coal use in power generation and industry are important pollution sources.

Considering the important fuel substitutions processes taking place in the energy sector with the implementation of climate policies along with the adoption of pollution control technologies and the progressive phasing out of heavily polluting traditional biomass use in households, the emissions of $PM_{2.5}$ would increase at a slow rate 0.5%/year until 2020, before stabilising in the next decade, and would decrease thereafter, to about 40% of the 2010 level in 2050 (Figure 99).

Figure 99. $PM_{2.5}$ emissions by sources, World, in the 2°C scenario, and contributions to reductions 2010–2030 and 2030–2050



Note. Other includes solvents, waste and industrial processes. Fires are not included.

Source: POLES-JRC 2018

Changes in the energy mix prompted by ambitious strong climate policies would bring about large co-benefits of $PM_{2.5}$ emissions, with lower coal, gas and oil consumption. Biomass consumption would increase as a power sector input in particular (where pollution control technologies are more easily implemented, thanks to the sector's economies of scale), while biomass use in households would decrease overall due to the combined effect of reduced use of the traditional biomass and increased thermal efficiency. As a consequence, $PM_{2.5}$ emissions from biomass use would not increase over time with stronger climate policies, but would become the largest source of PM emissions on a global level in 2050.

The sectoral breakdown (Figure 100) confirms that buildings would reduce particulates emissions between 2010 and 2030, essentially through the reduced use of traditional

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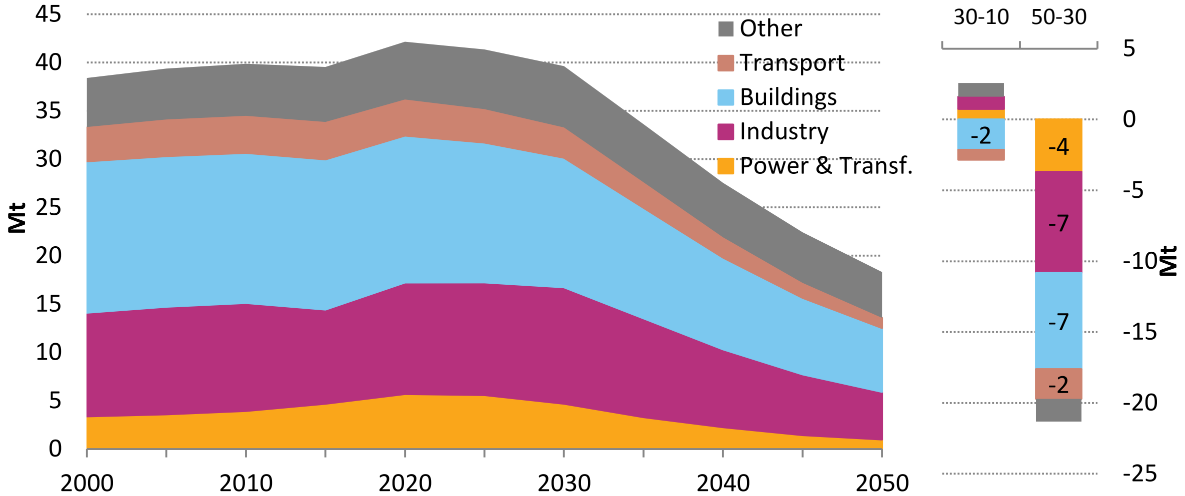
([70]) For instance, the World Health Organization estimates the impacts on mortality up to 20 times higher for $PM_{2.5}$ as compared to PM_{10} (WHO, 2013).

biomass and coal, followed by oil in transport. These gains would be compensated by higher emissions in industry, power and other industrial process, resulting in a quasi-stable total volume of emissions over 2015–2030. The gains observed by 2050 would again be strong in buildings (-7 Mt of biomass-related emissions with respect to 2030) and industry (-7 Mt compared to 2030, with contributions from all fossil fuels).

Figure 100. PM$_{2.5}$ emissions by sector, World, in the 2°C scenario, and contributions to reductions 2010–2030 and 2030–2050



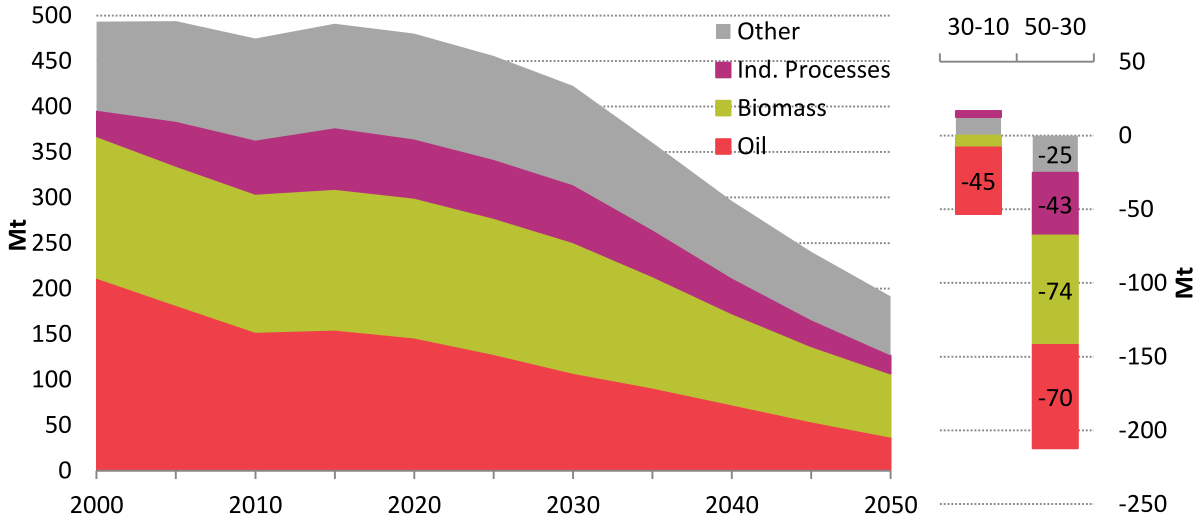
Source: POLES-JRC 2018

6.5 CO emissions

Carbon monoxide (CO) is a short-lived chemical that can be a poisonous health hazard in indoor pollution and plays a role in road traffic pollution in urban areas as a precursor of tropospheric ozone. With emissions from fires excluded, combustion of biomass (households) and oil (road transport) as well as industrial processes are then the most important CO sources.

CO emissions would decrease in the central 2°C scenario after 2015, given fuel substitutions in the energy mix, the phase-out of heavily polluting traditional biomass in households and the deployment of pollution control technologies. By 2050, they would represent less than half of the 2010 level (Figure 101).

Figure 101. CO emissions by sources, World, in the 2°C scenario, and contributions to reductions 2010–2030 and 2030–2050

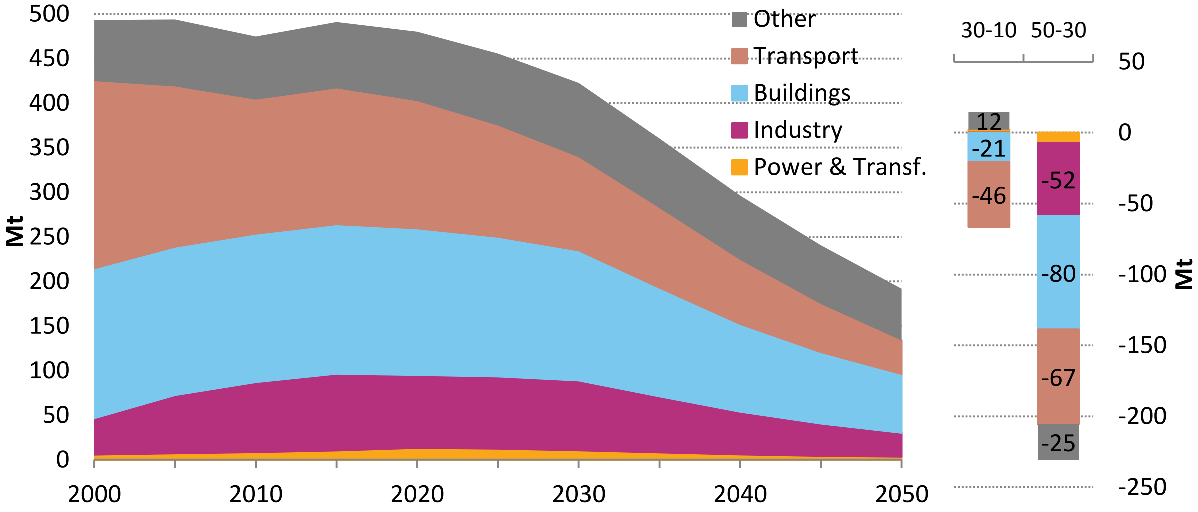


Note. Other includes coal, gas, solvents, agriculture and waste. Fires are not included. Coal makes up most of the "other" reductions.

Source: POLES-JRC 2018.

Breaking down CO emissions further at the sectoral level gives a more accurate view of the underlying dynamics of CO emissions. Between 2010 and 2030, reductions would essentially be archieved in transport (oil, -46 Mt) and then in buildings for half of this amount (coal and traditional biomass phase-out, -21 Mt). Over 2030–2050, the reductions would be more evenly distributed across transport (efficiency and substitution of oil, -67 Mt), buildings (carried essentially by biomass, -80 Mt) and industrial processes with notable contributions from the cement and steel industries (Figure 102).

Figure 102. CO emissions by sector, World, in the 2°C scenario, and contributions to reductions 2010–2030 and 2030–2050



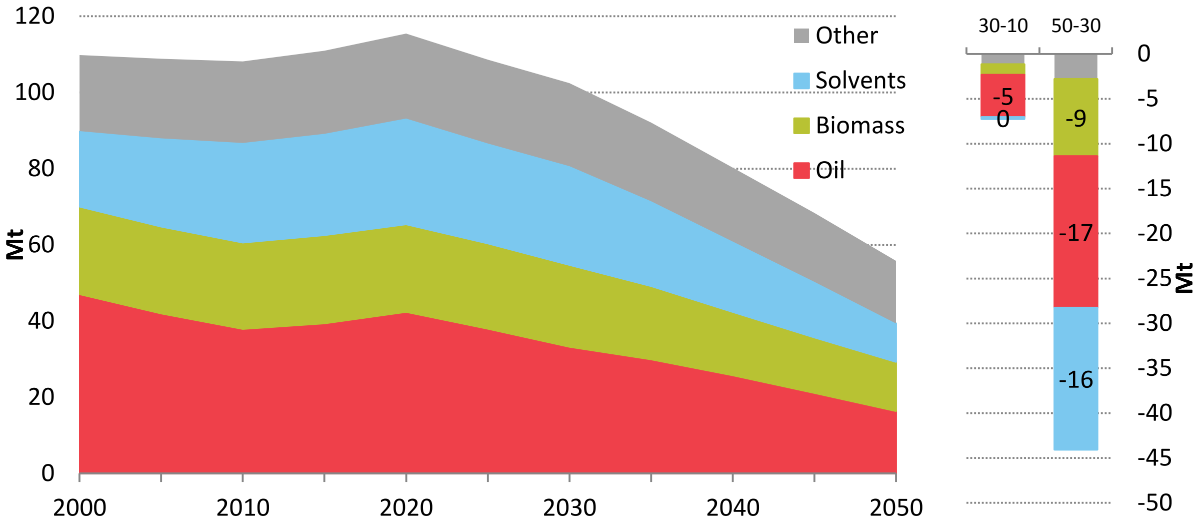
Source: POLES-JRC 2018.

6.6 VOCs emissions

Certain species of VOCs (Volatile Organic Compounds) have significant health impacts and are strongly regulated (indoor exposure via paints, cleaning products and other chemicals). The future evolution of VOCs emissions would be strongly linked to industrial processes and solvents production, as VOCs emissions from oil and biomass would decrease over time (due to decarbonisation and the phase out of traditional biomass, respectively). In this analysis, solvents emissions are to a large extent driven by the evolution of chemical industry total energy inputs and corresponding air pollution control policies, whereas the potential impact of climate change mitigation policies on VOC emissions from solvents is not captured here.

As a consequence, total VOCs emissions would continue growing at a slow rate, reaching a peak in 2020. By 2030, the drop in emissions would essentially be due to oil, for -5 Mt. By 2050, emissions from all sources are expected to drop in the central 2°C scenario, with a higher contribution of solvents (-16 Mt), becoming as important as oil (-17 Mt) and biomass (-9 Mt) (Figure 103).

Figure 103. VOCs emissions by sources, World, in the 2°C scenario, and contributions to reductions 2010–2030 and 2030–2050

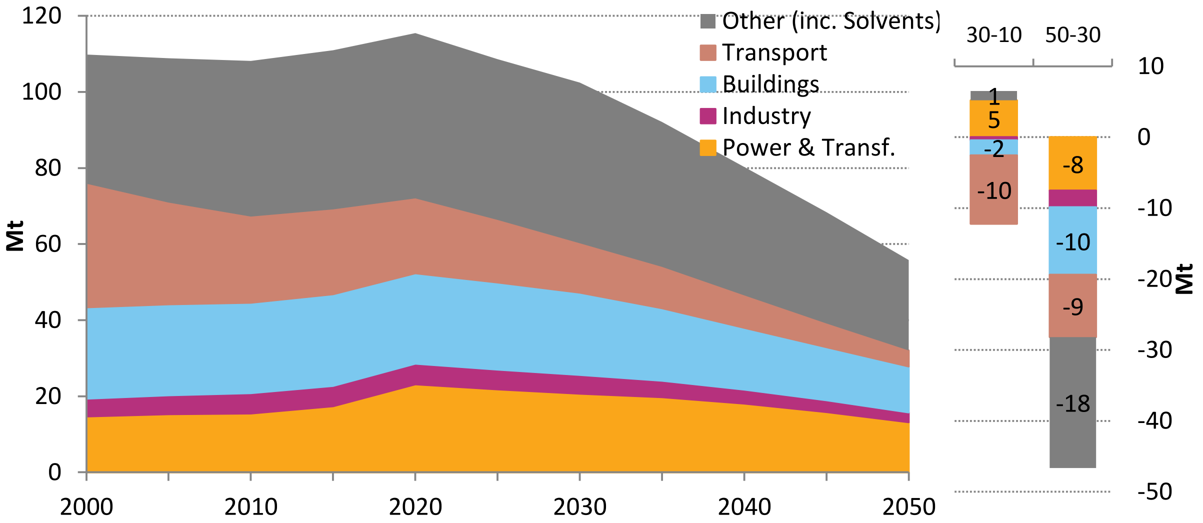


Note: Other includes coal, gas, agriculture, waste, industrial processes. Fires are not included. Industrial processes make up most of the "other" reductions.

Source: POLES-JRC 2018

As shown in Figure 104, the decomposition of sources and emissions reductions by sector indicate over 2010-2030 the key importance of oil in land transport (-10 Mt), and over 2030–2050 of biomass in buildings (-10 Mt). Since VOCs emissions are less related to energy use, the co-benefits with climate change measures are less pronounced and targeted regulations would have to play a key role in the abatement of VOCs emissions.

Figure 104. VOCs emissions by sector, World, in the 2°C scenario, and contributions to reductions 2010–2030 and 2030–2050



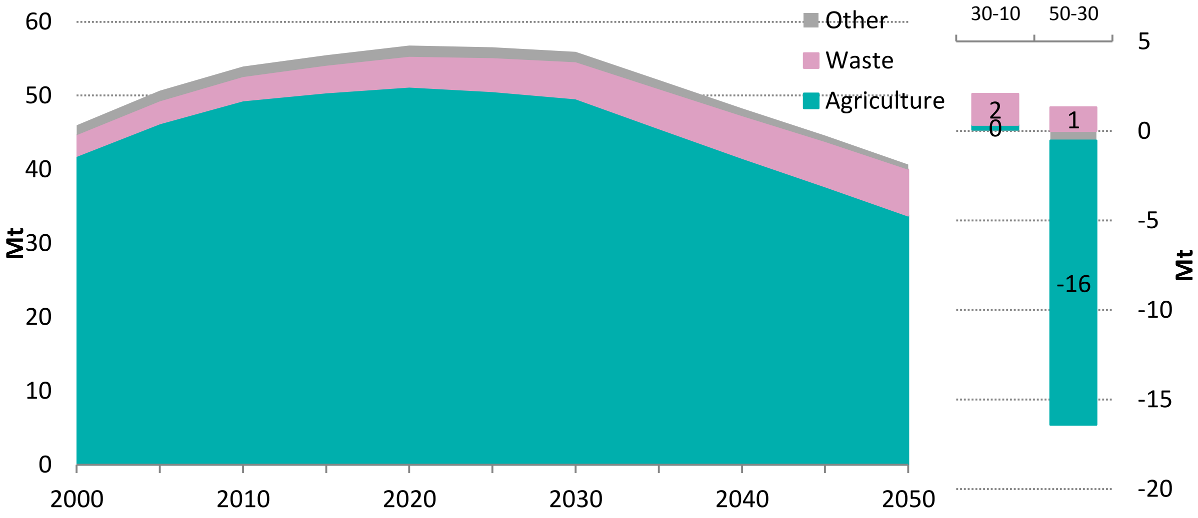
Source: POLES-JRC 2018.

6.7 Ammonia emissions

Ammonia (NH_3) emissions are responsible for eutrophication and soil acidification. NH_3 is also a precursor of secondary particulate matter. NH3 is originated almost entirely from the agriculture sector (from animal waste treatment and from the use of nitrogen-based fertilisers) but with some contribution also from road transport. Their evolution is thus mainly driven by the volume and composition of food production and climate mitigation measures in the agricultural sector.

In the central 2°C scenario, NH_3 emissions would plateau between 2010 and 2030 (with emissions from waste compensating for the reduced emissions of agriculture), before decreasing by 2050, to about 30% below 2010 emissions (Figure 105), with agriculture as the main reduction source (-16 Mt). Agriculture emissions would still constitute the bulk (about 75%) of NH_3 emissions throughout the projection period. Some techniques, such as precision farming, could provide synergies for climate and air quality, while for others this is less obvious (e.g. nitrification inhibitors).

Figure 105. NH_3 emissions by sources, World, in the 2°C scenario, and contributions to reductions 2010–2030 and 2030–2050



Note: Other includes coal, gas, oil, biomass, solvents and industrial processes. Fires are not included. Coal and oil make up most of the "other" reductions.

Source: POLES-JRC 2018.

7 Economics

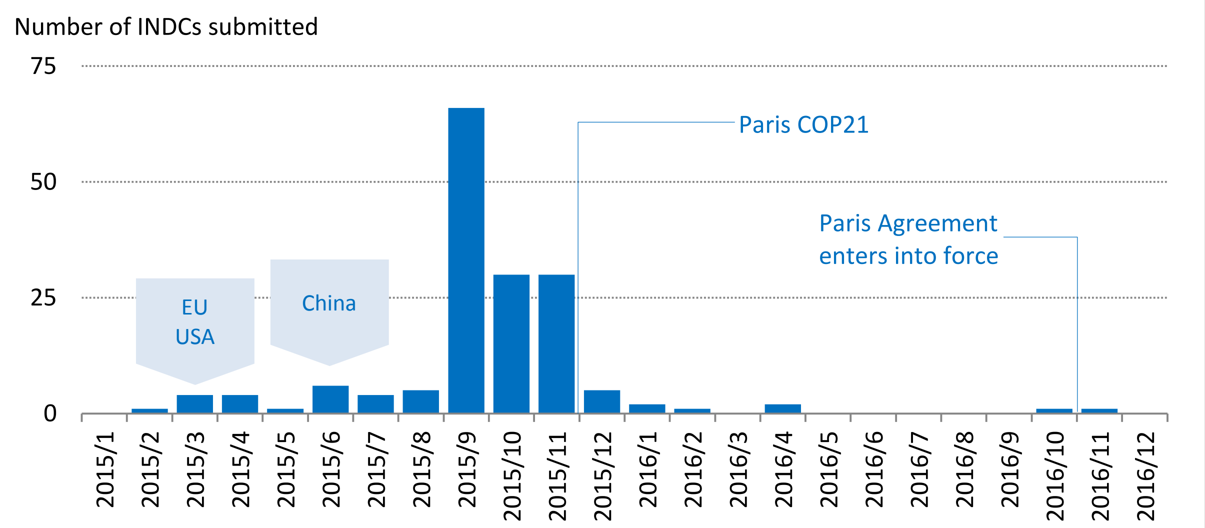
Getting more insight into the economy-wide implications of decarbonisation is crucial for anticipating and guiding structural changes in production, consumption, and labour markets. This chapter looks into the economic aspects of climate change mitigation, and is structured as follows.

The first section provides a broad overview of the global macroeconomic evolution in the coming decades for a world on a below 2°C-compatible pathway. We compare the economic implications across regions and sectors against a benchmark which includes the climate and energy policies as pledged in the Nationally Determined Contributions (NDCs) in the run-up to the Paris Agreement (Box 26). For the period extending beyond the time horizon of most NDCs (2030), we assume a continued global pace of GDP decarbonisation, albeit with global participation and the converging stringency of climate policy across regions, with convergence speed depending on income per capita.

Box 26. The (Intended) Nationally Determined Contributions

In the run-up (Figure 106) to the 21st Conference of the Parties (COP21), countries submitted mitigation pledges to the UNFCCC under the format of Intended Nationally Determined Contributions or INDCs. Since the Paris Agreement entered into force on 4 November 2016, the shorter term Nationally Determined Contributions (NDCs) is commonly used, and we follow this convention in the remainder of this report. The combined pledges in the NDCs imply global warming of 2.6–3.1°C (Rogelj, et al., 2016) by the end of the century compared to pre-industrial levels. Since this is above the 1.5°C and 2°C targets, the NDCs lead to an 'ambition gap' that could be closed by a ratcheting up of ambition levels in future NDC revisions.

Figure 106. Timeline of INDC submissions



Source: UNFCCC.

The second section focusses on the investments required to transform the economy and the energy system. Next, we shed light on the implications of a global shift to a low-carbon economy for international trade, and the emissions embodied in trade flows. The share of trade, measured as imports plus exports, in total GDP in the European Union has steadily risen over time and reached more than 85% in 2017 (56% globally) according to World Bank statistics. Trade is therefore a component that should not be overlooked in climate policy discussions. Fourth, we study the impact on labour markets and on the transition of jobs across sectors.

7.1 Macroeconomic pathway

Climate change is labelled by economists as an externality: the costs or impacts of climate change occur outside of the marketplace. The market price of fossil fuels covers the costs of extraction and transportation, and may include a profit mark-up, but does not include the damage to the environment or the social costs. Therefore, there is a tendency to consume more of the polluting good than is socially desirable, such that government intervention can improve welfare by lowering the consumption levels of the goods that cause environmental damage.

In this section, we study the economic implications of putting a price on greenhouse gas emissions, without accounting for the benefits of the policy – avoided damage of climate change. In other words, we estimate the cost of action, while a related strand of research looks into the impacts of climate change in case we do not limit global warming (). We use a Computable General Equilibrium model (JRC-GEM-E3), an approach that is frequently used for this type of exercise. The model is based on the household and firm optimisation of welfare and profit, respectively, and accounts for supply chain linkages across sectors and international trade. With this model, we analyse the economic consequences of implementing a 2°C pathway. Where absolute numbers are less meaningful to interpret, we present relative changes by comparing the 2°C pathway to a scenario in which the Nationally Determined Contributions (NDCs) are implemented, for which current policies in many regions need to be enhanced, closing the 'implementation gap'. The (costs of) emission reduction through land use (change) and forestry are not included in this chapter.

Box 27 The costs of inaction

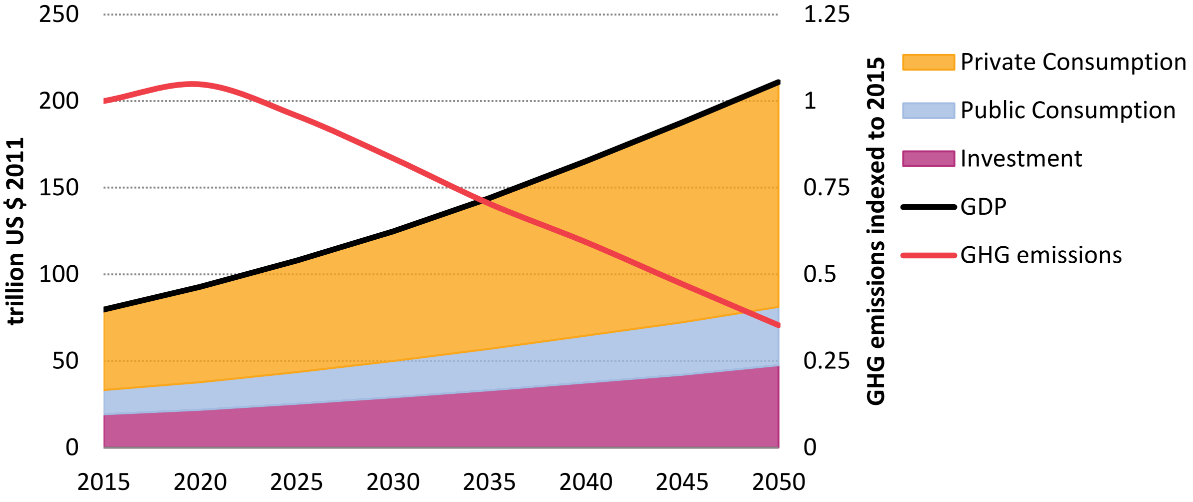
Climate change impacts include drought intensity, coastal floods, river floods, energy consumption, agricultural productivity, biodiversity, and water availability. Limiting global warming to 1.5°C would limit the sea level rise, species loss, and other impacts, as summarised in the IPCC Special Report on 1.5°C warming (IPCC, 2018). There are typically two ways to quantify the impacts of a changing climate.

The first method is bottom-up, using biophysical impact models, potentially combined with economy-wide models. The study of (Dottori, et al., 2018), for example, assesses the impact of climate change on river floods. Results indicate end-of-century welfare (consumption) losses of 0.27%, 0.40% and 0.53% at 1.5, 2 and 3 °C warming, respectively. Another example is a recent study by (Carleton, et al., 2018) that looks into the effects of climate change on premature mortality by estimating a mortality-temperature relationship with global coverage and regional heterogeneity. Economic losses related to mortality and estimated value of life are estimated around 0.5% of global GDP in 2050, and 3.7% of global GDP in 2100 under an RCP8.5 scenario that corresponds to global warming between 4°C and 6°C by the end of the century.

7.1.1 Global view and regional comparison

On a global level, the 2°C pathway is consistent with robust economic growth, amounting to a growth of 128% between 2020 and 2050 (Figure 107). GDP and all of its components – investments as well as public and private consumption – continue to grow as emissions are reduced over time. The components of GDP are affected differently when comparing to an NDC scenario, Structural changes imply higher investment (+0.7% globally in 2050), in order to finance the transition towards low-emission infrastructure. These investments are financed by savings, so less income is available for private consumption (-0.9% globally in 2050). Overall, the globally aggregated GDP is 0.4% lower than in the NDC scenario, not accounting for the impacts of climate change. In terms of annual economic growth rates, this boils down to a reduction from 2.79% in the NDC to 2.78% in the 2°C scenario for the period between 2020 and 2050. Therefore, the key message is that the simulation highlights that economic growth can be decoupled from greenhouse gas emissions.

Figure 107. Decoupling of economic growth and greenhouse gas emissions

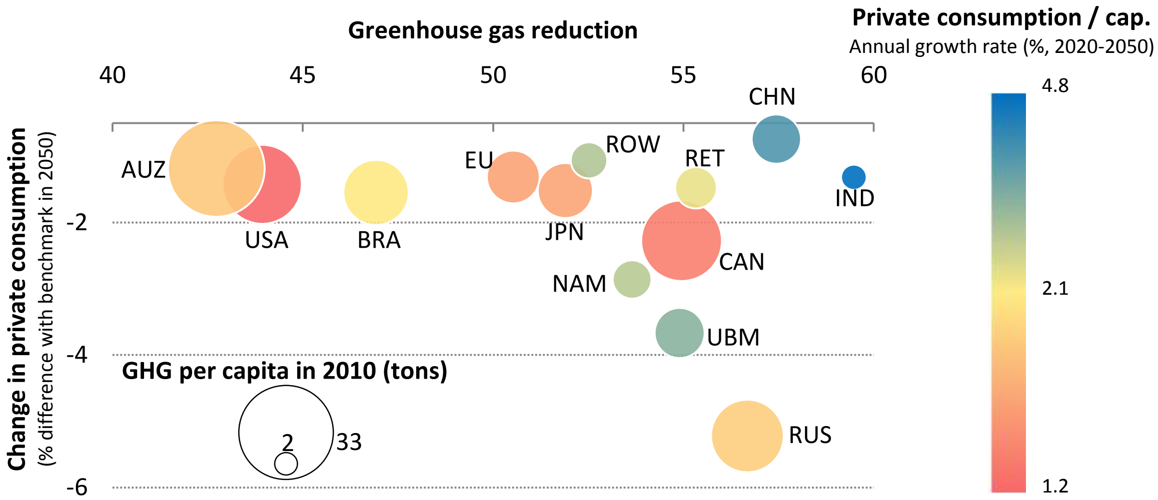


Source: JRC-GEM-E3 2018.

The economic impact of climate policy differs across regions. Fossil fuel-exporting regions, such as Russia (RUS) and North Africa and Middle East (NAM), experience stronger negative effects on welfare as the world shifts towards low-carbon sources of energy. Figure 104 presents the regional welfare results (household consumption can be considered to be a good proxy) for the year 2050 expressed as percentage difference from a scenario in which all countries meet their NDC. An important caveat to keep in mind is that these results do not include the benefits of avoided impacts of climate change and improved air quality. Also, recall that the scenarios here are developed based on reduction targets that emerge from policies considered and implemented in the POLES model (see Annex 4). In any scenario, the relative distribution of the abatement costs could be altered by shifting the targets for abatement between regions, given that the global emission cap is held constant.

Figure 108 shows that the decrease in private consumption in the 2°C scenario relative to the NDC scenario ranges between 0 and 6% in 2050. Unsurprisingly, fossil fuel-producing regions such as Russia (RUS), Ukraine-Belarus-Moldova (UBM), and North Africa and the Middle East (NAM) are affected more strongly, under the assumption that the economy in these regions is not structurally reformed in the NDC scenario. For most other regions, the consumption decrease relative to the NDC scenario is around 1%, which implies a reduction in annual consumption growth rates of approximately 0.03–0.04 percentage points (e.g. from 2% to 1.97%) over the period 2020–2050. The colour in the bubbles in Figure 108 represents the annual growth rate of private consumption, which remains positive for all regions and high for fast-growing countries. Pursuing more stringent emission reductions to reach the 1.5°C target would avoid some of the damages of climate change, while the faster and deeper economic transformation can be expected to be more costly (Box 28).

Figure 108. The impact of climate change mitigation on private consumption in a 2°C scenario



Source: JRC-GEM-E3 2018.

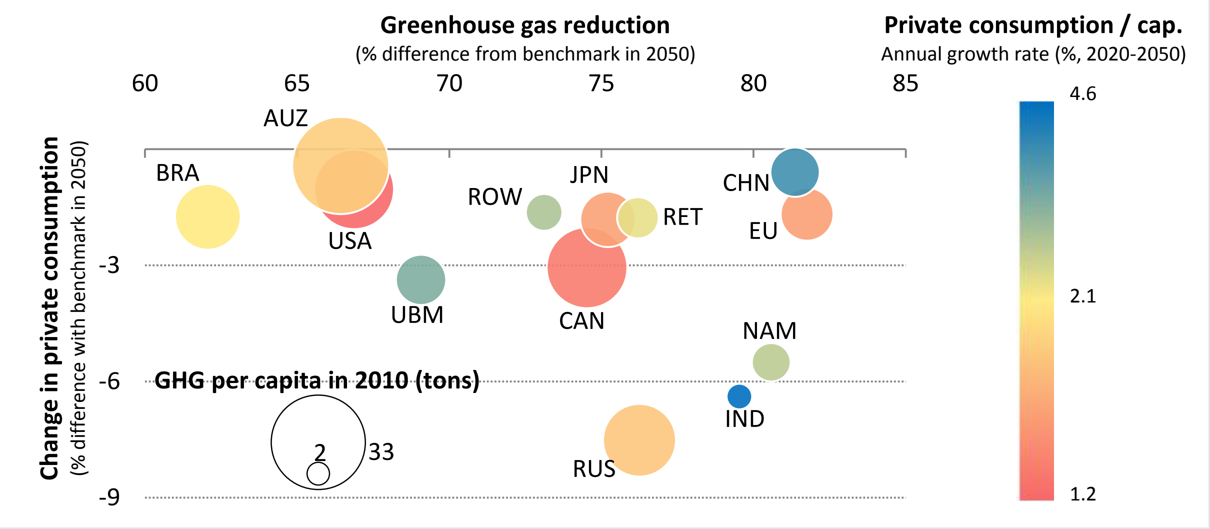
Box 28. Economic impact across regions in the 1.5°C

Going beyond the ambition level of 2°C to meet the 1.5°C target requires a deeper transformation of the economy and the energy system. As a means of sensitivity analysis, this box provides estimates of the economic cost of curbing global greenhouse gas emissions to be consistent with a 1.5°C pathway. Since not all mitigation options that are known to be important in a 1.5°C (notably, lifestyle changes) are included in the analysis, these results could be biased upwards and should therefore be interpreted with caution.

In terms of global GDP, the 1.5°C scenario leads to a reduction of 1.3% relative to the NDC scenario. In 2050, investment is 0.1% higher than in the NDC scenario, but a faster transition earlier on increases investment to 2.2% above the NDC scenario value in 2025. Globally, private consumption is reduced by 2.1% in 2050.

For most regions, the results in Figure 109 show a reduction in consumption compared to the NDC scenario that is roughly twice the reduction in the 2°C scenario. India is one of the regions where the difference with the 2°C is more pronounced. One of the reasons is the size of the agricultural sector in India, with corresponding non-CO2 greenhouse gases that are typically associated with abatement that is costly or has limited potential, taking into account that lifestyle changes are not fully represented in the modelling framework. Excluding LULUCF emissions, agriculture represents approximately 30% of all remaining greenhouse gas emissions in India in the year 2050 in the 2°C scenario. In the 1.5°C scenario, the share of agriculture in greenhouse gas emissions further increases to roughly 40% in 2050. Clearly, these numbers strongly depend on the assumed evolution of the sectoral structure in the NDC scenario. The economic structure in a country with modest ambition in the NDC scenario would be relatively emission-intensive, while regions where stringent policies are implemented earlier would develop a competitive advantage in low-carbon activities. Hence, advantages of early action – and, conversely, disadvantages of late action – are reflected in the estimates. Despite the higher cost of mitigation, annual consumption growth rates in India remain above 5% per year for the period 2020–2050, with per capita income increasing approximately 4.6% per year over the same period.

Figure 109. The impact of climate change mitigation on private consumption in a 1.5°C scenario.



Source: JRC-GEM-E3 2018.

7.1.2 Sector perspective

Global economic output in the scenario that is compatible with below 2°C global warming will grow by roughly 3% per year over the 2015–2050 period for all sectors shown in Table 14, with the exception of the fossil fuels industry (-0.1% per year) and the power sector with 1.5%. These energy sectors are growing less as a result of energy efficiency measures and in the case of fossil fuel sectors due to the decarbonisation of the energy system.

Table 14 shows that industry and service sectors grow at faster rates than energy and agricultural sectors as additional income is increasingly spent on these goods. Interestingly, the share of agriculture in value added declines stronger in individual regions than globally as regions with initially high shares of agriculture are growing faster and hence increase their share in world output.

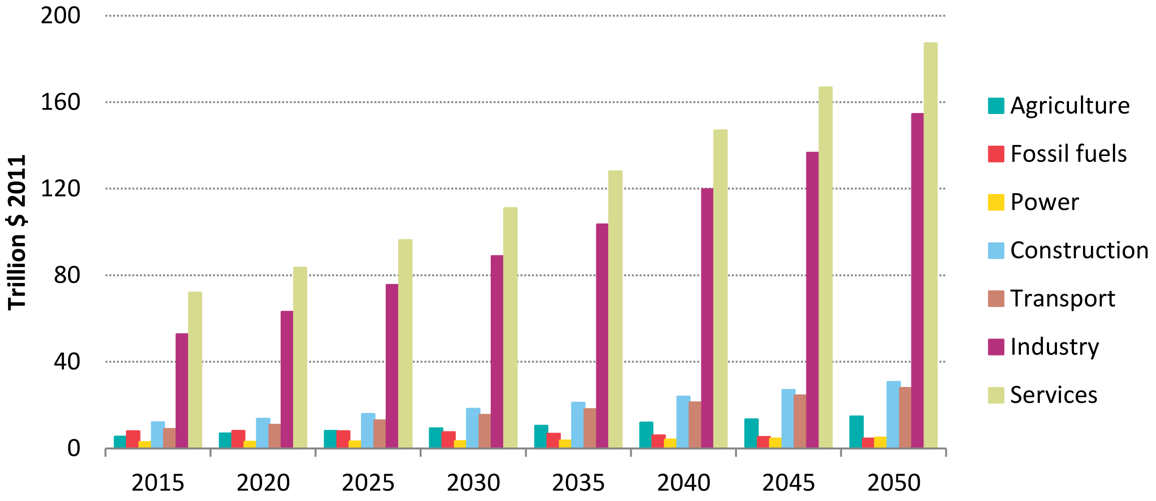
The table also shows how the individual sectors are affected relative to a scenario in which the world only implements the current NDCs. It becomes obvious that there is a strong deviation of output in the fossil fuel sectors and a reduction in the transport sector output, which continue to be predominantly fossil-fuelled under the NDC scenario. Agriculture output increases in the 2°C scenario relative to the NDC scenario due to increased demand for bioenergy. Enhanced electrification trends in industry and final demand lead to higher output of the power sector. Some industrial sectors and the construction sector also benefit from the additional investment demand that is required to build a low-carbon capital stock. Finally, note that output changes on the global level resulting from the difference between an NDC scenario and the 2°C scenario are often less than one year of growth (except for fossil fuels).

Table 14. Changes of global output by sectors in the 2C scenario (first two columns) and relative to the NDC scenario

Changes in output	2050 vs. 2015	Annual growth rates	2°C vs. NDC in 2050
Agriculture	160%	2.8%	3.1%
Fossil fuels	-2%	-0.1%	-41.4%
Industry	192%	3.1%	0.5%
Construction	152%	2.7%	1.2%
Services	161%	2.8%	-0.3%
Transport	216%	3.3%	-1.6%
Power	66%	1.5%	2.0%

Source: JRC-GEM-E3 2018.

Figure 110. Output by sector on the global level under the 2°C scenario



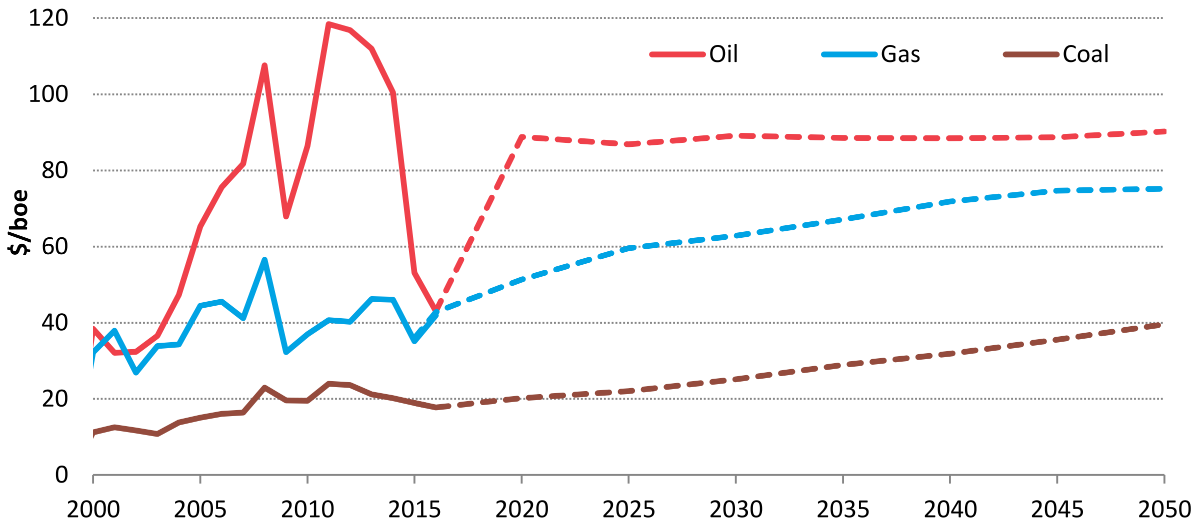
Source: JRC-GEM-E3 2018.

7.1.3 Fossil fuel prices

Properly functioning markets for electricity, natural gas, oil, coal and pollution allowances are essential for the rational allocation of resources. Overall, prices for internationally traded energy commodities follow an evolution reflecting the balance of demand and supply, and the cost-effective attainment of environmental goals. Demand is determined by energy needs, technology costs and inter-fuel substitution; supply is determined by production costs (capital and technology), transport costs and the evolution of reserves for fossil fuels – with many of these factors being inter-dependent.

The energy markets dynamics in the central 2°C scenario is driven by the market impact of environmental policies, the rapid deployment and falling costs of key renewables technologies, the growing electrification of energy demand, and the gradual deployment of carbon capture technologies from 2030.

Figure 111. International fossil fuel prices in the central 2°C scenario



Source: POLES-JRC 2018.

As of 2018, fossil fuel markets are still adapting to the changes set by the under-investment in supply in recent years due to the economy contraction and shrinking demand. In the short- to medium-term, fossil fuel prices would experience major changes. In the central 2°C scenario, the international oil price would remain relatively stable, while gas and coal prices would progressively rise over the next three decades (Figure 111).

Oil market prices typically oscillate between lower levels at times of low demand, and the marginal production cost at times when the market is tighter. The latter is projected to increase with investment needs in new production capacities and higher extraction costs. Despite gains in efficiency, resources such as tight oil require a continuous renewal of investments as single wells see their production decline quickly. On a decadal time scale, extraction costs would rise due to geological scarcity in some markets and a shift towards more unconventional resources that are associated with energy-intensive extraction processes (and therefore their associated emissions would be subject to the carbon pricing considered in this scenario). This would shift the supply curve upwards and limit the downward impact on the price of a demand that would be decreasing. In the central 2°C scenario, these two effects would compensate each other, resulting in a stable oil price. The application of climate policies in energy consumption on top of these oil market dynamics in a 2°C world would entail heavy structural changes in the transportation sector, with determinant factors being the speed at which disruptive technologies in transportation would be adopted, the economic transition underway in major demand centres (China), and the pace of fossil fuel subsidy reform. Despite extensive decarbonisation, oil demand would persist for road freight and petrochemicals.

Gas markets would be similarly impacted. Gas production is – and would remain – less energy and carbon-intensive than oil production, and the cost of energy inputs (including carbon pricing) would increase less than for oil. Due to the high oil price levels reached during the late 2000s to early 2010s, the decoupling of world gas markets from oil markets slowed down. However, decoupling is expected to happen again, due to increasingly different uses for these fuels and to the expansion of LNG, for which contracts are not indexed to oil prices. As a consequence of this price decoupling process, increasing production costs and a slowly decreasing gas demand, gas prices would gradually increase in the central 2°C scenario. Natural gas supplied 22% of the primary energy used worldwide in 2015, and made up nearly a quarter of electricity generation, as well as playing a crucial role as a feedstock for industry and heating in buildings. With strong climate policies, the substantial penetration of renewables in the power sector as well as the accelerated insulation in buildings would decrease gas demand.

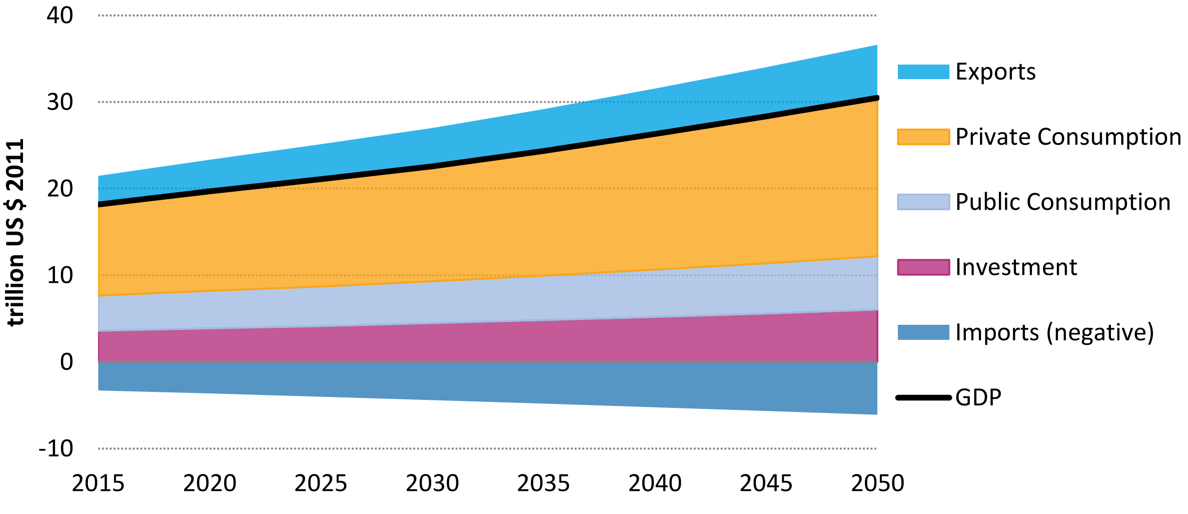
Coal demand would be deeply impacted by climate policies. However, coal prices are projected to grow slightly. Prices would be impacted by the rising costs of inputs in production (notably energy inputs), and higher transport costs. Coal supplied 28% of all primary energy used worldwide and made up 39% of electricity generation in 2015; it played a crucial role in industries such as iron and steel. In the central 2°C scenario, coal would continue to play a role in industry and in power generation in select markets, however, most coal demand for energy uses would be nearly completely phased out. While these prices show stability or a rise despite a falling demand for these commodities, their increase would be the same or lower than in a case where climate policies are not pursued and demand for these fuels is kept unconstrained. In such a case, the absence of carbon pricing in the energy inputs to production would be counter-balanced by an increase in extraction costs; indeed, despite evolving extraction technologies, more demand would mean accelerated investments to renew reserves and resources that would be geologically more difficult to produce.

7.1.4 Focus on Europe

This section zooms in on the economic effects for the European Union (28). A general macroeconomic outlook for a low-carbon future is presented, along with a decomposition of the changes in GDP compared to an NDC scenario, sector-specific outcomes, and a sensitivity analysis with respect to model and policy parameters.

As on the global scale, bringing the economy onto a pathway that is consistent with below 2°C warming goes hand in hand with continued economic growth in the European Union (Figure 112). The simulation results of the JRC-GEM-E3 model suggest that the contribution of final demand components to GDP under a 2°C scenario hardly changes compared to today.

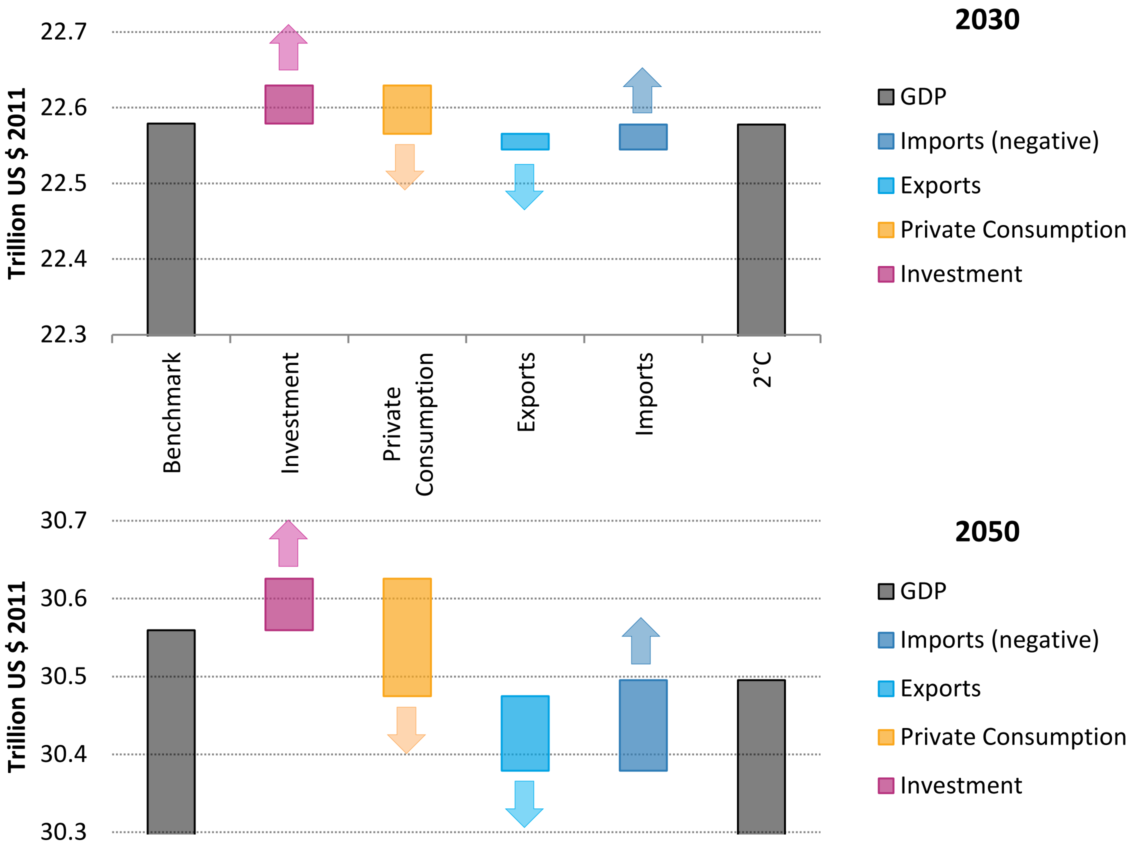
Figure 112. EU GDP and components in a 2°C-compatible scenario



Source: JRC-GEM-E3 2018.

The transition to a low-carbon economy requires investments and has implications for international trade flows in the European Union. Figure 113 highlights that components of GDP can change, despite the overall limited impact on GDP relative to the NDC scenario case. As mentioned above, there is a shift from consumption to investment. The impact of trade is slightly positive as net trade (exports less imports) improves. For the EU, both imports and exports decline, and the contraction in imports is larger than the decline in exports.

Figure 113. Decomposing the EU GDP impact relative to an NDC scenario



Source: JRC-GEM-E3 2018.

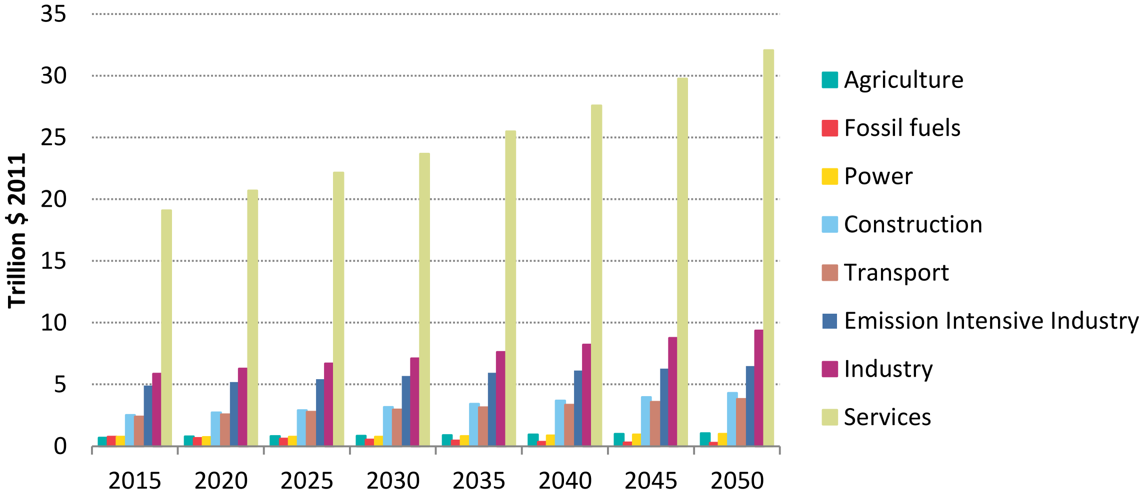
As on the global level, sectors are affected differently in the 2C pathway. Figure 114 shows that the services dominate output, although industries have an important role, as well. Output of the fossil fuel industry nearly halves, while industry and services grow with growth rates of about 1.5% per year (Table 15). Growth in agriculture is lower, despite increases relative to a scenario where the world is only implementing the NDCs due to the additional production of bioenergy. The power sector has relatively low growth rates thanks to efficiency improvements that limit electricity consumption despite increases of electrification in industry and final demand.

Table 15. Changes of EU output by sector in the 2°C scenario (first two columns) and relative to the NDC scenario

Changes in output	2050 vs. 2015	Annual growth rates	2°C vs. NDC in 2050
Agriculture	40%	1.0%	7.4%
Fossil Fuels	-46%	-1.7%	-33.0%
Other Industry	60%	1.4%	-0.1%
Construction	69%	1.5%	1.0%
Services	69%	1.5%	-0.7%
Transport	64%	1.4%	-2.5%
Electricity Supply	19%	0.5%	9.2%
Emission Intensive Ind.	33%	0.8%	-0.3%

Source: JRC-GEM-E3 2018.

Figure 114. Output by sector on the EU level under the 2°C scenario



Source: JRC-GEM-E3 2018.

Box 29. How results change with model assumptions and policy design

Here we present a sensitivity analysis based on additional JRC-GEM-E3 runs that change the assumptions on how the emission targets were achieved in Europe. Economic costs are not only a function of emission reductions, but are also affected by the design of policies to achieve emission reductions. Furthermore, regions act in an international context and are interconnected through trade. A change in the relative prices of goods influences the competitiveness of sectors. In general, emission-intensive sectors will have price increases, reducing demand correspondingly.

In our default 2°C scenario, we assume that industries factor in opportunity costs from grandfathered permits, i.e. firms raise the output price to reflect a carbon price on the market. Free allowances would give rise to windfall profits in this case. However, free allowances are often proposed to prevent emission leakage through relocation of output to regions with lower carbon prices. It can thus be a measure to offset losses in competitiveness. We therefore change the producer behaviour in a sensitivity run from profit maximisation (opportunity costs included in output price) to a 'market share maximisation' (opportunity costs excluded) approach. We adjust producer behaviour in sectors currently in the EU ETS and benefitting from free allowances. Differences in competitive positions are often the result of different carbon prices across countries, reflecting different ambition levels. Therefore, we also run the scenarios under "fragmented action", where we assume that the greenhouse gas reduction targets for Europe are the same as in the default 2°C scenario, while climate action in the rest of the world is limited to the NDC policies. To make the distinction clear, the default 2°C scenario in which all countries step up climate action relative to the NDCs will be termed "global action" in this box.

Another determinant on economic outcomes is how the revenue obtained from auctioned permits (or carbon taxes) is used. In the default 2°C scenario, we assume that it is re-distributed lump-sum to households (the government budget and purchases are fixed). An alternative revenue recycling assumption would utilise the carbon revenues to lower labour taxes and thus reduce pre-existing distortions. When unemployment is not assumed to be fixed (as in the default scenario) but flexible, lowering labour taxes could increase employment and lead to GDP gains. This assumption takes the notion that unemployment is responsive to wage changes, contrasting the assumption of the default scenario that uses fully flexible wages (fixed unemployment), the latter motivated by the long-time horizons and options to re-allocate resources without changing the unemployment rate. The effect can be expected to be larger the more revenues there are to be used to reduce labour taxes. In the default scenario, revenue is only generated from carbon permits auctioned to the power sector; permits in other sectors are grandfathered. In an alternative scenario, we analyse the effects of permits being auctioned (or equivalently, a tax being charged) to all sectors of the economy.

Table 16 shows how GDP in Europe in 2050 responds modestly to a change of the assumptions, with GDP impacts ranging between -0.28% and +0.12%. A first observation is that aggregate GDP is higher under fragmented action (lower losses). While individual sectors might lose competitiveness and reduce output, the dominant driver is foreign demand from the rest of the world. As the GDP in the rest of the world is modestly lower under global action, demand for exports from Europe also declines and GDP losses in Europe are higher.

When producers in the emission intensive industries adopt the market share maximisation strategy, GDP losses can be minimally reduced. With labour tax recycling, negative GDP effects can be mitigated (or even turn into gains) when tax revenues are reduced to lower distortive labour taxes. GDP is highest when this option is combined with full auctioning.

Table 16. EU GDP impact relative to NDC scenario in 2050 under different assumptions

	Fragmented action	Global action
Default 2°C scenario	-0.13%	-0.28%
Market share maximisation	-0.10%	-0.25%
Labour tax recycling	-0.03%	-0.26%
Market share maximisation, labour tax recycling	0.05%	-0.18%
Full auctioning in all sectors, labour tax	0.12%	-0.11%

Source: JRC-GEM-E3 2018.

The labour tax recycling makes employment more attractive, such that employment increases relative to the default scenarios (Table 17). Again, effects are largest under full auctioning of permits. The increase in employment raises disposable income and drives GDP upward.

Table 17. EU Employment in 2050 under different assumptions

	Fragmented action	Global action
Labour tax recycling	0.17%	0.10%
Market share maximisation, labour tax recycling	0.29%	0.23%
Full auctioning in all sectors, labour tax recycling	0.54%	0.49%

Source: JRC-GEM-E3 2018.

Table 18 presents how ETS sectors react when producers opt for the market share maximisation strategy and do not pass on opportunity costs from receiving free allowances. The individual sectors' output adjustments depend on the trade exposure and emission intensity. On average, the ETS sectors increase output by 1.5% while non-ETS sectors' output is slightly reduced as the ETS sectors are using more production factors of the economy.

Table 18. EU sector impacts in 2050 of market share maximisation in ETS sectors relative to default 2°C scenario (fragmented action)

Sector	Impact vs. default 2°C
Oil refining	7.10%
Ferrous metals	7.10%
Non-ferrous metals	0.50%
Chemical products	0.70%
Paper Products	0.00%
Non-metallic minerals	2.20%
Air transport	5.00%
ETS sectors (average)	1.50%
Non-ETS sectors (average)	-0.10%

Source: JRC-GEM-E3.

7.2 Investments

Bringing the global economy on a transition pathway towards a 2°C world will require mobilising investments. In part, this is a shift in investment, as investment currently flowing to the fossil fuel sectors will be re-directed to clean energy technologies. This section spells out the investment requirements and depicts changes in investment patterns that predominantly affect energy supply and power sectors.

7.2.1 Economy-wide investments by sector

The sectoral changes in output are reflected in sectoral changes in investment. To build the capital stock required for increased output, investment activities in all sectors increase in 2050 relative to 2015 (Table 19). The highest growth of investment both absolute and relative to output growth happens in the power sector. In the 2°C scenario, the share of the power sector in total investment in the global economy increases from 2.9% to 4.0% between 2015 and 2050. Power sector investment will be discussed in detail in section 7.2.3.

The increase in investment beyond the power sector relative to a scenario in which only the NDCs are achieved can be explained by moving towards a more capital-intensive production. In other words, energy is substituted for capital in order to implement more energy efficient production technologies in all sectors of the economy.

Table 19. Investment and output changes for the 2°C scenario relative to NDC scenario

	Changes in investments		Changes in output	
	2050 vs 2015	**2050 2°C vs NDC**	**2050 vs 2015**	**2050 2°C vs NDC**
Agriculture	124%	3.0%	160%	3.1%
Fossil fuels	11%	-39.4%	-2%	-41.4%
Industry	152%	1.8%	192%	0.5%
Construction	154%	2.3%	152%	1.2%
Services	147%	0.2%	161%	-0.3%
Transport	172%	0.9%	216%	-1.6%
Power	201%	13.2%	66%	2.0%

Source: JRC-GEM-E3.

7.2.2 Energy supply

The total investments (71) required in the energy sector for supply and energy transformation (fossil fuel production, power, hydrogen, biofuels) would reach 24 trillion dollars (tn$) over the 2010–2030 period (1.2 tn$/year on average) and 40 tn$ over 2030–2050 (2 tn$/year on average) in the central 2°C scenario. These projections fall within the range of recent cross-models comparisons (McCollum, et al., 2018).

These energy supply and transformation investments would still represent about 6–7% of total investment levels of the economy throughout the projection period (that share was about 7% over 1990–2015) (72).

This expected growth would sustain increasing energy needs, most notably in non-OECD regions (whose share of world investments would steadily grow from 56% for the period

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(71) Investment volumes in this report are given in real USD of 2015, non-levelised.

(72) Historical figures are gross capital formation from World Bank (2017); projections used POLES-JRC for energy supply investments and JRC-GEM-E3 for total investments.

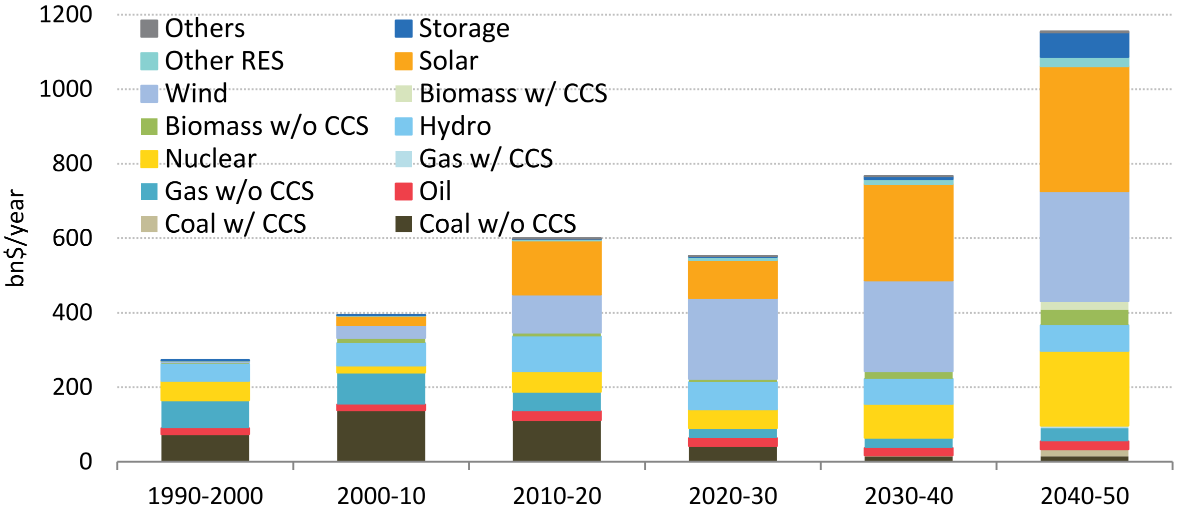
1990–2010 to 72% for the period 2030–2050), as well as a shift towards capital-intensive production means. The share of power in investments would grow slightly over the projection period (around 40% in 1990–2010 compared to 47% in 2030–2050).

7.2.3 Power sector

Global investments in new power capacities are projected to rise in the central 2°C scenario, as the electrification trend is expected to gain importance (Figure 115), despite the expected decrease of certain technology costs. Investments during the 2010–2020 decade are already expected to be 50% higher than those made in 2000–2010. Investments are expected to reach about 0.6 tn$/year over the 2010–2030 period and almost 1 tn$/year over the 2030–2050 period (compared to about 0.5 tn$/year in the 2000–2015 period).

As a general trend, climate policies favour technologies with higher capital costs and lower operating (fuel) costs. As a result, whereas investments in primary fossil fuels supply are expected to decrease, investments in power production would represent a growing share of total investments in energy supply.

Figure 115. Investments in power generation capacities per decade and per technology, World, central 2°C scenario



Source: JRC-GEM-E3.

Another major trend in the central 2°C scenario would see the deployment of renewables and low-carbon technologies over time, in the framework of ambitious GHG mitigation policies: most investments will go to solar and wind, followed by nuclear and CCS technologies (coupled with coal, gas or biomass), as shown in Figure 115. On the other hand, coal would almost disappear from the investment landscape in the central 2°C scenario, despite the deployment of CCS after 2040.

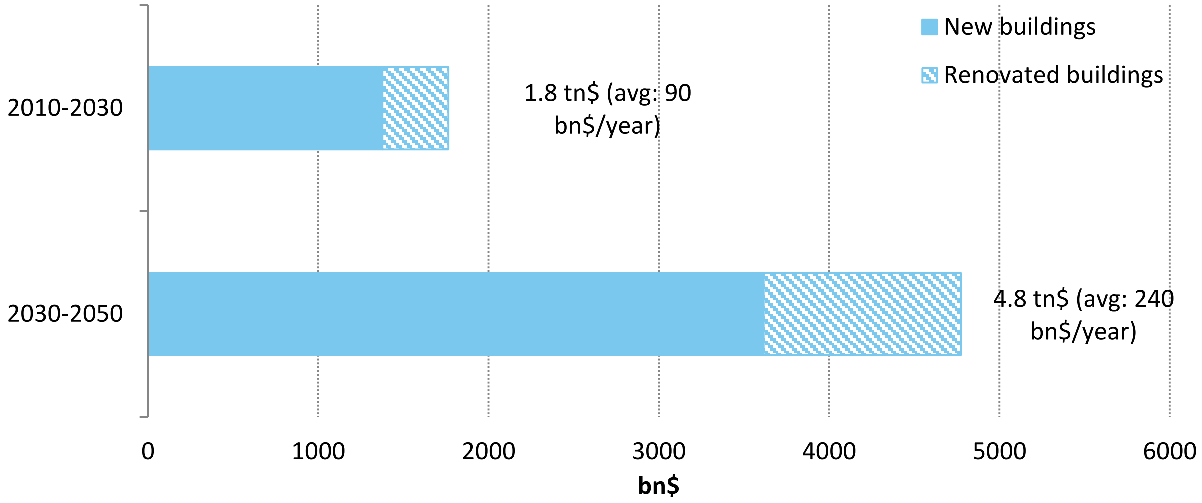
These investments do not, however, represent the total investments in the power sector since they do not include investments in transmission and distribution infrastructure.

7.2.4 Energy demand

Investments in final users of energy would include the purchase of energy-consuming equipment and related infrastructure, as well as additional investment to improve their efficiency (in transport, industry and buildings).

In particular, additional investments in more energy-efficient building envelopes over 2015–2050 could reach 6.4 tn$, rising in importance over time and by comparison amounting to one fourth of the total investment needs in the power sector by 2050 ([73]).

Figure 116. Investments in increased insulation for buildings envelopes, new and renovations, central 2°C scenario



Source: JRC-GEM-E3 2018.

Box 30. Energy investments in the 1.5°C scenario

In the 1.5°C scenario, the similar electrification trend results in investment levels comparable to the central 2°C scenario: 11 tn$ and 19 tn$ over the 2010–2030 and 2030–2050 periods, respectively.

Regarding investments in buildings insulation, the importance of energy efficiency is increased in the 1.5°C scenario, with the considerable insulation effort deployed in 2020–2030 in the central 2°C scenario extended to the 2030–2050 decades. This would lead to an increase of investments in efficient building envelopes: 20% higher in 2030–2050 compared to the central 2°C scenario.

([73]) By comparison, these figures are higher than the IEA figures for investments in energy efficient buildings in the New Policies Scenario (~75 bn$/year out of around 200 bn$/year between 2017 and 2040; (IEA, 2017)). In the central 2°C scenario, investments would be double this amount, which can be explained by much higher improvements in energy efficiency compared to IEA's NPS (which is comparable to an NDC scenario). Note that the situation in the EU would be different: the EU exhibits higher demand-side investments due to higher building insulation needs because of its cooler climate, as well as less power sector investment needs due to a more moderately increasing power demand (European Commission, 2016).

7.3 International trade

7.3.1 Trade intensity of GDP

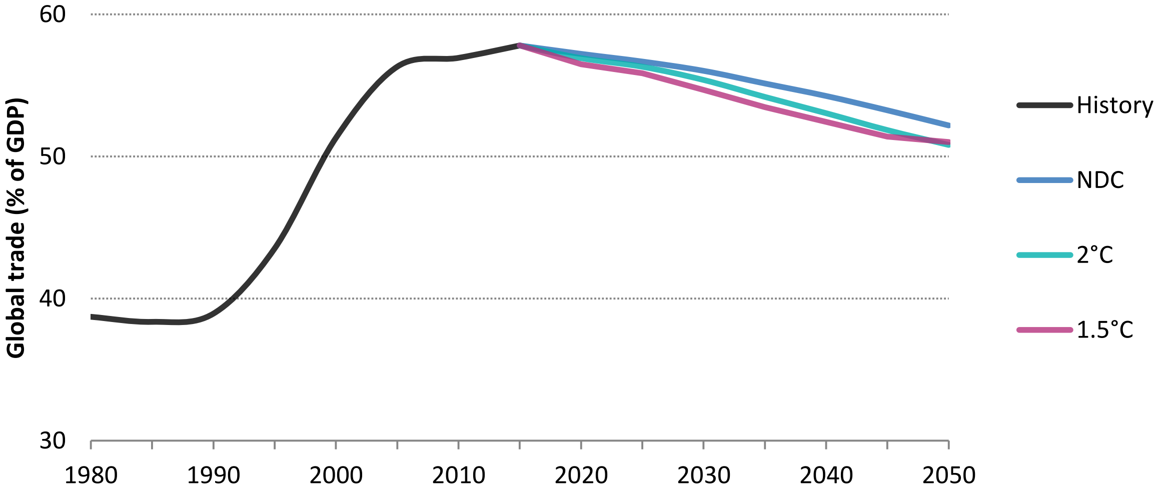
International trade, as measured by the sum of imports and exports relative to globally aggregated GDP (World Bank statistics), rose from under 40% in the period 1980-1990 to over 55% in the year 2005. In recent years, the rise of global trade intensity has experienced a slowdown, stabilising at around approximately 56% in the year 2016.

Simulations with the JRC-GEM-E3 model suggest that global trade intensity would gradually fall over the next decades, with levels decreasing towards 52% and 51% in the NDC and 2°C (1.5°C) scenarios, respectively. To some extent, this result is driven by the exogenous assumption in the underlying baseline (which includes only currently implemented policies) that trade deficits and surpluses move towards zero in the very long run. However, this explanation is common for the three scenarios shown in Figure 117, which leaves room for additional reflections on the differences across scenarios.

One of the factors that plays an important role is the carbon intensity of transport. The rising global trade intensity over the past decades was stimulated by the failure to include the external costs to the environment and to human health in the pricing of transport fuels, particularly oil. Broad-based climate action, as is assumed in this report, would imply that carbon pricing results in higher end-user prices in transport and, correspondingly, rendering transporting goods more costly.

There is a second element that should be considered in the international trade flows of energy goods. The 2°C and 1.5°C scenarios imply lower use of coal, oil, and gas, which for some regions are products that need to be imported almost entirely. Energy efficiency is one explanation. Electrification is a second one: a shift from fossil fuels to electricity, generally less tradeable, would imply reduced trade flows, as discussed in section 7.3.2. These results come with the caveat that trade in renewable energy infrastructure goods is likely too fine-grained to be represented realistically in the economy-wide modelling framework, and the production origin of these goods in 30 years from now is rather uncertain.

Figure 117. Global trade in goods and services



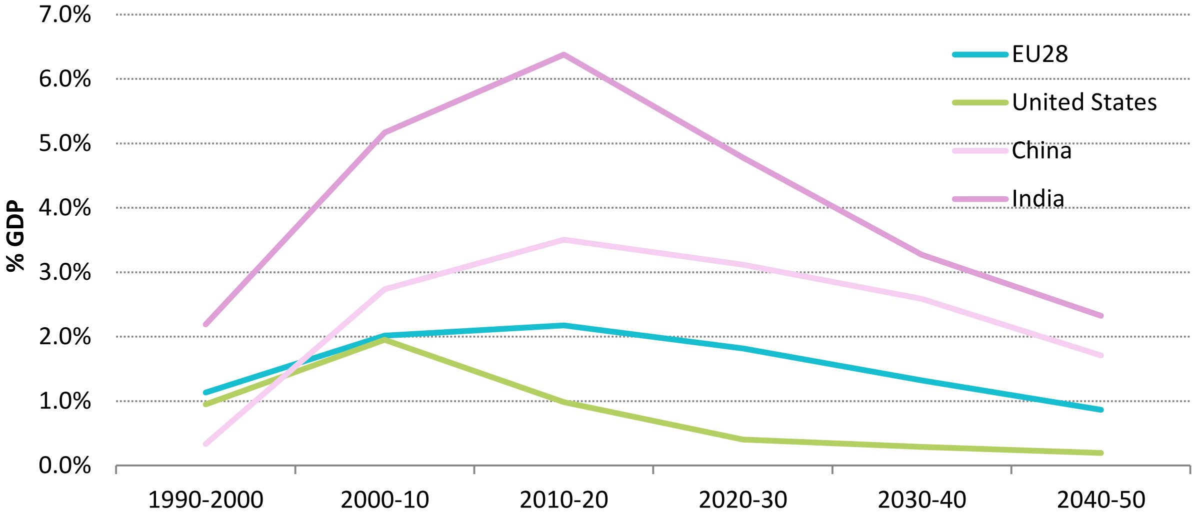
Source: JRC-GEM-E3 2018.

7.3.2 Energy trade

Energy trade entails a financial burden to energy importing countries that amounts to a significant percentage of the economy of those countries. In the context of a transition towards deeply decarbonised economies, importing countries would experience different trends in their energy import bill as the result of the interplay between their own domestic demand and international prices.

As an important co-benefit of ambitious climate policies, energy import expenditures would be significantly limited in the central 2°C scenario. Total world energy trade would intensify in the future, with regional differences in the structure of exporters and importers over time (Figure 118). However, changes in energy demand and energy efficiency with ambitious climate policies could limit this growth. Lowering the domestic consumption in relative terms and relying more on local renewable energy resources would contribute to mitigating the external energy bill and improving indicators on security of supply. As a consequence, net energy imports bills of major energy importing economies would peak (as a percentage of GDP) between 2000 and 2020; afterwards, economic growth and energy imports expenditures would show a decoupling trend.

Figure 118. Total net energy trade as a percentage of GDP, central 2°C scenario ([74])



Note: Includes trade of oil, gas, coal and solid and liquid biomass.

Source: POLES-JRC 2018.

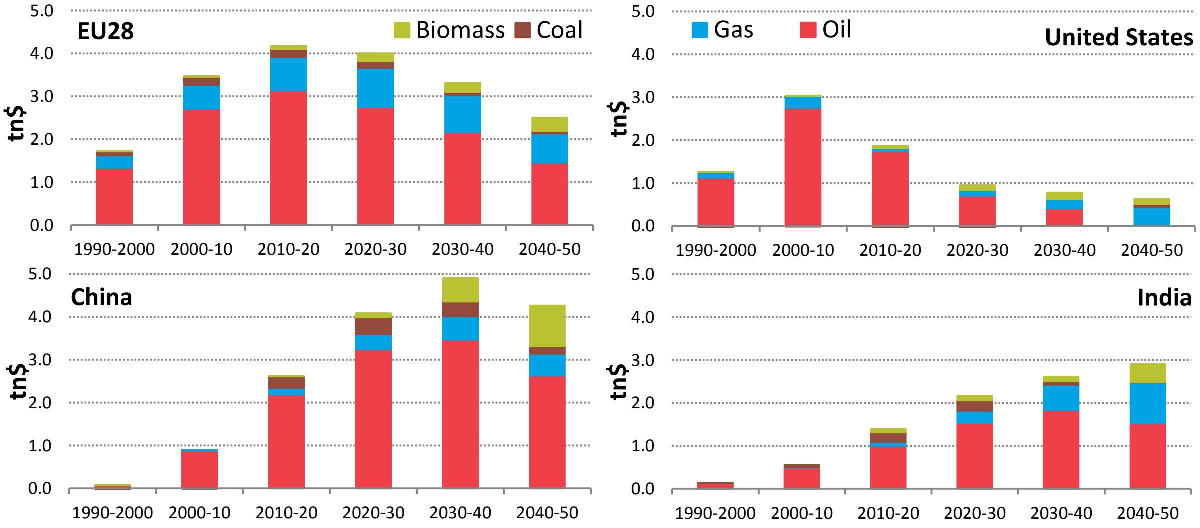
A more detailed analysis, by volume and fuel (Figure 119), shows a major trend in the reduction of oil bills and an almost complete phase-out of coal expenditures, as opposed to an intensification of gas and biomass trades. This would have potentially significant geopolitical consequences.

Some regions could be initiating a drop in energy trade as early as the current decade (United States) or the 2020s (EU). The United States experienced a major change of their domestic energy landscape with the development of unconventional resources which, along with efficiency improvements, induced an important improvement of their trade balance. Meanwhile, the continued effort of the EU to decarbonise its economy would continue to prove fruitful in the near future, especially through a stabilisation and reduction of its oil bill. In the central 2°C scenario, the United States' net imports could drop to almost zero in 2050, mainly due to an oil balance becoming quasi-neutral by 2050, and the EU's import bill would reach as low as 1% of the region's GDP by 2050, compared to around 2% in the 2000s and 2010s.

([74]) Trade volumes are in real USD of 2015; shares of GDP were calculated with volumes using GDP MER.

China and India's energy expenditures would steadily grow in volumes until at least 2040 (China) and 2050 (India), sustained by high economic growth rates; however, they would experience a decoupling of that growth with the growth of their economies. In both cases, oil imports would decrease after 2040. In China, this trend would drive the total energy bill down, but would be compensated by higher gas expenditures in India.

Figure 119. Total net energy trade by decade and fuel, central 2°C scenario



Source: POLES-JRC 2018.

7.3.3 Emissions embodied in trade

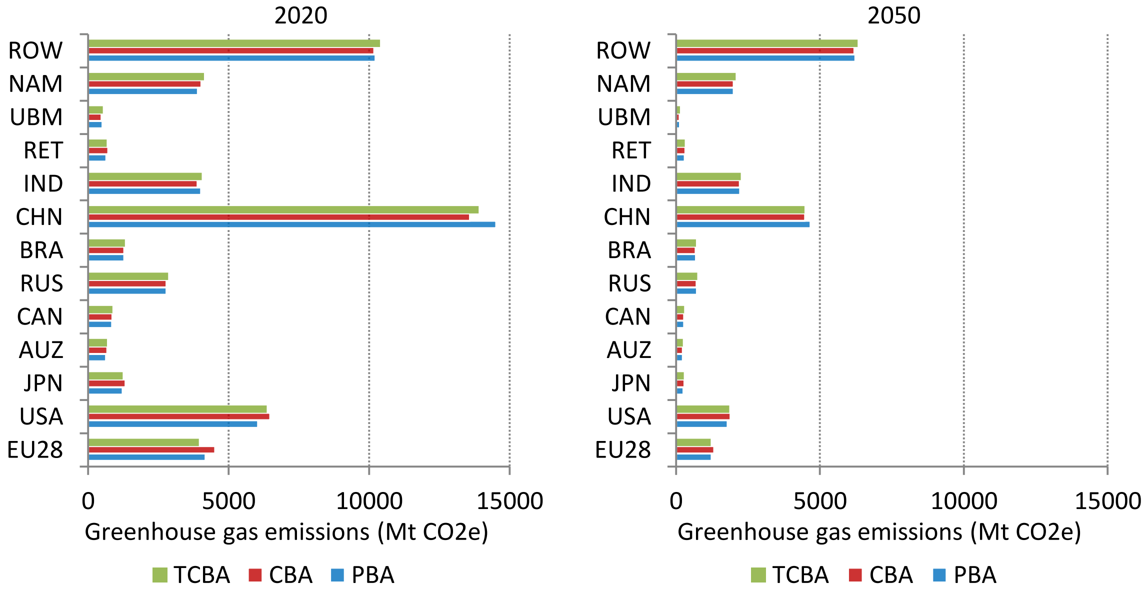
Emissions can be assigned either to the country or region where they are emitted during production (production-based accounting, PBA) or to the country or region where the final product is consumed (consumption-based accounting, CBA). While production-based accounting is used for UNFCCC reporting, consumption-based accounting can indicate how many emissions are caused by the consumption in a given country or region. Consumption-based accounting considers emissions along the entire value chain, including emissions from the production of intermediate or final goods abroad.

The difference between (domestic) production-based emissions and consumption-based emissions is often referred to as the balance of emissions embodied in trade. In recent years, China was the largest exporter of emissions embodied in trade due to the coal-based energy system, relatively high energy intensity of production and a large trade surplus. However, since the financial crisis, emissions embodied in Chinese exports have declined along a transition to cleaner production and a focus of investment-driven rather than export-driven growth (Mi, et al., 2017). Important regions that are net importers of emissions are the USA and the EU.

Consumption-based accounting has the shortcoming that it does not account for emission reductions in exporting sectors. In other words, all export-related emissions are associated with final consumers; hence any increase in the emission efficiency of the exporting sectors is credited to the importers of these goods. Technology-adjusted consumption-based accounting (TCBA) adjusts for emission intensity of exports by relating exports in a sector to the global average emission efficiency (Kander, et al., 2015). To calculate CBA emission, emissions embodied in imports are subtracted and emissions embodied in exports are added to PBA emissions. For TCBA, emissions at the average world carbon intensity are subtracted and, hence, countries or regions exporting cleaner than the world are credited with emission reduction efforts. For example, TCBA emissions for Europe are below PBA and CBA as European exports are relatively clean, while this is not the case for the USA.

The development of consumption and production-based emissions can be calculated using a computable general equilibrium model as the model reflects the input-output structure (Weitzel & Peterson, 2011). In particular, it is possible to analyse how climate or other policy influence consumption and production-based emissions. Changes that are caused by climate policy are of interest as they can serve as a measure of leakage, i.e. whether climate policy is able reduce emissions rather than relocate emissions to regions without or with less stringent climate policy. Furthermore, reductions in domestic production-based emissions and (technologically-adjusted) consumption-based emissions can serve as indicators of domestic abatement efforts.

Figure 120. Emissions in 2020 and 2050 based on PBA, CBA, and TCBA accounting principles



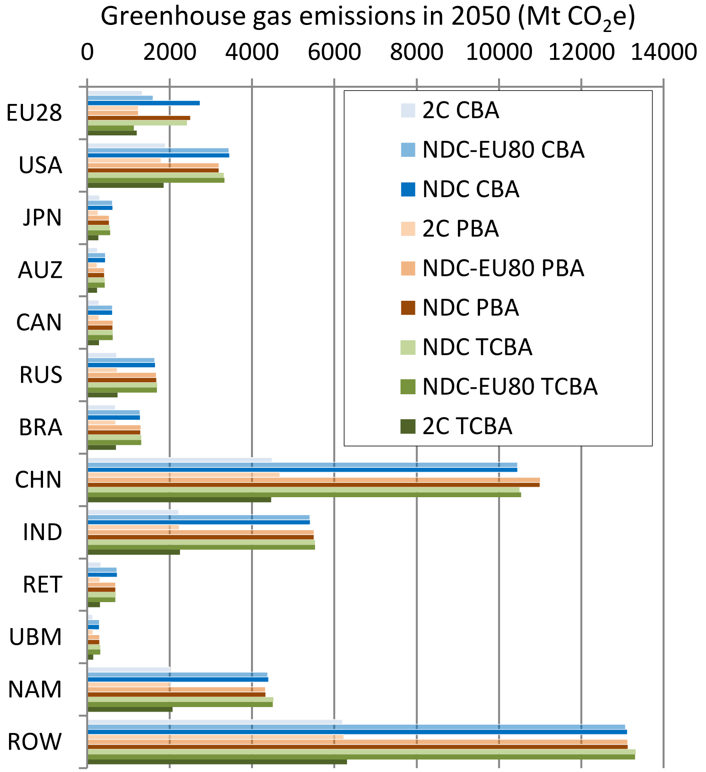
Source: JRC-GEM-E3.

When the world is on a trajectory to 2°C, all regions likewise reduce production and consumption-based emissions (Figure 120). In general, individual regions remain net exporters or importers of emissions throughout the modelling period as the reduction rates for consumption and production-based emissions are usually similar. Under a global mitigation effort, trade flows that are particularly carbon intensive will become relatively more expensive and are hence avoided by importers. In addition, it is assumed in JRC-GEM-E3 that currently observed trade imbalances are reduced over time. Most regions therefore reduce the difference between the two measures over time, both in absolute and in relative numbers. TCBA emissions remain in their relative position, e.g. TCBA emissions in the EU remain lower than PBA and CBA emissions, although the differences between measures decline over time.

To illustrate how fragmented climate policy can change these indicators, Figure 121 presents a scenario where only the EU28 raises climate policy ambition above the NDC level to an 80% reduction in 2050 (NDC-EU80) in line with the 2°C emission trajectory. EU production-based emissions reach the same target in both NDC-EU28 and 2°C scenarios, but consumption-based emissions in Europe are higher when imports to Europe are more emission-intensive. When the EU unilaterally ratchets up emission reduction efforts, emissions in other regions could increase (typically referred to as emission leakage) through two main channels. First, lower EU fossil fuel demand lowers international prices, which stimulates the consumption of fossil fuels in other regions, partially offsetting the EU effort. The current analysis does not capture this channel well due to a stylised modelling of the international oil market. Second, energy-intensive firms may relocate to areas where greenhouse gas emission regulation is less stringent. The results in Figure 121 illustrate that raised EU ambition levels reduce consumption-based emissions also in the rest of the world, through exports of relatively clean EU products. When using TCBA and accounting for cleaner exports in the EU towards EU emissions, the EU reduction under the fragmented action is even higher than under global action as the average emission intensity of world trade is higher and the EU is credited with more emission reductions.

Figure 121. Emissions in 2050 under a global 2°C scenario and a scenario where the EU abates 80% while all other regions follow NDC ambitions (NDC-EU80) compared to the NDC scenario, under PBA, CBA and TCBA accounting principles.

	% vs NDC, 2050					
	NDC-EU80			**2C**		
Based on	PBA	CBA	TCBA	PBA	CBA	TCBA
EU28	-50.5	-41.7	-53.3	-50.5	-51.4	-50.3
USA	-0.1	-0.4	0.5	-43.9	-45.2	-44.2
JPN	0.1	-0.5	0.6	-51.9	-51.8	-51.3
AUZ	0.1	-0.7	0.1	-42.7	-45.0	-43.9
CAN	0.0	-0.6	0.1	-55.0	-54.3	-54.1
RUS	-0.4	-0.8	-0.5	-56.7	-56.8	-56.7
BRA	0.1	-0.2	0.0	-46.9	-47.0	-46.8
CHN	0.1	0.0	0.3	-57.4	-57.0	-57.5
IND	0.0	-0.2	0.0	-59.5	-59.0	-59.4
RET	0.0	-1.3	-1.1	-55.3	-54.7	-55.2
UBM	0.1	-0.4	-0.1	-54.9	-55.0	-55.1
NAM	-0.1	-0.6	-0.3	-53.7	-54.4	-54.1
ROW	-0.1	-0.4	-0.1	-52.5	-52.7	-52.6
World	-2.8	-2.8	-2.8	-53.9	-53.9	-53.9



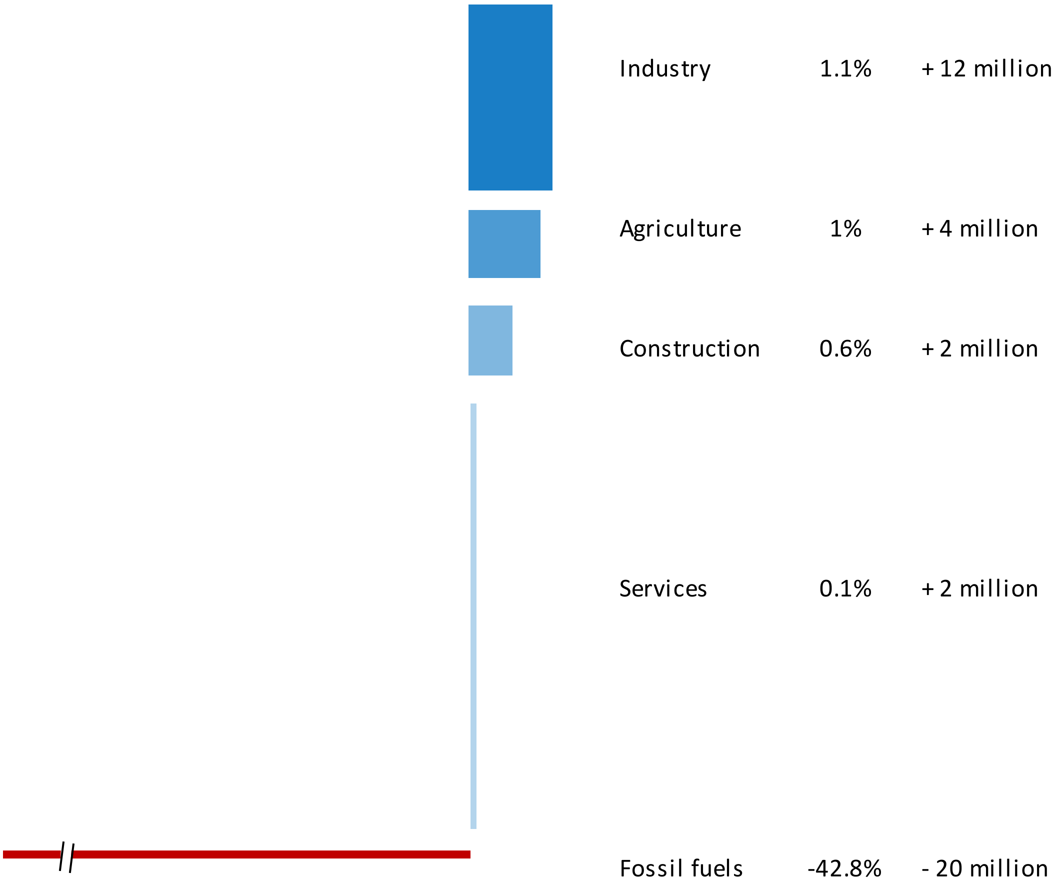
Source: JRC-GEM-E3.

7.4 Employment transition

Understanding the impact of policy measures on employment is fundamental, as jobs provide the income necessary to improve the well-being of families around the world. In the long run (here: 2050), most studies find that the effect of climate change mitigation policy on unemployment is neutral overall, because supply and demand adjust over time. In this long-run context, the current study assumes that wages are flexible to adjust. The results of the analysis with JRC-GEM-E3 thus highlight the transition of jobs away from greenhouse gas emission=intensive fossil fuel sectors towards other sectors. Figure 122 represents both absolute and relative changes by scaling the height of the bars to the employment in the NDC scenario in 2050. The width of the bars indicates percentage change, such that the surface represents the absolute changes in the number of jobs by sector.

Figure 122 shows that, only the fossil fuels sector is experiencing a reduction in the number of jobs, of approximately 20 million jobs globally in the 2°C scenario relative to the NDC scenario. As demand for fossil fuels declines and the sector shrinks, fewer jobs are available and employment shifts to sectors that are driving the transition. This includes agriculture, where increased demand for biofuels raises the number of jobs. Employment in the construction sector and some industry sectors is boosted by the additional investment that is required for the energy system transformation. The figure also shows the job changes relative to the labour force of different sectors in 2050. This highlights the concentration of job decline in the fossil fuel sector as the employment is reduced by 42.8%. This concentrated job loss can provide challenging transitions for specific regions with stronger job dependence on coal (Box 31). For a sensitivity analysis on employment results for the EU, we refer to Box 29 in section 7.1.4.

Figure 122. Global changes in employment structure in 2050 compared to an NDC scenario.

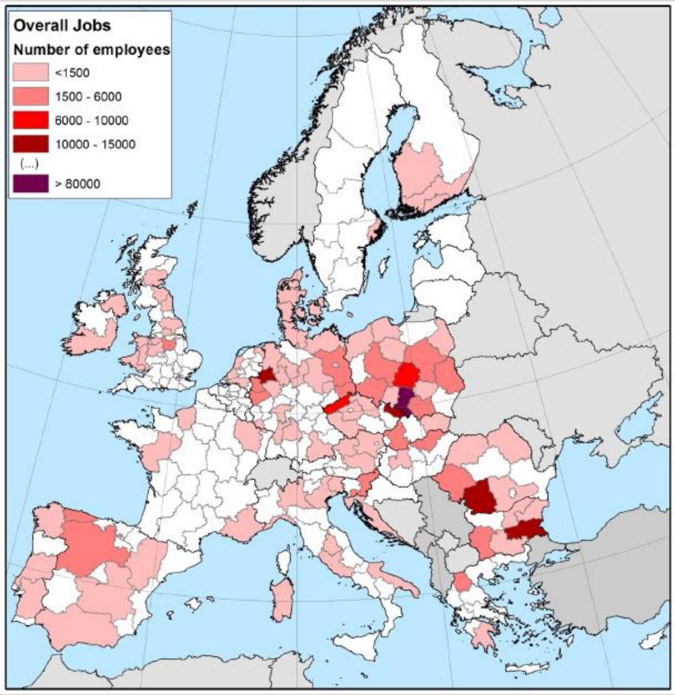


Source: JRC-GEM-E3 2018.

Box 31. Jobs at risk and regional resilience

The academic literature and the analysis presented above suggest that, overall, economy-wide employment may not be affected much by climate policy. However, particular sectors may experience substantial changes, such as coal mines and coal-fired power plants. As these sectors tend to be concentrated geographically, the transition to a low-carbon economy can disproportionately affect some regions. Figure 123 illustrates for the EU which regions may be particularly affected, which is informative for stimulating proactive change in order to enhance regional resilience.

Figure 123. Overall number of jobs in coal power plants and coal mines in NUTS2 regions



Source: (Alves Dias, et al., 2018).

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List of abbreviations and definitions

Acronyms & Abbreviations

BECCS: Bio-Energy combined with Carbon Capture and Sequestration

BGR: German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe)

CCS: Carbon Capture and Sequestration

CCU: Carbon Capture and Use

CDD: Cooling Degree-Days

CDR: Carbon Dioxide Removal

CFC: Chlorofluorcarbon

CGE: Computable General Equilibrium model

COM: Communication from the European Commission

COP: Conference Of the Parties

DACCS: Direct Air CO_2 Capture and Sequestration

EC: European Commission

EFTA: European Free Trade Association

EIA: US Energy Information Administration

ETS: Emission Trading Scheme

EV: Electric Vehicle

GDP: Gross Domestic Product

GECO: Global Energy & Climate Outlook

GHG: Greenhouse Gases

GLOBIOM: The Global Biosphere Management Model

GTAP: Global Trade Analysis Project

GWO: Global Warming Potential

HDD: heating degree-days

HFC: Hydrofluorocarbon

ICE: Internal Combustion Engine

IEA: International Energy Agency

IIASA: International Institute for Applied Statistical Analysis

ILO: International Labour Organisation

IMF: International Monetary Fund

INDC: Intended Nationally Determined Contribution

IPCC: Intergovernmental Panel on Climate Change

JRC: Joint Research Centre of the European Commission

LNG: Liquefied Natural Gas

LULUCF: Land Use, Land Use Change and Forestry

MARPOL: Convention for the Prevention of Pollution from ships

MER:	Market Exchange Rate
NDC:	Nationally Determined Contribution
NREL:	US National Renewables Energy Laboratory
OECD:	Organisation of Economic Co-operation and Development
PFC:	Perfluorocarbons
POP:	Population
PPP:	Purchasing Power Parity
PV:	Photovoltaics
R/P:	Ratio Reserves by Production
RES:	Renewable Energy
SDGs:	Sustainable Development Goals
UN:	United Nations
UNFCCC:	United Nations Framework Convention on Climate Change
USGS:	US Geological Survey
WEC:	World Energy Council
WMO:	World Meteorological Organisation

Regional codes

Balk: other Balkans countries, includes Albania, Bosnia-Herzegovina, Kosovo, Macedonia, Montenegro, Serbia

C Am: Central America, includes: Bahamas, Barbados, Belize, Bermuda, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, NL Antilles and Aruba, Panama, St Lucia, St Vincent and Grenadines, Trinidad and Tobago

CIS: Commonwealth of Independent States, includes: Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyz Rep., Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan. Georgia is also included here (although withdrawn from CIS since 2008)

EFTA: Iceland, Liechtenstein, Norway, Switzerland

EU28: European Union with 28 Member States (as of October 2018). Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom

Europe: EU28, EFTA, Other Balkans (Albania, Bosnia-Herzegovina, Kosovo, FYR of Macedonia, Montenegro, Serbia)

LDC: Least Developed Countries (UN concept). Refer here to regions where income is inferior to 5 k$/cap in 2030, i.e.: Rest of Central America, Egypt, Rest of Sub-Saharan Africa, India, Rest of South Asia, Indonesia, Vietnam, Rest of South-East Asia, Pacific Islands, according to POLES-JRC

OECD: Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States

OPEC: Organisation of the Petroleum Exporting Countries, includes (as of June 2017): Algeria, Angola, Ecuador, Equatorial Guinea, Gabon, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, Venezuela

Pacif: Pacific, includes: Fiji Islands, Kiribati, Papua New Guinea, Samoa (Western), Solomon Islands, Tonga, Vanuatu

R CIS: Rest CIS, CIS excluding Russia and Ukraine

R Gulf: Rest Gulf, includes Bahrain, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Syria, United Arab Emirates, Yemen

S Am: South America, includes Argentina, Bolivia, Brazil, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela

S Asia: South Asia, includes Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka

SE Asia: South-East Asia, includes: Brunei, Cambodia, Indonesia, Korea (PR), Lao PDR, Malaysia, Mongolia, Myanmar, Philippines, Singapore, Taiwan, Thailand, Vietnam

SS Afr: Sub-Saharan Africa (Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Congo DR, Cote d΄Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe)

Glossary

Agriculture sector includes the energy consumed in agriculture, forestry and fishing. It covers the exploitation of vegetal and animal natural resources (the growing of crops, raising and breeding of animals, harvesting of timber and other plants).

Electric processes & appliances: Energy demand for end-uses where electricity is necessary. Covers electric industrial processes, white and grey appliances, lighting, space cooling. It does not include electricity demand for space heating and cooking.

Energy for Power Generation covers energy for electricity and heat production. It covers fuel use in electricity plants, heat plants and combined heat and power (CHP) plants. Self-consumption is included.

Final Energy Demand is the sum of energy consumption by the different end-use sectors. It is broken down into the energy demand in the following sectors: agriculture; industry; transport; residential; services. It excludes international marine and aviation bunkers, except at world level where they are included in the transport sector. It can also be broken down into the energy demand in the following end-uses: heat uses; electric processes & appliances; mobility; non-energy uses.

Heat uses: Energy demand for end-uses for the production of low- and high-temperature heat. It covers thermal industrial processes and space heating.

Industrial sector includes the manufacturing industry, construction and mining; it does not include energy transformation activities; it includes non-energy uses of energy fuels. It consists of the following subsectors:

- Iron and Steel industry (includes blast furnaces and coke final consumption);
- Non-Metallic Minerals;
- Chemicals (consumption for energy uses of chemicals and petrochemicals industry);
- Other Industry (energy uses in other manufacturing industries, construction and mining);
- Non-Energy Uses (non-energy uses of energy fuels in rubber and plastics and chemical feedstocks production).

The energy used for transport by industry is not included here but reported under transport.

Mobility: Energy demand for mobility end-uses. Coincides with the energy demand of the Transport sector.

Non-energy uses: Non-energy end-uses of energy fuels in rubber and plastics and chemical feedstocks production. It is consumed along with the energy uses of fuels in the chemicals sector in industry.

Other Energy Transformation & Losses is the energy own use and losses of the energy transformation industry not shown elsewhere, such as energy for fossil fuel and uranium extraction, refining, transport and distribution (including gasworks); production of synthetic fuels (coal-, gas- and biomass-to-liquids, hydrogen, synthetic methane); coke ovens. Also includes transfers and statistical differences. Losses include losses in energy distribution, transmission and transport.

Primary Energy Demand represents the total energy demand, including net imports. It is the sum of energy demand for power generation, other energy transformation sector & losses and total final demand.

Residential sector includes all household energy uses.

Services sector includes commercial energy uses (office buildings, hotels, shopping centres, IT centres, …), and public services energy uses (public street lighting).

Transport sector includes all fuels (oil, gas, biomass, coal, hydrogen, electricity) used for transport, for all passenger and freight transport, irrespective of the economic sector within which the activity occurs. It covers domestic aviation, road, rail, waterways and domestic navigation. Road transport includes light goods vehicles, heavy goods vehicles, light duty vehicles and passenger carrying vehicles for public and private transport. Country and regional balances refer to domestic consumption; international air and maritime bunkers are included only in the world total balance. It does not include the pipeline transport of energy goods and related losses.

Units

Energy

EJ	Exajoule	1000 000 000 000 000 000 J

toe	tonne of oil equivalent	
ktoe	thousand tonnes of oil equivalent	1000 toe
Mtoe	million tonnes of oil equivalent	1000 000 toe
Gtoe	giga tonnes of oil equivalent	1000 000 000 toe

Mbl/d	million barrels per day	1000 000 bl/d
Tbl	tera barrels	1000 000 000 000 bl

Gt	giga metric tonnes	1000 000 000 t
Mt	million metric tonnes	1000 000 t

Electricity

GW	gigawatts	1000 000 000 W
TWh	terawatt-hours	1000 000 000 000 Wh

Prices

$/bbl	$ per barrel of oil
$/boe	$ per barrel of oil equivalent

Emissions and related

tCO$_2$	tonne CO$_2$	
tCO$_2$-eq	tonne CO$_2$-equivalent	
MtCO$_2$e	million tonnes of CO2-eq	1000 000 tCO$_2$-eq
GtCO$_2$e	giga tonnes of CO2-eq	1000 000 000 tCO2-eq
ppm	particulates per million	
µm	micrometre (1x10^{-6} metre)	
µgm^{-3}	microgram (1x10^{-6} gram) per cubic metre	

Monetary units

k$	thousand dollars	1000 $
M$	million $	1000 000 $
bn$	billion $	1000 000 000 $
tn$	trillion $	1000 000 000 000 $

List of boxes

List of figures

List of tables

Annexes

Annex 1. Description of the energy/GHG model POLES-JRC

For a fuller description of the model, see (Després, et al., 2018) ([75]).

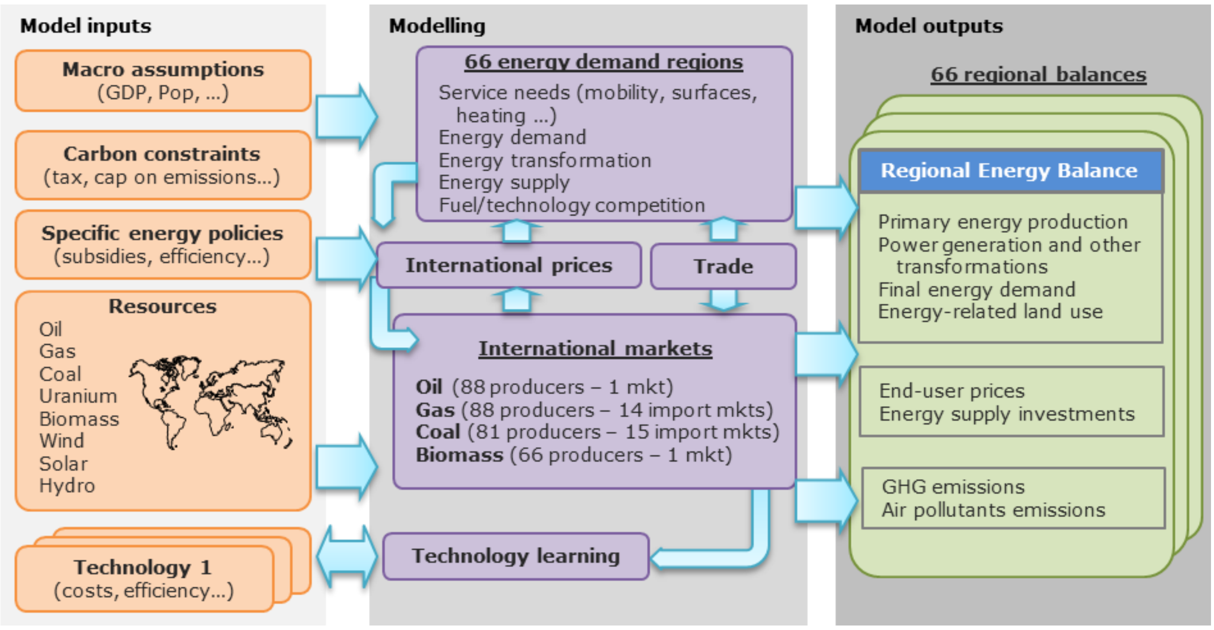
Model

POLES-JRC is a world energy-economy partial equilibrium simulation model of the energy sector, with complete modelling from upstream production through to final user demand. It follows a year-by-year recursive modelling, with endogenous international energy prices and lagged adjustments of supply and demand by world region, which allows for describing full development pathways to 2050 (see general scheme in Figure 124).

The model provides full energy and emission balances for 66 countries or regions worldwide (including detailed OECD and G20 countries), 14 fuel supply branches and 15 final demand sectors.

This exercise used the EC POLES-JRC 2017 version. Differences with other exercises done with the POLES-JRC model by EC JRC, or with exercises by other entities using the POLES model, can come from different i/ model version, ii/ historical data sets, iii/ parameterisation, iv/ policies considered.

Figure 124. POLES-JRC model general scheme



Source: POLES-JRC model.

Final demand

The final demand evolves with activity drivers, energy prices and technological progress. The following sectors are represented:

- industry: chemistry (energy uses and non-energy uses are differentiated), non-metallic minerals, steel, other industry;
- buildings: residential, services (detailed per end-uses: space heating, space cooling, water heating, cooking, lighting, appliances);
- transport (goods and passengers are differentiated): road (motorcycles, cars, light and heavy trucks; different engine types are considered), rail, inland water, international maritime, air (domestic and international);
- agriculture.

([75]) Also http://ec.europa.eu/jrc/poles

Power system

The power system describes the capacity planning of new plants and the operation of existing plants.

The electricity demand curve is built from the sectoral distribution.

The load, wind supply and solar supply are clustered into a number of representative days.

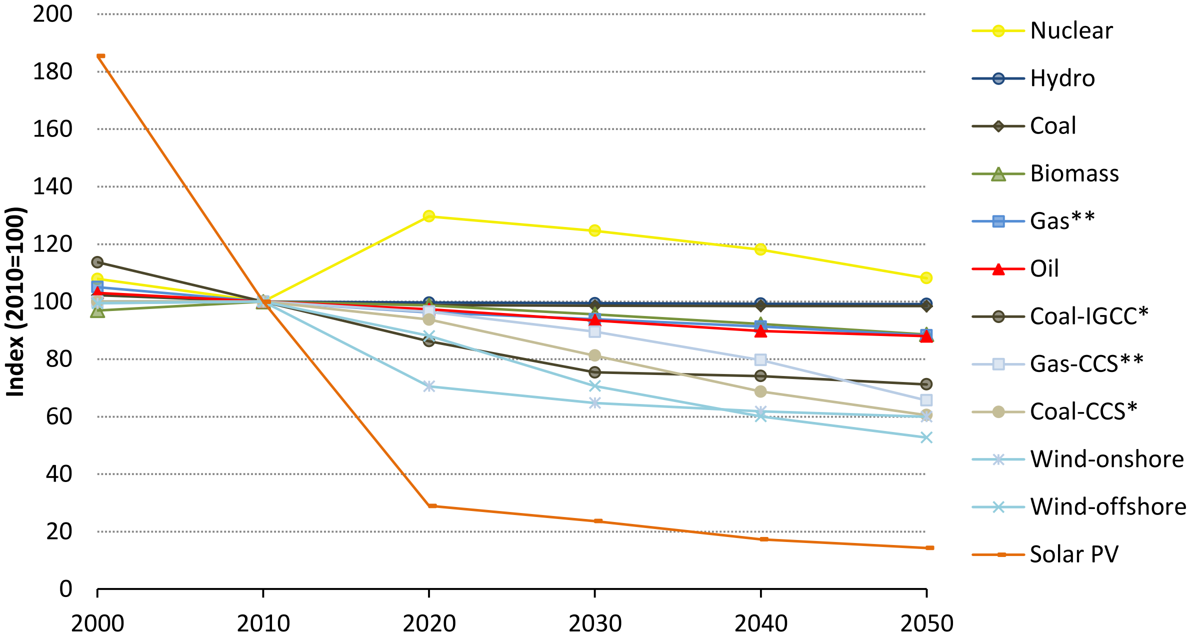
The planning considers the existing structure of the power mix (vintage per technology type), the expected evolution of the load demand, the production cost of new technologies and the resource potential for renewables.

The operation matches electricity demand considering the installed capacities, the variable production costs per technology type, the resource availability for renewables and the contribution of flexible means (stationary storage, vehicle-to-grid, demand-side management).

Electricity price by sector depend on the evolution of the power mix, of the load curve and of the energy taxes.

Figure 125 shows the investment costs for selected technologies, collected from the literature.

Figure 125. Power generation investment costs, central 2°C scenario, World (indexed to 2010)



Note: Solar PV decreases its cost significantly; the 2020 and 2050 values would be 30 and 15, respectively.

Source: POLES-JRC model.

Other transformation

The model also describes other energy transformations sectors: liquid biofuels, coal-to-liquids, gas-to-liquids, hydrogen, centralised heat production.

Oil supply

Oil discoveries, reserves and production are simulated for producing countries and different resource types.

Investments in new capacities are influenced by production costs, which include direct energy inputs in the production process.

The international oil price depends on the evolution of the oil stocks in the short term, and on the marginal production cost and ratio of the Reserves by Production (R/P) ratio in the longer run.

Gas supply

Gas discoveries, reserves and production are simulated for individual producers and different resource types. Investments in new capacities are influenced by production costs, which include direct energy inputs in the production process.

They supply regional markets through inland pipeline, offshore pipelines or LNG.

The gas prices depend on the transport cost, the regional R/P ratio, the evolution of oil price and the development of LNG (integration of the different regional markets).

Coal supply

Coal production is simulated for individual producers. Production cost is influenced by short-term utilisation of existing capacities and a longer-term evolution for the development of new resources. They supply regional markets through inland transport (rail) or by maritime freight. Coal delivery price for each route depends on the production cost and the transport cost.

Biomass supply

The model differentiates various types of primary biomass: energy crops, short rotation crop (lignocellulosic) and wood (lignocellulosic). They are described through a potential and a production cost curve – information on lignocellulosic biomass (short rotation coppices, wood) is derived from look-up tables provided by the specialist model GLOBIOM-G4M (Global Biosphere Management Model*)*. Biomass can be traded, either in solid form or as liquid biofuel.

Wind, solar and other renewables

They are associated with potentials and supply curves per country.

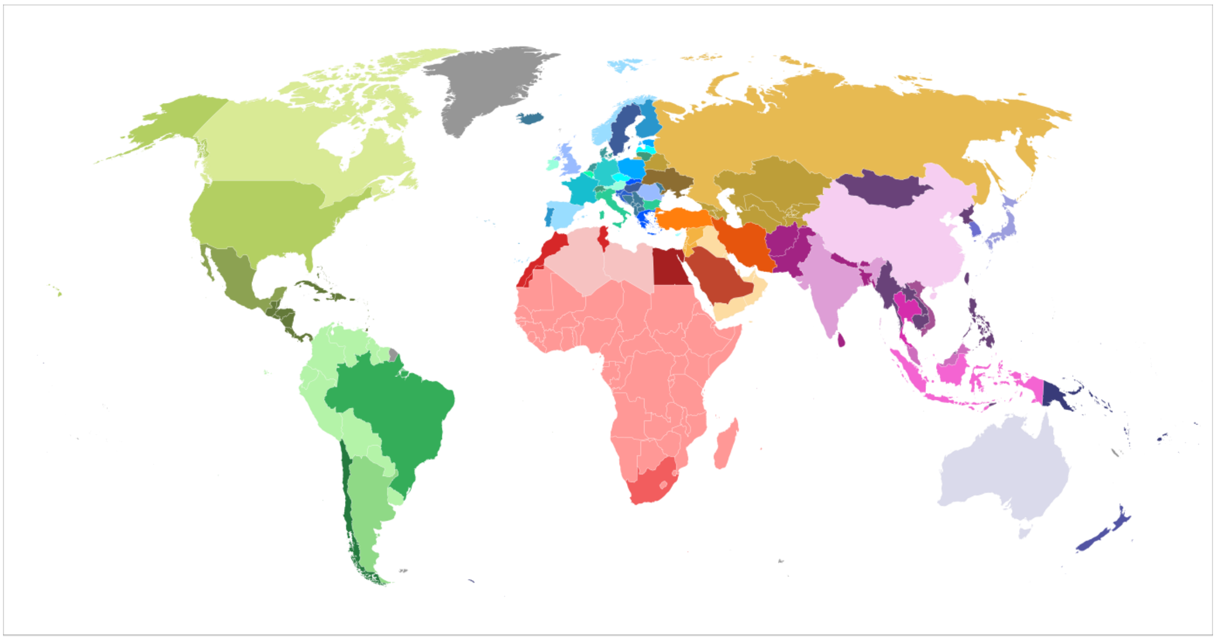
GHG emissions

CO_2 emissions from fossil fuel combustion are derived directly from the projected energy balance. Other GHGs from energy and industry are simulated using activity drivers identified in the model (e.g. sectoral value added, mobility per type of vehicles, fuel production, fuel consumption) and abatement cost curves. GHG from agriculture and LULUCF are derived from GLOBIOM-G4M lookup tables.

Countries and regions

The model decomposes the world energy system into 66 regional entities: 54 individual countries and 12 residual regions (Figure 125, Table 20, Table 21), to which international bunkers (air and maritime) are added.

Figure 126. POLES-JRC model regional detail map (energy balances)



Source: POLES-JRC model.

Table 20. List of 54 individual countries represented in POLES-JRC (energy balances)

Non-EU individual countries	EU28 Member States
Argentina	Austria
Australia	Belgium
Brazil	Bulgaria
Canada	Croatia
Chile	Cyprus
China	Czech Republic
Egypt	Denmark
Iceland	Estonia
India	Finland
Indonesia	France
Iran	Germany
Japan	Greece
Malaysia	Hungary
Mexico	Ireland
New Zealand	Italy
Norway	Latvia
Russia	Lithuania
Saudi Arabia	Luxembourg
South Africa	Malta
South Korea	Netherlands
Switzerland	Poland
Thailand	Portugal
Turkey	Romania
Ukraine	Slovak Republic
United States	Slovenia
Vietnam	Spain
	Sweden
	United Kingdom

Note: Hong-Kong and Macau are included in China

Source: POLES-JRC model.

Table 21. Country mapping for the 12 regions in POLES-JRC (energy balances)

Rest Central America	**Rest Balkans**	**Rest Sub-Saharan Africa (continued)**	**Rest South Asia**
Bahamas	Albania	Burkina Faso	Afghanistan
Barbados	Bosnia-Herzegovina	Burundi	Bangladesh
Belize	Kosovo	Cameroon	Bhutan
Bermuda	Macedonia	Cape Verde	Maldives
Costa Rica	Moldova	Central African Republic	Nepal
Cuba	Montenegro	Chad	Pakistan
Dominica	Serbia	Comoros	Seychelles
Dominican Republic	**Rest CIS**	Congo	Sri Lanka
El Salvador	Armenia	Congo DR	**Rest South East Asia**
Grenada	Azerbaijan	Cote d’Ivoire	Brunei
Guatemala	Belarus	Djibouti	Cambodia
Haiti	Georgia	Equatorial Guinea	Lao PDR
Honduras	Kazakhstan	Eritrea	Mongolia
Jamaica	Kyrgyz Rep.	Ethiopia	Myanmar
Nicaragua	Tajikistan	Gabon	North Korea
NL Antilles and Aruba	Turkmenistan	Gambia	Philippines
Panama	Uzbekistan	Ghana	Singapore
Sao Tome and Principe	**Mediterranean Middle East**	Guinea	Taiwan
St Lucia	Israel	Guinea-Bissau	**Rest Pacific**
St Vincent & Grenadines	Jordan	Kenya	Fiji Islands
Trinidad and Tobago	Lebanon	Lesotho	Kiribati
Rest South America	Syria	Liberia	Papua New Guinea
Bolivia	**Rest of Persian Gulf**	Madagascar	Samoa (Western)
Colombia	Bahrain	Malawi	Solomon Islands
Ecuador	Iraq	Mali	Tonga
Guyana	Kuwait	Mauritania	Vanuatu
Paraguay	Oman	Mauritius	
Peru	Qatar	Mozambique	
Suriname	United Arab Emirates	Namibia	
Uruguay	Yemen	Niger	
Venezuela	**Morocco & Tunisia**	Nigeria	
	Morocco	Rwanda	
	Tunisia	Senegal	
	Algeria & Libya	Sierra Leone	
	Algeria	Somalia	
	Libya	Sudan	
	Rest Sub-Saharan Africa	Swaziland	

	Angola	Tanzania	
	Benin	Togo	
	Botswana	Uganda	
		Zambia	

Source: POLES-JRC model.

Data sources

Table 22. POLES-JRC model historical data and projections

Series		Historical data	GECO Projections
Population		UN, Eurostat	JRC, EC
GDP, growth		World Bank	EC, IMF, OECD
Other activity drivers	Value added	World Bank	POLES-JRC model
	Mobility, vehicles, households, tons of steel, …	Sectoral databases	
Energy resources	Oil, gas, coal	BGR, USGS, WEC, sectoral information	
	Uranium	NEA	
	Biomass	GLOBIOM model	
	Hydro	Enerdata	
	Wind, solar	NREL, DLR	
Energy balances	Reserves, production	BP, Enerdata	
	Demand by sector and fuel, transformation (including. power), losses	Enerdata, IEA	
	Power plants	Platts	
Energy prices	International prices, prices to consumer	Enerdata, IEA	POLES-JRC model
GHG emissions	Energy CO_2	Derived from POLES-JRC energy balances	POLES-JRC model
	Other GHG Annex 1	UNFCCC	POLES-JRC model, GLOBIOM model
	Other GHG Non-Annex 1 (excl. LULUCF)	EDGAR	POLES-JRC model, GLOBIOM model
	LULUCF Non-Annex 1	National inventories, FAO	POLES-JRC model, GLOBIOM model
Air pollutants emissions		GAINS model, EDGAR, IPCC, national sources	GAINS model, national sources
Technology costs		POLES-JRC learning curves based on literature, including but not limited to: EC JRC, WEC, IEA, TECHPOL database*	

*: developed in several European research projects: SAPIENT, SAPIENTIA, CASCADE MINTS

Source: POLES-JRC model.

Annex 2. Description of JRC-GEM-E3

The JRC-GEM-E3 model, a Computable General Equilibrium (CGE) model, is used to assess the direct and indirect impacts of mitigation efforts until the year 2050. The JRC-GEM-E3 model is a multi-sector, multi-region model that includes the interactions between the energy system, the economy and the environment. It is built on sound microeconomic foundations and integrates multiple data sources such as trade statistics, input-output data and information on the emissions of greenhouse gases. Furthermore, existing tax structures and unemployment mechanisms are incorporated. The version of the model used here is global (13 regions, see Table 23) and covers all industrial sectors, disaggregated into 31 sectors, of which there are 10 electricity-generating technology sectors.

In a general equilibrium framework, results regarding impacts of imposed policies are presented comparatively with the Reference projections of the economy, thus in terms of percentage differences from the Reference scenario. The JRC-GEM-E3 Reference is constructed on the basis of a variety of data sources. First, GDP growth rates are based on the PRIMES and POLES models for the EU and non-EU regions, respectively. Second, International Labour Organisation (ILO) database was used to project population and labour statistics such as labour force, unemployment rate and the share of skilled and unskilled workers. Third, the input-output tables and the data on bilateral trade flows are derived from the Global Trade Analysis Project (GTAP) 9 database. Fourth, the emission levels of greenhouse gases (totals and by sector) and the shares of electricity generation technologies are harmonised with the Baseline in the POLES model. For the EU, the Baseline is consistent with the 2018 reference of the PRIMES model. The Reference is built under the assumption of current climate and energy policies (and NDCs?)

The JRC-GEM-E3 model is a recursive dynamic CGE model representing multiple regions, sectors and agents. The interactions between three types of agents are included: households, firms and governments. Household behaviour derives from the maximisation of a Stone-Geary (Linear Expenditure System) utility function. Unemployment is modelled via a wage curve mechanism. Firms maximise profits subject to sector-specific nested constant elasticity of substitution production technologies. The behaviour of governments is exogenous, and government budget balance relative to GDP is assumed to be at the level of the Reference in all scenarios.

Table 23. Regional aggregation in the JRC-GEM-E3 model

European Union	EU28
USA	USA
China	CHN
India	IND
Russia	RUS
Brazil	BRA
Canada	CAN
Japan	JPN
Australia	AUS
North Africa and Middle East	NAM
Ukraine, Belarus and Moldova	UBM
Rest of Europe (Switzerland, Norway, Albania, Iceland, Bosnia, Serbia, Turkey…)	RET
Rest of the world	ROW

Source: GEM-E3 model

Annex 3: Socioeconomic assumptions

The GDP projections follow EC (The Ageing Report, (European Commission, 2018)), IMF (World Economic Outlook, (IMF, 2018)) and the OECD CIRCLE project (OECD, 2014). The population assumptions follow the JRC report on Demographic and Human Capital Scenarios for the 21st Century (Joint Research Centre, 2018), except for the EU Member States (which are taken from The Ageing Report).

The central 2°C scenarios considered includes a set of socio-economic hypotheses concerning country-level population, GDP growth and economic activity at sectoral level represented by its value added.

Economic growth is sustained in all regions and the global average GDP per capita triples in the period 2010–2050. OECD, high-income economies are expected, however, to keep on growing at a much moderate pace that the non-OECD ones. The strong growth in countries with low-income levels in 2010 would enable them to join middle-income levels by 2050.

Population estimates used in this study are taken from (JRC, 2018) for all world countries and regions (CEPAM medium scenario – SSP2), except for the EU which are taken from the 2018 Ageing Report (European Commission, 2018).

The world will see important changes in population distribution in the forthcoming decades: while population growth in the OECD countries slows down (decreasing to 15% of world population by 2050), the population in Africa has the highest growth rate by far, with its population more than doubling in 40 years. The population of Asia is expected to stabilise by 2050 at around 4.5 billion inhabitants, with India becoming the single most populated country.

Non-OECD regions are expected to benefit from a higher economic growth rate than OECD regions over the forthcoming years up to 2050, in line with the 1990–2010 developments and a foreseeable further shift of their economy towards services. The yearly growth rate in the OECD remains 1 percentage point below the one of the world average throughout 2050.

The structure of the economy is expected to evolve slowly towards more services in all regions, with the share of services gaining 5 percentage points to reach around 70% by 2050 (+6% to 78% in the OECD, but +15% to 67% in non-OECD countries), at the expense of industry (from 31% to 25%), while the share of agriculture remains roughly stable in the OECD and decreasing in non-OECD countries to 7%.

The differences in growth rates across OECD and non-OECD regions comes short of bringing GDP per capita of non-OECD regions to OECD levels, even when expressed in ppp. In addition, by 2050 a clear distinction is projected in GDP per capita between the Least Developed Countries (LDCs ([76])) and other non-OECD countries.

The countries' level of income is differentiated as follows: ([77])

- High income: North America remains the wealthiest region, followed by other high-income regions (Pacific OECD and EU).
- Middle income: emerging economies which are already upper-middle income countries, like China (which reaches one of the highest non-OECD per capita level in 2050: 40 k$ ppp), Latin America (Brazil, Mexico) or Middle-East further increase their income levels.
- Low income: for countries with currently lower-middle income or low-income levels, in which half the world population is located, GDP per capita remains

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([76]) LDCs, as defined by the UN, gather countries mostly from Sub-Saharan Africa and South Asia.

([77]) GDP and GDP per capita levels in the entire report are expressed in real US dollars of 2005 in purchasing power parity (PPP) terms, unless indicated otherwise.

comparatively lower than in other regions: i.e. developing Asia (14 k$ ppp per capita) and Sub-Saharan Africa (7 k$ ppp).

Monetary figures in the remainder of the report are expressed in present-value dollars (2005), affected by ppp correction.

Table 24. 2018 Regional population, GDP and income per capita

	Population				**GDP**			**Income per capita**						
	M inhabitants				*CAGR*			k$/cap				*CAGR*		
	1990	2010	2030	2050	1990–2010	2010-30	2030-50	1990	2010	2030	2050	1990–2010	2010-30	2030-50
EU28	478	503	524	528	1.8	1.4	1.4	20	28	35	46	1.6%	1.2%	1.4%
Australia	17	22	28	33	3.2	2.8	2.5	24	35	47	67	1.9%	1.6%	1.7%
Canada	28	34	40	44	2.4	2.0	1.9	27	35	44	58	1.3%	1.2%	1.4%
Japan	125	129	121	107	0.9	0.9	1.1	26	31	39	55	0.8%	1.2%	1.7%
Korea (Rep.)	43	50	52	48	5.1	2.7	1.7	11	27	44	66	4.4%	2.5%	2.1%
Mexico	85	117	146	161	2.7	2.9	3.4	10	12	18	32	1.1%	1.8%	2.9%
USA	253	309	354	392	2.5	2.0	1.8	33	44	57	74	1.5%	1.3%	1.3%
Rest of OECD	82	107	129	139	3.2	3.6	2.4	12	17	29	43	1.8%	2.7%	2.0%
OECD	1066	1232	1360	1423	2.2	1.8	1.8	23	31	40	54	1.5%	1.3%	1.6%
Russia	148	143	141	136	0.4	1.7	1.1	13	14	20	26	0.5%	1.8%	1.2%
Rest of CIS	128	135	148	151	0.4	4.6	3.2	6	6	14	26	0.1%	4.2%	3.1%
China	1179	1367	1434	1316	10.1	6.0	2.8	1	7	21	40	9.2%	5.8%	3.2%
India	870	1231	1520	1681	6.6	7.2	4.7	1	3	10	22	4.7%	6.1%	4.1%
Indonesia	181	243	292	308	4.7	5.4	4.0	2	4	9	19	3.2%	4.4%	3.7%
Rest of Asia	574	814	1035	1177	5.1	4.8	4.2	2	3	7	14	3.3%	3.6%	3.6%
Argentina	33	41	49	55	4.2	2.4	2.4	7	13	18	26	3.0%	1.5%	1.8%
Brazil	149	197	227	236	3.1	1.7	2.4	7	10	12	19	1.7%	1.0%	2.2%

Rest of Latin America	164	224	273	300	3.6	4.0	3.7	5	7	13	24	2.0%	3.0%	3.2%
North Africa	121	170	226	262	3.9	4.8	4.1	4	6	11	21	2.1%	3.4%	3.4%
Sub-Saharan Africa (excl. South Africa)	475	827	1361	1921	4.5	6.2	6.2	1	1	3	7	1.6%	3.6%	4.4%
South Africa	38	52	64	71	2.7	2.3	3.0	7	9	12	19	1.1%	1.2%	2.5%
Iran	56	75	92	100	4.5	3.3	3.4	6	11	17	31	3.0%	2.2%	3.0%
Saudi Arabia	16	27	40	48	4.0	2.9	2.2	19	25	30	39	1.4%	1.0%	1.2%
Rest of Middle-East	62	116	175	229	6.5	4.0	2.7	5	10	15	19	3.2%	1.9%	1.4%
Non-OECD	4263	5722	7130	8038	5.0	5.1	3.6	3	5	11	20	3.4%	4.0%	3.0%
World	**5329**	**6954**	**8489**	**9461**	**3.2**	**3.5**	**2.9**	**7**	**10**	**16**	**25**	**1.9%**	**2.5%**	**2.4%**

Sources: various (OECD, UN, EC, World Bank).

Annex 4. Policies considered

The scenario presented in this report builds on past work (Kitous, et al., 2017). A full list of the policies considered in the GECO 2018 central scenario and their implementation are provided in this annex.

In general, projections of CO_2 and other GHG emissions and country contributions to the global mitigation effort are driven by income growth, energy prices and cost-based competition with expected technological development (see POLES model documentation). Country-specific patterns in technology choices are replicated at the beginning of the simulation with weighting factors that are relaxed over time.

Projections also include policies at different time horizons. They include adopted energy and climate policies in world countries for 2020 and following years; they achieve certain energy and climate objectives for 2020 announced in the years leading to the Paris Agreement (notably the Copenhagen Pledges); they include policies to achieve the energy and climate objectives of the NDCs supplied to UNFCCC during 2015 and the updated NDCs supplied since (up to February 2018).

The low-carbon scenarios presented here go into deeper emissions cuts compared to the mitigation achieved with these adopted or announced policies. In addition to the abovementioned, the scenarios implemented the following modelled policies in order to achieve the desired global warming target:

Policies:

- Copenhagen Pledges (2020) and several energy-related policies announced in the NDCs and NDCs (renewables deployment, energy efficiency) are reached or exceeded (2025–2035)
- Carbon prices are at least their level necessary to reach the NDC level of emissions (2025–2035)
- International maritime: the IMO objective for 2050 (-50% emissions vs 2008) is assumed to be reached
- HFCs: the objectives described in the Kigali amendment are reached

Carbon price:

- Energy fuels consumption is subject to a certain equivalent carbon price in all sectors of the economy
- The carbon price increases over time at a decreasing annual rate
- The carbon price by country is differentiated according to per capita income until 2050, same price afterwards
- For land sectors (agriculture and emissions related to land use, land use change and forestry): the carbon price is capped (where necessary) to the maximum carbon price point provided by the soft-linking with a specialised sectoral model (78)
- All other sectors of the economy are subject to the same carbon price
- Sectoral measures:
- Buildings:
    - increased rate of renewal of the stock and of renovation of existing surfaces
    - new and renovated surfaces move closer to best-available practices in terms of insulation (country-dependent on the basis of HDD, CDD and energy prices)
- Transport:
    - Scenarios assume gradual development of refuelling infrastructure and consumer acceptance over time for electric vehicles

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(78) The projections for agriculture and land use metrics in this report were made by soft-linking the specialised model GLOBIOM (IIASA, 2017) with the energy system model POLES-JRC.

  - Private cars: countries' new sales follow the gains of EU average new sales emissions as defined by EU policy 2007–2021 and 2021–2030 (10-year delay for non-OECD)
  - Freight: the gains in emissions across the car fleet in EU over 2007–2021 and 2021–2030 are used as a basis for the gains in emissions for freight, with a 10-year delay (20-year delay for non-OECD)
- Industry:
- Energy efficiency value (differentiated across countries on the same basis as carbon price differentiation, i.e. income per capita)

In order to reflect different financing capabilities as well as to represent an equitable mitigation effort across nations, the ambition level of these policies has been differentiated across countries according to their income level per capita. The corresponding carbon price followed the differentiation presented in Table 25, with 100% representing a "leading" carbon price that increases over time; other sectoral measures followed a similar regional distinction, where relevant.

Table 25. Carbon price differentiation in the GECO 2018 scenarios

Income in 2030 (USD (2005) per capita)	Countries	2020	2030	2050 and beyond
> 30,000	EU-28, Australia, Canada, Iceland, Japan, Korea (Republic), New Zealand, Norway, Switzerland, United States	100%	100%	100%
20,000-30,000	Chile, China, Malaysia, Russian Federation, Saudi Arabia, Turkey	60%	100%	100%
10,000-20,000	Algeria and Libya, Argentina, Brazil, Iran, Mediterranean Middle-East, Mexico, Rest of Balkans, Rest of CIS, Rest of Persian Gulf, Rest of South America, South Africa, Thailand, Tunisia, Morocco and Western Sahara, Ukraine	40%	100%	100%
<10,000	Egypt, India, Indonesia, Rest of Central America and Caribbean, Rest of Pacific, Rest of South Asia, Rest of South-East Asia, Rest of Sub-Saharan Africa, Vietnam	20%	67%	100%

Source: POLES-JRC 2018.

Annex 5. Air pollutant control policies

Table 26 shows the contribution of fires and fossil fuels; their contribution can be significant depending on the pollutant.

Table 26. Global pollutants emissions in 2010 and contributions from fires and fossil fuels

Mt	Total	of which fires	*%fires*	Total excl. fires	of which fossil fuels	*%fossil fuels*
SO_2	94	3	3%	91	73	80%
NO_x	132	16	12%	116	102	88%
$PM_{2.5}$	98	57	58%	41	20	50%
CO	939	453	48%	487	194	40%
VOC	138	28	20%	111	40	36%
NH_3	61	7	11%	54	1	2%

Note: non-fire natural sources (dust, sea salt, volcanoes) are not included.

Source: POLES-JRC 2018.

Over time, an increasing number of countries around the world are expected to adopt more stringent air quality standards; for example, the EURO transport emission standards ([79]) will soon be enforced by China ([80]). Thus, emissions of pollutants are expected to grow less than their underlying fuel use or economic activity levels, and might even decrease. Pollutant emissions are also affected by adopted or planned climate policies that target GHG emissions and type of fossil fuel use.

The air quality policies and pollution control cases are characterised in the GECO 2018 scenarios by the evolution pathways of the emission intensity factors (the ratio between the emission levels and the emission driver). They describe a progressive "middle-of-the-road" trajectory of emission intensity factors by country group, between a no-improvement case and the maximum technically feasible reductions. This is described in Table 27 In particular, certain specific policies for the medium term were included: the China objectives for 2020 ([81]) and the EU objectives for 2030 ([82]).

([79]) As of May 2017 Euro 6 for light vehicles and Euro VI for heavy vehicles, see: http://ec.europa.eu/environment/air/transport/road.htm

([80]) China started to introduce the China 6/VI standards in 2017 and with full implementation on new cars in 2020.

([81]) China 13th Five-Year Plan.

([82]) EU Clean Air Package (Directive 2016/2284/EU), see: http://ec.europa.eu/environment/air/pollutants/ceilings.htm

Table 27. Evolution of pollutant emission intensity factors

Region income group	2030	2050
High	Current legislation	75% of 2030 best feasible emission factor
Medium +	Current legislation	75% of 2030 best feasible emission factor
Medium -	Current legislation	Convergence to group's best emission factor
Low	Current legislation	Convergence to group's best emission factor

Note: Current legislation refers to policies adopted by 2015 (EU: Directive 2016/2284/EU, China: China 13th Five-Year Plan; Rest of world: see IIASA (2017). Income groups defined following World Bank methodology for 2015 per capita income ([83]): low (<1 k$/cap); medium- (14 k$/cap); medium+ (4-12 k$/cap); high (>12 k$/cap).

Source: POLES-JRC 2018.

Pollutant emissions are commonly mitigated by targeted air quality control policies (so-called end-of-pipe or technical measures) but they are also a result of changes in the energy system.

The ancillary benefit of climate policies depends on the levels of air pollution or the stringency of controls already in place. They can be significant and can bring about pollutant emissions reductions that would be comparable to end-of-pipe measures in the absence of climate policies. Importantly, air quality benefits follow instantaneously upon mitigation and are mostly felt in the regions close to where the measures are being implemented.

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[83] https://datahelpdesk.worldbank.org/knowledgebase/articles/906519

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