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Global Energy and Climate Outlook 2019: Electrification for the low-carbon transition

The role of electrification in low-carbon pathways, with a global and regional focus on EU and China

Keramidas, K., Diaz Vazquez, A., Weitzel, M., Vandyck, T., Tamba, M., Tchung-Ming, S., Soria-Ramirez, A., Krause, J., Van Dingenen, R., Chai, Q., Fu, S. and Wen, X.

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Contact information
Address: European Commission, Joint Research Centre, Edificio Expo; C/ Inca Garcilaso, 3, E-41092 Sevilla, Spain
Email: JRC-GECOutlook@ec.europa.eu

EU Science Hub
https://ec.europa.eu/jrc

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Contents

Abstract

This edition of the Global Energy and Climate Outlook (GECO) analyses the role of electrification in global transition pathways to a low Greenhouse Gas (GHG) emissions economy. Electricity is found to be an increasingly important energy carrier in final energy consumption already in the absence of stronger climate policies than those currently in place (Reference scenario), while enhanced electrification of final energy demand is a crucial element of the 2°C temperature change scenario, paving the way to climate neutrality. The 2°C target could be achieved by simultaneously transforming various elements of the energy system: shifting final energy demand from mainly fossil fuels towards electricity and low-carbon synthetic fuels mainly derived from electricity; decarbonising power generation; increasing energy efficiency in end-uses, which is favoured by further electrification; and mobilising novel options to better accommodate high shares of intermittent renewable electricity sources, such as demand-side load management and power storage. This report further shows that the 2°C target is technically possible at relatively low cost for the overall economy (global GDP reduction below 1% across all sensitivities compared to Reference in 2050). This would also bring along co-benefits for air quality. In order to explore the role that electrification can play as an emissions mitigation option, a number of sensitivity variants on key parameters impacting the energy system – energy prices, cost of technologies, non-economic drivers related to behaviour and policy – are conducted. The role of electricity is examined by large sector (industry, transport, buildings, power generation), with a particular regional focus on the EU and China and a sectoral focus on road transport electrification.

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This report was mainly written by: Kimon Keramidas, Ana Diaz Vazquez, Matthias Weitzel, Toon Vandyck, Marie Tamba, Stéphane Tchung-Ming, Antonio Soria-Ramirez (Joint Research Centre, C6).

Chai Qimin and Wen Xinyuan (NCSC) and Fu Sha (EFC) authored section 7.

Jette Krause, Monica Grosso, Biagio Ciuffo and Amandine Duboz (Joint Research Centre, C4) contributed in section 4.2 in the context of the “Societal impacts of disruptive mobility scenarios” (SIMOD) project.

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- Joint Research Centre: Kimon Keramidas, Jacques Després, Andreas Schmitz, Stéphane Tchung-Ming (C6), Rita van Dingenen (C5)

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Executive summary

The present release of the Global Energy and Climate Outlook (GECO) focuses on the shift towards clean electricity to limit global warming to below 2°C by the end of the century as put forward in the UNFCCC Paris Agreement. The report is a collaborative effort between the European Commission's Joint Research Centre (JRC), the Chinese National Centre for Climate Change Strategy and International Cooperation (NCSC), and the Energy Foundation China (EFC).

This edition analyses global and sectoral pathways towards a deep decarbonisation of the energy system, highlighting the role of electrification as a key option in the transition to a low-greenhouse gas (GHG) economy. The quantitative analysis combines global energy/GHG system modelling and macroeconomic modelling, and explores different assumptions on a number of underlying drivers for electrification across all sectors of the economy: transport, buildings and industry.

Furthermore, this report presents a special insight into the role of electricity in regional GHG emission reduction pathways for the European Union and China. Dedicated sections for these two regions present overviews of their respective policy frameworks, and build on region-specific modelling results. EU[1] figures are illustrated with model results from POLES-JRC and from the EU's proposed long-term strategy "A Clean Planet for all" (European Commission, 2018); Chinese figures are illustrated with model results from POLES-JRC and NCSC's model PECE.

Key conclusions

Current global average temperature is already 1°C above pre-industrial levels (WMO, 2019); and today's emissions and energy consumption trends are not on track to meet the 2°C target.

The scenarios presented in this study show possible pathways to contain global warming to 2°C by the end of this century with different roles for electricity as a crucial energy carrier. The assessment of the global energy system transition towards low carbon scenarios shows an increase of electrification rates for all energy-consuming sectors: industry, buildings and transport. Technologies such as heat pumps in heating and cooling applications as well as batteries in road transport are extensively mobilized, along with energy-efficient design in buildings and vehicles.

This evolution is accompanied by GHG emissions reductions in the power sector. The full decarbonisation of this sector is indeed considered not only technically feasible but also economically cost-attractive as a key element for the transition towards a clean energy system. Key low-carbon power generation technologies are already fully marketable and highly competitive in many regions, with lower generation cost than the fossil fuel-based technologies. The use of electricity in demand sectors offers efficiency gains; this together with increasing renewable technologies in power generation present benefits in reducing air pollution.

This study shows that the 2°C target is technically possible at relatively low cost for the overall economy: globally aggregated GDP reduction ranges between 0.2% and 1.0% across electrification scenarios in 2050, relative to a current policy reference. The range highlights that strong enabling conditions for electrification can play a significant role in lowering the macroeconomic costs of action. Importantly, these numbers do not take into account the costs of inaction. Putting these cost estimates in the context of expected economic growth over the coming decades helps to get some perspective on their magnitude: the high end of the cost range (1% in 2050) represents a reduction in annual growth rate over the period 2020-2050 of only 0.03 percentage points. In other words, the economy would grow at 2.57% per year instead of at 2.60% per year.

Main findings

Global emissions trends

In order to materialize the transition to a low carbon economy meeting the 2°C target, global greenhouse gas emissions need to drop to net zero in the second half of the century. GECO 2019 analyses different pathways towards this temperature target that vary in the level of end-use electrification.

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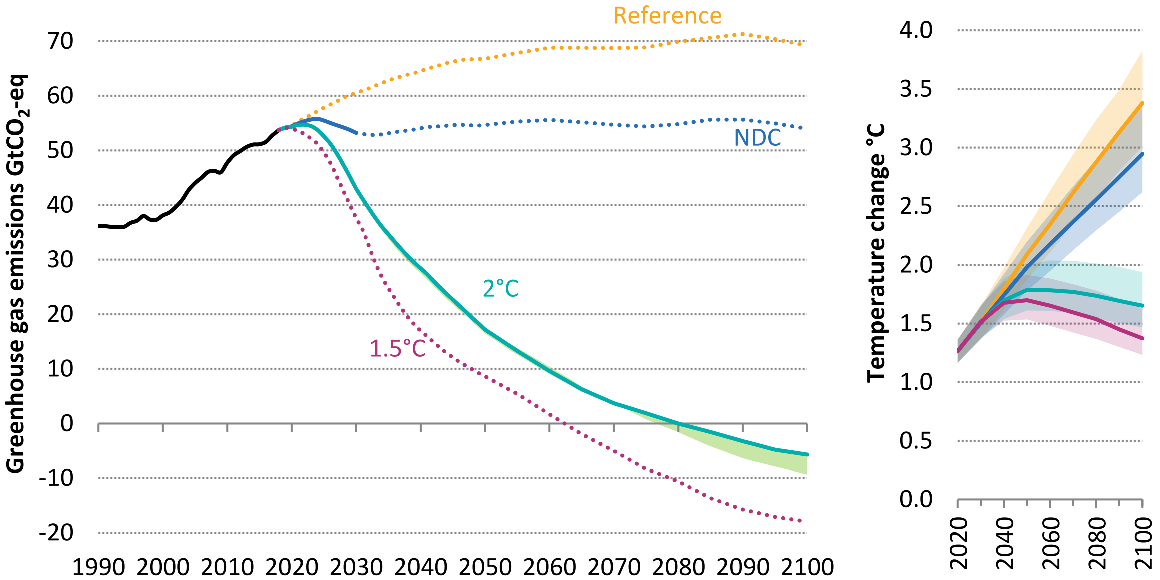
(1) European Union results are presented with the EU as of December 2019 (28 Member States including the United Kingdom).

Figure 1. Global GHG emissions and global mean temperature change in the GECO2019 scenarios



Note: Shaded area for the 2°C scenario emissions represents the range of the 2°C sensitivities (2°C – Low Electrification and 2°C – High Electrification). Plain lines note medians. Shaded areas for temperatures represent 25%–75% probability. The 2°C and 1.5°C scenarios were designed with a probability not to exceed their temperature change at the end of the century of 75% and 66%, respectively.

A robust transition towards a low-carbon economy would rely on four main technological dynamics that have to unfold at the same pace:

- The decarbonisation of power generation, lowering the carbon intensity of electricity.
- The shifting of energy carriers in thermal and mobility end-uses from mainly fossil fuels towards electricity and synthetic fuels mainly derived from electricity (hydrogen; e-fuels).
- The increase of energy efficiency in end-uses, which is favoured by further electrification: electric technologies such as heat pumps in buildings and electric vehicles improve the energy efficiency of the system.
- The mobilization of novel options to better accommodate high shares of intermittent renewable electricity sources, such as demand-side load management and power storage.

In terms of overall contribution, the three largest mitigation options would be the expansion of renewable energy sources; an increasing role of electricity in the energy we consume; and improvements in energy efficiency.

Electrification

Even without the policy push towards 2°C-compatible GHG mitigation, as shown at the Reference scenario, both the electricity demand and the share of electricity in final energy demand would globally accelerate over time, the latter expanding from 22.4% in 2017 to 36.5% in 2050. Climate policies striving for 2°C would push the electrification rate further in all regions, reaching 45% globally in 2050.

This report identifies key factors that enable electrification and reveals how their evolution over the next decades will impact the role of electricity in climate change mitigation. The sensitivities on energy prices, technology costs, and policy/adoption assumptions conducted on the 2°C scenario all show an increase of the electrification rate over time, ranging from 39% to 51% in 2050.

Electrification of final energy demand coupled with the decarbonisation of the production of energy carriers (electricity, hydrogen, synthetic fuels) is essential in the transformation ahead.

Air pollution

Electrification, when combined with a transition towards renewable electricity, can have positive effects for air quality and human health. As emissions from transport and buildings tend to correlate closely with population density, further electrification of these sectors has the potential to reduce exposure to harmful levels of air pollution in cities and regions across the globe. The scenarios presented here illustrate that the best air quality is obtained in a future with ambitious climate policy, stringent air pollution control, and favourable conditions for the penetration of electricity in energy use. These results highlight the co-benefits between air and climate policies, and point towards clean electrification as a potential strategy that builds on these synergies.

Economic implications

The report also looks into the macro-economic implications of climate change mitigation, showing that the 2°C target is technically possible at relatively low cost for the overall economy (global GDP reduction below 1% across all sensitivities compared to Reference in 2050). In addition, the report pays particular attention to the effects of road transport decarbonisation. Findings clearly show that road transport electrification is a valuable option in a 2°C world, as globally aggregated GDP would be 1-3% lower in 2050 if the 2°C target would need to be met without road transport decarbonisation. The transition from conventional vehicles to electric vehicles drives changes in production structure and maintenance requirements. How these changes impact sectoral employment patterns is also quantified in the report. In 2050, over 4 million workers that would have been active in the manufacturing of conventional vehicles globally are projected to be employed in other sectors of the economy, such as electric vehicles (EV) manufacturing and the sectors related to the bio-economy.

Policy context

The 2015 UNFCCC Paris Agreement has set the goal to limit global warming to well below 2°C or 1.5°C above pre-industrial levels. Parties are invited to submit long-term low greenhouse gas emissions development strategies. The European Commission (EC) has made a proposal for a Long-Term Strategy (LTS) for decarbonisation of the EU economy (European Commission, 2018); the objective of climate neutrality by 2050 was endorsed by the European Parliament and the European Council; a submission to UNFCCC is expected during 2020. China is expected to submit an LTS to the UNFCCC during 2020.

Related and future JRC work

This report is the fifth 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 release offers a global view of decarbonisation scenarios, as well as regional views for EU and China, in the context of collaborative research between JRC and NCSC.

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, with a particular focus on electrification in these pathways. In addition, variant 2°C scenarios were produced by changing a number of parameters in order to explore low and high electrification pathways. **Section 2** presents these scenarios. **Section 3** provides an in-depth analysis of energy and GHG projections by sector of activity – industry, buildings, transport, power generation – and the role of electricity therein. **Section 4** provides details on the macroeconomic impact of these climate policies and focuses on the macroeconomic effects of road transport electrification in particular. **Section 5** shows the overall impacts of climate policies on air pollutants emissions. Finally, **sections 6 and 7** provide current policy background and 2°C-compatible projections for EU and China, respectively, with a particular focus on the role of electricity in these projections.

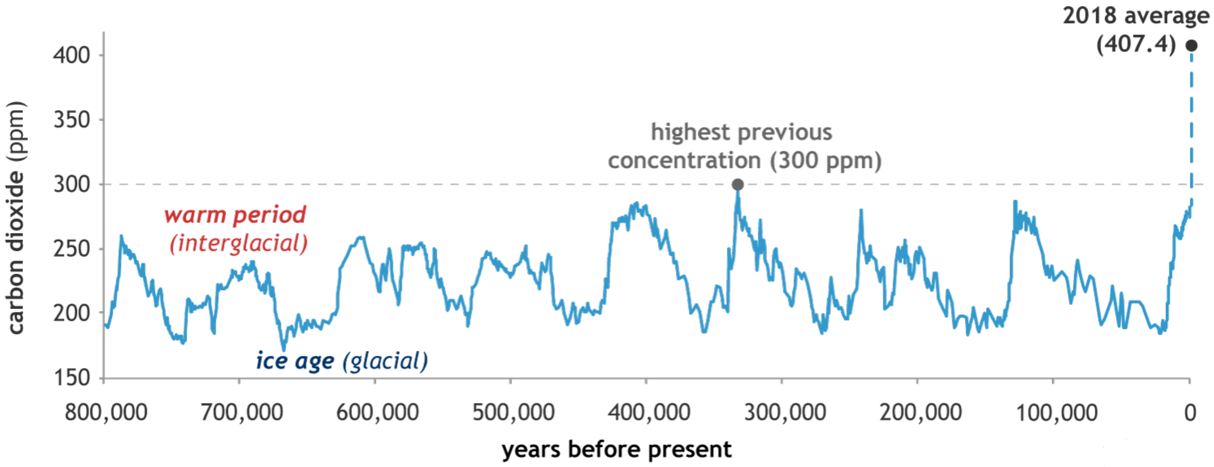
1 Introduction

1.1 Global emissions and climate context

According to the UN's World Meteorological Organization (WMO) the global average atmospheric concentration of carbon dioxide (CO_2) hit a record high in 2018 reaching 407.8 parts per million (ppm)[2], up from 405.5 ppm in 2017. Over the summer of 2019 carbon dioxide atmospheric concentration has reached an eloquent maximum historical value of 415 ppm. In June 4th, 2019 the NOAA's Mauna Loa Atmospheric Baseline observatory has announced the highest monthly average peak recorded in 61 years of observation, 414.7 ppm. The 2019 peak value was 3.5 ppm higher than the 411.2 ppm reached in May 2018. During May 2019, Mauna Loa has recorded a few daily readings above 415 ppm. This was the highest monthly average ever registered, and according to the ice core records, it is the highest value in at least the last 400,000 years. Carbon dioxide levels today are 50% higher than in 1750, the start point of the industrial revolution, and higher than at any point in at least the past 800,000 years, see **Figure 2**, according to the National Oceanic and Atmospheric Administration (NOAA)[3].

Global fossil CO_2 emission have grown consecutively for the last two years 1.5% in 2017 and 2.1% in 2018 to 36.6GtCO_2/year (Friedlingstein, et al., 2019). Recent studies on historical CO_2 emissions (Le Quéré, et al., 2018) found the major drivers of the 2018 increase were: more coal burning in China and India as their economies grew; more oil used in transport; more gas use in industry; renewable energy grew rapidly, but not enough to offset the increased use of fossil fuels. According to the Global Carbon Budget global CO_2 emissions are deaccelerating during 2019, with a growth by only 0.6% from 2018 levels. Emission would decline in the United States and the EU, but projected to increase in China, India and the rest of the world. (Jackson, et al., 2019).

Figure 2: Atmospheric carbon dioxide concentrations in ppm for the past 800,000 years, based on EPICA (ice core)[4] data.



Source: National Oceanic and Atmospheric Administration (U.S. Department of Commerce)

Considering the dominant greenhouse gases (GHGs) present in the Earth's atmosphere as a whole (CO_2, CH_4 and N_2O), their concentrations also reached new record highs, caused by human activities such as fossil fuels combustion, industrial processes, agriculture and land use. The WMO report on the Global Climate in 2015-2019, released to inform the United Nations Secretary-General's Climate Action Summit, says that the global average temperature has increased by 1.1°C since the pre-industrial period i.e. since 1750, and by 0.2°C compared to 2011-2015, (WMO, 2019) (Poushter, 2018). 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

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(2) with a range of uncertainty of plus or minus 0.1 ppm

(3) with a range of uncertainty of plus or minus 0.1 ppm

(3) https://www.noaa.gov/

(4) EPICA European Project for Ice Coring in Antarctica http://archives.esf.org/coordinating-research/research-networking-programmes/life-earth-and-environmental-sciences-lee/completedesf-research-networking-programmes-in-life-earth-and-environmental-sciences/european-project-for-ice-coring-in-antarctica-epica-page-1.html

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.

1.2 The need for a collective and concerted action

The scientific community presently agrees that human activities have already caused approximately an increase of 1.0°C global warming above pre-industrial times, with a confidence 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 is expected to cause serious disruptions to ecosystems, important impacts to advanced and developing economies, and generalised societal shocks, with different timescales and levels of damage. The severity of the global climate change threat is widely acknowledged by scientists, corporations, and all kinds of social 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[5].

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 latest JRC PESETA III project (Szewczyk, Ciscar Martinez, Mongelli, & Soria Ramirez, 2018), with a focus on Europe, established that rising temperatures will result in reductions in labour productivity; shifts in flower/plant blooming season and changes in soil water content will affect agriculture productivity and habitat suitability.

Climate adaptation can reduce the adverse consequences of unmitigated climate change, as well as harness 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 severe damages to nature and socio-economic systems, that are, above all else, unpredictable and irreversible.

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. The evidence gathered in the Stern Review (Stern, 2007) concluded that “ignoring climate change will eventually damage economic growth”; the Review also pointed out that “the benefits of strong and early action far outweigh the economic costs of not acting”.

Climate change is, undoubtedly, the more important global environmental problem ever faced by mankind. As a genuinely global issue, it has to be tackled at global scale: mitigation actions have to be conducted by all countries and sectors, keeping an appropriate balance between the efficiency of the efforts and the equity of the financial burden supporting them.

The international institutional setup to cope with the problem is therefore crucial. Deepening international cooperation in terms of information exchange, capacity building, identification of cost-effective mitigation niches, technological deployment and financial architecture is needed to foster quick, effective action and avoid to get locked into suboptimal GHG mitigation paths. The global energy transition needed has, on the other hand, many additional benefits (energy independence, air quality improved, higher production mix efficiency, etc.) that need to be valued and factored-in to enhance its quick implementation.

Since the industrial revolution, a peak in CO_2 emissions is not in sight. Despite the Kyoto protocol, -the major attempt of an international agreement binding parties to reduce GHGs emissions in 2005 - global energy-related CO_2 emissions have increased steadily. In 2018 driven by the high energy demand, global energy related CO_2 emissions reached a historical high of 33.1GtCO_2, (International Energy Agency, 2019) around 23% higher than 2005, representing an annual growth of 2%.

Changes observed 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 (IPCC, 2014).

An additional effort has to be made, therefore, to enhance the concerted strive to get a GHG-neutral society. This calls for identifying cost-effective technological transition patterns, incorporating lifestyle changes and implementing those win-win shifts balancing the interests and needs of all social groups.

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(5) 93% of EU citizens see climate change as a serious problem and 79% see it as a ‘very serious’ problem” (European Commission, 2019). By contrast, results of a similar US survey shows only 56% of Americans see climate change as a threat (Poushter, 2018).

1.3 The role of electricity in transition pathways

About 80% of CO_2 emissions globally originate from the energy sector. Back to the industrial revolution in the 19th century, energy production based on fossil fuel combustion has been crucially responsible of the ongoing climatic change. Leaving apart the large hydropower projects implemented in the medium years of the century all around the globe, the massive global electrification of the world during the 20th century was indeed based on low efficient thermally generated electricity. Coal burning still represents today a substantial share of the global electricity production, and is a key GHG-emitting activity at world level.

Electrification of final demand sector is a long term trend that has been primarily motivated by the advantages of electricity as a final energy carrier in residential and services sectors, as well as in many industrial applications. This demand-driven trend is expected to continue according to all energy scenarios analysed in any sector and country. A crucial factor, however, that is likely to further accelerate this electrification trend is a supply-driven radical change triggered and consolidated in the last two decades.

Prompted by environmental concerns, a technological transition appeared from 1990 onwards, namely the emergence of progressively commercialized wind power and solar power technologies. They share with hydropower the characteristic of being highly efficient primary-to-power conversion technologies, but – contrary to hydropower – possess a huge potential niche, far from being saturated even in the highest technology penetration scenarios.

The availability of a large generation capacity of primary, carbon free power from these sources provide the economic rationale to incorporate larger shares of clean and efficient electricity in the final energy mix. Electrification would therefore become a crucial vehicle to substantially decarbonise the overall energy system. In addition, a crucial demand sector (transport) that has shown a very low degree of electrification is likely to revert this situation thanks to the quick development of electric vehicles or the uptake of electricity-derived synthetic fuels, establishing the basis to a substantially more electrified, less carbon intensive energy sectors.

Based on the existing literature on long-term energy scenarios[6] (Huppmann, et al., 2019), there seems to be a global consensus on the following points. First, it is likely that reaching ambitious long-term stabilization targets (2°C and below) will require, on average, an accelerated penetration of electricity uses in the economy (**Figure 3**) in the next three decades. This would contribute to decarbonizing end-uses; the trend may be more pronounced for more stringent (1.5°C) climate targets. However, this strategy would be sustainable only provided that power generation itself would be decarbonized. The same dataset reveals that indeed, climate change mitigation is likely to drive a strong push of renewable sources in the world generation mix (**Figure 4**), especially over the next 20 years.

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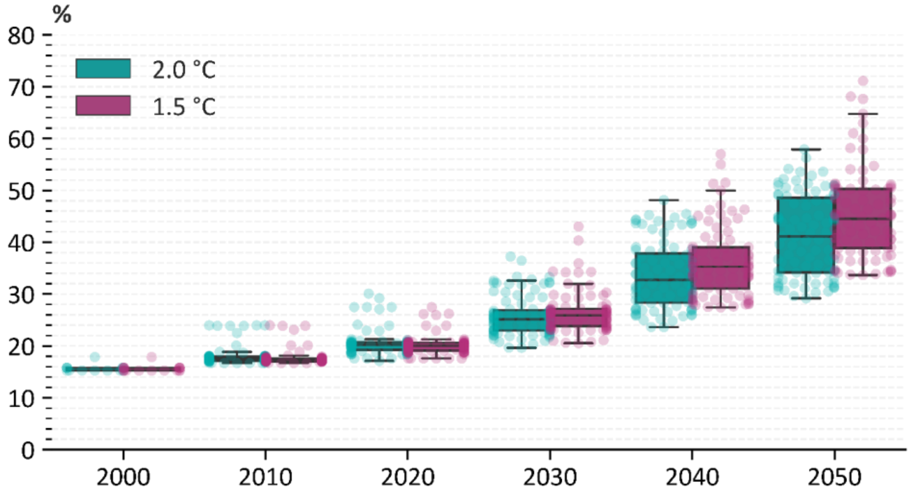
(6) The IAMC 1.5°C Scenario Explorer and Data hosted by IIASA (Huppmann, et al., 2019) is a multi-model long-term energy scenarios dataset, gathered from multiple collaborative projects. From this dataset, the "2.0°C" and "1.5°C" scenarios categories were identified as follows:

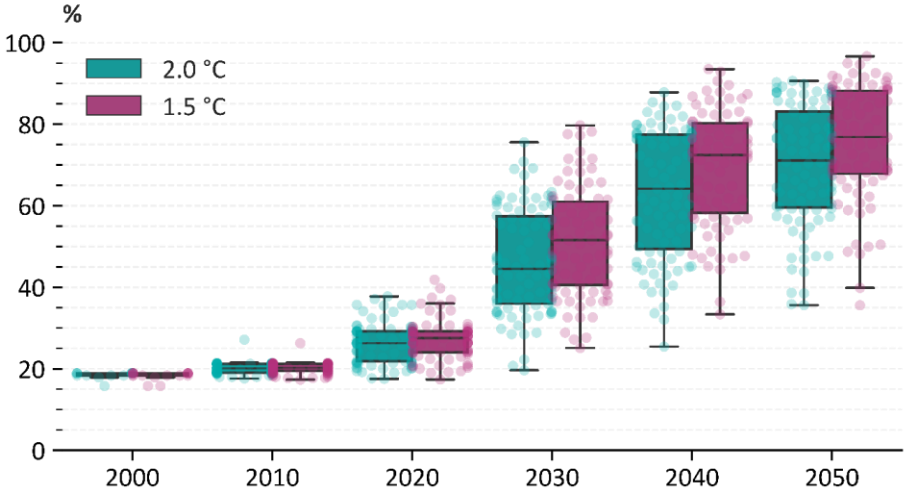
- 2°C scenarios have a higher than 66% chance of stabilizing global mean temperature increase below 2°C, based on MAGICC6 diagnosis;
- 1.5°C scenarios have a higher than 50% chance of stabilizing global mean temperature increase below 1.5°C, based on MAGICC6 diagnosis.

Figure 3. Share of electricity in total final energy demand, World, multi-model comparisons



Note: IAMC 1.5°C Scenario Explorer and Data hosted by IIASA, version 2.0 (Huppmann, et al., 2019).

Figure 4: Share of renewable in power generation, World, multi-model comparisons



Note: IAMC 1.5°C Scenario Explorer and Data hosted by IIASA, version 2.0 (Huppmann, et al., 2019).

If one relies on global average trends, one can reasonably assume that these end-uses electrification and power decarbonisation trends will (i) continue (possibly at an accelerated pace) and (ii) are necessary tools of climate mitigation packages. However, multi-models scenarios analysis also shows a very wide spread of results across models and scenarios. In the set of 2°C scenarios, the share of electricity in final electricity consumption in 2050 ranges from 30 to more than 55%, while the share on renewables in power generation varies between 35% and 90%. Therefore, if the evolution of the energy system towards an electric-intensive, low-carbon generation system, is compatible with stringent climate mitigation, the magnitude and consequences of the phenomenon are still to be debated.

The perspective adopted in this report embraces the evidence of past trends – indicating that electricity use has been continuously increasing over the last decades – and the inevitable, pervasive uncertainty embedded in any projection.

1.4 Contribution of the report

This report examines:

- Global decarbonisation scenarios testing the effect of a variety of parameters on electrification rates; these scenarios are explained in **section 2**.
- How the adoption of electric technologies for energy end-uses in the main economic sectors can contribute to decreasing GHG emissions, accompanied by the decarbonisation of energy vectors production (electricity, hydrogen); global sector-level effects are presented in **section 3.**
- What are the macroeconomic impacts of GHG emissions mitigations in general and of electrification of transport more particularly in **section 4.**
- What are the environmental implications of electrification in terms of air quality and health **section 5**.

Box 1: Differences with GECO 2018

This report mainly presents scenarios with high mitigation (2°C, 1.5°C warming) rather than focussing on no additional policies or announced objectives (Kitous, et al., 2017) 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 below 2°C by 2100 with a 67% probability, based on the online MAGICC 6 model (Meinshausen, Raper, & Wigley, 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 NDC scenario does not assume that additional mitigation policy effort is undertaken beyond 2030.

The energy and emissions modelling was done using the POLES-JRC model (Després, Keramidas, Schmitz, Kitous, & Schade, 2018), (**Annex 2**). The model was further updated, notably in: increased technologies representation (carbon capture and sequestration (CCS) power plant retrofit, Power-to-Gas and Power-to-Liquids production, efficiency in buildings energy consumption), updated energy and technology costs (oil and gas supply, direct air capture of CO_2 (DACCS), liquid biofuels, light and heavy vehicles efficiency); updated mitigation data in agriculture and land use. Socio-economic assumptions were also updated.

The modelling of the JRC-GEM-E3 model (**Annex 3**) was updated to represent electric vehicle production to capture electrification in the transport sector.

As with GECO 2018, global warming potential figures presented use the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) 100-year values.

Electricity generated from nuclear energy is directly considered as primary energy in primary energy accounts (no conversion was applied to consider waste heat).

European Union results are presented with the EU as of December 2019 (28 Member States including the United Kingdom).

The scenarios in this report were finalised in December 2019.

2 Global scenarios definitions

The 2019 edition is focused on plausible electrification scenarios including not only supply-side analyses depicting a deeper role of electricity within the final energy demand mix, but also the end use technology adoption patterns across all sectors through 2050 that may trigger and further facilitate the electrification trend.

The report dedicates a special focus on electrification as a key climate change mitigation option. Historical time series referred to final energy mix show a consistent trend across countries, with a somehow differentiated behaviour across sectors. There is abroad consensus amongst scientists on the crucial role that an accelerated electrification of final energy demand could play in the decarbonisation process. On the one hand, an increasingly larger share of carbon-free primary electricity generation thanks to cheaper, quickly deployed renewable technologies will offer new substitutes to combustion-based final energy options. On the other hand, there is a growing emergence of many new competitive electric technologies in sectors traditionally anchored to combustion processes (transport, industry). The appraisal exercise presented here is designed to examine in detail how electric technology developments, and their adoption for end uses in all major sectors would contribute to the required economy decarbonisation process, as well as to shed evidence on the impact of these changes in electricity demand, power load profiles, future power system operation: in a word, to assess the economic and environmental implications of a widespread electrification of energy demand.

2.1 The reference and 2°C-Medium scenarios

One global mitigation 2°C scenario and two sensitivities are mainly examined in this report, consistent with a likely chance of meeting the long-term goal of a temperature increase over pre-industrial times below 2°C. An appropriate climate simulation tool is being used in order to evaluate the impact of radiative forcing changes (MAGICC 6.0, (Meinshausen, Raper, & Wigley, 2011)).

Where necessary, projections from a Reference and a NDC scenario are presented as a counterfactual case to the 2°C-Medium scenario.

Box 2: Scenarios description

The **Reference** scenario corresponds to a world where currently existing policies for GHG emissions, renewables deployment and energy efficiency are carried out and where no additional policies are implemented compared to what had been legislated as of June 2019. Specific sectoral policies are considered for Europe as well as other regions (see **Annex 1** for list of policies considered). Thereafter, CO_2 and other GHG emissions are driven by income growth, endogenously calculated energy prices and technological development. Nevertheless, market forces will favour greater efficiencies and greater learning for low-carbon technologies. This scenario, in particular, does not consider stated policies that have not been translated into law and accompanied by concrete action plans, nor does it consider the objectives put forward in countries' NDCs; it does not attempt the deep structural decarbonisation process needed for a 2°C emissions trajectory.

The **NDC scenario** is a stated policies scenario which takes the assumption that the objectives in the NDCs (including conditional objectives) are reached in 2025-2030. To this end, carbon values and other regulatory instruments are put in place on top of existing, legislated measures. Beyond 2030, it is assumed that no additional effort is made (carbon values are frozen), leading to a stabilization of global emissions.

The **2°C/1.5°C scenarios** assume a global GHG trajectory consistent with a likely chance of meeting the long-term goal of a temperature rise over pre-industrial times below 2°C (resp. 1.5°C) for 2100. The 2°C and 1.5°C scenarios were designed with a probability not to exceed their temperature change at the end of the century of 75% and 66%, respectively (see **Figure 5**).

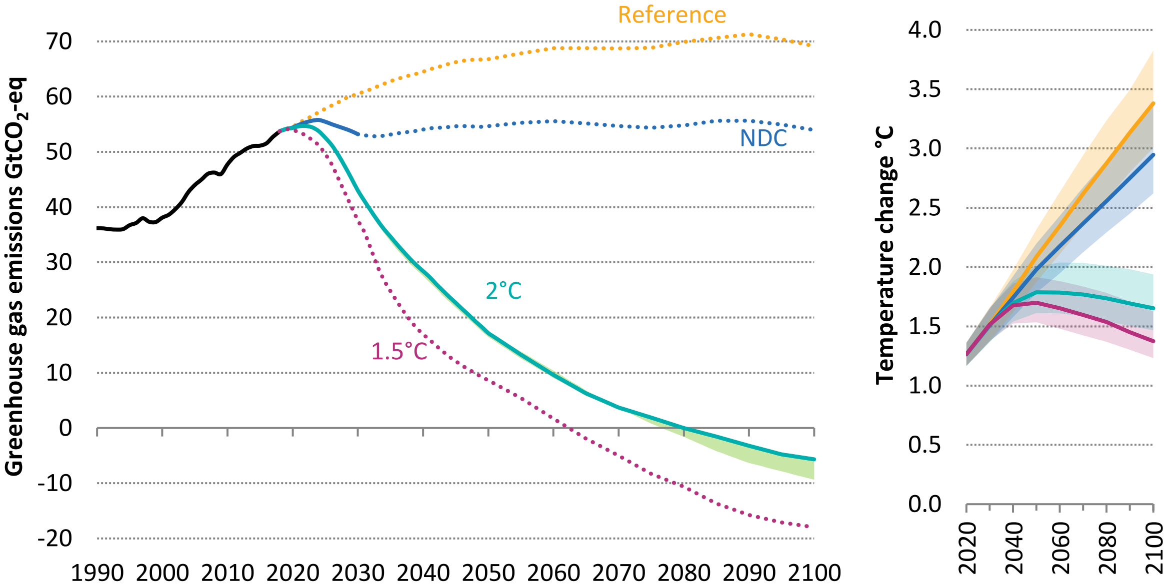
To achieve this, mitigation strategies should be massively and quickly adopted, leading to a drastic reduction of global GHG emissions. For each country and economic sector considered, the emissions reduction is reached through a progressively increasing carbon value starting from 2019, considering a carbon price differentiation between regions to account for each country's financial capacity and response flexibility; countries' carbon values progressively converge after 2030 depending on their per capita income. In addition, market acceptability factors for electric vehicles in road transport are increased, reflecting a faster and wider availability of recharching infrastructure. Only carbon prices were used as the main modelling tool; modelling parameters to reflect sector-specific policies in the Reference and NDC scenarios were not included, for EU as well as for other regions (see **Annex 1**).

The scenarios are produced with the same socio-economic assumptions and energy resources availability. Energy prices are the result of the interplay of energy supply and demand, and are thus scenario-dependent. Country- or region-level energy supply, trade, transformation and demand, as well as GHG emissions, are driven by income growth, energy prices and expected technological evolution, within the constraints defined by energy and climate policies. In sum, scenarios differ on the climate and energy policies that are included, with repercussions on the projections of the energy supply and demand system and GHG emissions.

Figure 5 shows the GHG emissions reduction needed to reach the 2°C target, along with reference, NDC and 1.5°C trajectories, with cumulated CO_2 emissions for the 2°C scenarios over 2011-2100 ranging from 1080 to 1110 $GtCO_2$ (1110 $GtCO_2$ for the 2°C-Medium scenario) and a probability of not exceeding 2°C at the end of the century of 75% for all three scenarios.

- Current policies (Reference scenario) lead to temperature increases ranging between 2.9-3.8°C at the end of the century.
- Implementation of the current NDCs lead to a 2.7°C median; additional policies are needed to increase decarbonisation.
- For the 2°C-Medium scenario, total GHG emissions in 2050 are reduced by 68% compared to their 2018 levels (cut by half compared to their 1990 levels), reaching net-zero emissions around 2080. The 2°C objectives would trigger in-depth changes to the energy system. The sensitivities applied on the 2°C-Medium scenario impact the energy system in different ways; but the resulting global emissions are relatively little affected (shaded green zone).
- For a global mean temperature increase of 1.5°C, global GHG emissions in 2050 are reduced by 84% from the 2018 levels reaching net-zero around 2060.

Figure 5. Global GHG emissions and global mean temperature change in the GECO2019 scenarios



Note: Shaded area for the 2°C scenario emissions represents the range of the 2°C sensitivities (2°C – Low Electrification and 2°C – High Electrification). Plain lines note medians. Shaded areas for temperatures represent 25%–75% probability. The 2°C and 1.5°C scenarios were designed with a probability not to exceed their temperature change at the end of the century of 75% and 66%, respectively.

An overview of the mitigation options adopted by the 2°C-Medium scenario is presented in **section 3.1** where the top four mitigation drivers are: increasing the use of renewable sources, energy efficiency, reduction of non-CO_2 emissions and electrification.

2.2 Influence of various factors on electrification in a 2°C world

The key scenario presented in this study consists of a medium, 2°C-compatible scenario, from which an upper (*high electrification* 2°C scenario) and a lower (*low electrification* 2°C scenario) variants are derived. The purpose of these variants is to study the impact of different paces of electrification into the key variables of interest, remaining coherently framed within a 2°C-compliant energy system by 2050.

Electrification is defined here as the share of electricity over total final energy consumption. Electricity used in the transformation of fuels is not part of that definition, thus electricity-derived fuels such as hydrogen with electrolysis and e-fuels do not contribute in electrification. In addition, final energy consumption of fuel cells is defined here as hydrogen, as the marketed fuel consumed by fuel cells is hydrogen and is only converted into electricity locally; as a consequence, fuel cells do not contribute in electrification here.

As there is not a single path towards a low-carbon energy system, but rather a wide number of plausible futures to explore, the elaboration of scenarios variants aims at presenting alternative pathways towards the same climate mitigation goal. The analyses, however, are not normative in the sense of advocating in favour (or against) the development of electricity in the energy mix, or at assessing the economic or policy convenience of a strong push towards electricity as a mitigation option.

For the above-described purposes, the scenario analysis presented in this report identifies and groups together several scenario-framing factors which could affect electricity generation, demand and uses. Four main groups of parameters have been characterised based on their potential impact on the development of electricity uses; they have been quantified and fed into the POLES-JRC model to consistently generate the alternative scenarios that will be presented and discussed. The numerical assumptions are mainly the result of expert judgment and literature reviews. The assumptions are presented in **Table 1**, with complementary information in **Annex 5**.

1. *Primary energy prices* on the primary supply side, different fossil fuel prices affect (on top of climate policies, especially carbon values) upwards or downwards the competitiveness of low-carbon energy sources and technologies, including those being used for power generation. The competitiveness of electricity as a final energy carrier crucially depends on the relative evolution of the price of fossil fuels specialised on power generation (e.g. coal) with respect to those with higher use as final energy carrier. Similarly, at end-use level, where electricity competes with natural gas and oil products in transport (in road mode in particular), residential and services (for cooking, space and water heating) and industry (process heat). Moreover, biomass prices are also likely to affect electricity uses, since they also compete with electricity for final demand. Sensitivity analyses on extraction costs will include changing oil, gas and biomass prices, all together, upwards (making electricity more competitive) or downwards (making electricity less competitive), compared to the medium scenario.
2. *Costs of electricity supply technologies* unlike well-established fossil-fuel technologies, the future costs of low-carbon power generation options are subject to wide uncertainties. However, these assumptions play a key role in the assessment of the competitiveness of these technologies; this is especially true for investment costs, since these technologies have low variable costs. Recent literature reviews (see e.g. (Tsiropoulos, Tarvydas, & Zucker, 2018)) show, across different studies, a globally decreasing trend, especially for wind and solar technologies. Nevertheless, actual investment costs assumptions vary widely depending on the study. In turn, those costs will affect the average electricity prices, and in the end the competitiveness of electric end-use technologies. The POLES-JRC model uses a one-factor learning model to project future investment costs based on endogenously calculated cumulated installed capacities. Ranges for learning rates are taken from literature studies, assuming higher learning rates (i.e., rapidly falling investment costs) in the high electrification scenario.
3. *Costs of electric end-use technologies* Energy prices will affect the running costs of energy equipment; and relatively cheaper carbon-free electricity is crucial to deliver a higher electrification shares, but not the only one. A key driver to unlock the potential of electricity in end-uses is lies on electric end-use costs and their relative competitiveness with non-electric ones. Assumptions were made on the costs of heat pumps, batteries for electric vehicles and hydrogen fuel cells, which are uncertain and may deeply affect consumers' choices. In an energy system becoming more efficient,

the cost structure of energy expenditures is likely to give more weight to fixed costs as opposed to variable costs (European Commission, 2018). Moreover, some electricity technologies have an important potential in terms of efficiency compared to conventional ones (e.g. heat pumps, electric vehicles). This sensitivity analyses section shall provide some conclusions on the underlying cost/efficiency trade-off.

4. *Technology adoption dynamics and other non-economic drivers*. This fourth group of parameters includes important consumer behaviour parameters, as well as some institutional ones. Beyond economic indicators, many drivers may affect economic agents' decisions to use electricity, but are essentially not covered by the economic mechanisms endogenously described in POLES-JRC. This applies to some political choices (promoting some industrial pathways, regulating operations in energy production/generation/distribution, investment in electric vehicles recharging infrastructure, etc.), to consumer adoption dynamics (evolving preferences related to advertisement, exposure levels, etc., (Sterman, 2000), (Struben & Sterman, 2008), and finally also to other behaviour-related elements (such as the propensity to adopt new information technologies and respond to economic signals to manage electric load, etc…).

Table 1. List of parameters and values used in the sensitivity analysis

Group	Description	Parameter	Unit	Values **Low electrification**	**Medium electrification**	**High electrification**
Energy prices	Oil and gas prices	Varying extraction cost proportionally across all producers (progressive to 2050; 2020:100%)	%	50%	100%	150%
	Biomass	Tax on solid biomass use (progressive to 2050; 2020:0)	$/GJ	0	45	90
Energy supply technologies costs	Costs of on-shore wind power	Learning rate	%	2%	5%	21%
	Costs of off-shore wind power	Learning rate	%	5%	11%	20%
	Costs of solar PV	Learning rate	%	10%	20%	37%
	Costs of CSP	Learning rate	%	7%	18%	30%
	Costs of stationary storage	Learning rate	%	8%	12%	16%
	Hydrogen production costs	Electrolysis cost	$/kWel in 2050	491	568	645
End-use technologies costs	Cost of light EV battery	Battery cost (as part of vehicle cost)	k$/veh in 2050	10.9	7.4	3.9
	Cost of heavy EV battery	Battery cost (as part of vehicle cost)	k$/veh in 2050	191	127	64
	Cost of light vehicle fuel cell	Fuel cell cost (as part of vehicle cost)	k$/veh in 2050	6.3	6.7	7.1
	Cost of heavy vehicle fuel cell	Fuel cell cost (as part of vehicle cost)	k$/veh in 2050	27.6	29.4	31.2
	Costs of heat pumps	Investment cost	$/kWel in 2050	774	635	503
Non-economic parameters: adoption, other policies etc…	Potential of demand-side management	Share of load that can be shifted by DSM	%	2.5%	5%	10%
	Potential of demand-side management	Share of load that can be shifted with batteries	%	25%	50%	75%
	Potential of demand-side management	Share of private electric vehicle recharging that can be done at workplace instead of at home	%	25%	50%	75%
	Penetration cap for distributed PV	Maximum penetration share of distributed PV in residential buildings load	%	15%	30%	60%
	Penetration cap for distributed PV	Maximum penetration share of distributed PV in commercial buildings load	%	30%	60%	90%

	Phase out of oil, all end-uses, buildings	Market acceptability factor in 2050		Full acceptance	Intermediate acceptance	Full phase-out
	Phase out of gas, all end-uses, buildings	Market acceptability factor in 2050		Full acceptance	Towards full acceptance	Intermediate acceptance
	Households with biomass water heating equipment	Maximum share of households equipped with biomass space heating that can also have biomass water heating	%	75%	50%	25%
	Appliances	Maximum annual improvement rate of energy efficiency of appliances	%	3%	2%	1%
	Transport, adoption of technologies	Market acceptability factor per technology type		Transport system oriented towards gas & hydrogen	Transport system oriented towards battery-electric mobility	Transport system oriented towards battery-electric mobility, with progressive phase-out of ICEs
	Steel industry	Annual increase of recycling rate (secondary steel into electric arc furnaces), 2050	%	0.25%	0.50%	1%

References used for the sensitivity analysis include (Rubin, Azevedo, Jaramillo, & Yeh, 2015), (Knobloch, Pollitt, Chewpreecha, Daioglou, & Mercure, 2019), (Schmidt, Hawkes, Gambhir, & Staffell, 2017), (Grosse, Christopher, Stefan, Geyer, & Robbi, 2017), (Tsiropoulos, Tarvydas, & Zucker, 2018), (IRENA, 2018), (IRENA, 2019), (Lilliestam, Labordena, Patt, & Pfenninger, 2017), (Köhler, Stobbe, Moser, & Garzia, 2018), (Pitz-Paal, 2017), (Creutzig, et al., 2017), (Kittner, Lill, & Kammen, 2017), (Jadun, et al., 2017), (Cano, et al., 2018), (IEA, 2015), (Thompson, et al., 2018).

Rather than analysing a complex matrix of sensitivity variants combining the above-described four sets of parameters, a simpler scenario architecture is proposed. Three main projections were identified, corresponding to different storylines.

- In the *2°C–Low Electrification (2C_L)* scenario, electricity use is increasing mainly as a consequence of climate policy, as compared to the Reference Scenario. Hurdles to a strong penetration of electricity are numerous. Decreases in the costs of renewable power generation and electric end-use technologies are slow. Low fossil fuels and biomass prices further reduce the competitiveness of electricity. Adoption is slowed down by policies favouring other energy vectors, such as gas and hydrogen. In this context, the 2C_L scenario does not incorporate features that would contribute to a radical change in terms of consumer preferences.
- In the *2°C–Medium scenario (2C_M)*, public choices are directed towards electricity pathways. Electric mobility is promoted by a dynamic deployment of recharging infrastructure; actions are taken to encourage reductions in the use of fossil fuels-based equipment (communication, standards, fiscal incentives, etc). Higher energy prices and lower costs of renewables and electric technologies encourage a move towards electricity. In this scenario, electric technologies adoption is dynamic.
- Finally, the *2°C–High Electrification (2C_H)* scenario depicts a breakthrough in terms of penetration of end-use electric technologies in the energy system. Enabling conditions include higher energy prices, high learning rates for electric technologies to drive prices downwards at accelerated pace. Strong actions are taken to phase-out/ban fossil fuels technologies in buildings and transport.

All three scenarios result in total world greenhouse gas emissions that are broadly similar (see **Figure 5**); they share the same assumptions on carbon prices as drivers for emissions mitigation (see **Annex 1**).

Building renovation rates have been kept the same across the sensitivities examined here (however, renovation is accelerated with the decarbonisation effort compared to the Reference case).

Regarding these parameters, the Reference, NDC and 1.5°C scenarios were modelled with the same parametrisation as 2°C-Medium scenario.

3 Global energy system impacts of electrification in a 2°C context

Within the 2°C temperature increase cap, this section studies the electrification of the demand side. The 2°C goal in a high-electrify scenario can only be reached coupled with a strong decarbonisation of the power sector and an overall efficiency improvement. Decarbonisation and electrification together have the potential to substantially reduce economy-wide emissions of carbon dioxide associated with fossil fuels combustion. Additionally, the boosting electrification of the energy-uses includes the adoption of more efficient technologies for energy services requirements in buildings, modal shift in combination with the penetration of more efficient vehicles types in the transport sector and more efficient processes for the industry sector.

Furthermore, changes in the fuel mix can contribute directly towards achieving the Sustainable Development Goals (SDG)[7] as the Universal access to affordable and clean energy, Climate action, Sustainable cities and communities, improving good health and Protecting life on land and below water.

Strengthened electrification has already been observed along the past decades (**Figure 3**), prompted by different mechanisms, most of them based on the versatility, efficiency and comparative advantages of electricity as a final energy carrier. Despite the growing electrification trend in every sector, as will be developed further in this section, there are still energy uses that are difficult to electrify.

Country-wise, a substantial increase in access to electricity by rural communities has been noted also. According to the World Bank[8] only 63% of the global rural population had access to power supply in 1990, whereas this share is reported to reach 78% in 2016. This has been driven by important investment in distribution and transformation networks in all continents, most importantly in Africa, the continent that is still, however, lagging behind.

A widespread increase in electrification of end-use services across all demand sectors would lead to a significant increase of electricity consumption; however improvements in the energy efficiency of end-use devices and thermal insulation can substantially limit the growth in load. Furthermore, despite driving large increases in total load, temporal flexibility in some end uses, such as secondary fuels production (hydrogen, synthetic methane and liquids) and electric storage charging/discharging (stationary or in vehicles), can offset the increased peak demand. Electrification together with such solutions has the potential to reduce variability or "peaky-ness" of the load, which can aid in the integration of new resources — particularly variable renewable resources.

In summary, a rational transition pathway towards a low-carbon economy making use of electrification would require:

- The **decarbonisation** of electricity generation, lowering the carbon intensity of the electricity generation.
- The **shifting** of energy carriers in thermal and mobility end-uses from mainly fossil fuels towards electricity and derivative fuels (initially partly grey then nearly entirely green hydrogen or grid-electrolysis[9]; e-fuels[10]).
- The increase in the energy **efficiency** of end-uses.
- The mobilization of **new energy solutions** such as demand-side load management, storage and low-carbon-powered synthetic fuels production.

3.1 Historical trends and projections for greenhouse gas emissions

Global GHG emissions are dominated by fossil CO_2 and increased steady over the entire period 1990-2018 (**Figure 6**). Historically, the United States and EU have been the world's largest CO_2 emitters, together accounted for more than 50% of total fossil CO_2 emissions[11] over the period 1970-1989; however, the

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(7) https://www.undp.org/content/undp/en/home/sustainable-development-goals.html

(8) https://data.worldbank.org/indicator/eg.elc.accs.ru.zs

(9) Grey hydrogen is derived from natural gas steam reforming, results in CO_2 emissions; green hydrogen is derived from solar steam reforming or from decentralised electrolysis from excess wind and solar power production; hydrogen with grid-electrolysis is derived from grid electricity, results in CO_2 emissions if annual average emissions content of grid electricity is used

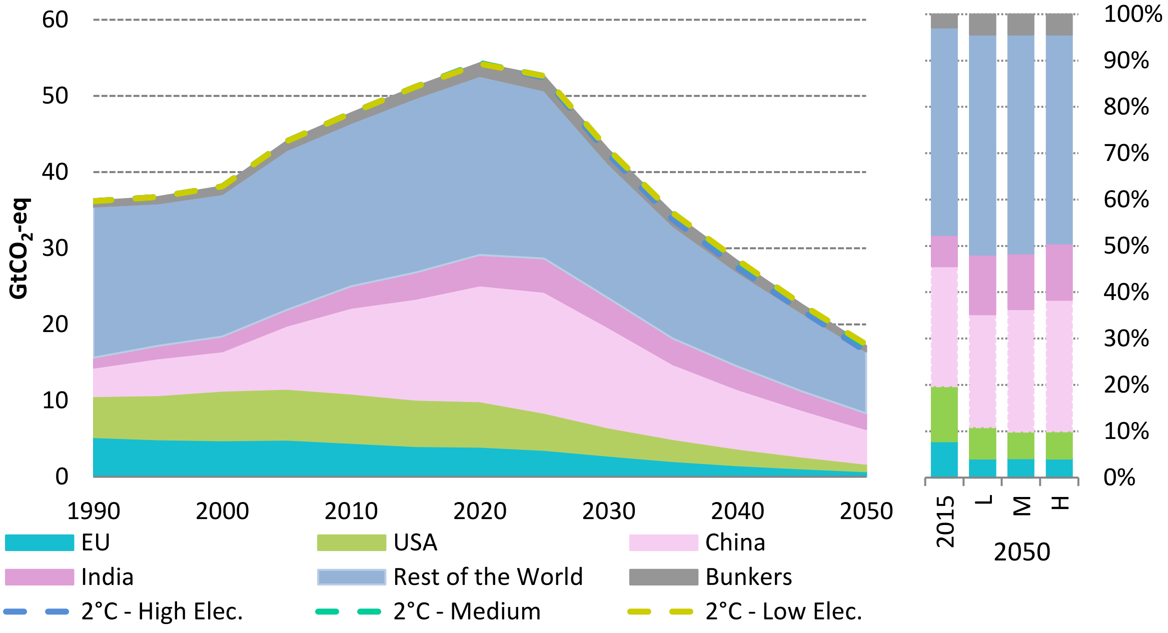
(10) e-fuels (Power-to-Gas and Power-to-Liquids) result from the production of hydrocarbons based on the direct air capture of CO_2 and hydrogen. They are used in transport activities.

(11) Fossil CO_2 emissions include emissions from fossil fuel use and industrial processes.

geographical distribution for CO_2 emissions has shifted significantly in recent decades, with 2015 emissions for the world's largest emitters being: China (30%), United States (14%), EU (12%), India (6%) (Crippa, et al., 2019). A great disparity across countries in terms of emissions per capita or per unit of GDP still remains.

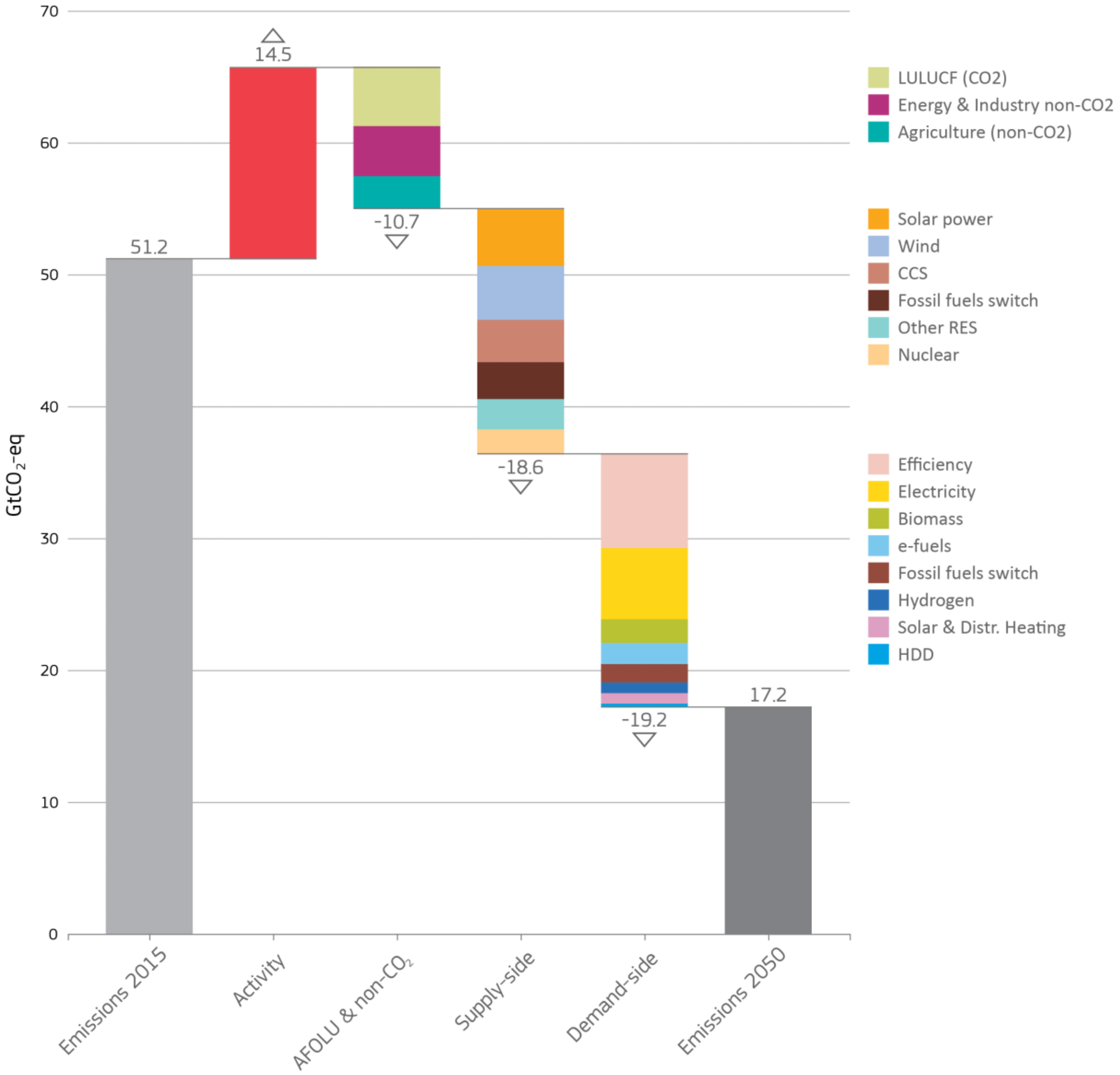
Nevertheless, with the ambitious climate policies assumed in the 2°C-Medium scenario, all regions must drastically reduce their emissions, developing their economies while also boosting low-carbon technologies together with promoting strong energy efficiency measures. For the 2°C-Medium scenario, global GHG emissions decrease by an annual average of 4.0% between 2020 and 2050.

Figure 6: Regional distribution of GHG emissions, 2°C-Medium scenario



Source: POLES-JRC model.

Figure 7. Drivers of GHG emissions growth and mitigation options and role of electrification in the 2°C-Medium scenario, 2015–2050, World

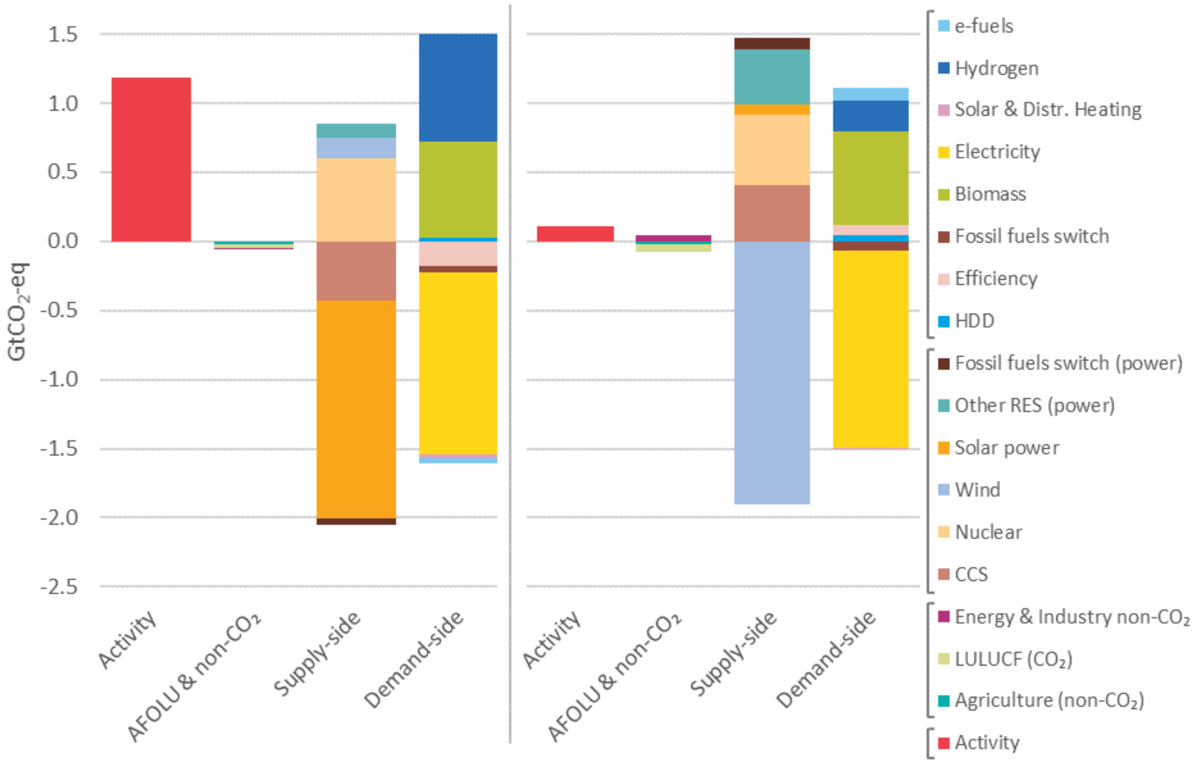


Notes: "Activity": emissions growth due to the growth of population and the economy, and to associated income-based consumption (industrial value added, transport activity, dwelling size, electricity consumption). "AFOLU": Agriculture, Forestry and Other Land Use. "Biomass - Traditional": refers to the phase-out of traditional biomass for reasons other than climate policies, resulting in an energy demand gap that has to be met by other fuels. "HDD": emissions from buildings' space heating prevented by the evolution over 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). "Energy & Industry non-CO$_2$": including emissions reductions from fossil fuel extraction and transport directly related to the decrease in the use of fossil fuels in all energy demand sectors. "Synthetic methane", "Synthetic liquids", "Hydrogen", "Biomass - Modern", "Electricity": emissions prevented by the use of these fuels in final demand sectors (emissions for their production distributed in the other options here). "Biomass – Modern": includes liquid biofuels. "Efficiency": structural efficiency and efficiency in the provision of energy services not attributable to the other technological options detailed here.

While electrification is presented in the figure above (**Figure 7**) in a narrow sense, i.e. meaning just directly substituting other fuels in final end-uses, electrification can have indirect effects mutually reinforcing that contribute to other options as well yielding an overall electrification of the energy system as a whole. The key trends involve technology deployment both in the demand-side (energy efficiency, electricity storage) and in the supply-side (cheaper and more competitive renewable power, basically wind and solar PV, easier penetration of variable renewables thanks to buffering technologies and interconnections, larger role of clean power options other than solar PV and wind, as well as nuclear).

The 2°C scenarios differ little in total GHG emissions through the projection period (5% difference between 2°C-Low and 2°C-High in 2050), however they reach this mitigation with different pathways over time. The influence of the drivers and options on total mitigation presented in **Figure 7** are displayed in **Figure 8** in a comparison between 2°C scenarios pathways. The significant role of electricity is displayed moving from low to medium to high electrification: demand-side emission reductions are achieved with more electricity and less biomass and hydrogen, while supply-side emission reductions are achieved with more solar and wind and less nuclear and biomass; AFOLU ad non-CO_2 emissions are roughly similar across scenarios.

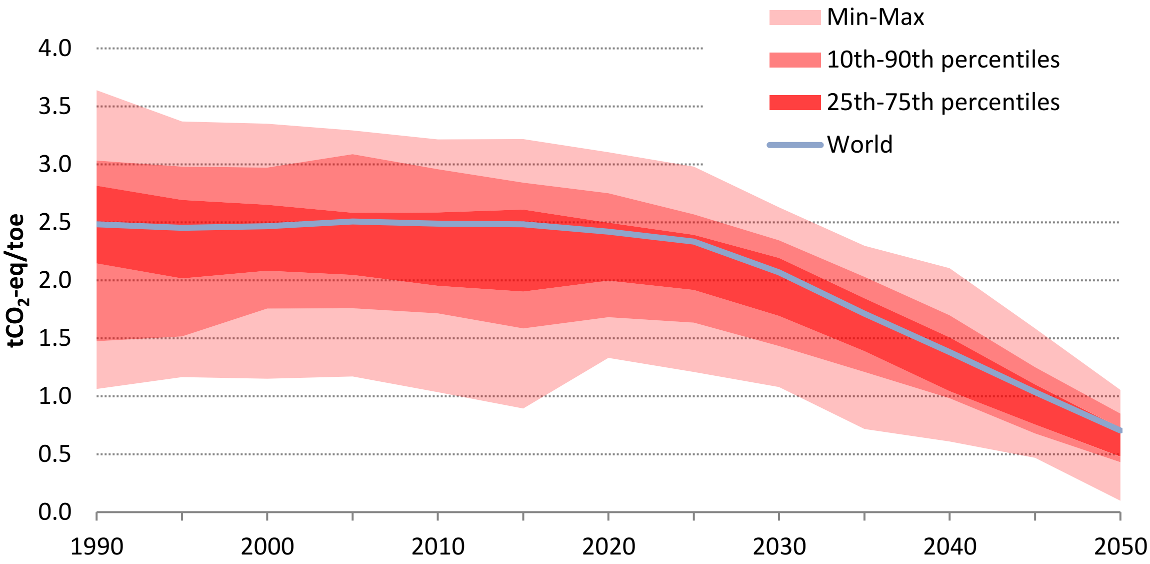
Figure 8. Drivers of GHG emissions growth and mitigation options and role of electrification, differences between the 2°C-Low and 2°C-Medium scenarios (left), and between the 2°C-Medium and 2°C-High scenarios (right), 2015–2050, World



Note: For each comparison, the sum of the decomposition represents the difference in emissions between scenarios; this quantity is small compared to total emissions levels and total mitigation over time in **Figure 7**. Differences in "Activity" emissions relate to increased electricity consumption across scenarios, which is mitigated with a different mix of options in "Supply-side"; from medium to high electrification, the different mitigation pathways notably in heavy duty vehicles transport counter-balance the growth of "Activity".

Plotting GHG emissions over primary energy consumption is shown in **Figure 9**. This coefficient can be understood as a GHG emissions intensive indicator of the energy mix. The decarbonisation of the primary energy began in the early nineties, with only India outside this trend up to 2000.

Figure 9: World regions average energy-related tCO_2-eq emission per primary energy produced, historical data 1990–2015, and the 2°C-Medium scenario projection 2015–2050



Source: POLES-JRC model.

In the 2°C-Medium scenario, the GHG intensity of primary energy drops at a compound annual growth rate of 3.5%/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 1.7%/year to -5.1%/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 2°C-Medium scenario.

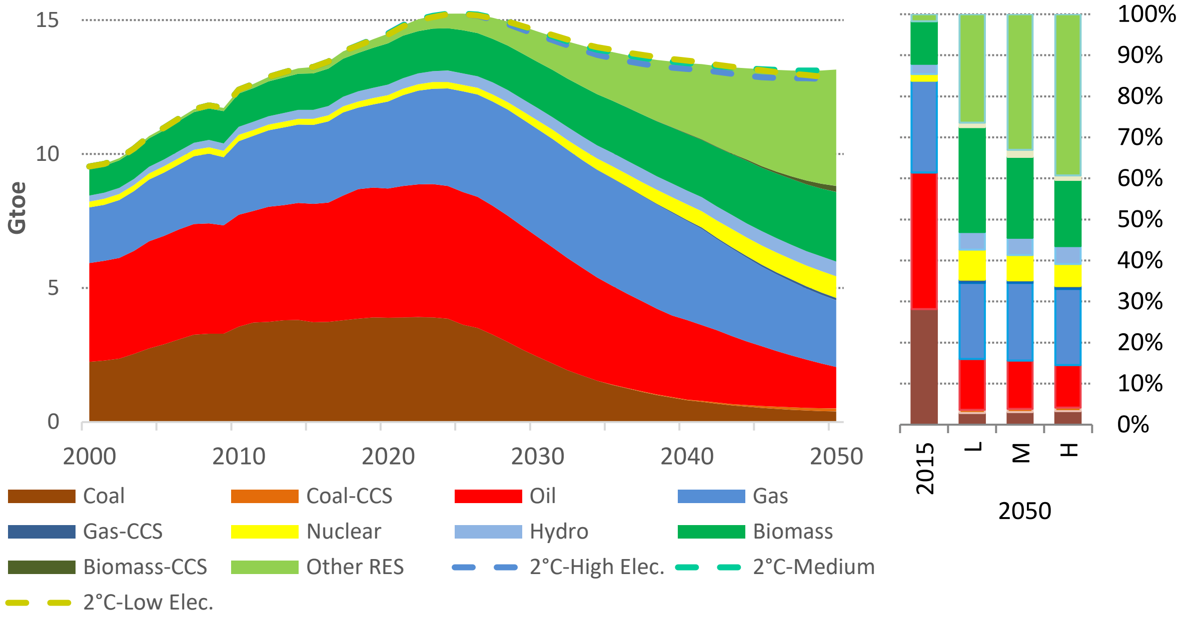
3.2 Primary Energy demand and supply

Archiving objectives for limiting climate change will trigger deep changes in the energy system through accelerated fossil 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 report. In the 2°C-Medium scenario, from a global perspective, primary energy demand would peak at around 14.8 Gtoe in 2020, and from there it would fall to 13.1 Gtoe in 2050.

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) and losses. In 2017, total primary energy demand worldwide reached 13.8 Gtoe. More than three quarters (83%) 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 2017 reached 15%, 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 2°C-Medium scenario, all fuels except renewable and nuclear would decrease their share in the primary energy mix throughout 2050 (**Figure 10**). Non-GHG-emitting sources, consisting of renewables, nuclear and fossil fuels associated with carbon capture and sequestration (CCS), would rise to 58% of the total energy mix.

Figure 10. World primary energy demand by fuel 2000–2050, 2°C-Medium scenario



Source: POLES-JRC model.

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 59% by 2050, almost fourfold of the share in 2020.

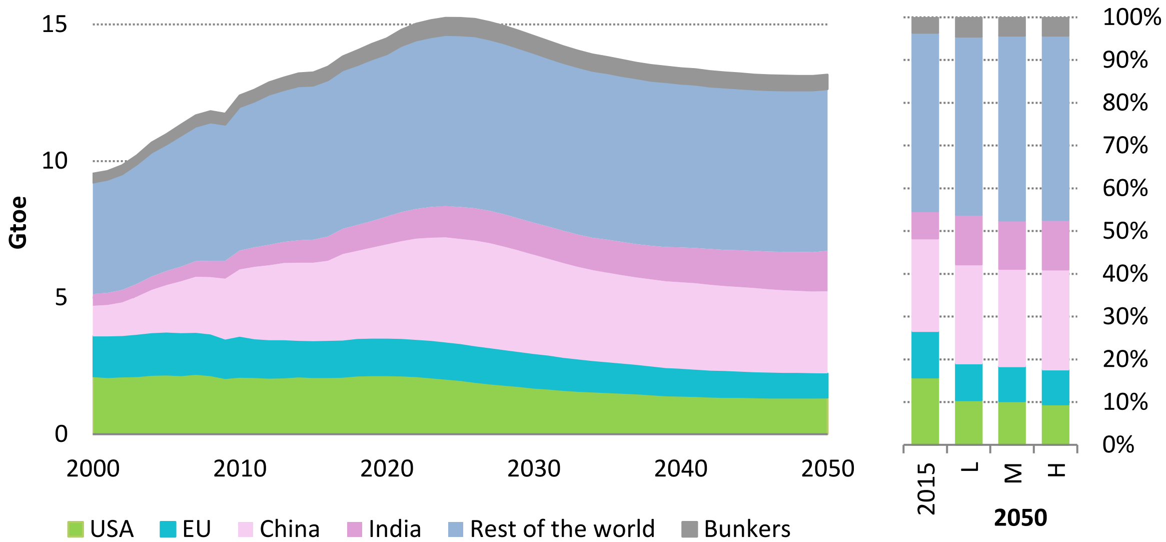
The renewables expansion is followed by nuclear. World nuclear supply is projected to grow in the coming decades, increasing twofold over 2017–2050 in the 2°C-Medium scenario up to 4% in 2050 of total primary energy vs. 2% in 2017. This would be mainly due to the expansion of nuclear power in non-OECD countries (mostly concentrated in China, India, South-East Asia, Medium 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 -3.3%/year over 2017–2050. By 2035 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 -2.4%/year between 2030–2050.
- **Coal** demand would be most strongly and quickly impacted by stringent climate policies. Coal demand would peak in 2020 and decline at -6.6%/year over 2017–2050, 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 3% 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).

Figure 11 shows the world primary energy demand by region in the 2°C-Medium scenario. China is projected to almost stabilise their share in the world energy demand, getting to 22.7% by 2050 compared to 11.7% in 2000, although socioeconomic assumptions describe a growing population and a quickly expanding economy. USA would still account for 10% in 2050, compared to 15.8% in 2015, with their demand per capita being significantly higher than in non-OECD countries. EU reduces its demand by 1% annually since 2015, reaching 6.7% share in 2050 compare to the 10% in 2015.

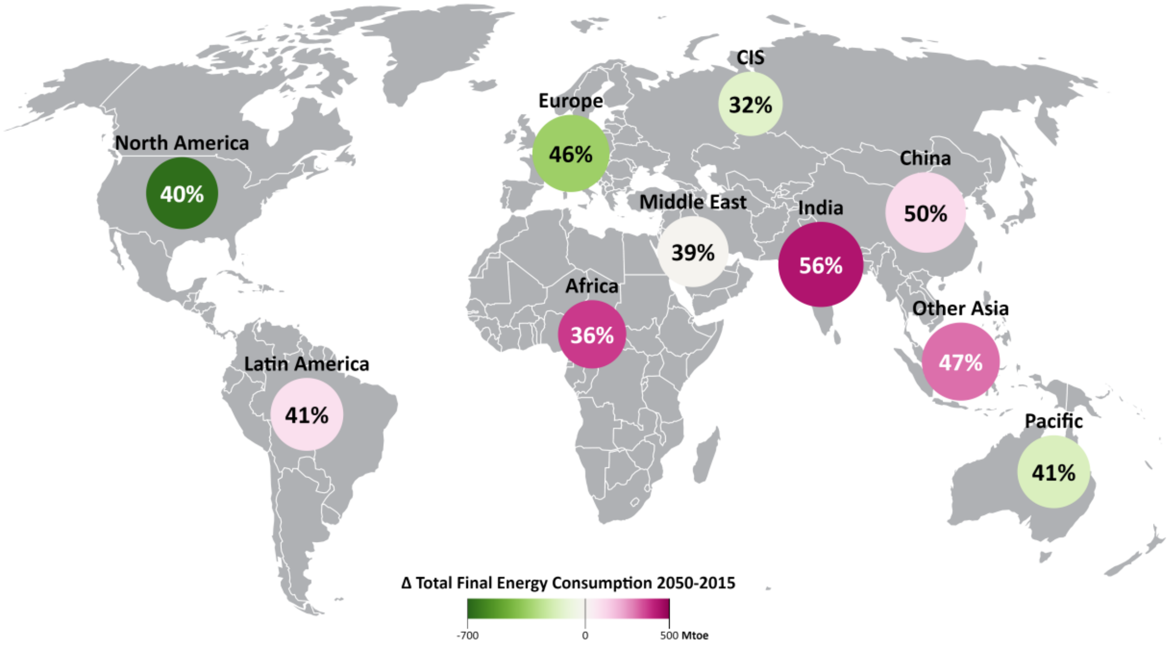
Figure 11: World primary energy demand by Region 2000-2050, 2°C-Medium scenario



Source: POLES-JRC model.

The electrification of final energy consumption, has increased steadily over the last decades, across the world. Every region in the world has experienced an increase of the electricity share at the final energy consumption (**Figure 12**). In a 2°C scenario India would accomplish the biggest relative growth, from 15% electricity share (88 Mtoe electricity consumption) in 2015 to 56% in 2050 (577 Mtoe of electricity consumption). While China would accomplish the biggest growth in absolute terms reaching 1064 Mtoe of final electricity consumption (50% share) in 2050, from 413 Mtoe (21% share) in 2015.

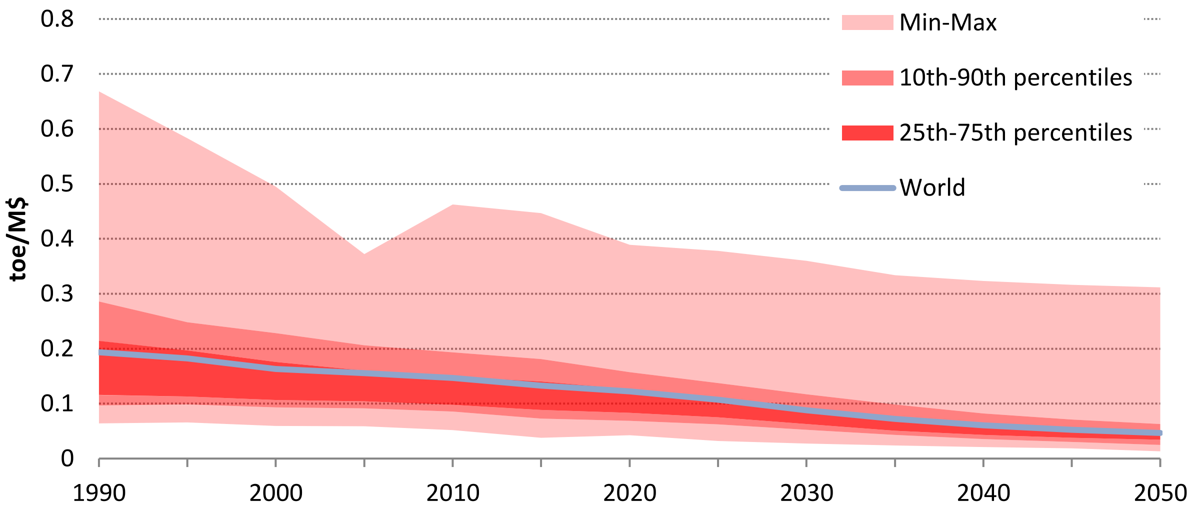
Figure 12. Electrification penetration share by Region in 2050 (bubbles), and the projected change in total final energy consumption between 2015-2050 (colour scale), for the 2°C-Medium scenario



Source: POLES-JRC model.

In the 2°C-Medium scenario, the primary energy intensity of the economy is plotted as the coefficient of primary energy use per GDP (**Figure 13**). This is a measure of the decoupling of economic growth from energy consumption. The drop of primary energy use per GDP unit in the different world regions started in the 1980s, with a drop at a compound annual growth rate of 2.5% annually during the period of 1990-2015 and a drop of 2.3% annually between 2015-2050.

Figure 13: World regions average energy-intensity of the economy, historical data 1990–2015, and 2°C-Medium scenario projection 2015–2050



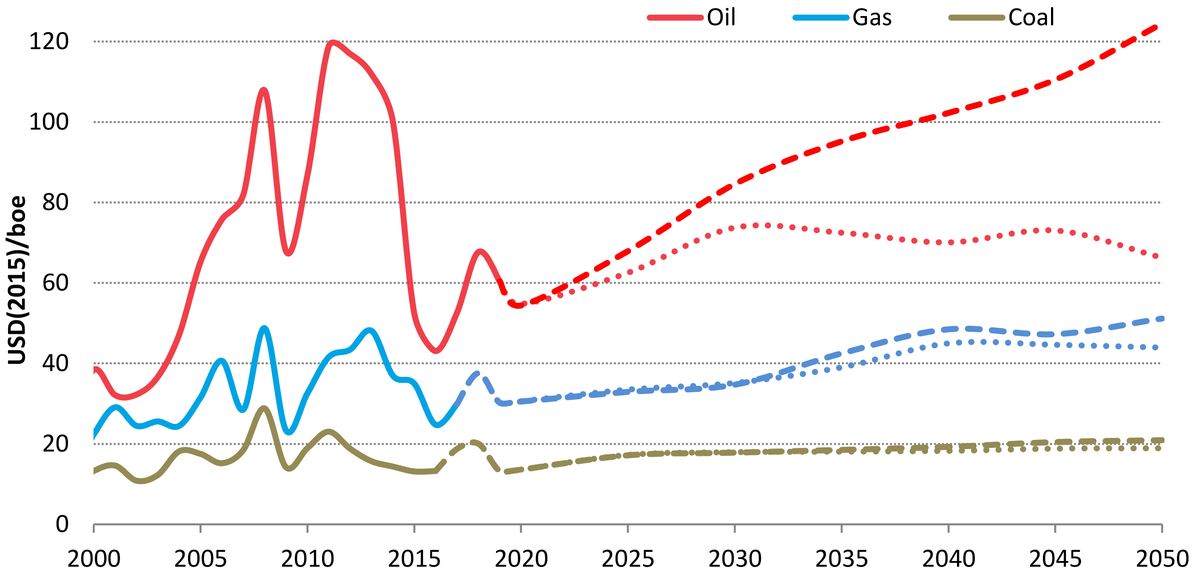
Source: POLES-JRC model.

3.3 Fossil Fuel prices

Fossil fuel price projections for the Reference and the 2°C-Medium scenarios are presented in **Figure 14**.

Overall, prices for internationally traded energy commodities follow an evolution reflecting the balance of demand and supply, with demand being influenced by energy services needs, technology costs and inter-fuel substitution, and supply being determined by production costs, transport costs and the evolution of available reserves for fossil fuels. The market impact of environmental policies is felt not only via the carbon price, but also in the accelerated learning of key renewables technologies and in diminished supply tensions, due to globally stabilizing or shrinking markets for fossil fuels and decreased investment needs in new production capacities.

Figure 14. International fossil fuel prices, Reference (thick dashes) and 2°C-Medium (fine dashes) scenarios



Note: Oil prices refer to Brent; gas and coal prices refer to the average imports to the European market.

Oil prices:

- Reference scenario: the price increase is driven by an increase in the marginal production cost, in a context of rising investment needs in new production capacities. Extraction costs are projected to increase to renew depleting wells (in particular for such resources as tight oil), due to geological scarcity in some markets, and due to a shift towards more unconventional resources that are associated with energy-intensive extraction processes.
- 2°C-Medium scenario: the application of climate policies on the energy demand side would entail heavy structural changes in the transportation sector in particular, with a rapid rise in the adoption of alternative technologies such as battery-electric vehicles and fuel cells; oil demand would persist for road freight and petrochemicals. As a result, the oil market stabilizes and then shrinks, releasing tensions in supply; the international oil price then follows a different path from the Reference scenario, with a relatively stable trajectory after 2030.

Gas prices:

- Reference scenario: the world gas markets and oil markets are expected to progressively become more decoupled over the projection period, due to increasingly different uses for these fuels and to the expansion of LNG, for which contracts are not indexed to oil prices. Gas prices increases are also driven by increasing production costs, due to the investment needs in the considerable amount of new resources to be put into production.
- 2°C-Medium scenario: climate policies result in a substantial penetration of renewables in the power sector and an accelerated insulation in buildings, which result in a stabilization of world gas demand in the 2030s decade and a shrinking demand afterwards. As a consequence, the 2°C scenario projects lower extraction costs and lower prices compared to the Reference scenario.

Coal prices:

- Reference scenario: coal prices are projected to rise slightly as a consequence of rising extraction costs (geology) and costs of inputs in production (notably energy inputs and labour costs), as well as higher transport costs.
- 2°C-Medium scenario: coal demand is deeply and immediately impacted by climate policies, resulting in decreasing demand despite the deployment of CCS retrofit on coal power capacities after 2030. Coal prices are projected to grow slightly, to a lesser extent compared to the Reference scenario.

3.4 Electrification in final energy consumption: the total picture

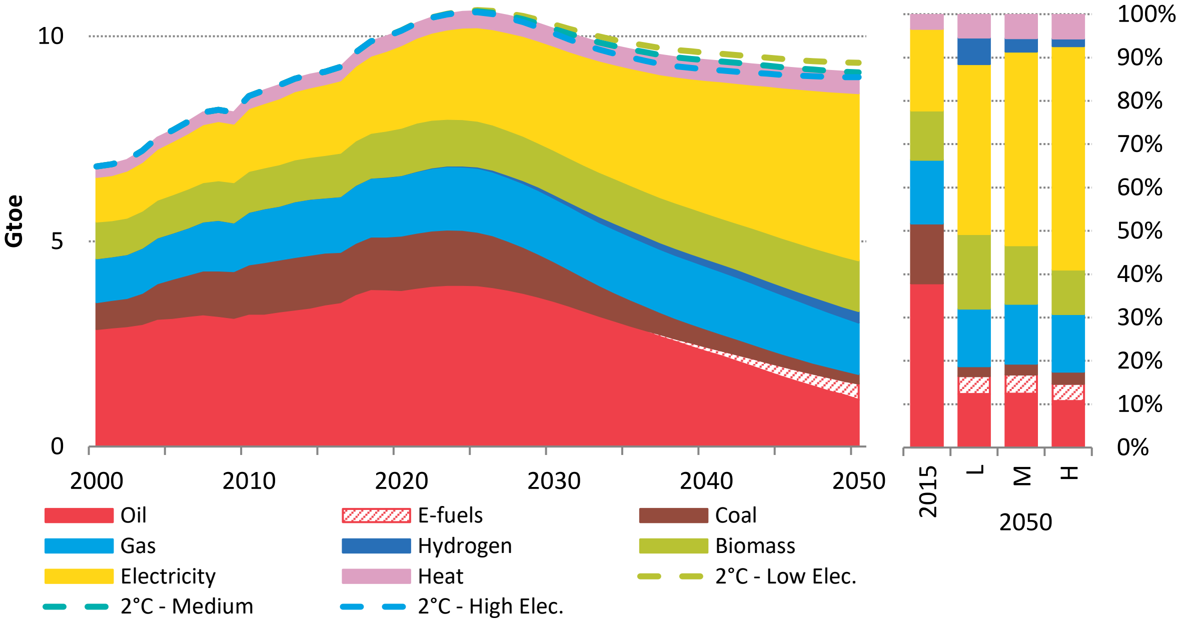
3.4.1 Final energy consumption trends

In recent years, final energy consumption[12] has kept rising, despite the world economic slowdown. In 2017 global total final energy consumption reached 9.6 Gtoe, 4% higher than 2016, to be compared with 1.7%/year on average over the previous five years[13].

In the 2°C-Medium scenario ambitious climate policies and energy efficiency efforts would result in a decelerating growth of final energy consumption beyond 2020 (**Figure 15**). 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 (2010-2017, +1.7%/year), total final energy demand is projected to peak around 2025 (10.6 Gtoe), and then remains broadly stable, despite a growing global economy, decreasing very progressively over the 2030-2050 decades (by -0.5%/year) to reach 9.1 Gtoe in 2050.

The growing dominance of electricity at the energy mix is the result of declining technological costs, change in end-use equipment and favourable policies. The electricity share in the final global energy demand accounts for around 19% in 2017 and is projected to reach 45% of the total final energy consumption in 2050 for the 2°C-Medium scenario.

Figure 15: World total final energy consumption by fuel, 2°C-Medium scenario



Note: includes non-energy uses. E-fules includes e-gas and e-liquids. (POLES-JRC model)

Final energy consumption is decomposed by end-use energy service in **Figure 16**. Heat uses, in industry and buildings (residential and services), are currently the largest energy consumption worldwide. This will continue to be so in the 2°C-Medium scenario throughout 2050. Nevertheless, improving efficiency and an increased in the participation of electricity (29% in 2050 vs 10% in 2015) are two key changes in projected heat uses.

Moreover, over the period 2020-2050 final electricity consumption for all energy sectors almost duplicate, at an average annual growth of around 2% per year. Over the same period, the strongest average annual growth is observed in the transport sector (9.3%), followed by the building sector (2.4%), and the Industry sector (1.4%). Electricity participation in transport is projected to have the major average annual growth, mainly because it has been almost zero before 2020. The transport sector would still remain reliant to a significant

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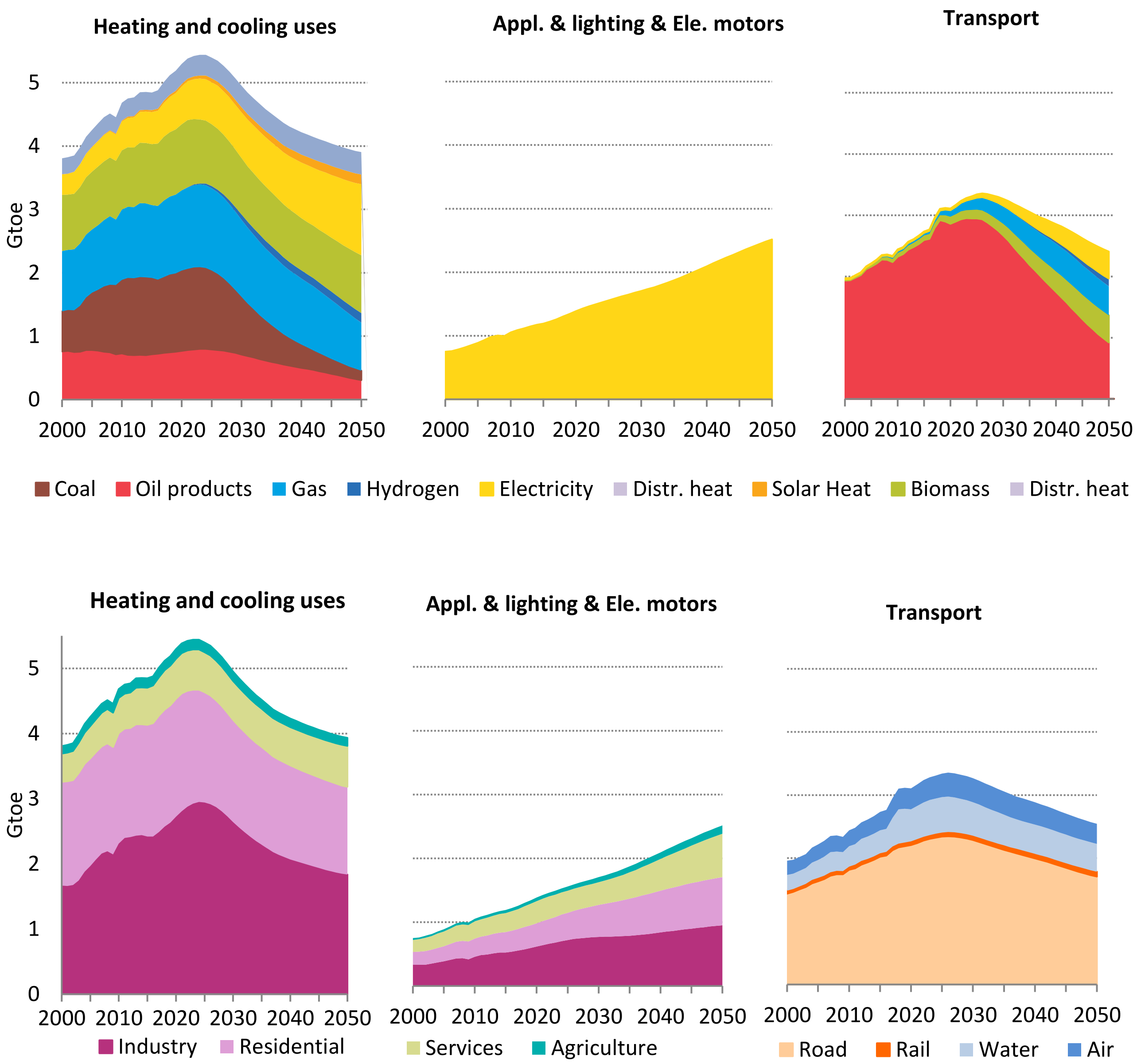
(12) In this report, a country's final energy consumption includes non-energy uses in industry and energy consumption of international aviation and maritime bunkers; it does not include transport and distribution losses.

(13) Final energy consumption estimated at 10.2 Gtoe in 2018, a 2.0% increase compared to 2017.

degree on oil products throughout 2050, albeit to a more reduced extent, with an increased role for gas (20% in 2050), biofuels (18% in 2050), electricity (18%) and hydrogen (5%).

Captive uses of electricity for electric processes and appliances would expand significantly, due to economic growth and increasing equipment rates for appliances.

Figure 16. World final energy consumption by end-use and fuel (top), by end-use and sector (bottom), 2°C-Medium scenario

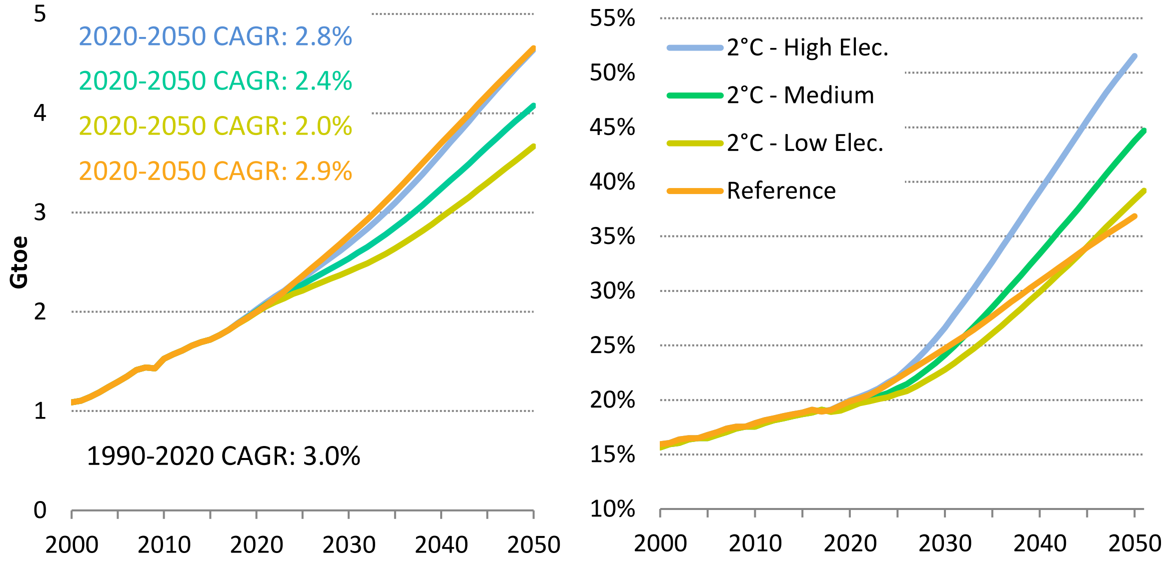


Note: For transport, gas includes e-gas, and oil includes e-liquids. (POLES-JRC model).

3.4.2 Final energy consumption electrification

Electrification itself – being the share of electricity consumption over the total final energy consumption – can increase because of an increase in electricity consumption that is faster than the increase in total consumption, or even because of moderately increasing electricity consumption while total consumption stagnates or decreases. In the 2°C-Medium scenario and all of its derived sensitivities, the combination of underlying economic growth, energy efficiency and fuel substitution brought about by the decarbonisation effort pushes electricity consumption and electrification upwards over time (**Figure 17**).

Figure 17: Global Final electricity consumption (left) and share of electricity in total final energy consumption (right)



Source: POLES-JRC model.

The increasing electrification is observed also in the Reference Scenario. Indeed, there is a strong increasing trend of electrification over time in all scenarios, this general pattern being more important than the variability between the scenarios examined.

- Reference: from 19% in 2017 to 37% in 2050, a 18p.p increase over 2017-2050
- 2°C-Medium in 2050: 45% (+8% vs Reference), a 27p.p increase over 2017-2050
- 2°C sensitivities in 2050: range from 39% to 51% (+2p.p to +14p.p vs Reference)
- Low to high 2°C sensitivities electrification scenarios spread: 26% increase in final electricity consumption

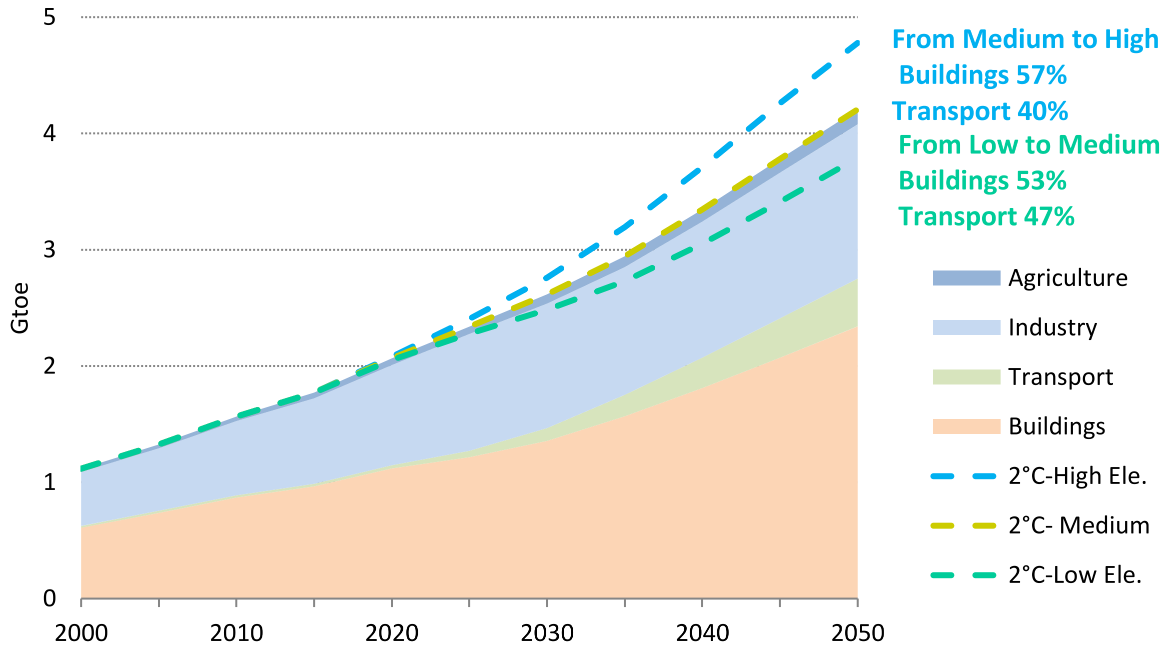
Decomposing electricity demand by sector reveals, which sector is most impacted by the scenario sensitivity variants (**Figure 18**). Electricity consumption in 2050 will be more than double its 2015 value, for the 2°C-Medium scenario.

At the period 2015-2050 the buildings sector id leading the electricity demand rise, its pronounced uptake of electricity for heating and cooking accounts, at the 2°C-Medium electrification scenario, for 57% of the additional electricity demand – followed by the Industry (29%), and Transport (19%). Therefore worldwide, the buildings sector is projected to be the most significant contributor to the increase in electricity consumption, both over time and across the sensitivity scenario variants analysed.

The key technology driving this transition is heat pumps in its wide typology. On the one hand, heat pump-based heating systems will replace many existing heating equipment in dwellings in developed economies in the projection period. On the other hand, this technology will be the primary choice for houses being endowed for the first time with space heating, mostly in developing countries, thanks to its high efficiency and the relatively low electricity prices foreseen due to cheap electricity from renewable energy sources.

The additional electricity demand between the low and 2°C-Medium scenario sums 0.4 Gteo, while reaching almost 0.6 Gtoe for the transition between the Medium to High 2°C scenario. Nevertheless, transitioning between the 3 sensitivities scenarios are driven by the increased in electricity demand for the buildings sector followed by the transport sector (see **Figure 18**). The electricity demand increase for the industry sector across sensitivities is comparatively small.

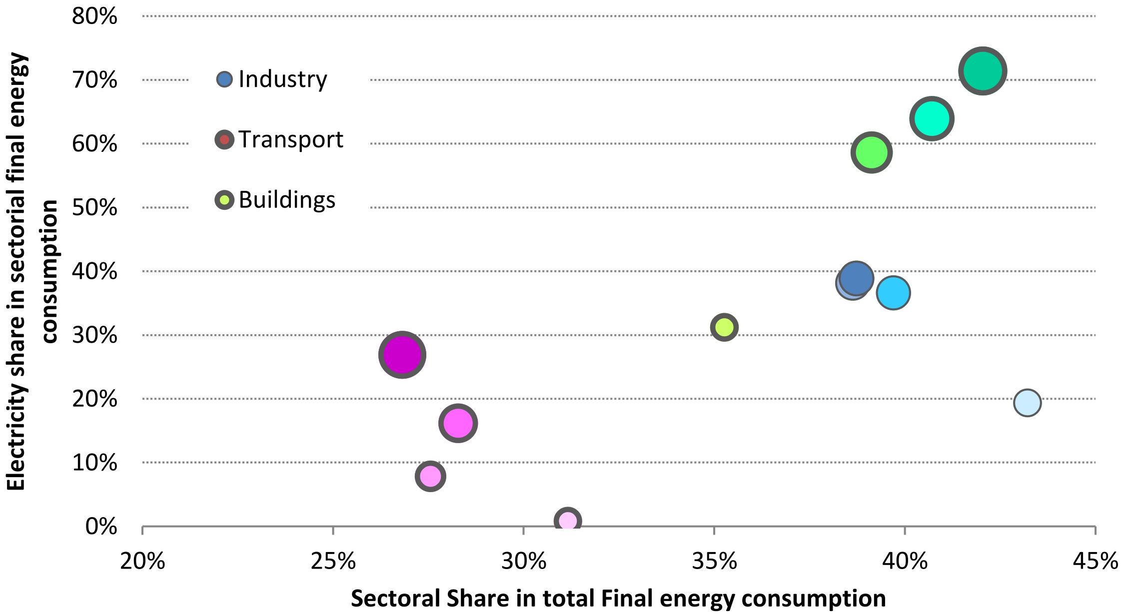
Figure 18. Global final electricity consumption by sector in the low electrification scenario, with sectoral increments for the medium and high electrification scenarios



Source: POLES-JRC model.

This increase in volume is reflected also in the increase in the electricity share, as shown in **Figure 19**. The buildings sector is the sector that reaches the highest electrification and also becomes the largest sector in terms of total final energy consumption, globally.

Figure 19. Sector-level electrification (y-axis) vs sectoral share in total final energy consumption (energy uses) (x-axis), World



Note: Lightest: 2015; light: 2°C-Low Elec.; dark: 2°C-Medium; darker: 2°C-High Elec. (POLES-JRC model)

This substantial increase in electricity consumption would be accompanied by an increase in the demand of many resources involved in the production of batteries, solar panels or wind turbines. In turn, these would require the mining and refining of various metals (lithium, cobalt, rare earths, etc…). Due to the energy-intensive nature of extraction and, for several of these, a potential limited geological availability without additional exploration effort, the move towards more electrification would have to be accompanied by a simultaneous development of more resource efficiency and circular economy. Apart from an example in steel-making (see **section 3.7**), the energy effects of non-fossil resource demand, extraction and recycling are not considered further in this report.

3.4.3 Low-carbon fuels and energy transformation

With the decarbonisation of power generation, electricity progressively becomes a low-carbon fuel. Apart from electricity, the 2°C scenarios also see the wider adoption of other low-carbon energy carriers, either in the form of solid biomass or in the form of fuels synthesized from others: liquid biofuels, hydrogen, e-gas, e-liquids.

Figure 20 presents two Sankey diagrams in 2015 and 2050 of the entire energy system from primary energy supply (*Fossil fuels, Nuclear, Biomass, Non-bio Renewable Energy Sources*) to enery transformation (*Extraction & Refining, Power & Heat, Synthetic fuels & Direct Air Capture*[14]) to final energy consumption (*Fossil fuel products, Biomass – solid, Synthetic fuels, Electricity, Heat*) to estimated useful energy consumption (*Non-Energy Uses, Mobility, Heat & Cooling, Electric Processes*). Totals in primary supply and transformation are the same. Total transformation equals total final consumption and *Waste heat & Losses*. Total final consumption and *Ambient heat* equals total useful consumption and *Waste heat*. Total primary energy supply is comparable for the two years 2015 and 2050 (13.3 and 13.5 Gtoe, respectively).

These diagrams display the transformation of the energy system from one that uses predominantly fossil fuels to one where the power system is much more important in relative size. The electrification of final energy consumption can be seen with the increasing relative size of electricity. The contribution of electrification in energy efficiency can also be seen in the smaller size of waste heat from final to useful energy.

The decarbonisation effort also results in the development of synthetic fuels, in particular in sectors that are difficult to abate, such as energy-intensive industry, heavy transport and aviation. However, the production of sythetic fuels is an energy-intensive process itself, in particular displayed by the self-consumption of the synthetic fuels transformation sector (mainly consisting of use of hydrogen in the production of e-fuels) and other energy inputs (electrolysis using electricity from power production or wind energy shown here flowing from primary non-biomass renewables).

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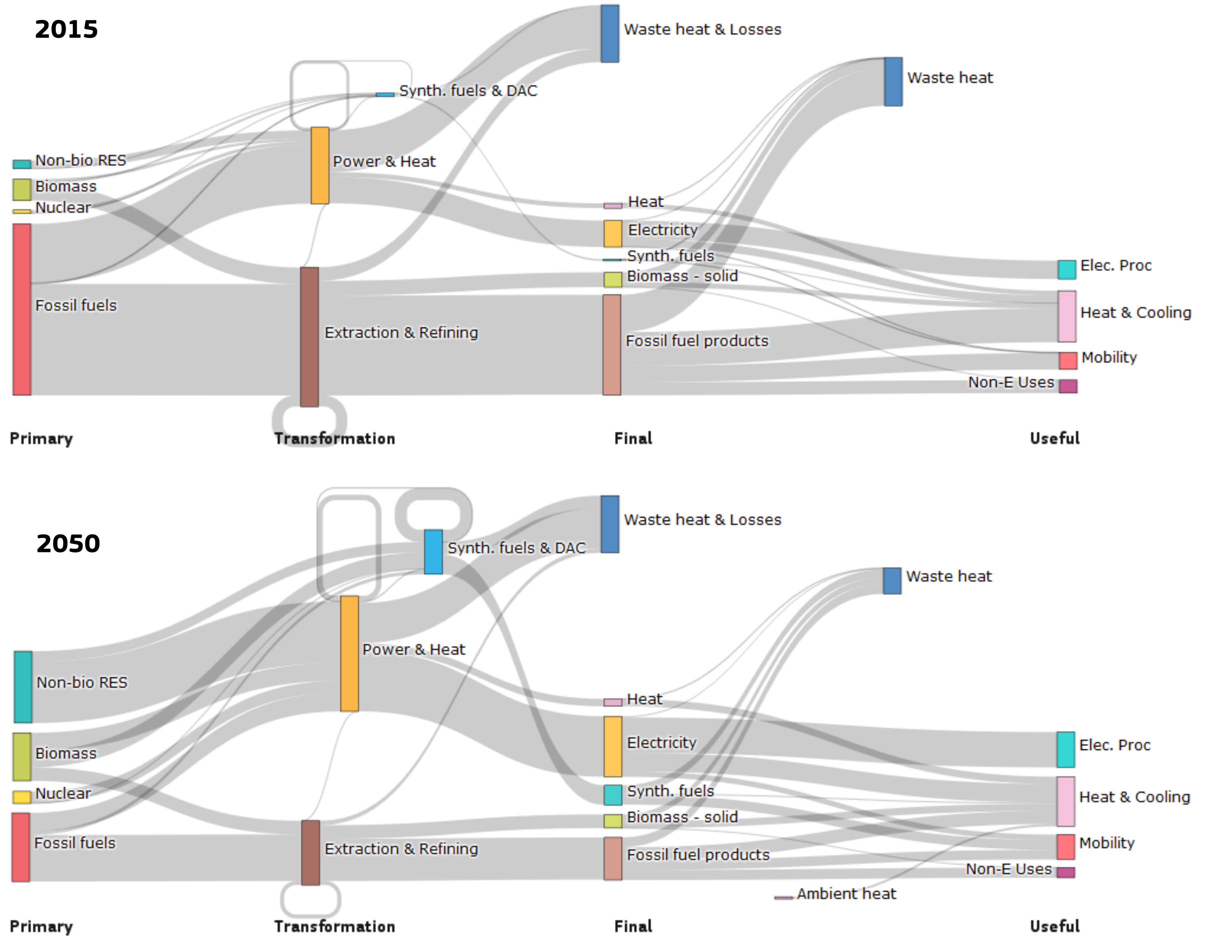
(14) DAC: Direct air capture of CO_2; captured CO_2 can then be used as a raw material to e-fuels production, or be sequestered.

Figure 20. Diagram of energy flows from primary supply to transformation to final consumption to useful consumption, 2015 (top) and 2050 (bottom), 2°C-Medium scenario, World



Notes: "Extraction & Refining" consist of fossil fuels and biomass primary production activities and their transformation into oil, gas, coal and biomass products that can be used in other sectors (does not include solid biomass conversion to liquid biofuels). "Synth. fuels & DAC" consists of the energy transformation sector that produces liquid biofuels, hydrogen, e-gas and e-liquids, and the energy consumption of direct air capture of CO_2 (part of that CO_2 is used as raw material for e-fuels production). Wind energy only used for hydrogen electrolysis is consider to feed directly from "Non-bio RES" to "Synth. fuels & DAC". Electricity generated from nuclear energy is directly considered as primary energy (no waste heat was considered). Self-consumption of the energy transformation processes is displayed as flows feeding the energy transformation sectors. "Waste heat & Losses" includes transport and distribution losses. "Heat" final consumption consists of solar heat and of district heating. "Synth. fuels" consists of the final energy consumption of liquid biofuels, hydrogen, e-gas and e-liquids. Useful energy consumption figures are estimates; appliances and lighting are assumed to have a 1:1 conversion efficiency from final to useful energy. "Elec. Proc" consists of appliances, lighting and electric motors (stationary uses). "Ambient heat" consists of energy used by heat pumps, it does not appear elsewhere in energy balances (heat pumps only consume electricity in final energy consumption). International bunkers energy consumption is included in final and useful energy.

As a result, the overall efficiency of the energy system consists in a shift of losses principally from waste heat and losses from fossil fuels combustion towards waste heat and losses from more sources (fossil fuels with CCS, more biomass and geothermal in power, synthetic fuels production and DAC), but also more energy re-used in energy transformation (auto-consumption). Overall world system efficiency final-to-primary would remain roughly similar from 2015 to 2050 at 72%; overall world system efficiency useful-to-primary is estimated to evolve from 49% to 59%, respectively.

3.5 Electrification in final energy demand: Transport

The transport sector accounted for 28% of total final energy consumption and is responsible for approximately 24% of total GHG emissions) worldwide in 2015 (including international bunkers). GHG emissions primarily involve fossil fuels burned for all transport modes: road, rail, air, waterways and maritime. Currently, nearly all of the world's transportation energy comes from petroleum-based fuels, largely gasoline and diesel (95% in 2015).

Future energy demand in transport is driven by a strong growth in transport services needs resulting from economic growth. Passenger transport activity is projected to increase across all modes of transport, with the strongest annual growth in air transport (2.3%/year as a world average); climate policies are projected to usher a limited modal shift from private cars transport (1.9%/year) to public land transport (2.2%/year), which would need to be accompanied by the corresponding investments in infrastructure. Transport of goods across all modes (road, rail and waterborne) is projected to grow as well, but at a slower pace (1.7%/year). Passenger and freight activities are also slightly impacted by energy prices, resulting in slightly different activities across the 2°C electrification scenarios, mainly due to different assumptions on international oil prices; in the case of freight, most of the impact is explained by less demand for internationally traded fossil fuels.

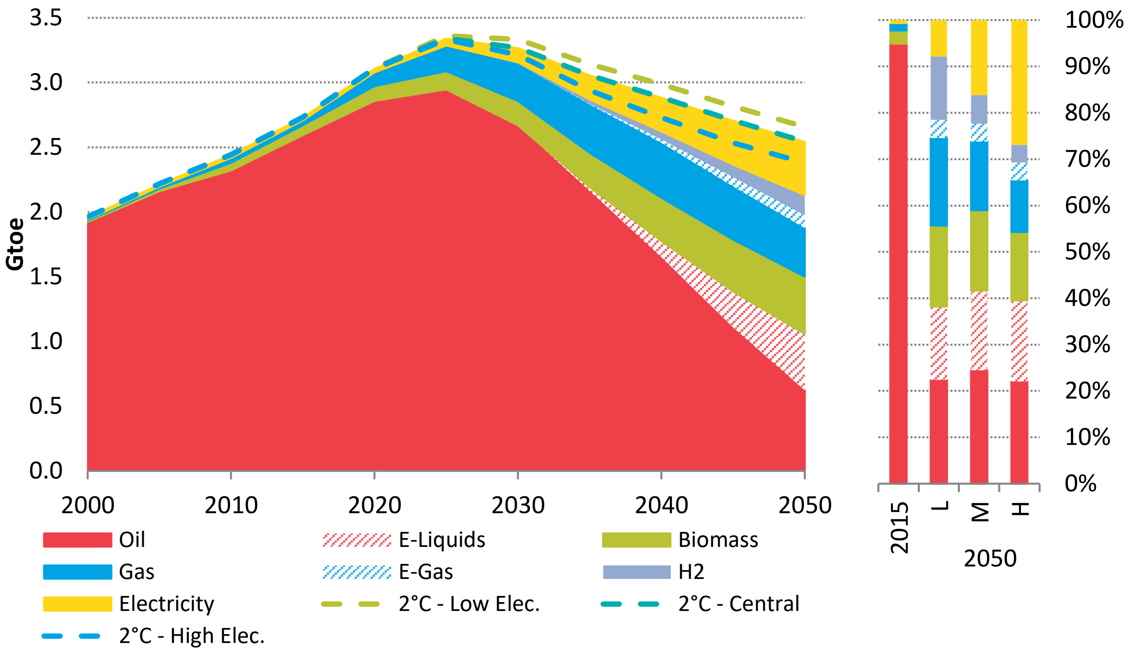
Total transport energy demand is shown in **Figure 21**. Total demand is projected to stabilize first and then decrease, principally as a consequence of important efficiency improvements in powertrains especially for road and air transportation. The overwhelming share of oil products will diminish over time, these fuels being substituted by alternative fuels: liquids (biofuels, e-fuels) and gases (natural gas, synthetic methane) in vehicles with internal combustion engines (ICE) as well as alternative powertrains (hydrogen fuel cells, electric motors), the latter progressively gaining market relevance across the electrification scenarios. Therefore the path to decarbonisation of the transport sector will be reached through electrification but also with the substitutions of liquids and gas fossil fuels by low carbon options as E-gas, E liquids, Biomass and H_2.

TRANSPORT

		2015	2050 LOW	2050 MEDIUM	2050 HIGH
ACTIVITY	PRIVATE CARS Tpkm	31.9	60.9	60.1	59.9
	PUBLIC TRANSPORT Tpkm	18	39.4	39.7	40
	AIR TRANSPORT Tpkm	10.6	22.9	22.7	22.6
	TOTAL FREIGHT TRAFFIC Ttkm	121.7	225	220	217.5
ENERGY	TOTAL TRANSPORT ENERGY USE Gtoe, % of total final energy use	2.7 28%	2.7 27%	2.5 26%	2.4 25%
	ELECTRIFICATION % of energy use	1%	8%	16%	27%
	ELECTRICITY CONSUMPTION TWh	300	2400	4800	7400
	DIRECT RENEWABLE PARTICIPATION (BIOFUELS) % of energy use	3%	18%	17%	15%
	E-FUELS IN LIQUIDS AND GAS USE % of total transport	0%	25%	27%	31%
	ENERGY INTENSITY: PRIVATE CARS kgoe / kpkm	33.3	15.2	14.5	13.3
	ENERGY INTENSITY: HEAVY TRUCKS kgoe / ktkm	27.1	11.2	10.6	9.9
EMISSIONS	CO$_2$ EMISSIONS GtCO$_2$, % of total CO$_2$	8.0 24%	3.0 31%	2.8 29%	2.2 25%
	CARBON INTENSITY OF ENERGY BY PASSENGER CARS tCO$_2$ / toe	3.0	1.9	1.7	1.4
	CARBON INTENSITY OF ENERGY BY HEAVY VEHICLES tCO$_2$ / toe	3.1	2.1	2.3	2.0
TECHNOLOGIES	PLUG-IN HYBRID AND FULL ELECTRIC: PRIVATE VEHICLES % share in stock	0%	24%	50%	65%
	PLUG-IN HYBRID AND FULL ELECTRIC: HEAVY VEHICLES % share in stock	0%	2%	10%	30%
ECONOMICS	TOTAL COST OF OWNERSHIP OF ELECTRIC VEHICLE (OVER ICE)	$ $ 200%	$ 100%	$ 93%	$ 85%

Note: Light vehicles consist of passenger cars and vans; heavy vehicles consist of busses and trucks. Total cost of ownership includes the purchase cost of the vehicle (amortised over its lifetime with a discount rate and fuel costs; here it is expressed as a ratio over the total cost of ownership of an ICE vehicle. E-fuels refer to fuels from Power-to-Gas and Power-to-Liquids.

Figure 21. World final energy consumption of transport by fuel, 2°C-Medium scenario



Note: International aviation and maritime bunkers are included. E-fuels separated into e-liquids and e-gas. Coal consumption small at world scale (<5 Mtoe).:(POLES-JRC model).

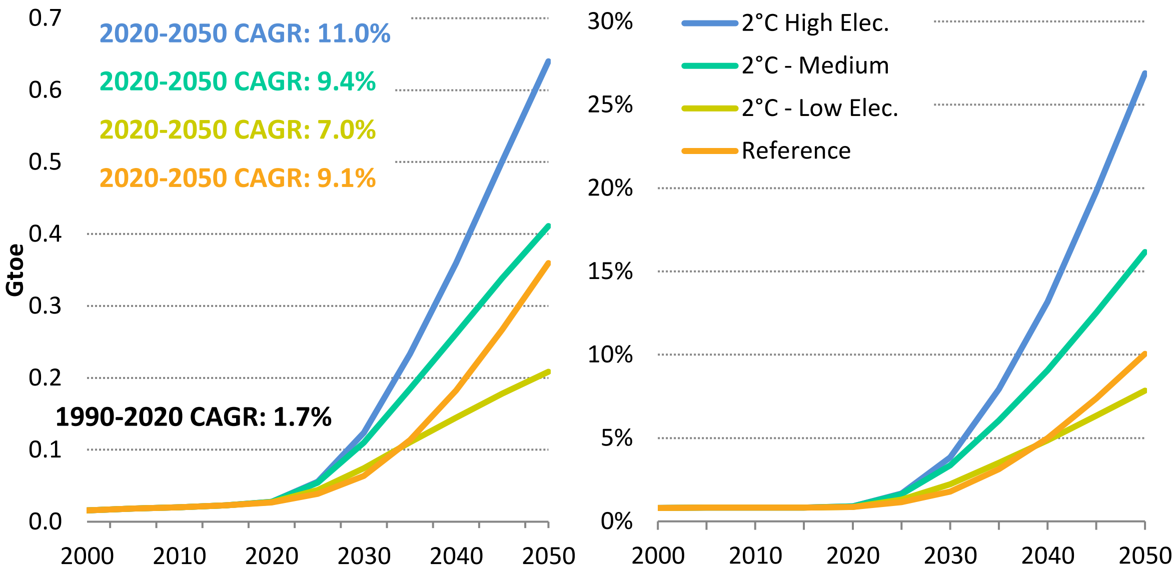
As it starts from a close-to-zero electricity market share in final energy terms, transport is the sector with the highest expected relative increase of electrification over the coming decades. Electrification in transport is defined here as the share of electricity used in the sector's final energy consumption, and does not refer to the type of fuel consumed by the propulsion motor itself. In particular, fuel cell vehicles, where methane or hydrogen is used to produce electricity to propel an electric motor, are not accounted in electrification; such vehicles would appear in the final energy mix within the methane or hydrogen share. In addition, e-fuels (synthetic liquids or Power-to-Liquids, and synthetic methane, or Power-to-Gas) require electricity for their manufacturing, however they are accounted as liquids in final energy demand; the energy for their manufacturing is accounted for in the energy transformation sector.

A strong increase of electricity consumption can be already observed in the Reference scenario, despite the fact that the scenario does not include strong climate policies.

- Reference: the electrification share rises from 1% in 2017 to 10% in 2050, a 9p.p increase in share over 2017-2050
- 2°C-Medium in 2050: the electrification share reaches 16% (+6p.p vs Reference), a 15p.p increase in share over 2017-2050
- Low to high 2°C sensitivities electrification scenarios in 2050: the electrification share ranges from 7.8% to 27% (-2p.p to +17p.p vs Reference)
- The transport sector in the 2°C-High scenario consumes 3 times as much electricity as the 2°C-Low scenario

Transport electricity consumption and transport electrification share are shown in **Figure 22**.

Figure 22. World final electricity consumption in transport (left) and share of electricity (right) in total transport energy consumption

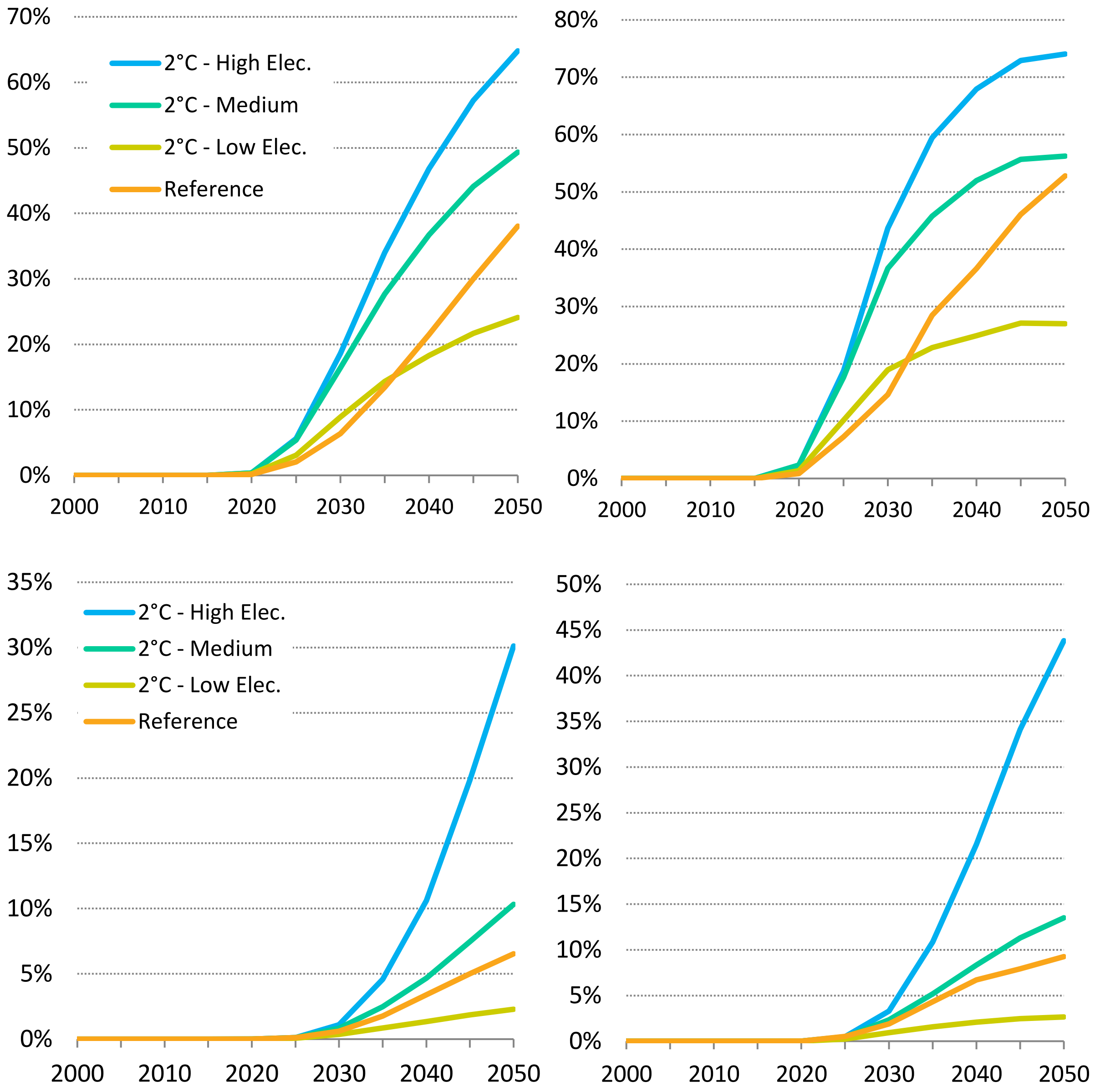


Note: International aviation and maritime bunkers are included. (POLES-JRC model)

The bulk of the electrification process expected in transport would be taking place in land-based transport. Electrification in water transport and aviation may take place in short-to-medium range ferry and charter services, relying on the availability of battery racks powerful enough to provide an appropriate energy delivery, and backed by a regular operation schedule that would ease the recharging process. For waterborne transport, there is evidence that such technology combination is closer to commercial breakeven. For short-haul aviation, while showing interesting potential, expected technology maturity does not allow a significant industrial deployment over the next 10-15 years. Long-haul maritime transport and aviation (which is the fastest growing transportation mode in the projected time horizon) have little electrification potential considering the technology portfolio assumed in this report. The focus of the rest of this section will be on land transport, and road transport in particular. The macroeconomic impacts of road transport electrification are discussed in **section 4.2**.

Overall, for LDVs, the 2°C-High scenario presents a higher penetration of BEVs and PIHVs, the 2°C-Low scenario presents a stronger persistence of ICE vehicles and a higher penetration of FCVs, and the 2°C-Medium scenario presents a more varied picture with several technologies for powertrains co-existing (see **Figure 24**). Historically, road transport has been largely dominated by a single type of powertrain and fuel type. The projected development of multiple supply chains for multiple fuels simultaneously might prove challenging, both economically (density of supply/recharging points) and in terms of consumer preference (practicality); thus, it is possible that the structure of road transport technologies might stabilize towards the dominance of a single fuel, rather than shifting towards multiple fuels with no prevalence of one over another. For HDVs, the picture is less contrasted, without a clear majority “winner” across all scenarios and a stronger persistence of ICE technologies; thus, the fuel supply chain and infrastructure planning for the decarbonisation of road transport as a whole is a complex issue.

Figure 23. Market shares in road transport vehicles, LDVs (top) HDVs (down) electric (battery-electric and plug-in hybrids): total stock (left), new annual sales (right), World



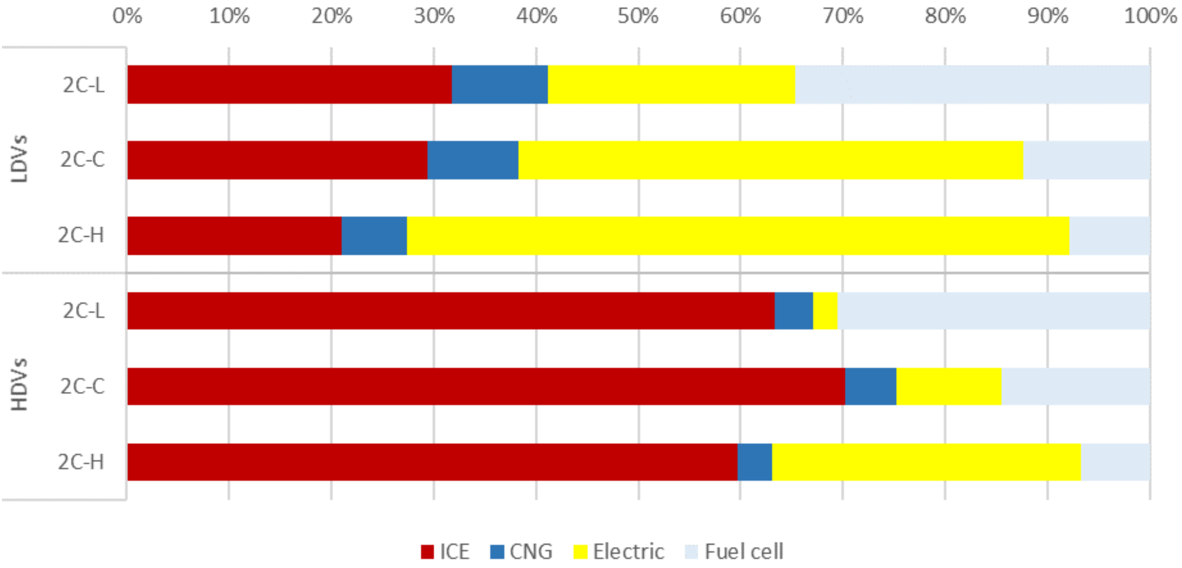
Note: Light vehicles consist of passenger cars and vans; heavy vehicles consist of busses and trucks. (POLES-JRC model)

Fully electric vehicles with batteries (BEVs) start representing a large share of total annual sales in the 2020-2030 decade, with light-duty vehicles (LDVs, i.e. private cars and vans) leading the way compared to heavy-duty vehicles (HDVs, i.e. lorries and busses), see **Figure 24.**

- At the global level, BEVs occupy over 25% of LDV annual sales in 2030 and 40% in 2050 in the 2°C-Medium scenario, as much as 60% in 2050 in the 2°C-High scenario (which includes low battery costs assumptions); BEVs could represent as much as half the total LDV stock by 2050.
- On the contrary, HDVs would remain less prone to technological substitution: BEVs represent 1-23% market share in total stock in this subsector by 2050. This uptake would mostly be driven by electric busses and short-distance trucks used in the urban environment. However, the foreseeable evolution of the battery power/weight ratio often needed for HDVs involving very long distance trips sheds some doubts on the technology uptake speed, for lorries and coaches.
- Hydrogen-powered fuel cell vehicles sales slowly start in the 2020-2030 decade and come to represent 11-13% of total LDV stock by 2050. That share is somewhat higher in HDVs, 14%, given

the lower propensity of some HDV segments (long-range lorries) to adopt battery-electric vehicles. With higher battery costs in the 2°C – Low Electrification scenario, the push to decrease emissions would be met with a higher penetration of hydrogen fuel cells in the HDV stock, 31%.

Figure 24. Market shares in road transport vehicles, in the total stock in 2050, world, in the three 2°C scenarios



Note: ICE vehicles include range extension hybrids; Electric consists of battery-electric vehicles and plug-in hybrids; Fuel cell consists of fuel cell vehicles using methane and hydrogen; LNG vehicles were not modelled.

Several factors influence the market uptake of electric vehicles.

Battery costs form a significant part of the total purchase cost of full-electric vehicles: estimated at two-thirds of the purchase cost in 2010 but decreasing to a quarter of the purchase cost in the early 2020s. Thus, battery costs are a key driving factor for the electrification of this sector. Battery cost assumptions for road vehicles are displayed in **Annex 5.**

Counterbalancing the upfront cost of vehicle purchase with its battery, full-electric vehicles have proportionally lower ***maintenance costs*** compared to ICE vehicles (see **Box 4**) and lower ***fuel use*** (few losses in electric engines and powertrains, versus an efficiency of about 30-40% in ICE due to the conversion of chemical into kinetic energy). As a consequence, variable costs (fuel and maintenance) represent >16% of the complete user cost for ICE vehicles and about 10% for BEV, while these numbers may vary depending on the country. Conversely, efforts to increase overall vehicle efficiency might impact the vehicle purchase cost, with efficiency options in the body of the vehicle for all types of vehicles (tyres, design, materials, weight) and some efficiency options specific to ICE vehicles (start and stop management, dual clutch transmission, direct injection in engine, range extension hybridisation). Moreover, climate policies might impact fuel costs (implicit or explicit carbon prices) which might reduce transport activity; this would have an impact on the amortization of costs for all vehicle types.

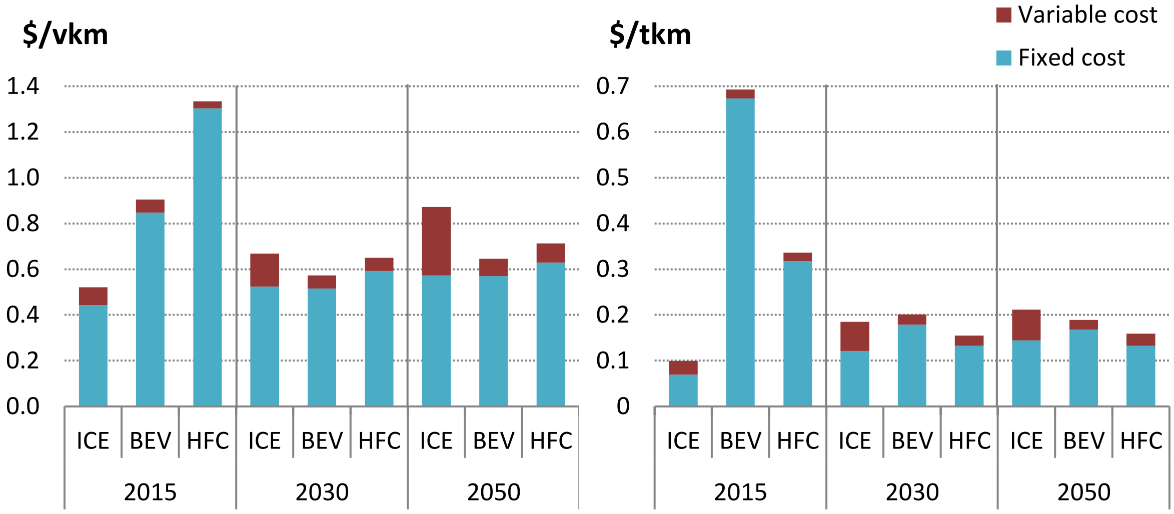
Moreover, bottlenecks for the emergence of battery electric vehicles would be related to the investments into deploying a practical network of ***charging points*** with sufficient speed to satisfy the increasing capacity of quick charging devices. The *logistics* of mass production of battery packs could also become a bottleneck, with the need for new industrial-scale supply chains for primary lithium production and battery components. Such bottlenecks might influence the overall availability of electric vehicles and the user perception of them as attractive competitors to ICE vehicles.

Finally, for specific market segments, like long-haul transport, ***other fuels or technologies*** might be more relevant, such as ICE vehicles using biofuels or e-fuels and fuel cell vehicles.

Other **behavioural factors** might also influence the development of the passenger cars market, including changing values regarding car ownership or consequences of ICT and connected vehicles (car-sharing, autonomous driving)[15].

With the cost decrease of batteries and the market dynamics of the 2°C-Medium scenario, the breakeven point for BEVs with ICEs for total user cost in LDVs is expected in the near future, already ongoing in many markets. For HDVs, the battery size hinders BEVs from becoming more competitive; HDVs powered by hydrogen fuel cells emerge as the next most economically attractive option beginning from the 2020-2030 decade (**Figure 25**).

Figure 25. Total cost of ownership of LDV transport (left) and HDV transport (right), USA as example, 2°C-Medium scenario



Note: Costs in real USD (2015) include the purchase cost of the vehicle, amortised over its lifetime (typically 12 years) with a discount rate (12% for LDVs, 9% for HDVs), and fuel costs (for a given year, adjusted for powertrain and vehicle efficiency, all taxes included), over the vehicle's use in a year (region-dependent).

In terms of GHG emissions, the attractiveness of BEVs compared to ICEs is dependent on how clean power generation is if indirect emissions in power generation are to be taken into account. Considering the whole well-to-wheel cycle[16], BEVs would emit less than ICEs already from the early 2020s as a world average, due to the quick effects of the decarbonisation of the power sector in both Reference and 2°C scenarios (**Figure 26**). Indeed, the technological richness of power generation allows the power sector to reduce its emissions at a fast pace, resulting in decreasing indirect emissions for BEVs. Conversely, in ICE vehicles, where thermal conversion efficiency directly translates into carbon emissions, emissions from ICE decrease more progressively; ICE efficiency improvements are more gradual.

While this is already the case in many markets (EU, USA), this is not yet true everywhere: for example, BEVs would not emit less in China before 2050 in the Reference scenario and before 2030 in the 2°C scenario with the decarbonisation of the power sector.

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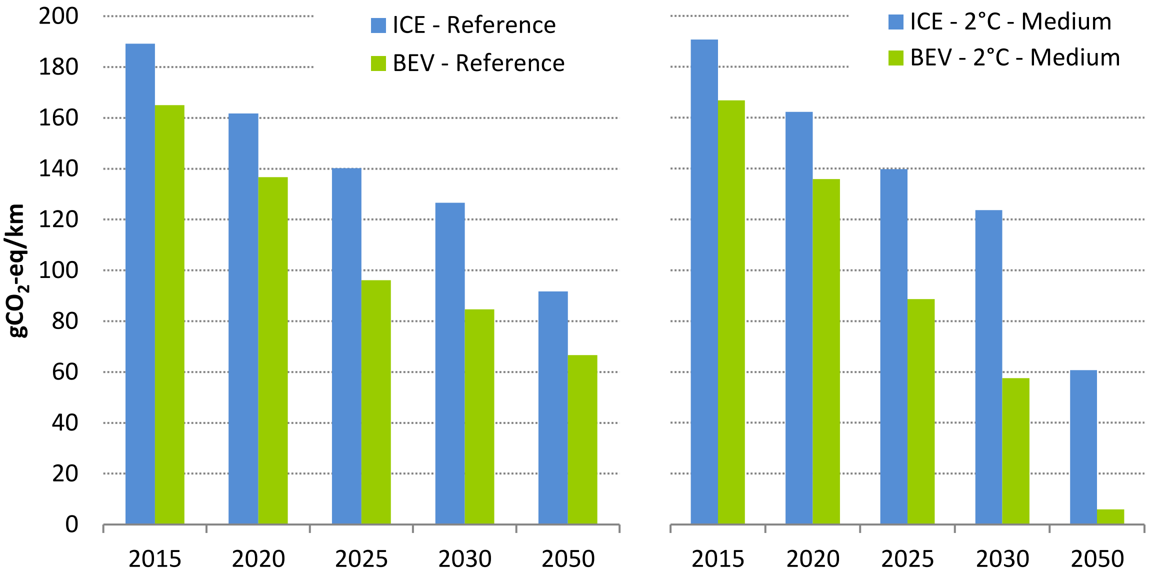
(15) See (Alonso Raposo, et al., 2019) for a comprehensive overview of the implications from automated, connected, low-carbon and shared mobility.

(16) Considered here are direct exhaust emissions for ICE (CO_2) and indirect emissions from oil extraction for ICE (CH_4) and from power generation for BEV (CO_2). Other indirect emissions, such as emissions from mining materials needed to construct batteries for BEV are not considered.

Figure 26. Emissions of LDVs (gCO_2-eq/km), consisting in direct exhaust emissions for ICE and indirect emissions from oil extraction for ICE and from power generation for BEV, World average, 2°C-Medium scenario



Source: POLES-JRC model.

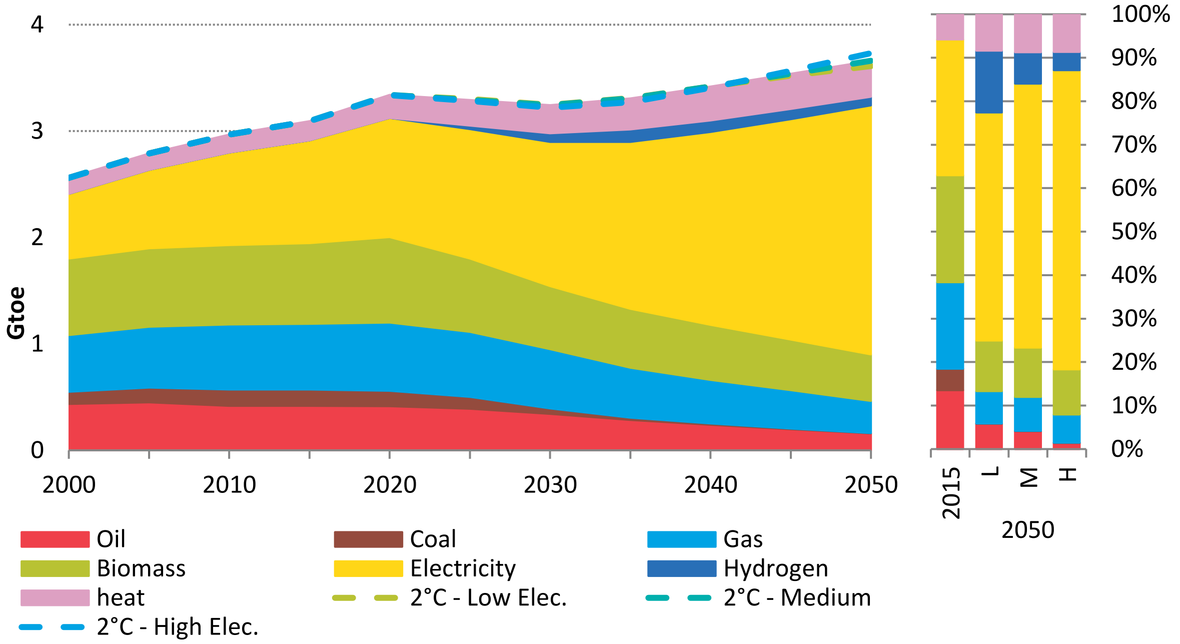
Further decarbonisation in road transport is projected with the use of alternative fuels. By 2050 in the 2°C-Medium scenario, liquid e-fuels (30%) and liquid biofuels (26%) would make up more than half of the liquids consumed in road transport; overall, liquid biofuels, hydrogen and liquid and gaseous e-fuels would make up 41% of the world's energy road transport consumption, compared to 3.7% in 2017 (all being biofuels). Thus, road transport electrification in 2050 in the 2°C-Medium scenario would be 21% if only electricity in BEVs and PIHVs is accounted; but this figure would rise to 49% if all hydrogen and e-fuels would also be included.

3.6 Electrification in final energy demand: Buildings

The buildings sector, consisting of households and commercial/services buildings, in 2015 accounted for 32% of the global final energy consumption and 8% of the total CO_2 emissions.

Total energy use in buildings is projected to increase throughout 2050 (**Figure 27**), despite significant improvements in efficiency of energy-consuming equipment and building shells insulation.

Figure 27. World final energy consumption of buildings by fuel 2°C-Medium scenario



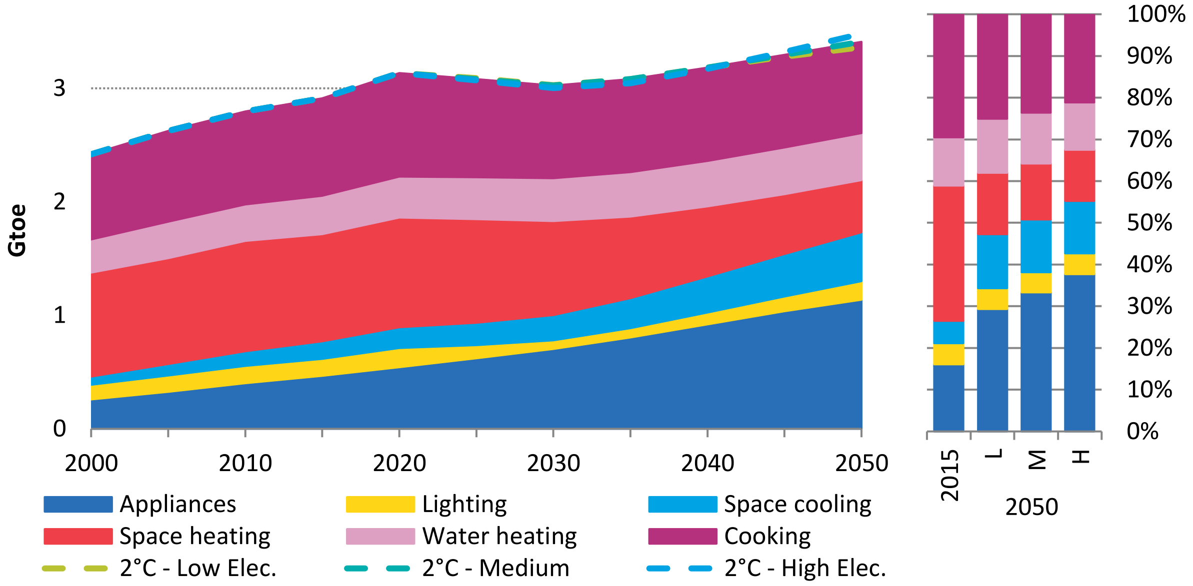
Source: POLES-JRC model.

Much of energy use takes place in captive electricity uses (space cooling, appliances, lighting): from an estimated 26% of total energy consumption in 2015 to 50.7% in 2050. Energy demand for these uses is expected to increase in the future, in particular for appliances and space cooling, due to rising living standards and associated increasing equipment rates.

BUILDINGS

		2015	2050		
			LOW	MEDIUM	HIGH
ACTIVITY	RESIDENTIAL SURFACES Gm²	152	251	251	251
	ANNUAL MARKET FOR NEW AND RENOVATED RESIDENTIAL % of total surfaces	2.4%	3.0%	3.0%	3.0%
ENERGY	TOTAL BUILDINGS ENERGY USE % of total final energy use	32%	36%	38%	39%
	TOTAL BUILDINGS ENERGY USE Gtoe	3.1	3.6	3.7	3.7
	GENERATED ON-SITE (DISTR. ELECTRICITY AND SOLAR HEAT) % of total building energy use	2%	15%	22%	25%
	ELECTRIFICATION % of energy use	31%	59%	64%	71%
	ELECTRICITY CONSUMPTION TWh	11200	24600	27200	31000
	DISTRIBUTED PV % of electricity consumption in buildings	1.3%	17.6%	26.3%	29.1%
	DIRECT RENEWABLE PARTICIPATION % of energy use	26%	28%	33%	36%
	TRADITIONAL BIOMASS % of energy use	22%	8%	8%	8%
EMISSIONS	CO_2 EMISSIONS % of total CO_2	10%	15%	13%	9%
	CO_2 EMISSIONS $GtCO_2$	3.4	1.5	1.2	0.8
TECHNOLOGIES	DWELLINGS WITH HEAT PUMPS % of dwellings' heating systems	0%	14%	16%	19%
ECONOMICS	ENERGY EXPENDITURE (BILL) PER DWELLING $ / month / dwelling	53	194	214	203

Figure 28. World final energy consumption of buildings by end-use, 2°C-Medium scenario



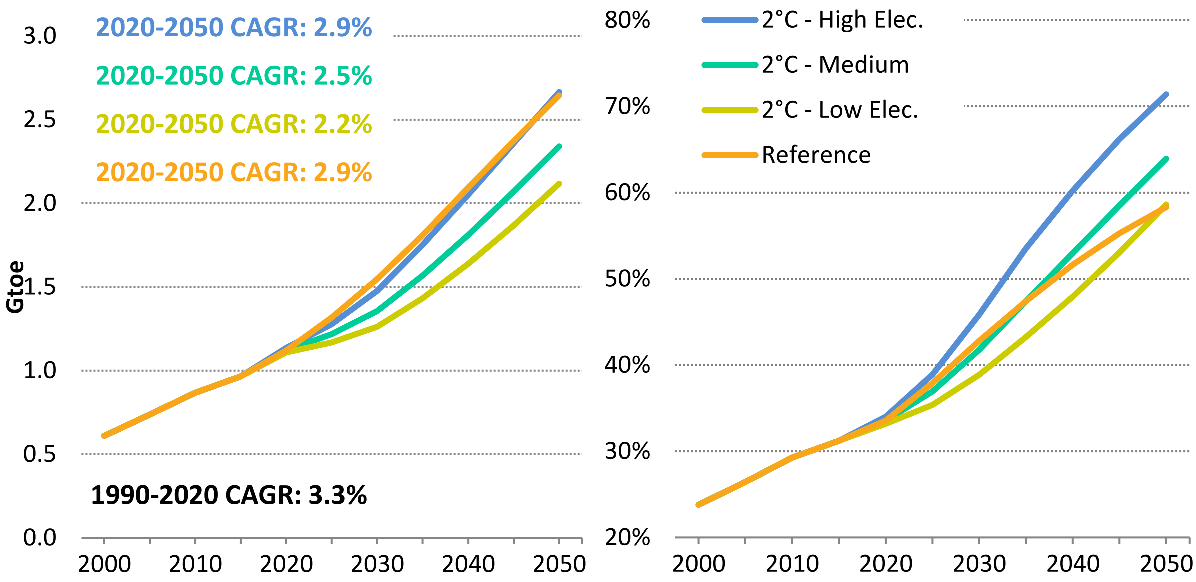
Source: POLES-JRC model.

The remaining 74% of total energy demand (as of 2015) corresponds to thermal uses: space heating, water heating and cooking. Thermal energy services are expected to grow faster than the corresponding energy consumption. On the one hand, energy demand in these uses has a large energy efficiency improvement potential, the performance of new equipment being well above that of the existing stock, with further ameliorations expected on many applications (conventional to condensing boilers, cooking ovens etc). The role of technology standards and similar policies (Ecodesign, etc) is important. On the other hand, fuel substitution in residential thermal uses will substantially support the GHG footprint of the sector, in particular for what concerns space heating. Less efficient coal and diesel oil-fuelled systems would be replaced by natural gas boilers and heat pumps, becoming the preferred options for new installations and/or retrofits.

As a consequence of this, the electrification rate of final energy demand in buildings increases in all the scenarios considered (see **Figure 29**):

- Reference: from 32% in 2017 to 58% in 2050, a 26p.p increase over 2017-2050
- 2°C-Medium in 2050: 63% (+5p.p vs Reference), a 31p.p increase over 2017-2050
- 2°C sensitivity variants in 2050: range from 59% to 71% (+1p.p to +13p.p vs Reference)
- Low to high 2°C sensitivities electrification scenarios spread: 25% increase in final electricity consumption

Figure 29. Global final electricity consumption in buildings (left) and share of electricity (right) in total buildings energy consumption



Source: POLES-JRC model.

Figure 30 reports the increasing electrification in thermal uses at global level. Electrification is higher when referred to useful energy[17] than to final energy, due to efficiency gains in the various equipment used to provide the energy services: space heating, water heating, cooking. This also results in a wider spread across the sensitivity scenario variants in terms of useful energy. Indeed, comparing useful and final energy use:

In cooking, the spread of results in electrification between scenarios is mainly related to biomass availability for the buildings sector, which is most restricted in the 2°C-High scenario: the accelerated phase-out of low-efficiency traditional biomass (about 20% efficiency) results in the use of higher-efficiency gaseous fuels (about 80% efficiency) or electricity (close to 100%).

In space heating, the higher electrification values in useful energy compared to final energy are mainly related to the adoption of heat pumps. The seasonal coefficients of performance (COP) of air heat pumps are expected to grow from about 2.75 in 2015 to 4 in 2050 for USA, average EU and China (values reflecting averages across the different sub-regional climates for these regions; heat pumps operate less efficiently in colder climates see **Annex 5**).

In water heating, the spread is smaller, as the fuel options are of relatively close efficiency (typically, about 80% for gas boilers, close to 100% for electric boilers and solar water heaters).

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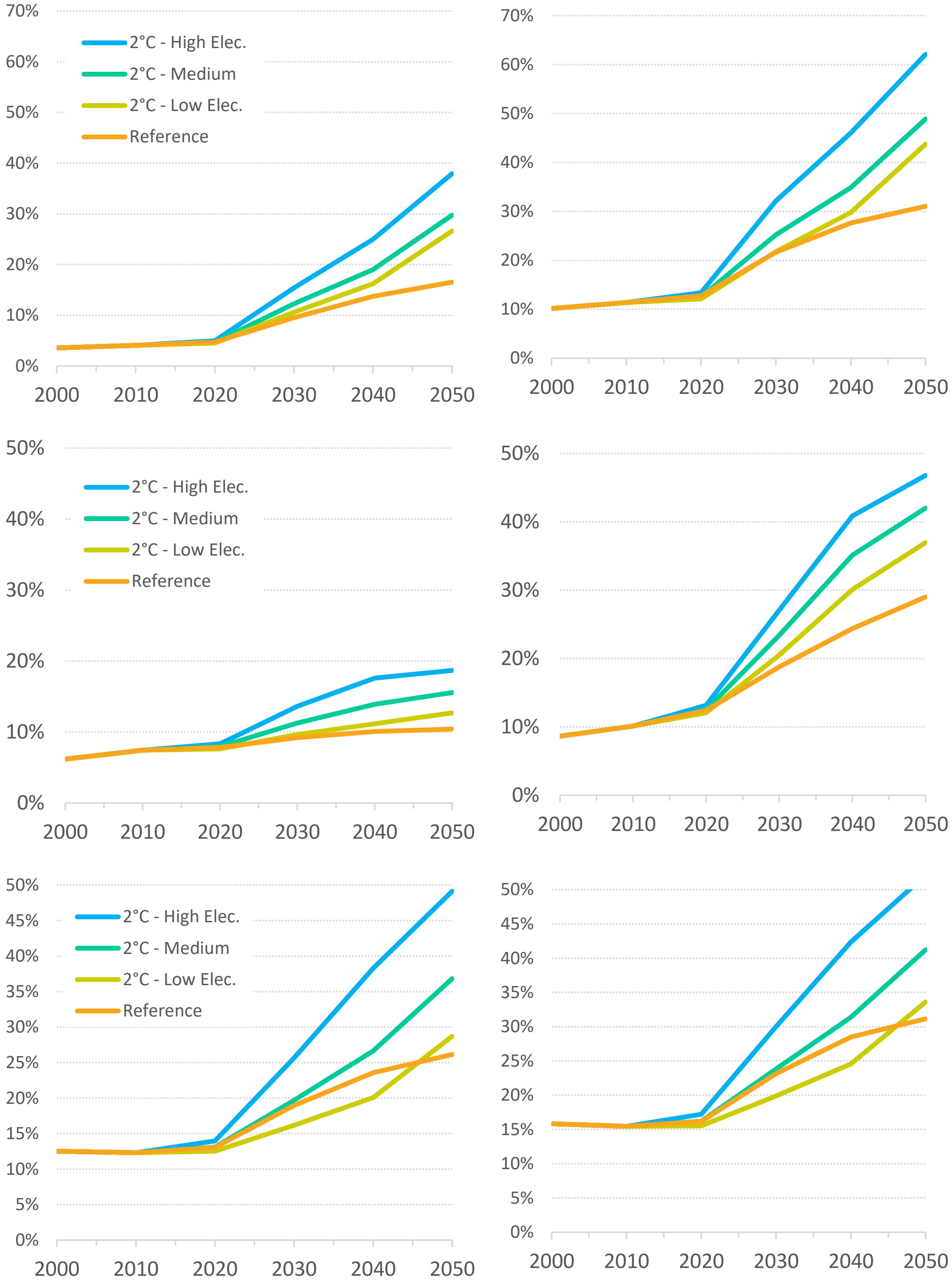
(17) Useful energy refers to the energy actually available to provide the required energy service. The combustion of fuels (accounted in final demand) is done with a certain technological efficiency, which results in actual available energy (useful energy) that is lower; heat pumps have “efficiencies” (coefficient of performance) higher than 100% as the electricity consumed (final energy) makes use of a an external energy source not accounted in energy balances (typically, heat in ambient air in air-air heat pumps).

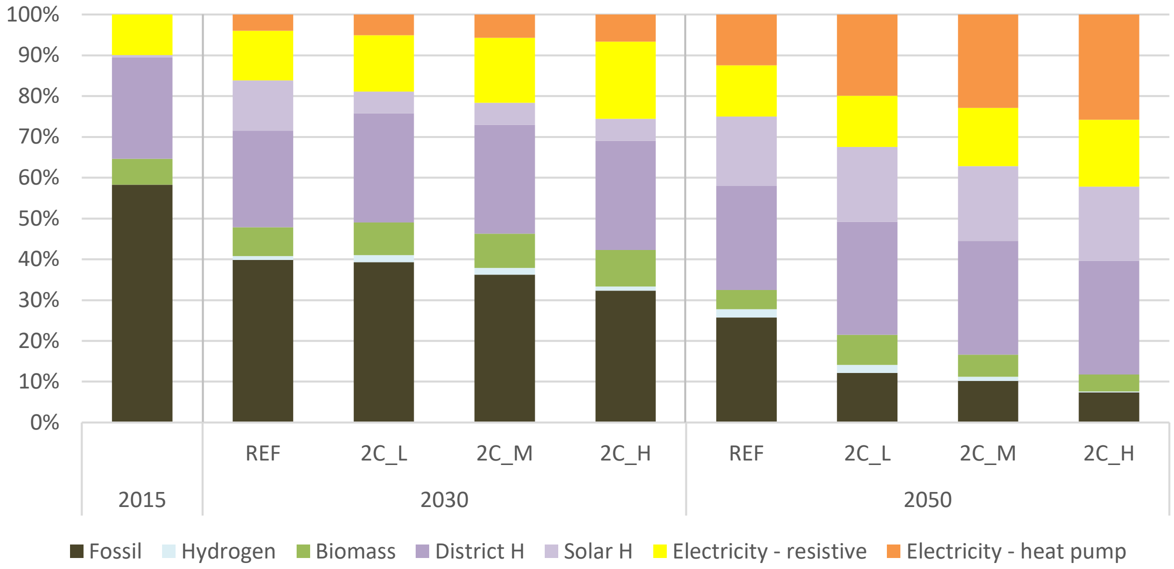
Figure 30. Electrification by thermal end-use in buildings: share of electricity; in World final energy (left) and in World useful energy (right); cooking (top), space heating (middle), water heating (bottom)



Source: POLES-JRC model.

These low-carbon pathways with strong electrification heavily rely on the deployment of heat pumps for space heating, which undoubtedly represents the key technology in this sector. Heat pumps have the potential to substitute heating systems that most often rely on fossil fuels thanks to its high efficiency, it is a solution that is adopted in all climates and in both new and retrofit buildings. Indeed accelerated retrofitting can be a facilitator for installing heat pumps systems, especially in countries where there is little new real estate compared to the existing stock (countries with low demographic growth and weak demand for new dwellings). It can replace also the standard electric heating systems, without additional infrastructure needs and lower running costs. Its gradual adoption results in a market share in heating systems of as much as 20% by 2050 (**Figure 31**).

Figure 31. World market share of equipment in residential space heating systems



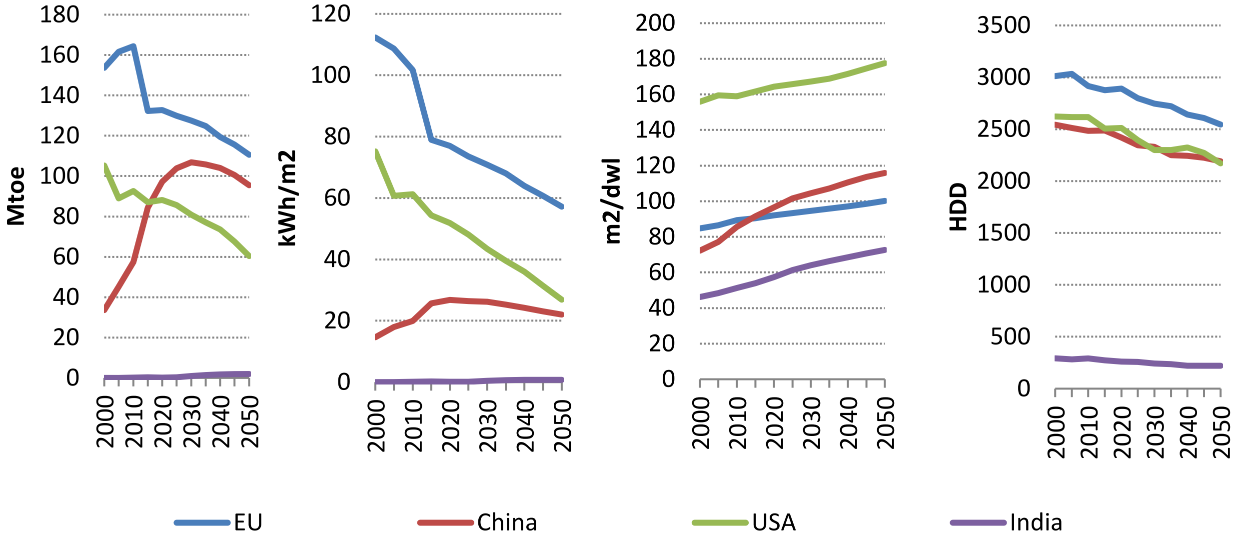
Note: Only countries with HDD values of more than 500 were used, to remove countries in low latitudes with little needs for space heating. See **Annex 5** for more information on HDD assumptions.

Achieving higher levels of thermal insulation in new (and renewed) buildings might decrease final energy demand and therefore affect also electricity consumption in households. The overall impact on the electrification rate (electricity as a share of a decreasing total) is unclear, depending on the prevailing building typology and age. However, improving building thermal integrity is a key measure in the mix of decarbonisation options all over the world irrespectively of the present structure of the final energy mix in the residential sector.

Therefore, in order to make the most of the heat pump deployment as the reference technology for space heating and conditioning, the refurbishment/renovation rate must globally increase from historical levels to significantly higher figures. In all the 2°C scenarios presented here, the decarbonisation effort is supported by a progressive acceleration of building retrofitting rates, from a historical average of 0.3%/year to as much as 2%/year for the 2020-2040 decades, when the crucial decarbonisation effort needs to be implemented.

Even if investment in building thermal insulation reduces useful energy needs per unit of surface, the evolution of total useful energy needs also depends on heating needs, with the climate warming compared to today, and on dwelling size, which grows with income (**Figure 32**).

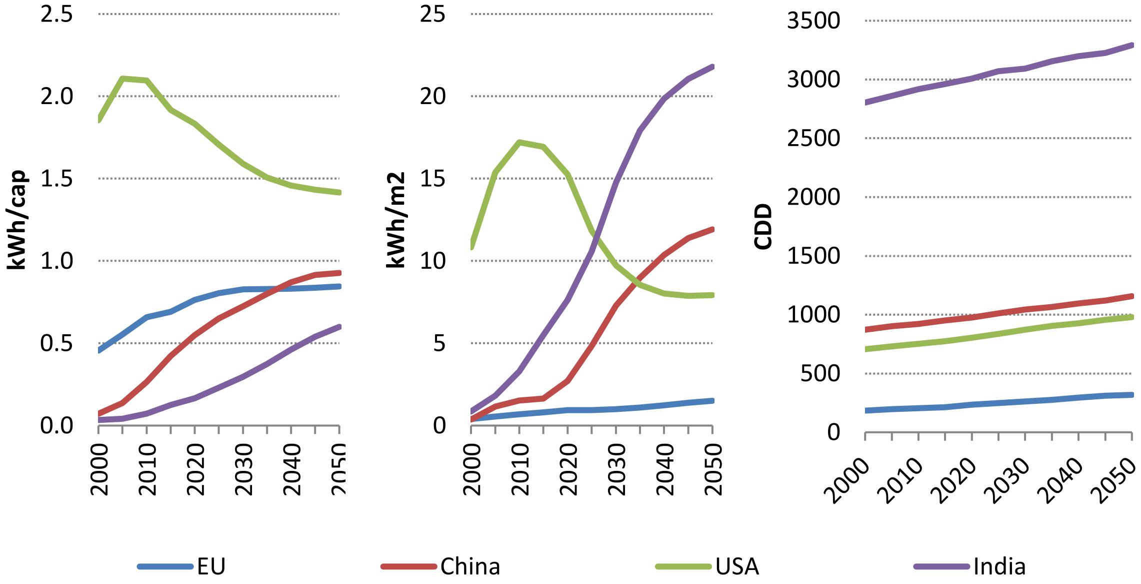
Figure 32. Total useful energy for space heating (left), useful energy per floor surface (middle-left), heating degree-days (middle-right) and average dwelling surface (right), 2°C-Medium scenario



Source: POLES-JRC model.

The strong increase of electricity demand in captive electricity uses (leisure, IT and other services) is associated to income growth. Most of that increase comes from appliances and space cooling. **Figure 33** presents electricity demand in appliances on per capita terms and space cooling per unit of dwelling surface, showing the roles of equipment rates, equipment efficiency evolution and cooling degree-days in the expected electricity demand. Indeed, despite the strong climate policies to limit global warming to below 2°C in these scenarios, a change in climate would occur, which would result in increasing cooling degree-days (CDD) across countries and regional climates (see **Annex 5** for more details); space cooling needs would also be strongly related to increasing equipment rates, particularly in emerging economies.

Figure 33. Evolution of residential electricity demand for appliances per capita (left), residential electricity demand for space cooling per unit of surface (middle) and cooling degree-days (right), 2°C-Medium scenario



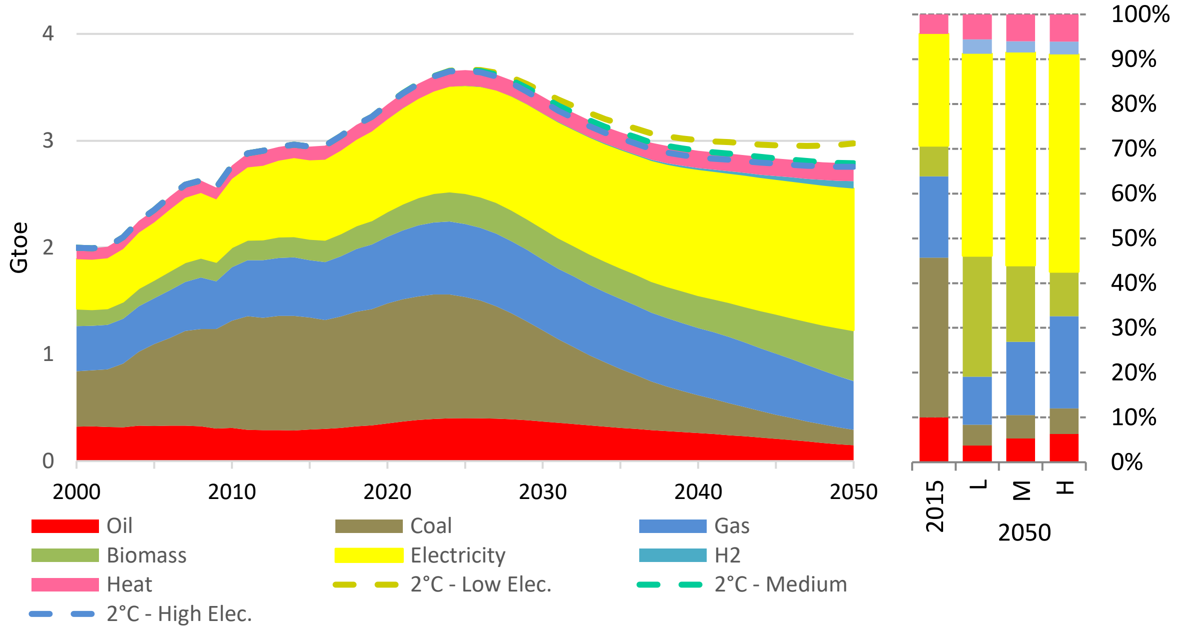
Source: POLES-JRC model.

3.7 Electrification in final energy demand: Industry

The world industrial sector accounted in 2015 for 39% of the global final energy consumption. The industrial sector consumes currently about 25% of its final energy needs as electricity. Key industrial process operate already exclusively with electricity, such as the electric-arc furnace (EAF) for secondary steel production or electrolysis for primary aluminium production. The industrial sector accounts currently for 18% of the global energy related CO_2 emissions (6.2 $GtCO_2$ of CO_2). Additionally, non-energy related process emissions are released from the chemical industry (3.0 $GtCO_2$ of CO_2 and 1.1 $GtCO_2$-eq of non-CO_2). Mitigating process emissions is more challenging, as they are intrinsic to the processes involved.

Industry's total final energy demand by fuel is presented in **Figure 34**. Total demand is projected to increase until 2025 and then decrease steadily throughout 2050, reaching 83% of the level in 2020.

Figure 34. World final energy consumption of industry by fuel for energy-uses, 2°C-Medium scenario



Note: Excludes non-energy uses. Heat consumption refers to heat supplied, mainly in form of steam, from centralized heat and power plants. (POLES-JRC model)

Industry is a sector with potential for more electrification. The electrification of the industrial sector is expected to deploy at slower pace than for the transport and building sectors, as the sector is less flexible and more dependent on investment decisions with long payback times. Indeed, operating plants have heat facilities that are already highly capital-intensive, highly integrated and efficient. Modifications in them in order to shift processes fed with fuel combustion to processes using electricity could only be considered under a cost-efficient perspective over the entire equipment's lifetime; in order to decide retrofitting or the construction of a new process line, one would have to take into account the shortened lifetime of existing equipment, availability of capital, as well as aversion to process disruption.

INDUSTRY

		2015	2050 LOW	2050 MEDIUM	2050 HIGH
ACTIVITY	VALUE ADDED tn$	32	82	82	82
ENERGY	TOTAL INDUSTRY ENERGY USE % of total final energy use	39%	37%	36%	36%
	TOTAL INDUSTRY FINAL ENERGY CONSUMPTION, FOR ENERGY USES Gtoe	3.8	3.7	3.5	3.4
	TOTAL INDUSTRY FINAL ENERGY CONSUMPTION, FOR NON-ENERGY USES Gtoe	0.8	0.7	0.7	0.7
	ELECTRIFICATION % of energy use	19%	37%	38%	39%
	ELECTRICITY CONSUMPTION TWh	8500	15600	15400	15500
	DIRECT RENEWABLE PARTICIPATION % of energy use	5%	22%	14%	8%
EMISSIONS	CO_2-ENERGY EMISSIONS % of total CO_2-energy	19%	17%	22%	28%
	CO_2-ENERGY EMISSIONS GtCO_2	6.2	1.6	2.1	2.5
	CO_2-PROCESS EMISSIONS GtCO_2	3.0	4.7	4.7	4.7
	NON-CO_2-PROCESS EMISSIONS GtCO_2e	1.2	0.3	0.3	0.3
ECONOMICS	ENERGY INTENSITY OF VALUE ADDED toe / M$2015	119.5	44.6	42.3	41.8
	ELECTRIC INTENSITY OF VALUE ADDED toe / M$2015	23.1	16.3	16.1	16.3

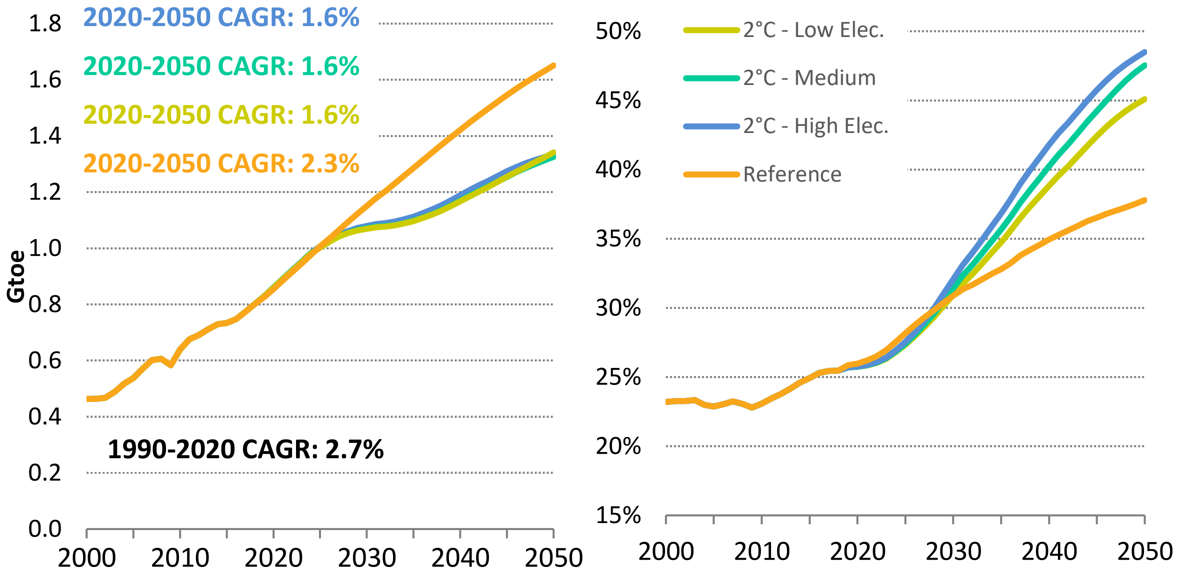
Note: Non energy uses cover those fuels that are used as a raw material for producing industrial products (e.g. polymers) and not to be transformed into other fuels or for any energy purpose.

Accordingly the scenarios studied reflect an increasing electrification in industry (excluding non-energy uses), see **Figure 35**:

- Reference: from 25% in 2017 to 38% in 2050, a 13p.p increase over 2017-2050
- 2°C-Medium in 2050: 48% (+10p.p vs Reference), a 23p.p increase over 2017-2050
- 2°C sensitivities in 2050: range from 45% to 48% (+7p.p to +10p.p vs Reference)
- There is a small differentiation between 2°C sensitivities in final electricity consumption (0.4% spread)

Despite a higher electrification share in the 2°C scenarios, final electricity consumption is lower than in the Reference scenario, due to higher energy efficiency that reduces the overall energy needs in industry as modelled in the 2°C scenarios.

Figure 35. World final electricity consumption in Industry (left) and share of electricity (right) in total industry energy consumption



Note: Excludes non-energy uses. (POLES-JRC model)

Already existing electricity process in industry will be improved in order to become more energy efficient and to emit less GHG.

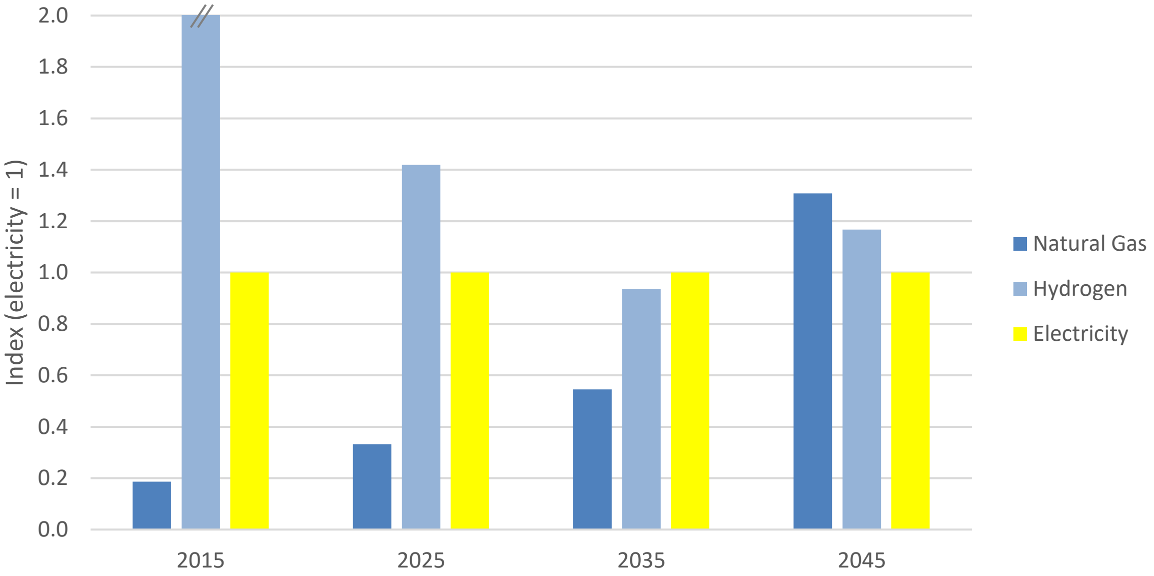
Examples:

- In the chemical industry, the chlor-alkali process consumes about 30% of the electricity in the chemical sector (Boulamanti & Moya, 2017). By employing high-performance bipolar membrane technology, energy efficiency could be improved substantially (Brinkmann, Giner Santonja, Schorcht, Roudier, & Delgado Sancho, 2014).
- Another example is the production of primary aluminium by electrolysis where process improvements will result in the substitution of the currently used carbon anode by an inert anode (U.S. Department of Energy (DOE), 2017). As a consequence, the process will not only consume less electricity, but will also avoid any non-energy related process emissions of perfluorocarbons (PFCs) and of CO_2 (consumption of the carbon anode).

Furthermore, it is very challenging to electrify high temperature (or high enthalpy) processes in energy-intensive (EI) industrial branches such as iron & steel, chemicals, non-ferrous metals and non-metallic minerals.

The *direct electrification* of high temperature processes (>600 °C) could be an option. Electric processes would be even more energy efficient due to better heat transfer; such processes are in use already today but mainly at very specific points in larger processes, for instance in glass melting (artificial glass, glass wool) or induction heating of metals. The main obstacle for a larger scale electrification of process chains would be electricity prices, which have been higher than those of competing fuels (see **Figure 36**).

Figure 36. Price comparison for natural gas, hydrogen and electricity for industry, USA, 2°C-Medium scenario

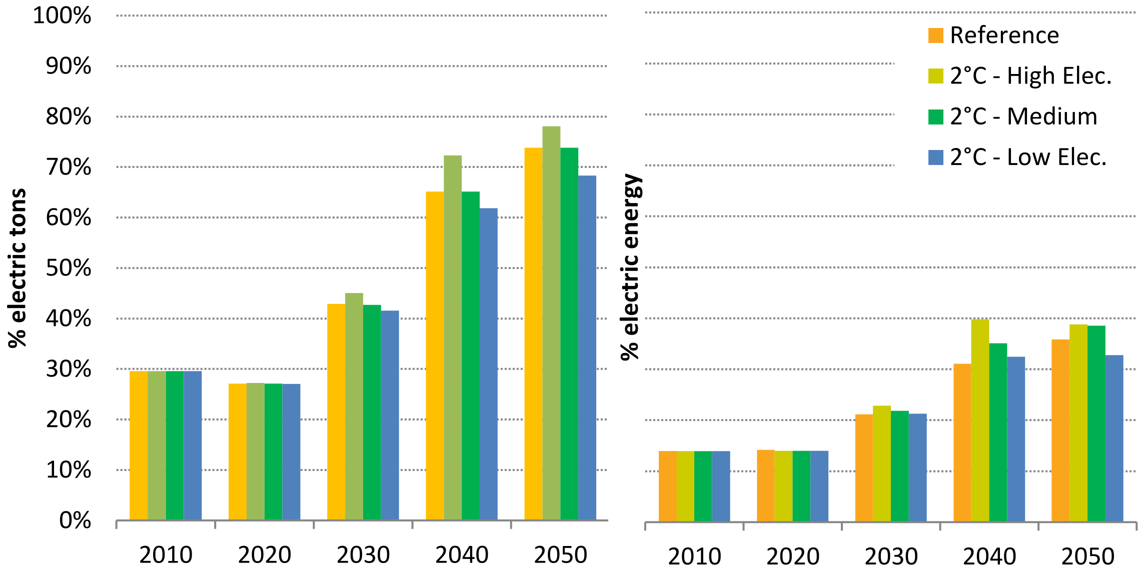


Note: Prices are indexed to electricity price for each year. Carbon prices impact natural gas prices directly and hydrogen and electricity prices indirectly through the pricing of the inputs to their production. Technology learning for select hydrogen and power technologies impacts their production costs. Climate policies in the 2°C-Medium scenario are modelled only via a carbon price on emissions; countries would be able to choose along a number of policy options to reduce emissions in this sector (carbon permit, carbon tax, low-carbon energy obligation in the fuel mix, standards, etc...). Hydrogen values for 2015 and 2025 from estimate and ambitious target for price at the pump, respectively, from US Department of Energy (IRENA, 2018); 2015 level for hydrogen at 6.1 versus electricity.

Synthetic fuels produced by renewable electricity (or solar heat) could play an important role to electrify *indirectly* the energy intensive industry; synthetic fuels to be used are *hydrogen* and *synthetic methane* (Power-to-Gas, or e-gas). The penetration of synthetic fuels will be driven by technological learning and deployment, and its competitiveness compared to other fuels such as natural gas. Price competitiveness and speed of scaling up would be the crucial issues determining the technology substitution processes (as exemplified in **Figure 36**).

Hydrogen could be produced from a number of sources, with gas steam reforming being one of the most cost-competitive sources currently; as natural gas prices become affected by carbon prices and technological learning brings costs for other options down, hydrogen production in the 2°C scenarios progressively moves towards biomass-based, solar heat-based and electricity (electrolysis from grid or dedicated wind) options. Synthetic methane production would come at a further additional cost of procurement of CO_2 from large combustion plants flue gas carbon capture or from direct CO_2 air capture, however it has the advantage that the current industry infrastructure based on methane could still be used.

Figure 37. World share of steel production with electric arc furnace (left) and electricity share in total iron and steel industry energy demand (right)



Source: POLES-JRC model.

Another decarbonisation option relies on increased *recycling* and a widespread implementation of the so-called *circular economy*, which can decrease total energy needs and increase the role of electricity as a share of the total. The end-of-life recuperation of equipment can be fostered so as to increase recycling rates and decrease the need for primary materials extraction and transformation; in many cases, recycling is a less energy-intensive process than primary production and can be more easily electrified, with limited impact on product quality. For instance, an increasing recycling rate of steel is accompanied by an increase in the electrification of total steel production (**Figure 37**).

Finally, solid *biomass* combustion can come as substitute to certain fossil fuels. However, biomass presents a lower energy density than other combustion fuels, which might be an issue in reaching the high temperatures required by certain processes.

Examples:

- In the iron and steel sector, primary steelmaking has mainly involved blast furnaces using coal and coke, while secondary (recycled) steelmaking makes use of electric arc furnaces (EAF, reaching temperatures up to 1800°C) and is nearly carbon-free. For primary steelmaking, an alternative and already established technology is the Direct Reduced Iron route (DRI) which uses as reducing agent natural gas or even hydrogen. Subsequently, the iron produced from DRI is refined by an EAF process using electricity. The high temperature processes further down the process chain in steelmaking (e.g. rolling) could also use synthetic fuels.
- In the chemical industry, ammonia synthesis requires about 5% of the sector's energy consumption (Boulamanti & Moya, 2017) and accounts for about 20% of the CO_2 emissions of the chemical industry. Currently, this process uses mainly natural gas, which is first transformed into hydrogen as an intermediate step. Therefore, the use of low-carbon synthetic methane or directly of green hydrogen could play an important role to indirectly electrify this process.

About 50 to 100% of the total heat demand in non-energy intensive industrial sectors are low temperature processes such as paper, wood, food, textiles and manufacturing refers to heat in the range of 60-150 °C (DENA, 2016), (Naegler, Simon, Klein, & Gils, 2015). Even in the chemical industry, about 25% of the total heat demand is low enthalpy heat.

Heat pumps are a very promising option to promote the electrification of the low enthalpy heat demand. The expansion of heat pumps depends on the availability of waste heat which calls for a further integration and optimisation of heat flows at industrial sites. Moreover, with technology progress heat pumps are expected to become more efficient and extend the temperature range over which they can operate (Arpagaus, Bless, Uhlmann, Schiffmann, & Bertsch, 2018), (Wolf, Fahl, Blesl, Voss, & Jakobs, 2014). As a result, a further penetration of heat pump use is very likely.

Drying processes refer to a substantial part of energy consumption at low temperatures. A range of drying technologies using electricity instead of combustion of fuels are already in use: microwave heating, infrared drying, UV drying (coatings). The shift to electric processes is often motivated not by energy savings, but in order to allow faster processing time or more targeted treatments.

Market-mature technologies for shifting heat demand from fossil fuel combustion toward electricity are already used today and are expected to expand further: electric-arc, heat pumps, induction, resistance, infrared, radio-frequency, microwave heating, etc. Promising innovative technologies such as laser, electron-beam and plasma-arc heating are emerging and would need to be further developed.

Hydrofluorocarbons (HFCs) are accounted as emissions in the industrial sector and currently refer to about 65% of the non-CO_2 emissions from industry. HFCs are very potent greenhouse gases: the global warming potential (GWP) of HFCs is typically a factor of thousand compared to CO_2. Most of the HFCs are used as refrigerants for heating and cooling applications (air-conditioners, heat-pumps, refrigeration) in buildings (see section **3.6**) and industry. Therefore, in the context of increasing equipment rates for heating and cooling applications, the mitigation of HFCs emissions is crucial.

It is current practice to substitute HFCs by gases with a significant lower GWP. An important driver for phasing-out certain HFCs with high GWP are international agreements (United Nations, 2016) and regulations (European Parliament And Council Of The European Union, 2014).

Technology alternatives to the use of HFCs as refrigerants exist (Goetzler W. et al., 2014). Some of these technologies are already commercially available such as compression heat pumps using ammonia, pentane or CO_2; evaporative cooling; or heat pumps based on absorption or adsorption. Other approaches are currently under development, such as solid-state technologies (e.g. thermoelectric, magnetocaloric).

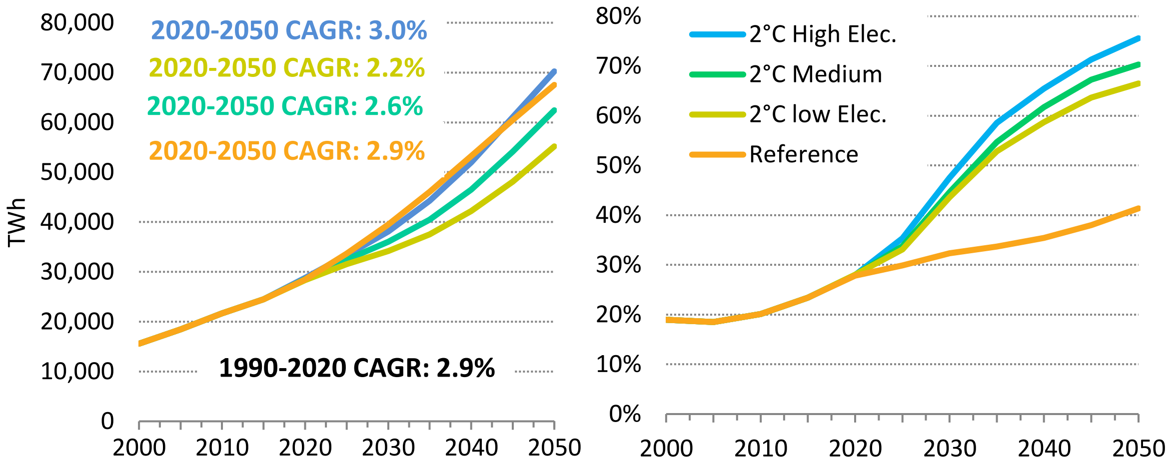
3.8 Electrification effects: Power generation

The power sector is an essential piece of the global decarbonisation puzzle. The main reason lies in the extraordinary technological diversity: since the first electrification wave in the last decades of the 19th century, the technological options to generate electricity at different scales have become more and more diversified and now offer the most widespread portfolio.

Higher electrification rates of end-use sectors would clearly confer a crucial role on the power sector. Therefore, economy-wide decarbonisation would strongly depend on lowering the carbon intensity of electricity generation.

Net electricity generation, including end-use demand, transport and distribution losses, as well as electricity generated from storage, is presented in **Figure 38.** At global level, it more than doubles compared to the 2017 level (25,700 TWh) in all 2°C scenarios, to satisfy the continuously growing demand.

Figure 38. Global power production (left) and renewable share in power mix (right)



Source: POLES-JRC model.

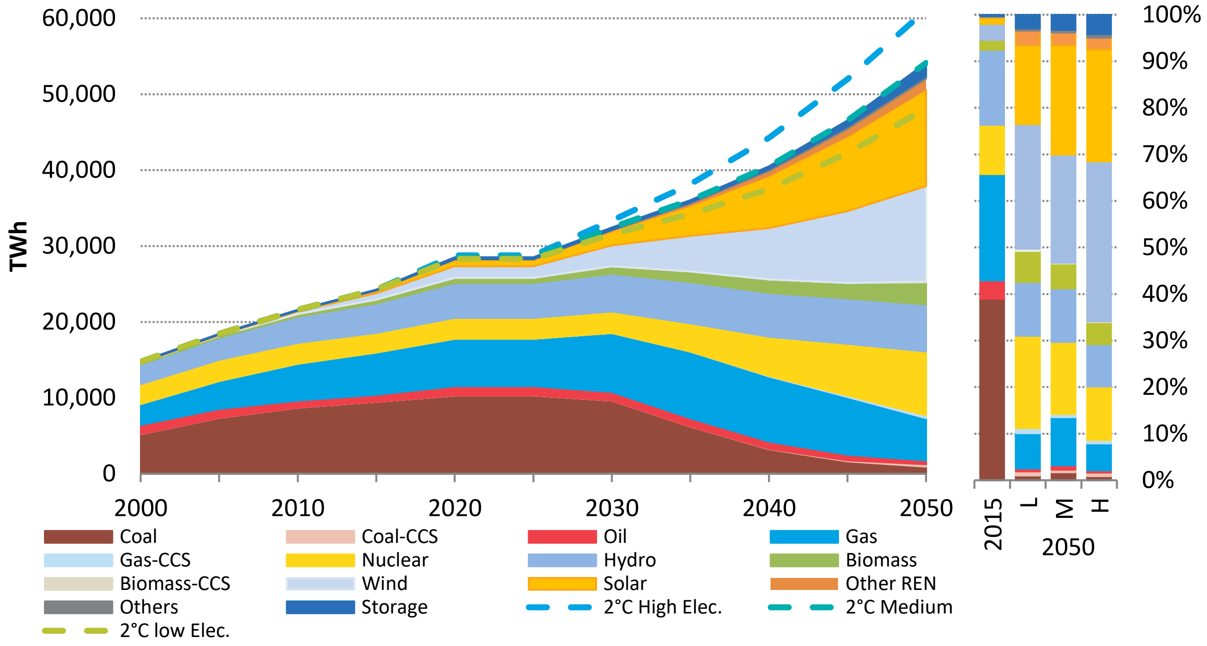
Electricity generation by source is presented in **Figure 39**. At the global level in the 2°C-Medium scenario, renewables represent 70% in 2050 (65-75% in sensitivities) of the power generation; low-carbon generation (renewables, nuclear, fossils with CCS) represents 86% (87-88% in sensitivities); decentralised generation (small units of PV, CHP, fuel cells and hydro) represents 12% (8-16% in alternative scenario sensitivity variants).

POWER

		2015	2050		
			LOW	MEDIUM	HIGH
ENERGY	TOTAL POWER PRODUCTION TWh	24000	55000	62000	70000
	PRIMARY ENERGY INPUTS Gtoe	4.5	5.7	6.3	6.8
	RENEWABLES GENERATION % of total power generation	23%	66%	70%	75%
	VARIABLE GENERATION: WIND AND SOLAR % of renewable generation	5%	44%	50%	58%
	GENERATION WITH CCS % of total power generation	0%	4%	4%	3%
EMISSIONS	CO_2 EMISSIONS % of total CO_2	37%	18%	18%	19%
	CO_2 EMISSIONS $GtCO_2$	12.3	1.7	1.7	1.7
TECHNOLOGIES	TOTAL ELECTRICITY STORAGE CAPACITY % of electricity capacity	2.4%	5.5%	9.4%	9.5%
	TOTAL ELECTRICITY STORAGE % of electricity produced	0.3%	3.1%	4.7%	4.3%
	VEHICLE-TO-GRID ELECTRICITY SUPPLY % share of electricity storaged at the EV that is supplied back to the grid	0%	13%	11%	7%
ECONOMICS	AVERAGE INVESTMENT IN LOW-CARBON ENERGY G$ / year	365	1610	1416	1309
	AVERAGE INVESTMENT IN LOW-CARBON ENERGY. SHARE OF TOTAL POWER INVESTMENTS % / year	47%	90%	87%	87%

Among the key low-carbon solutions globally are solar, wind and nuclear. In the 2°C-Medium scenario, electricity generated with solar increases by a factor of about 35 worldwide over the 2017-2050 projection period. Solar would become the single most important source of electricity in 2050, with a 25.2% share of total electricity production. Wind would become the second single most important source of electricity, with a 24.8 % share of the total, followed by nuclear with a 15% share. Across all 2°C scenarios, coal, oil and gas are nearly totally phased out by 2050 despite the progressive deployment of CCS options for retrofit and new-build.

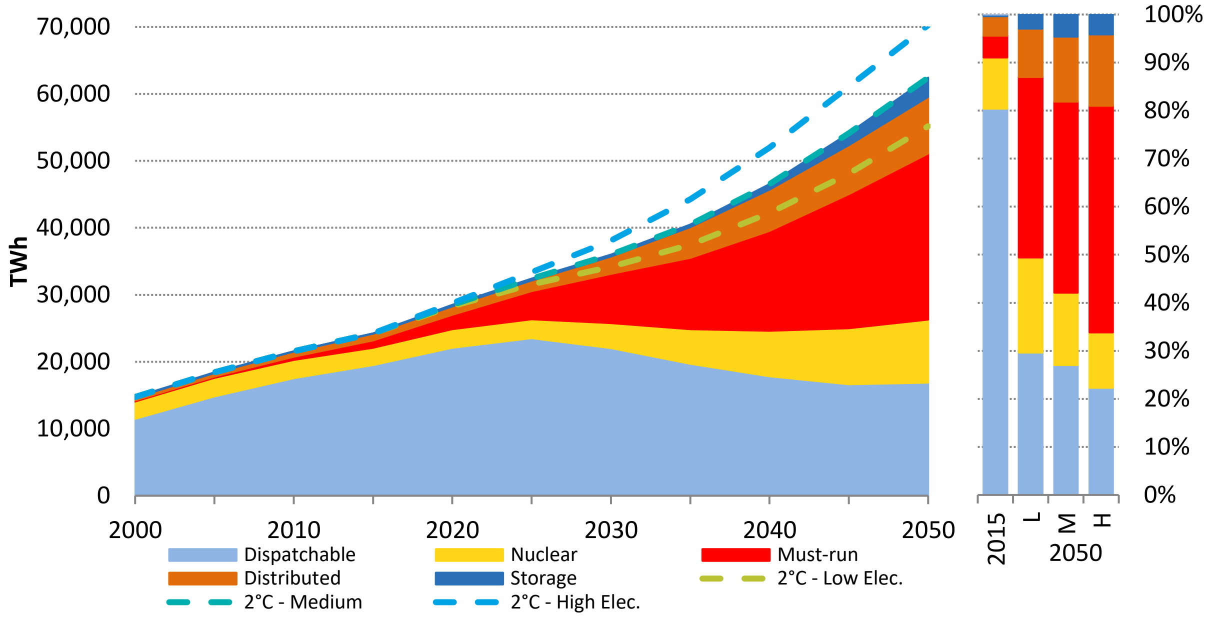
Figure 39. World total power production, 2°C-Medium, by fuel



Source: POLES-JRC model.

The largest changes in the power mix and the switch towards renewables are projected to be achieved in the 2020-2050 decades, with an accelerated deployment during these decades, resulting in a switch from a system dominated by fossil fuels combustion today to a system dominated by intermittent renewables in 2050, (see **Figure 40**).

Figure 40. Total power production, 2°C-Medium, by dispatch



Note: Dispatchable refers to all thermal plants (including biomass and geothermal) and CSP with energy storage. Must-run refers to solar PV, CSP without storage, wind, hydro run-of-river and ocean; Distributed refers to small units of PV, CHP, fuel cells and small hydro. Storage consists of battery, compressed air, hydro lake and pumped storage and vehicle-to-grid.

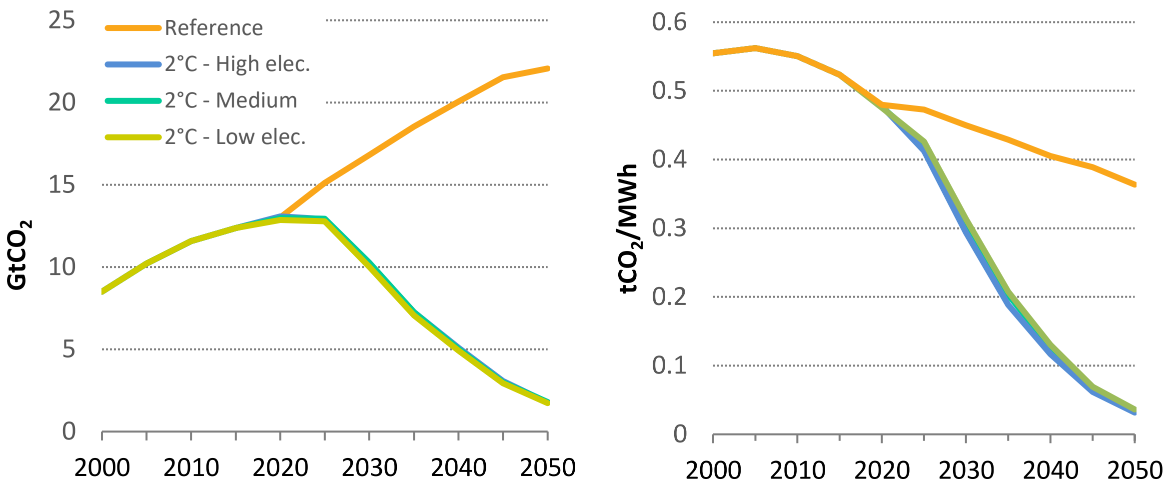
The electrification also paves the way to a more decentralized energy system due to the modular characteristic of the new power generation technologies, mainly solar photovoltaics panels and wind turbines, but also storages devices. This can bring about a broad range of co-benefits such as wider access to electricity in rural areas, power system resilience and enhanced efficiency.

The forthcoming electricity network transformation, reinforced by the digitalisation trend in other sectors of the economy, has the potential to substantially increase the energy system efficiency. This includes load-curve management with the implementation of elements as electricity storage devices, the spread of smart-grids and the use of energy demand-side management strategies. The power sector includes a large number of technologies where low-cost disruptive renewable technologies have already transformed the energy sector.

In the 2°C-Medium scenario, small decentralised units (PV, CHP, gas and hydrogen fuel cells and small hydro) and power generated from storage units (hydro pumped storage, compressed air, stationary batteries, electric vehicles-to-grid) come to represent 13% and 5% of total power generation in 2050, respectively.

The combination of strong end-use electrification and deployment of low-carbon power generation technologies results in sharply falling emissions from the power sector. In all of the 2°C scenarios explored in this report, the carbon intensity of world electricity generation drops by a factor of 15 over the projection period 2017-2050, falling to 0.03 tCO_2/MWh by 2050 (**Figure 41**). Beyond 2050, lower or even negative levels could be expected, due to the large deployment of negative emissions technologies such as bio-energy combined with carbon capture and storage (BECCS). Scenario variants are not very differentiated in terms of emissions: decarbonisation is mainly driven by the cost-competitiveness of renewables and to the pricing on carbon emissions that is common across all 2°C scenario variants.

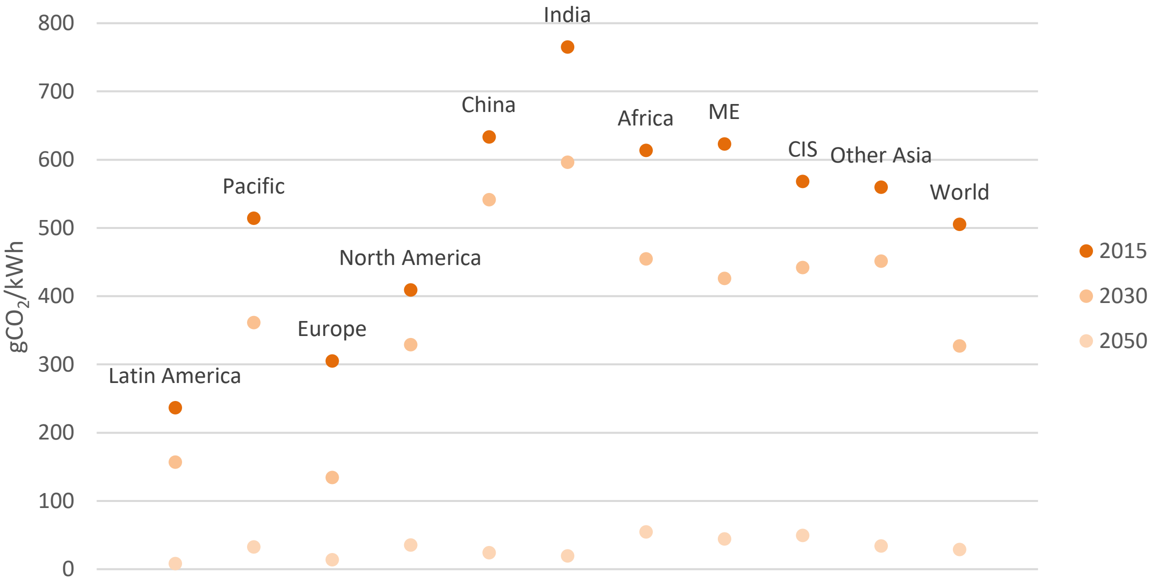
Figure 41. World emissions in the power sector (left) and electricity carbon content (right)



Source: POLES-JRC model.

The regional transformation towards low-carbon generation is shown in **Figure 42**. This transformation occurs even in the most coal-intensive regions of today, such as China and India, or the most oil- and gas-intensive, such as the Middle East: most of the regions decrease the carbon intensity of electricity by over 90% over the projected period.

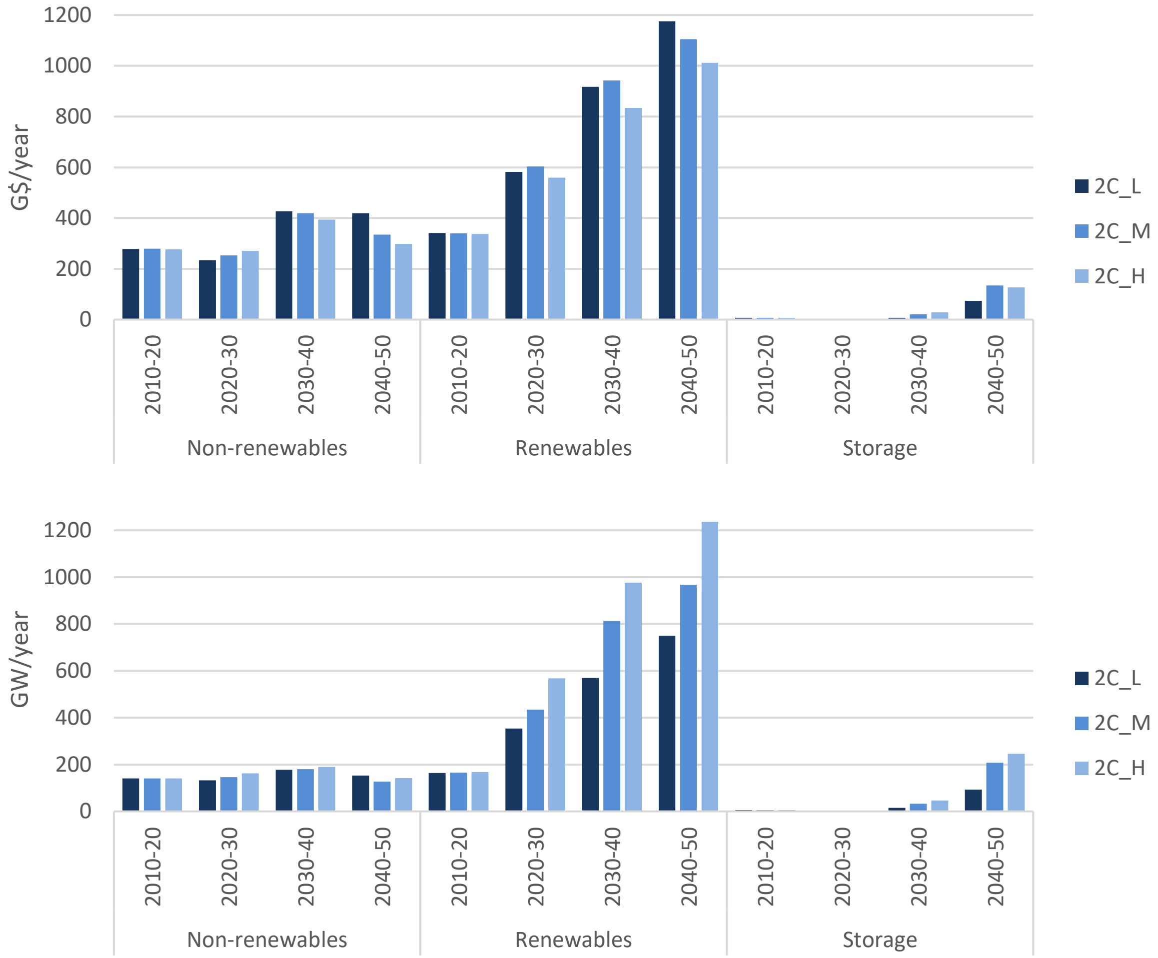
Figure 42: CO_2 emissions electricity intensity by region for the 2°C–Medium scenario



Source: POLES-JRC model.

Investment in power generation capacities increase over time in response to electricity demand growth. Total investments over the 2020-2050 period amount to 43 T$ in the 2°C-Medium scenario (+1% and -9% in the 2C_L and 2C_H, respectively). Investment in renewable capacities reaches around 70% of total power generation capacities investment for each decade over the 2020-2050 period in all 2°C scenarios (**Figure 43**). In particular, investments in renewables over that period are similar in 2C_M compared to 2C_L (+1%) and lower in 2C_H compared to 2C_M (-11%), as assumptions on more optimistic cost learning rates outweigh the effect of higher volumes of capacities to install in 2C_H.

Figure 43. World average annual investments (top) and installations (bottom) in power generation capacities by decade



Source: POLES-JRC model.

Note: Storage consists of stationary batteries, compressed air, hydro pumped storage and vehicle-to-grid.

4 Macroeconomic impacts

The profound changes in the global energy markets leading to a climate-friendly economy have been presented in the previous sections. The key drivers, such as increased efficiency in energy transformation and use, deep decarbonisation of electricity generation, and enhanced electrification of final energy demand, have been presented and discussed. In this section, we take a closer look at the macroeconomic impacts of some of these drivers. The computable general equilibrium (CGE) model JRC-GEM-E3 is used to assess macroeconomic consequences of the transition to a pathway compatible with 2°C. As this report focusses on the contribution of electrification of various end use sectors, the high, medium and low electrification scenarios developed in **Section 2** are assessed to study changes in GDP, consumption, investment, and employment. This is done by connecting the results from the POLES-JRC model to the JRC-GEM-E3 model. A description of the latter is provided in **Annex 3**, which also contains a more technical discussion of the soft-link between the two models.

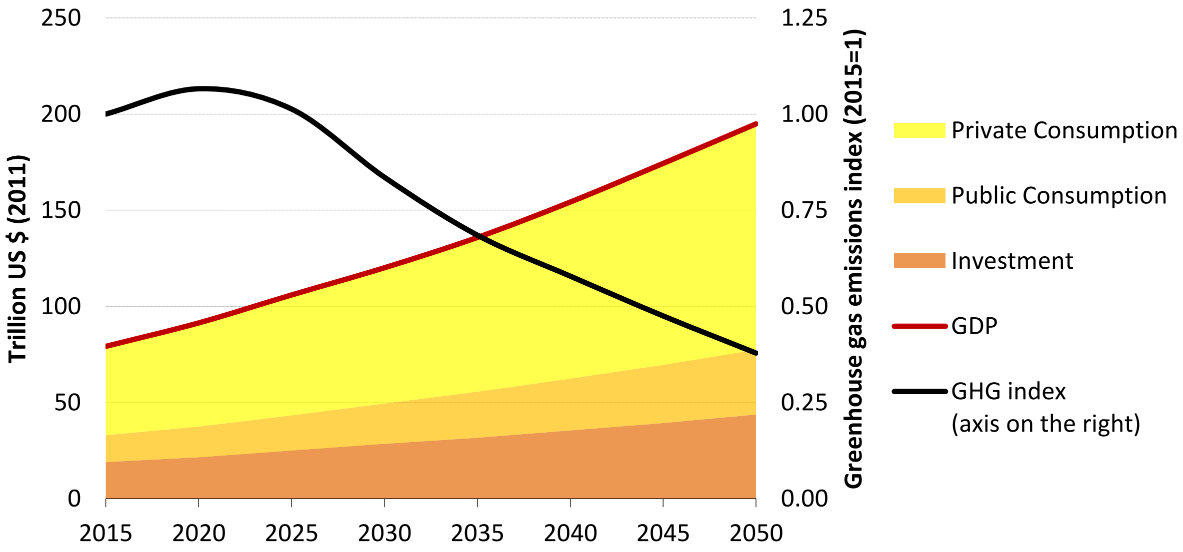
The linking between POLES-JRC and JRC-GEM-E3 takes into account many aspects of the energy transition and electrification, such as the electricity mix for power generation, fuel mix for household use, and fuel choices for transport sectors. This input ensures consistency and strengthens the technological background for the macroeconomic assessment, which then captures spill-overs across the entire economic system. While all key aspects of decarbonisation are captured in the models, in this section we pay particular attention to the sector that is expected to experience rapid electrification over the coming decades: road transport.

Electrification is expected to play a crucial role to decarbonise the transport sector, which is highly reliant on fossil fuels today. Especially in the high electrification scenario, in which battery costs are assumed to be falling rapidly, the share of electric vehicles is projected to rise quickly. Electrification may have considerable implications for the car manufacturing sector, as production and use of electric vehicles differ in key aspects from conventional vehicles. Here, we look into the potential implications of expected structural changes in vehicle production for jobs across the supply chain and economy-wide.

4.1 Overall macroeconomic impacts of mitigation

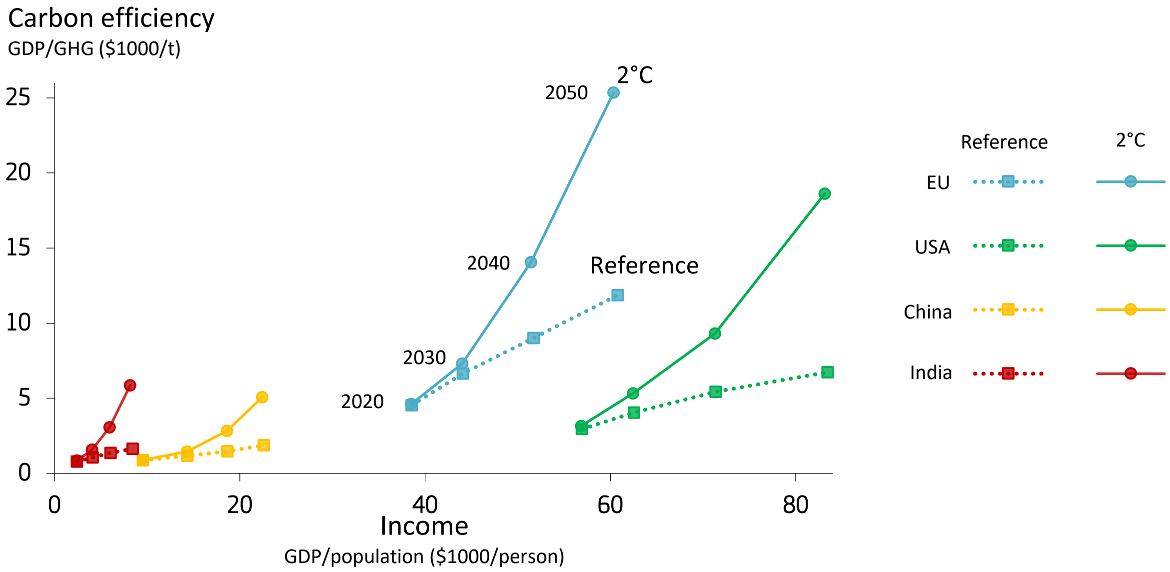
The 2°C pathway requires a global decoupling of economic growth from emission growth. **Figure 44** shows the robust economic development under the central (medium electrification) pathway and confirms that decarbonisation is compatible with robust economic growth. Between 2015 and 2050, global GDP is foreseen to more than double in the 2°C scenario, while a decoupling of GDP and GHG emissions materializes over the same period. GHG emissions steadily fall to more than 60% below 2015 levels in 2050. The numbers shown in the **Figure 44** include the cost of climate change mitigation, but do not consider the (avoided) impacts of climate change.

Figure 44. GDP and emission trajectories, World



The decoupling of income growth and greenhouse gas emissions is also observed on the regional level. **Figure 45** illustrates two possible scenarios – Reference and 2°C – for four regions. The Reference represents climate and energy policies that are currently implemented, while the 2°C scenario considers increasing carbon prices that converge globally by the year 2050. While robust growth in per-capita income is observed in both scenarios, economic performance in the 2°C scenario is substantially better in terms of carbon efficiency, expressed here as the volume of GDP per tonne of greenhouse gas emissions.

Figure 45: Regional income and carbon efficiency in different scenarios



While the continued economic growth is maintained in the 2°C scenario, some macroeconomic cost is associated with switching from the reference pathway to the 2°C pathway. The overall cost expressed in differences in GDP relative to the baseline is very is modest, with a global cost of 0.75% as central value for the decarbonisation scenario with medium decarbonisation in 2050. Taking the range of the high and the low electrification scenarios, global GDP could be between 0.2% and 1.0% lower than in the reference in 2050.[18] This would translate into a reduction of average annual growth rates between 2020 and 2050 from 2.60% in the reference to 2.57 – 2.60% in the 2°C scenarios.

The changes in GDP as well as its consumption and investment components are further plotted in Figure 46 for the three 2°C scenarios. The transformation towards a low carbon economy will require mobilising investments toward low carbon technologies. In all scenarios, the share of investment in GDP increases relative to the reference, as investment levels either rise above the reference level or decline at a lower rate than consumption. **Figure 46** shows relative differences to the reference for (private) consumption and investment in the three electrification scenario pathways.

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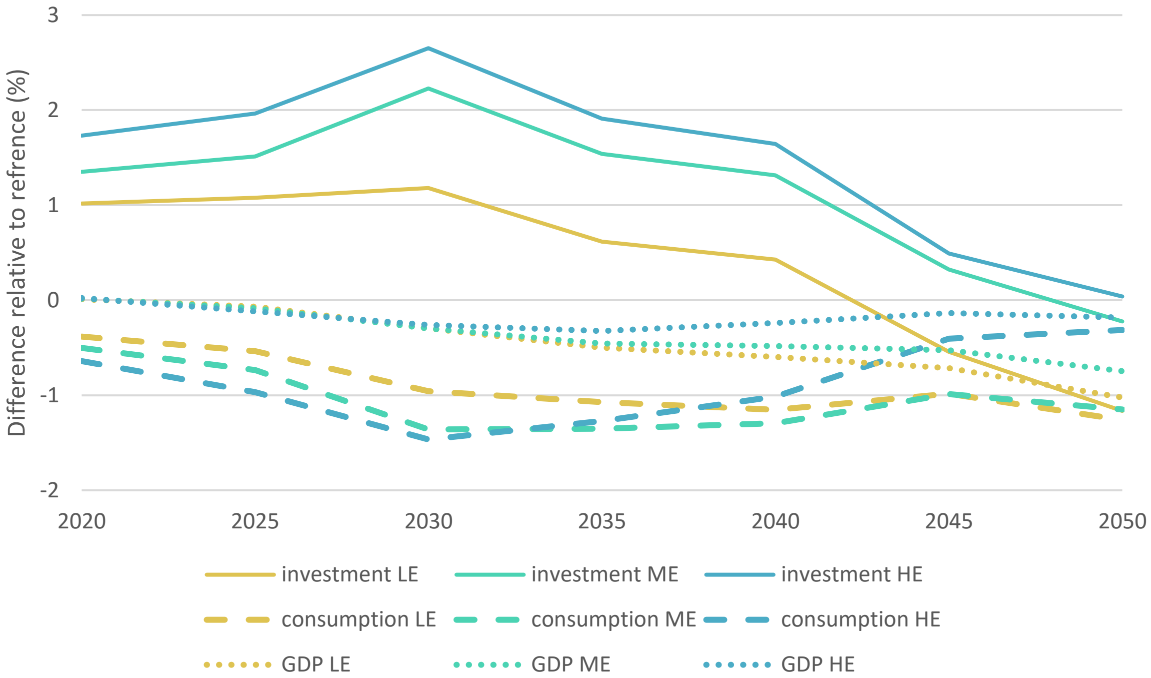
[18] The global cost reported in GECO 2018 (Keramidas, et al., 2018) falls in this range, the central value in 2018 was slightly lower than in this version of GECO, *inter alia* because the baseline in GECO 2018 was already assumed to be more ambitious, i.e. more climate action would already happen in the baseline.

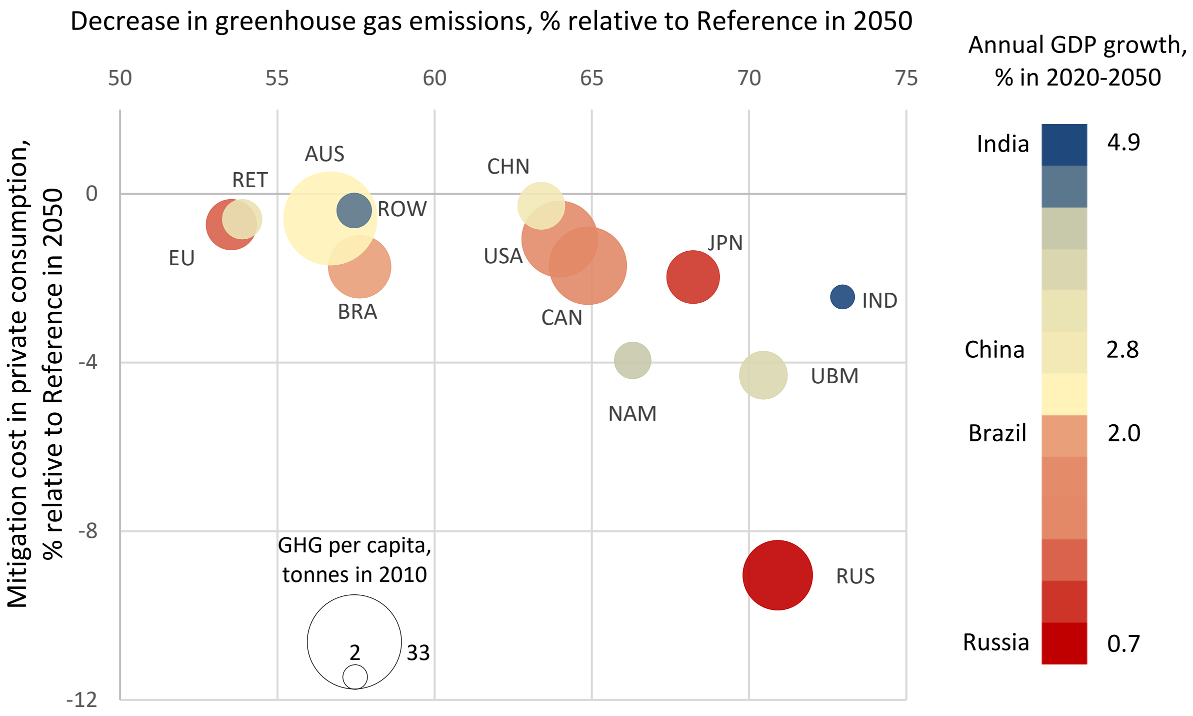
Figure 46. The impact of climate change mitigation on global macro-economic indicators in the 2°C scenario



In all scenarios, the largest percentage increase of investment relative to the baseline incurs in 2030. After this peak, increases in investment relative to the reference decline, which is driven by the need to start in the next decade to build the infrastructure that is needed for a 2°C economy. This is especially the case for regions that are fast growing and in regions where there is a wider gap in terms of emissions reductions between the reference and the 2°C scenarios. Further, towards 2050 many technologies used in the 2°C pathways are projected to become cheaper, thus reducing the cost of investments. In the analysis with JRC-GEM-E3, we project the highest increase in investments in the high electrification scenario, as this requires the most profound change of the energy system. In the initial years of the scenario, changes in private consumption are the mirror image of changes in investment. Resources that are needed for to investment cannot be consumed. Therefore, in initial years, the high electrification scenario has the highest consumption losses for private households. However, in later years, by design the high electrification scenario implies higher cost reductions through learning and a stronger transition towards these cheaper low emission technologies which limits the consumption loss in this scenario. This also explains why GDP losses are highest in the low electrification scenario and are lowest in the high electrification scenario in 2050. Further, while the GDP losses increase over time for the low and medium electrification scenario, the gains from cost reductions towards mid-century reduce GDP losses such that GDP loss (in percentage points) declines after 2035 in the high electrification scenario.

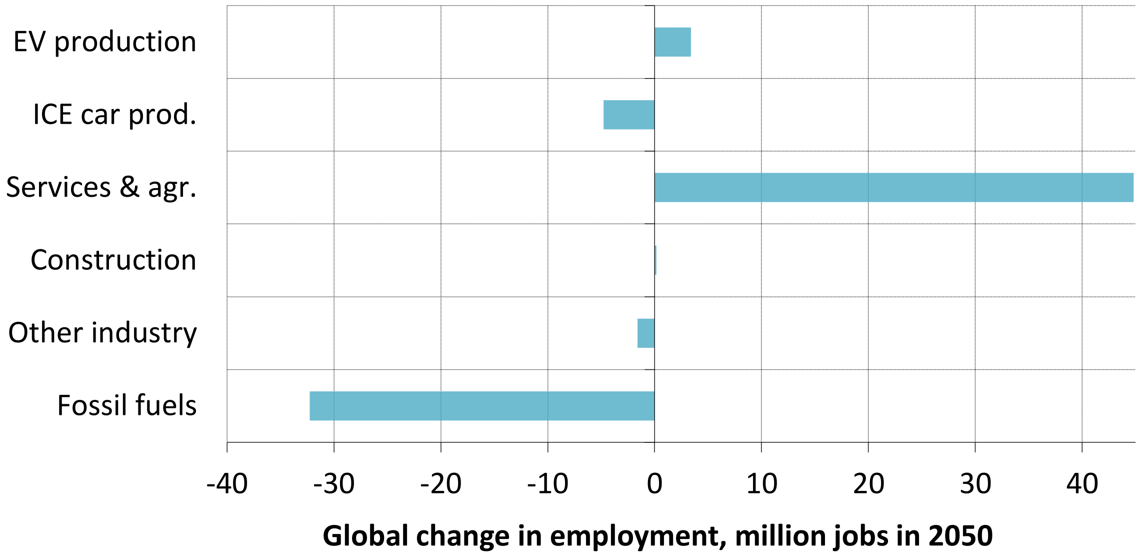
While global economic costs of achieving the 2°C are modest, the costs are not distributed evenly across world regions. **Figure 47** presents effects in consumption to select regions of the JRC-GEM-E3 model (see **Annex 3** for region codes). From the figure, it becomes apparent that the 2°C pathways requires different levels of emission reduction relative to the baseline levels for different regions. In general, the economic costs are correlated with the emission reduction requirements relative to the reference. Some regions already achieve relatively high emission reductions in the reference scenario and therefore their costs of further emission reduction in the 2°C scenario is limited. In addition, there are general equilibrium effects that JRC-GEM-E3 is taking into account. For example, emission reductions by fuel importers have spill-over effects on energy exporters as the latter would lose export revenue relative to the baseline. This is for example the case for Russia (RUS) which has the highest losses in consumption

Figure 47. The impact of climate change mitigation on private consumption in the 2°C scenario



Similar to the heterogeneity across regions, different economic sectors are affected differently from the transition to a 2°C pathway. In general, output – investment and employment in the fossil fuel industry – is expected to decline 40-50% below reference levels. In other sectors, the relative changes are much smaller. **Figure 48** displays employment effects at the global levels in 2050 under a medium electrification scenario that exogenously assumes stable long-term aggregate unemployment. The figure illustrates the jobs shifting from fossil fuel sectors to services and agriculture. Other industries have some modest declines, while the increases in investments lead to additional jobs in the construction sector. With regard to the transport sector, a shift is observed from the jobs in the manufacturing of internal combustion engines (ICEs) towards manufacturing of electric vehicles (EVs). New EV jobs are slightly fewer than lost ICE jobs relative to the baseline, because EVs are produced with a lower labour intensity and the demand for overall vehicles is slightly lower in the 2°C scenario.

Figure 48. The impact of climate change mitigation on global employment in the 2°C scenario



4.2 Macroeconomic impacts of road transport electrification

One key aspect of electrification to achieve decarbonisation compatible with a 2°C pathway is the transport sector. As reported in **Section 3.5** above, currently transportation is predominantly fuelled by oil and only a limited amount of biofuels contributes to avoiding emissions today. This picture is expected to change until the middle of the century and particularly the reduction of battery costs will be an important driver of the increase in electric vehicles. GECO 2019 therefore takes an in-depth look at the macroeconomic consequences of road transport electrification. While there are broader changes expected in the future of transport, e.g. automation and connectedness which might allow autonomous vehicles with changes in the ownership structure of vehicles on the road, in this GECO we focus on the transition to electricity powered vehicles.[19]

Unlike in energy models, where transport demand is expressed in activity levels, the transportation activities in a CGE models are captured in several places and it can be expected to affect the macro economy through different channels. In CGE models, transport is represented in a more fragmented fashion following the economic accounting of sectors and purchases by households.

In the version of JRC-GEM-E3 used for GECO 2019, the purchases of vehicles are accounted for in the output of vehicle manufacturing sectors, and the operation of vehicles is accounted in the purchases of fuel and other operating inputs such as maintenance services by private households and other sectors in the economy. To capture changes in the manufacturing of vehicles that result from a shift of conventional vehicles with internal combustion engine towards more electric vehicles, the vehicle manufacturing sector was explicitly represented and split into the production of conventional vehicles and electric vehicles. This captures important differences in the input structure in the two sectors, such as the large cost share resulting from the cost of the battery. **Box 3** describes these differences in more detail.

Electric and conventional vehicles are then purchased by households as part of their durable goods consumption purchases, or by the various economic sectors in the economy through their investment purchases. The shares of conventional and electric vehicle in new vehicle purchases are taken as exogenous shares into JRC-GEM-E3 in order to be consistent with the remainder of GECO. Therefore, the scenarios are "what-if" scenarios to assess how different electrification scenarios would affect different sectors, investment, consumption and employment of the economy.

The operation of vehicles and thus their fuel use is determined by firms in the economy and households. Households decide on the operation of vehicles given their stock of vehicles and the cost (including carbon prices) of the fuel and maintenance costs. With more electric vehicles in the fleet, we (exogenously) adjust the composition of fuels consumed by the vehicles. For firms, we adjust the operation of vehicles in the land

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(19) See (Alonso Raposo, et al., 2019) for a comprehensive overview of the implications from automated, connected, low-carbon and shared mobility.

transport sector by adjusting purchases for maintenance and fuels, again taking into account the different fuel requirements under an evolving vehicle fleet. For vehicles operated outside the transport sector, we are unable to follow this approach because we cannot distinguish different uses of energy in sectors outside the transport sector. Our estimates reported are thus conservative. Further caveats in our analysis is the lack of modelling of charging infrastructure requirements and a rather simple assumption on the production location of electric vehicles which follows that of conventional vehicles rather than allowing for the emergence of "new players".

Box 3: Manufacturing of Electric Vehicles: structure of the sector including labour intensity

The production structure of battery electric vehicles (BEV) differs substantially from that of conventional vehicles. Within the JRC project "Societal impacts of disruptive mobility scenarios" (SIMOD) (Alonso Raposo, et al., 2018) (Tamba, et al., 2019), the macroeconomic impacts of road transport electrification are examined using the macroeconomic model JRC-GEM-E3. For this purpose, the vehicle production sector was split into electric vehicle and conventional vehicle production. The structure of the electric car and van production sector was derived by modifying conventional vehicle production structure. To this aim, BEV production needed to be captured in a matrix of production coefficients, which specify the shares of intermediate inputs from different sectors, as well as labour and capital inputs (sectoral value added). **Table 2** shows the resulting average BEV production coefficients alongside those for conventional vehicles. To derive the coefficients, the following assumptions were made:

Battery electric vehicles have a body similar to conventional ones. The production of a BEV therefore needs 75% of the manufacturing sector inputs for producing an equivalent conventional vehicle (Cuenca, Gaines, & Vyas, 2000). The battery cost of the BEV is calculated as its pre-tax price difference versus a conventional car, plus 25% of the manufacturing costs of the conventional vehicle. The input from all other sectors as well as value added remains the same in absolute terms as for an equivalent conventional vehicle.

It is assumed that the total production value of vehicles equals their pre-tax retail product price. Pre-tax retail prices for comparable conventional and electric vehicles are taken from (Bloomberg New Energy Finance, 2017) for cars, and based on Renault's suggested pre-tax retail prices for vans. Matrices have been derived for small, medium and large cars as well as vans separately, and then weighted by market shares.

Table 2: Production structure of conventional and electrified vehicles

	Manufacture of conventional vehicles	Manufacture of electric vehicles
Manufacture of conventional vehicles	28.3%	0.0%
Manufacture of electric vehicles	0.0%	13.2%
Market Services	14.7%	9.2%
Other Equipment Goods*	14.1%	50.8%
Non-ferrous metals	8.5%	5.3%
Chemical Products	6.5%	4.0%
Ferrous metals	3.4%	2.1%
Transport (Land)	2.0%	1.3%
Consumer Goods Industries	1.0%	0.6%
Electric Goods	0.8%	0.5%
Non-metallic minerals	1.5%	0.9%
Others (< less than 0.01 each)	2.6%	1.6%
Value Added	16.7%	10.4%

While manufacturing of conventional vehicles relies most heavily on own inputs (capturing chassis and engine components and parts), approximately 50% of manufacturing costs for BEV are attributable to the "other equipment goods" sector, which produces the batteries. The share of value added, including labour and capital inputs, is substantially lower for BEV due to the reduced contribution of the vehicle manufacturing sector.

As mentioned above, the economics of electric vehicles is characterised by differences in production and operation. Besides differences in input shares, the overall cost of conventional vehicles is lower than for electric vehicles. This is mainly due to the high cost of the battery. However, as discussed in **Section 3.5** (cf. also **Figure 78** in **Annex 5**), fast progress in battery technologies can already be observed and is projected to further bring down cost of electric vehicles. While purchasing costs of electric vehicles are higher than conventional vehicles, savings can be made during the operation. In addition to differences in fuel costs, one further key difference is that electric vehicles are characterised by lower maintenance costs (**Box 4**). In the economic analysis with JRC-GEM-E3, we have carried out a decomposition analysis which attributes changes in a 2°C compatible economy.

Box 4: Maintenance requirements for Electric Vehicles

Literature suggests that battery electric vehicles (BEV) have lower maintenance costs than comparable conventional vehicles. This is attributed to the following factors: Fewer moving parts (Palmer, Tate, Wadud, & Nellthorp, 2018) ((Logtenberg, Pawley, & Saxifrage, 2018); (Mitropoulos, Prevedouros, & Kopelias, 2017); (Lebeau, Lebeau, Macharis, & Mierlo, 2013); (Feng & Figliozzi, 2012)); no need for changing oil and filters ((Moon & Lee, 2019); (Logtenberg, Pawley, & Saxifrage, 2018); (Lebeau, Lebeau, Macharis, & Mierlo, 2013)); and regenerative braking systems (Logtenberg, Pawley, & Saxifrage, 2018); (Hoekstra, Vijayashankar, & Linesh, 2017); (Lebeau, Lebeau, Macharis, & Mierlo, 2013)). The order of magnitude of maintenance cost reduction for BEV varies substantially among different studies, and depends on the type of vehicles considered, i.e., passenger cars (PC), light commercial vehicles (LCV) or heavy duty vehicles (HDV) and on their sizes. Moreover, the mileages covered, the geographical locations, technical and mechanical characteristics could have an impact on the cost savings attributable to BEVs. There is a wide range of maintenance cost reductions that are attributable to BEVs, ranging from a minimum reduction of 16% (Gnann, Plötz, Funke, & Wietschel, 2014) to a maximum of 75% (Lee, Thomas, & Brown, 2013). Table 18 in **Annex 3** provides a wider literature review.

For the purposes of the SIMOD project (see **Box 3**) and this report, an average value of 30% of maintenance cost reduction of BEV compared to conventional vehicles was used, which appears to be realistic and in line with the literature reviewed and balanced, taking into account the high range of values identified, from cautious and thoroughly calculated values provided in (Propfe, Redelbach, Santini, & Friedrich, 2012) to the highly disruptive and optimistic values in (Hoekstra, Vijayashankar, & Linesh, 2017), or (Lee, Thomas, & Brown, 2013).

In our decomposition analysis with the JRC-GEM-E3 model, we separate out:

- the additional costs from bringing electric vehicles into the fleet instead of conventional vehicles (stock effect);
- the cost reductions from learning expected in the battery component (learning effect);
- the reduced maintenance cost when replacing conventional vehicles with electric vehicles (maintenance effect);
- an interaction effect from the three effects above arising simultaneously;
- the consequences from different fuel consumption when replacing conventional vehicles with electric vehicles (fuel effect).

Figure 49 shows the total benefit of increased electric vehicles in the 2°C scenario relative to the baseline at the global level. The total effect could be interpreted as the value of additional electric towards climate mitigation, i.e. if these electric vehicles would not be there, the total GDP cost of climate mitigation would increase by about 1 percentage point over the level reported in the previous section. This total effect is higher in the high electrification scenario and lower in the low electrification scenario. The figure also includes another sensitivity (marked with a cross); the effect would be much higher if long term employment in 2050 would not be assumed to be fix but rather react to changes in the wage levels.

The total effect can be decomposed into the different components mentioned above. The stock effect shows additional costs resulting from purchases of additional electric vehicles in the 2°C scenario relative to the baseline. The additional GDP cost of purchasing more electric vehicles is overcompensated by reduced battery costs from learning. The learning effect is particularly high under the high electrification scenario which assumes the highest battery cost reductions. The maintenance effect is also positive. As driving electric vehicles will need fewer resources for maintenance, these can be used to produce other goods and services. For these scenarios, the assumptions on the labour market are of minor importance. Between these three effects, there is also a minor interaction effect, shown in the figure. The biggest effect is the fuel effect which adjusts the fuelling requirements of the vehicle fleet to fewer oil and more electricity.[20] This eases the constraint for the world economy the reduce carbon emissions in sectors outside the transport system, leading to increased production. This effect can triple under variable employment with a wage curve representation.

Figure 49: Decomposition of GDP impact from transport decarbonisation in a 2°C scenario on the global level

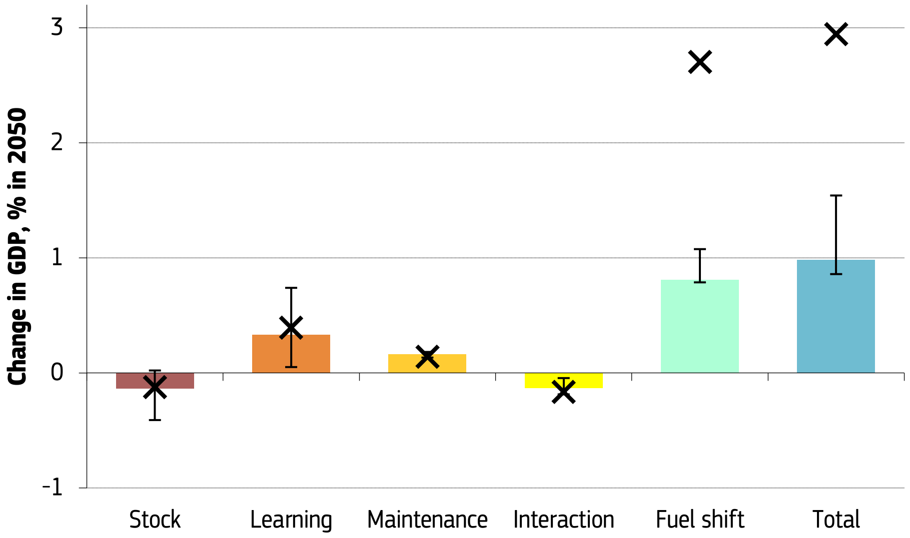

Figure 50 shows employment effects from the decomposition, collecting the stock, learning, maintenance and their interaction into production and maintenance changes. Not surprisingly, these changes lead employment shift between the electric vehicle and internal combustion engine production sectors. Not all jobs in ICE manufacturing can be converted into EV production because EV production is less labour intensive. Likewise, jobs in service sectors are lost relative to the baseline, because of reduced maintenance requirements. There are however positive spill overs from the EV sector to construction (driven by investments) and other industry which contains production of batteries.

The fuel effect on the other hand has only a minor effect on jobs in vehicle manufacturing; the gains are here concentrated in other sectors, especially services and agriculture. The reduction of oil demand is reflected in the reduction of jobs in the fossil fuel sectors.

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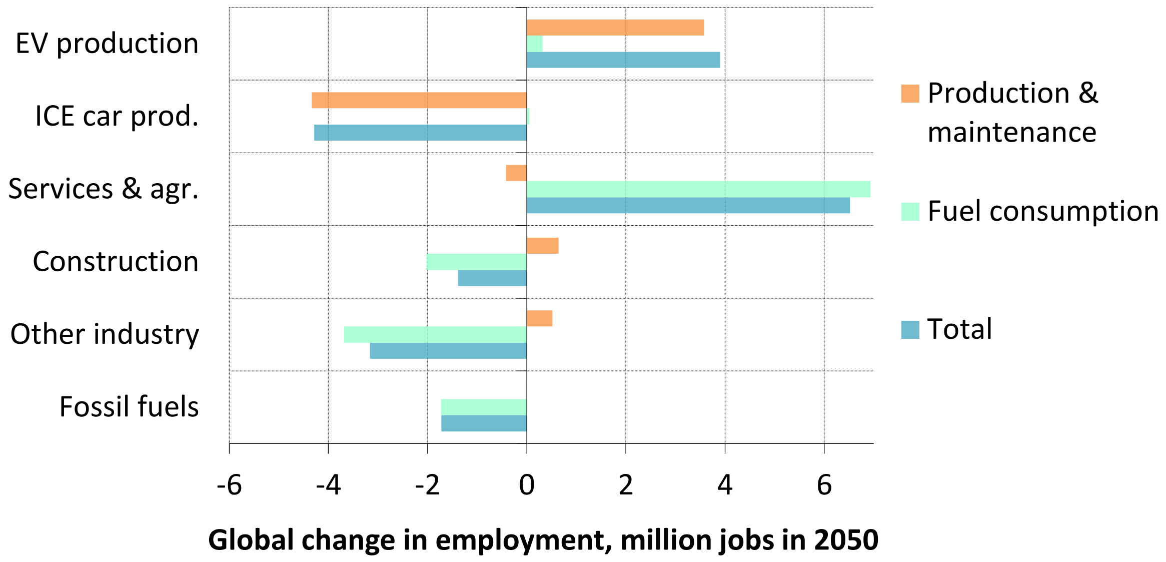
(20) The fuel effect also considers increased use of biofuels in the 2°C for which the energy models POLES-JRC and PRIMES project an increase.

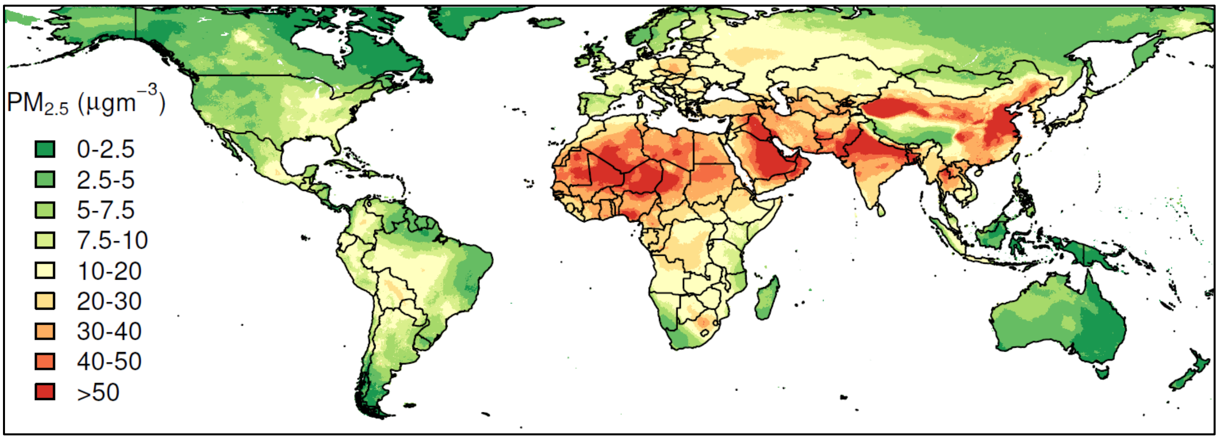
Figure 50: The impact of transport decarbonisation on the allocation of workers across sectors in 2050 (medium electrification scenario, flexible wages)



5 Global air quality impacts

The burning of fossil fuels goes along with emissions of greenhouse gases, contributing to global warming. In addition, fossil fuel use is one of the drivers of air pollutant emissions that cause damages for human health. Lung cancer, diabetes and stroke are among the diseases caused by inhaling toxic air pollutants. Estimates of the health damages are substantial: according to the World Health Organization, ambient air pollution caused 4.2 million premature deaths globally in 2016[21]. The European Environmental Agency (EEA, 2019) estimates that air pollution caused roughly 400,000 premature deaths in Europe in the same year. The OECD (OECD, 2016) projects that the economic costs of air pollution – labour productivity, crop yields and healthcare expenditures – could amount up to 1% of global GDP by 2060, while more recent work suggests higher costs (OECD, 2019). Climate change mitigation policies drive our energy system to clean and efficient technologies, leading to co-benefits for air quality. Research shows that keeping global warming well below 2°C can avoid roughly 1 million premature deaths annually in 2050 globally, the value of which would exceed climate change mitigation costs in most regions around the world (Vandyck, et al., 2018). This is particularly the case for South and East Asia, where air pollution levels are relatively high in densely populated areas (see **Figure 51**).

Figure 51. Concentrations of fine particulate matter in 2015



Note: The figure includes sea salt and dust. Source: own calculations based on (van Donkelaar, et al., 2016).

The scenarios we study here are differentiated along three dimensions. First, we consider two options for climate policy: a reference including current policies (Ref) or policies that limit global warming to below 2°C. Second, we assume that air pollutant controls (emission coefficients) stay unchanged from levels of the year 2020 (Frozen, Fzn) or that they become progressively more stringent over time (Progressive, Prg). Third, we distinguish between high, medium and low (H, M and L) electrification scenarios as defined earlier in this report. **Figure 52** shows the resulting emissions of primary fine particulate matter.

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(21) https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

Figure 52. Emissions of primary fine particulate matter in 12 scenarios, World

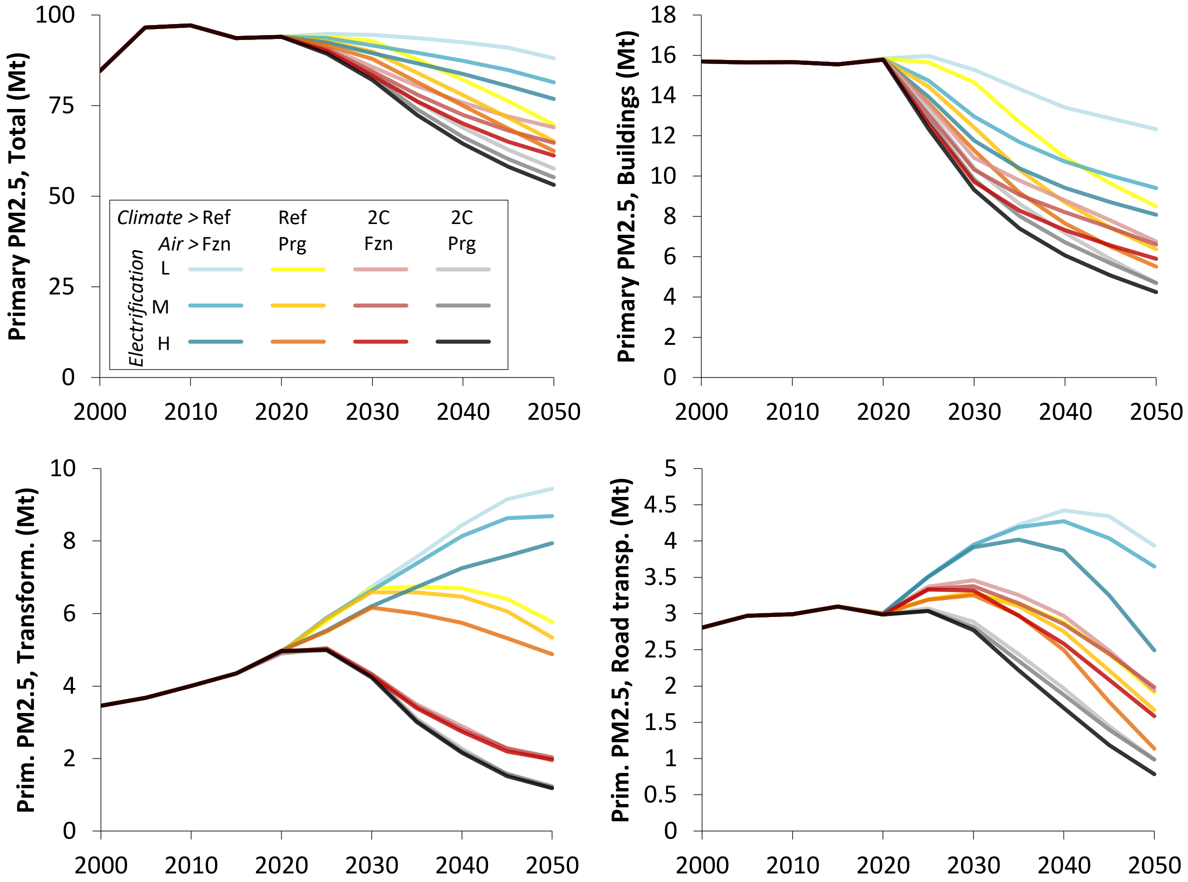


Figure 52 shows that the conditions underlying the High electrification scenarios lead to lower PM2.5 emissions compared to the Low electrification scenario. This gap is wider in absolute terms under current climate policies (Ref) and air pollution controls (Fzn), but narrows under ambitious climate (2C) and air (Prg) policies that enhance energy efficiency, the uptake of clean technologies and end-of-pipe air pollution controls. In the transformation sector, that includes electricity generation, the assumption about climate policy drives a wedge between outcomes, clearly having a strong impact on PM2.5 emissions. For transport and buildings, strengthening climate policy (Ref to 2C) or air pollution control (Fzn to Prg) has comparable effects for PM2.5 emissions. Importantly, the lowest emissions of fine particulate matter for all sectors are found in a setting with ambitious climate and air policies when combined with favourable conditions for electrification. The numbers for the transport sector furthermore illustrate that increasing population, incomes and activity would lead to a surge in emissions, if not countered by expected further technology penetration and vehicle fleet evolution that limit end-of-pipe emissions.

A similar picture for NOx emissions is shown in **Figure 53**. Consistent with the previous figure, the best outcome for air quality is found when combining stringent climate and air policies with strong uptake of electricity in transport and buildings. The major drivers of future NOx emissions, however, appear to be climate and clean air polices. Therefore, these results emphasize that the quality of the air that future generations will breathe will not only rely on technological progress, but will to a large extent be determined by political action over the course of the coming decades.

Figure 53. Emissions of nitrogen oxides in 12 scenarios, World

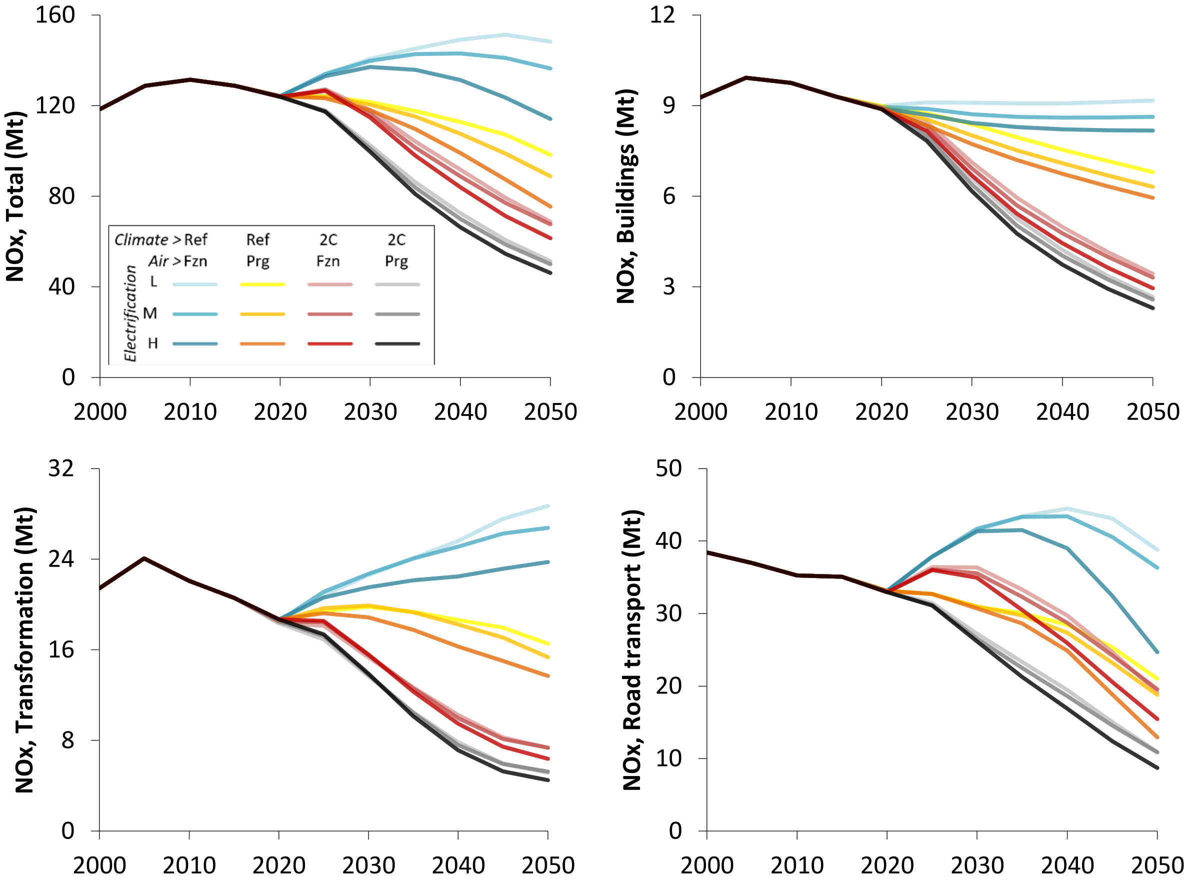
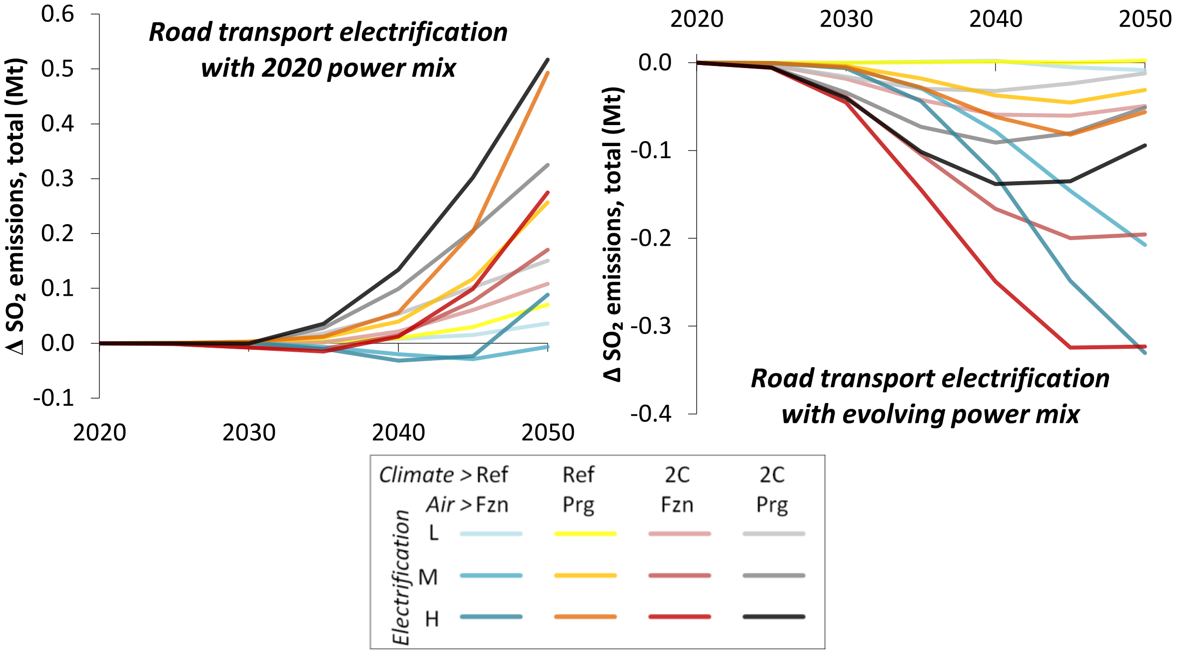


Figure 54. The impact of road transport electrification on total sulphur dioxide emissions in China

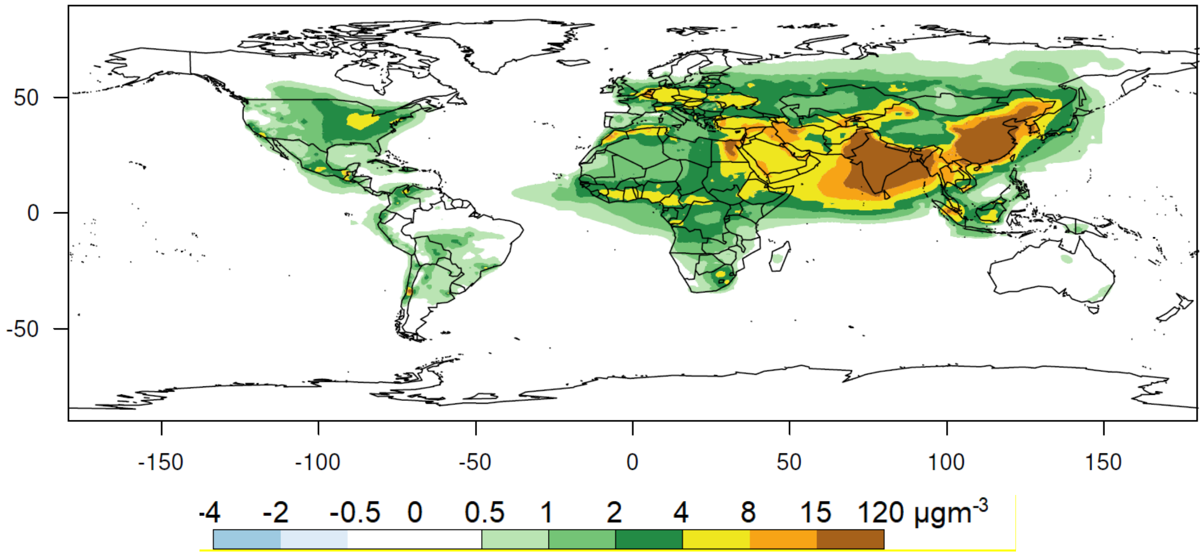


Increased penetration of electric vehicles has system-wide implications. On the one hand, replacing fossil-fueled cars by electric cars will lower the tailpipe emissions of air pollutants and greenhouse gases. However, the electricity will need to be produced, and this generation may come with emissions at the power plant. **Figure 54** illustrates this trade-off by showing the results of a particular case study: SO_2 emissions in China. The panel on the left-hand side shows that SO_2 emissions would increase from further penetration of electric vehicles if the electricity generation mix would stay unchanged from 2020 onwards. Here, the difference is shown with a hypothetical benchmark which keeps the share of electric vehicles in the fleet composition fixed at 2020 levels. This effect is stronger when electricity shares in transport fuels are high (H) and when progressive air pollution control has pushed downwards the SO_2 emissions in conventional vehicles.

When considering road transport electrification in combination with an evolving power generation system, the picture looks different. The right-hand side of **Figure 54** shows that the combined changes from road transport and from the corresponding electricity generation imply decreasing SO_2 emissions in China. Falling tailpipe emissions overcompensate increased emissions from power generation, when the latter shifts towards low-carbon generation technologies under current policy or 2°C-compatible pathways. These results highlight the importance of embedding transport electrification in a wider decarbonisation strategy that includes a modernisation of the power system. It should be mentioned, however, that the results only show nationwide emissions, and conceal the fact that locally air quality may deteriorate due to electricity generation to fuel electric vehicles.

Looking at concentrations of fine particulate matter ($PM_{2.5}$), we see that climate policy, air pollution controls and conditions for electrification jointly result in significantly different outcomes for air quality by mid-century. **Figure 55** maps the difference between our 2 most extreme scenarios out of the 12 scenarios discussed in this chapter: Reference climate policy, Frozen air pollution controls and Low electrification on the one hand, and 2°C climate policy, Progressive air pollution controls and High electrification on the other hand. Particularly in India and China we find substantial improvements in air quality, but also in the Middle East and in Eastern Europe.

Figure 55. Air quality improvement in 2050 due to climate policy, air pollution control policy and enabling conditions for electrification



Note: The figure shows the difference in $PM_{2.5}$ concentration between REF-FRZ-Low and 2C-PRG-High, with positive values indicating better air quality in the latter. Source: Based on calculations with the TM5-FASST model (Van Dingenen, et al., 2018).

6 Regional energy system impacts of electrification: focus on EU

6.1 Climate-related policy actions

The EU has been one of the world's forerunners on climate policies and climate-related energy policies for decades. As the EU has been constructing its integration over the years, policy-making in climate and energy has been growing in importance, ambition and depth of application over all Member States. The EU was a signatory of the Kyoto Protocol in 1997, where the EU committed a GHG emissions reduction of 8% against 1990 levels, over the 2008-2012 period. The EU Emissions Trading Scheme (EU ETS) was launched in 2005. While the EU was allowed to legislate on environmental issues from its inception, with the Lisbon Treaty of 2007 Member States agreed to handle more authority to the EU in the field of energy issues. In 2007, the EU set out binding objectives for 2020 with the first climate and energy package; this was followed in 2014 with the 2030 Framework for climate and energy. Throughout, the EU has legislated integrated monitoring and reporting rules to ensure progress towards its climate and energy targets.

These actions paved the way for the European long-term strategy. In November 2018, the European Commission presented its strategic long-term vision for a prosperous, modern, competitive and climate neutral economy by 2050 (European Commission, 2018). It covers ambitious climate goals for reducing GHG emissions by 80-100% in 2050. This vision aims to put the EU on track to its engagement under the Paris Agreement, whose objective is to keep the global temperature increase to well below 2°C by 2100, and pursue efforts to keep it below 1.5°C.

Following this publication, in December 2019 the European Council formally invited the European Commission to prepare a proposal for the EU's long-term strategy, with a view to its adoption by the Council and its submission to the UNFCCC in 2020[22].

Table 3. Key targets of EU energy and climate policy

	GHG emissions reduction vs 1990 **(all sectors)**	**ETS sector emissions reduction vs 2005**	**Non-ETS sectors emissions reduction vs 2005**	**Share of renewables in gross final energy**	**Energy efficiency vs 2007 Baseline**
2020 climate and energy package	-20%	-21%	-10%	20%	-20%
2030 climate and energy framework	-40%	-43%	-30%	32%	-32.5%
2050 long-term strategy*	-80-100%	n/a	n/a	n/a	n/a

Note: *: At time of publication, the EU objective of climate neutrality (net zero GHG emissions) has been endorsed by the European Council (heads of government of Member States) in December 2019. However, a long-term strategy for meeting this objective has not yet been agreed. Since 2009, the EU also has the objective to reduce emissions by 80-95% by 2050, in the context of necessary reductions according to the IPCC by developed countries as a group.

The long term strategy follows the new energy policy framework established under the Clean Energy for All Europeans package, published in November 2016. This comprehensive package aims to facilitate the transition to a decarbonised energy system and contains eight legislative acts:

1 Energy Performance of Buildings Directive 2018/844

2 The recast Renewable Energy Directive (EU) 2018/2001

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(22) https://www.consilium.europa.eu/media/41768/12-euco-final-conclusions-en.pdf

3 The revised Energy Efficiency Directive (EU) 2018/2002

4 Governance of the energy union and climate action (EU) Regulation 2018/1999

5 Regulation on risk-preparedness in the electricity sector (EU) 2019/941

6 Regulation establishing a European Union Agency for the Cooperation of Energy Regulators (EU) 2019/942

7 Regulation on the internal market for electricity (EU) 2019/943

8 Directive on common rules for the internal market for electricity (EU) 2019/944

6.1.1 Regulatory framework for GHG emissions

In 2014 a binding EU-wide target for GHG emissions reduction of 40% in 2030 compared to 1990 was adopted. The legislation and policies needed to achieve this target (the Climate and Energy Framework) were then adopted in the period 2014-18.

The **EU ETS** is the EU cornerstone tool for cutting GHG emissions in a cost effective way. It covers around 45% of the total EU GHG emissions, being the world's first major carbon market. The ETS is mainly applied to large-scale facilities in the power and industry sector, as well as the aviation sector, covering principally CO_2 from fossil fuels combustion and certain non-CO_2 GHGs in industry (N_2O, PFCs). It operates in 31 countries (EU[23] plus Iceland, Liechtenstein and Norway). The EU ETS's third phase (2013-2020) is characterized by a single EU-wide cap instead of the previous national-based system and gives a larger role to allowances allocation by auctioning. The next trading period (phase 4, 2021-2030) was revised in 2018 in order to align it with 2030 objectives:

- the pace of annual reduction of the cap was increased from 1.74% to 2.2% as of 2021 and the market stability reserve was reinforced[24];
- the free allocation of allowances was continued as a safeguard for the international competitiveness of industrial sectors at risk of carbon leakage, while ensuring that the rules for determining free allocation are focused and reflect technological progress;
- several low-carbon funding mechanisms were set up to help industry and the power sector to meet the innovation and investment challenges of the low-carbon transition.

The **non-ETS sector** (essentially transport, buildings and agriculture and land use) is covered by a mix of EU-wide and Member State-level instruments. The main legislation consists of:

- The **Effort Sharing Regulation (ESR)** [25] was adopted in 2018; it sets up binding annual emissions reductions for the non-ETS sector by Member State from 2021 to 2030. Member States reductions for 2030 range from 0% to -40% in 2030 compared to 2005 levels, aggregating into a -30% objective for the whole of the EU; it includes flexibility mechanisms with some trade allowed between countries and the possibility to use a limited amount of emissions removals in land-use sectors to meet part of their ESR targets. This mechanism follows on the Effort Sharing Decision which put 2020 objectives into law, where national emission targets for 2020 ranged from -20% to +20% versus 2005, with 10% for the EU as a whole. Member States are responsible for national policies and measures to limit emissions from the non-ETS sectors (reducing transport needs, promoting public transport, support schemes for retrofitting buildings, promoting renewable energy for heating and cooling, more climate-friendly farming practices, conversion of livestock manure to biogas, etc…).
- Under the **LULUCF Regulation**, which integrates emissions and removals from land into the 2030 climate and energy framework, Member States must also ensure that accounted emissions from land use in the period 2021-30 are entirely compensated by an equivalent removal of CO_2 (the 'no debit rule'). Any debit would need to be covered by surpluses under the ESR. There is also a possibility for

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(23) European Union as of December 2019 (including the United Kingdom)

(24) This mechanism was established in 2015 to reduce the surplus of emission allowances in order to improve the EU ETS's resilience to future shocks.

(25) The Effort Sharing Regulation covers the six greenhouse gases controlled by the Kyoto Protocol during its first commitment period (2008-2012) – carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) – as well as nitrogen trifluoride (NF_3).

Member States to use overachievement under the Effort Sharing Regulation to satisfy the “no debit” commitment, subject to strict quantitative limits.

- In 2019, the EU updated the Regulation for CO_2 emission performance standards for new light duty vehicles (passenger cars and vans), setting reduction objectives for 2025 and 2030; in 2030, the fleet-wide average CO_2 emissions of new cars and vans per km travelled will need to be cut by 37.5% and 31% compared to 2021 levels, respectively. This Regulation continues the targets for 2021 compared to 2015 levels, and targets for 2015 compared to 2007 levels.
- In 2019, the first EU-wide regulation for CO_2 emission performance standards for heavy duty vehicles entered into force. By 2025 and 2030, the EU-wide fleet average CO_2 emissions per km of new lorries covered by the regulation need to be reduced by 15% and 30%, respectively, compared to the reference period (1 July 2019–30 June 2020). As part of the 2022 review, the Commission should assess the extension of the scope to other vehicles types such as smaller lorries, buses, coaches and trailers. Taken together, these two measures aim to reduce CO_2 emissions from road transport by 23% compared to 2005 levels.
- The Fuel Quality Directive (2009) covers petrol, diesel and biofuels used in road transport and gasoil used in non-road-mobile machinery; it requires a reduction of the greenhouse gas intensity of transport fuels by a minimum of 6% by 2020.
- Regarding fluorinated GHGs (F-gases: HFCs, PFCs, SF6), the EU has adopted the F-gas Regulation (2006, updated in 2014) (European Parliament And Council Of The European Union, 2014) and the Mobile Air-Conditioning Directive (2006). They aim to limit and phase down the total amount of F-gases, banning the use of F-gases in many new types of new equipment (fridges, air conditioning, foams and aerosols) and preventing F-gases emissions by requiring maintenance and end-of-life recovery. The objective is to cut F-gas emissions by two-thirds by 2030 versus 2014 levels. Since 2018, the EU is also a signatory to the Kigali Amendment to the Montreal Protocol; according to that amendment, the EU commits to reduce its HFCs emissions gradually, down to 15% of its 2011-2013 average emissions by 2036.
- The regulation on **governance of the Energy Union and climate action** was also adopted in 2018, containing a governance system to help the EU and its Member States achieve their 2030 goals as regards GHG emission reductions, renewables and energy efficiency. Member States had to prepare national energy and climate plans for 2021-2030, due December 2019, and report on their progress in implementing the plans, mostly every two years, while the Commission will monitor the progress of the EU as a whole. In accordance with their integrated national energy and climate plans (NECPs) for the period 2021-2030, Member States also had to prepare long-term strategies, covering a period of at least 30 years from 2020 onwards.

6.1.2 Regulatory framework for renewable energy deployment

As part of the 2030 framework, the Renewable Energy Directive (2014) set up a binding EU-wide target for the share of renewable energy in gross final energy of 27%; this was revised upwards to 32% in 2018. (2018/2001/EU). In addition, 14% of the energy consumed in road and rail transport by 2030 should be renewable energy.

The earlier version of the Renewable Energy Directive (2009) set up a 20% objective for renewables in gross final consumption, which was differentiated by Member State. It further included a 10% objective for the share of transport fuels that come from renewable sources for 2020; due to sustainability concerns, in 2012 the latter objective was limited to 5% for the use of food-based biofuels to meet the 10% target.

6.1.3 Regulatory framework for Energy efficiency

As part of the 2030 framework, the Energy Efficiency Directive (2018) set up a binding EU-wide target for energy efficiency of 27% for 2030 (energy demand reduction compared to the Baseline calculated in 2007); it was revised upwards to 32.5% in 2018. The earlier version of the Directive for 2020 targets (2012) aimed for an EU-wide target for energy efficiency of 20%.

As part of their NECPs, Member States are required to outline how they intend to meet the energy efficiency and other targets for 2030. The NECPs replace and widen the scope of the National Energy Efficiency Action Plans (NEEAPs) that were set up in 2012 and were updated every three years. The binding EU-wide target is to be achieved collectively across the EU; the EU has published recommendations for EU countries to help them to fully transpose the different elements of the 2018 Directive into national law.

Regarding the energy efficiency of buildings specifically, the Energy Performance of Buildings Directive (EPBD, introduced in 2010 and amended in 2018) outlines specific measures for the building sector. Among others, it requires all new public buildings to be nearly zero-energy buildings (NZEBs) by the end of 2018; and all new buildings in general must be NZEBs from 2021 onwards. NZEBs consist of very high energy performance buildings, where the low amount of energy required comes mostly from renewable sources. The 2018 amendment introduced further elements such as the need to establish stronger national long-term renovation strategies, 'smart readiness' of buildings and supporting the roll-out of e-mobility infrastructure in buildings.

6.2 Energy transformation pathways by sectors in EU

This section summarizes the role of electrification in decarbonisation scenarios for the EU. Here, the main GECO2019 scenarios are compared with the scenarios presented in the EU's proposed long-term strategy[26] (LTS). The LTS proposal explored eight economy-wide scenarios achieving different levels of emissions reductions **(Table 4**). This comparison is presented in order:

- to illustrate the coherence between the LTS scenarios (developed by models focused on the EU only) and the GECO scenarios (developed by a global model) in terms of current policies emissions trajectories of the EU;
- to illustrate how current EU policies and objectives for 2030 (LTS Baseline scenario) compare to emission levels for the EU obtained from the regional distribution of the global effort to reduce emissions towards a 2°C world (GECO 2°C scenarios);
- to illustrate how strengthening EU policies after 2030 (eight LTS scenarios) compare to the regional emissions trajectories established by a global effort to reduce emissions towards a 2°C world (GECO 2°C scenarios), in particular for 2050.

Thus, it will be possible to do the following comparisons:

- The GECO2019 Reference scenario was built with the POLES-JRC model and includes currently existing sectoral policies for the EU and elsewhere. It is best comparable with the LTS Baseline scenario.
- The GECO2019 2°C scenarios were built with the POLES-JRC model and are driven, in the EU and elsewhere, by an economy-wide carbon value (all sectoral policies, currently existing or projected, have been removed). These scenarios can be compared with the eight LTS mitigation scenarios, which extend and reinforce EU policies to 2050. The comparison provides 2°C- and 1.5°C-compatible regional mitigation levels achieved with different means.

The policies in the GECO2019 scenarios are described in **Annex 1**.

The LTS scenarios cover the potential range of reductions needed in the EU to contribute to the Paris Agreement's temperature objectives. Reductions range between 80% (excluding Land Use, Land-Use Change, and Forestry (LULUCF)) and 100% (net-zero, taking into account LULUCF sinks) in 2050 compared to 1990 levels. These scenarios project a gradual, yet significant, change from the current situation. They all incorporate a wide, albeit varying, portfolio of mitigation options. Considering the inertia of the energy system and the economy as a whole, the resulting projections begin after 2030 and increasingly thereafter. Each scenario was assumed to have certain advantages in facilitating the uptake of some specific technological pathway.

([26]) In-depth analysis in support of the Commission Communication COM(2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy (European Commission, 2018).

Table 4. Summary description of the proposed LTS scenarios from COM(2018) 773

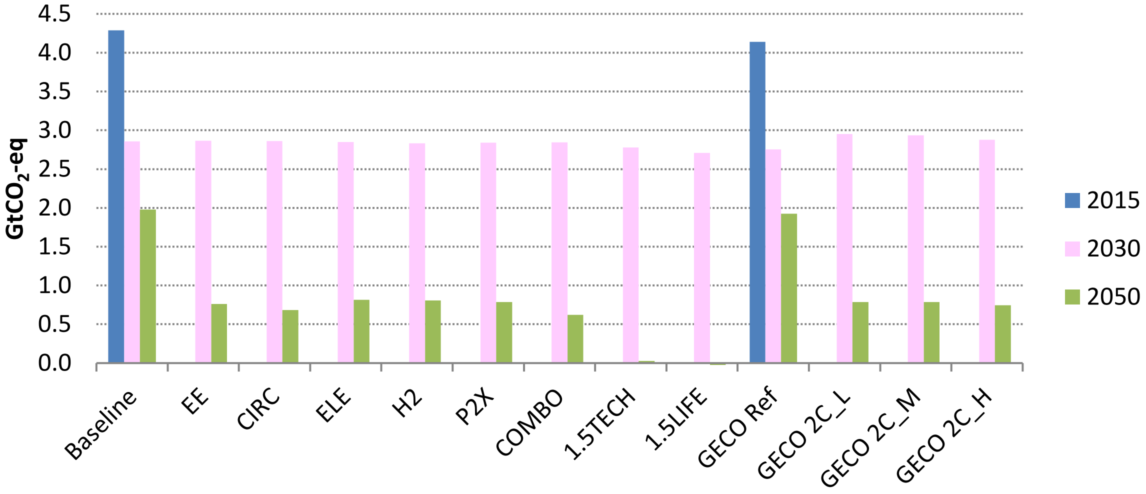
PRIMES scenario	Reduction % GHG emissions	Main mitigation option
EE	80%	Strong Energy efficiency measures Development of renewable energy Improvements in transport system efficiency
CIRC	80%	Transition to a Circular economy Energy efficiency measures Development of renewable energy Improvements in transport system efficiency
ELEC	80%	Focus on switching from the direct use of fossil fuels to zero/carbon neutral Electricity Energy efficiency measures Development of renewable energy Improvements in transport system efficiency
H_2	80%	Focus on witching from the direct use of fossil fuels to zero/carbon neutral Hydrogen Energy efficiency measures Development of renewable energy Improvements in transport system efficiency
P2X	80%	Focus on switching from the direct use of fossil fuels to zero/carbon neutral e-fuels Energy efficiency measures Development of renewable energy Improvements in transport system efficiency
COMBO	90%	Combines the actions and technologies of the five previous scenarios, without reaching though the level of deployment of each technology as in the first category Energy efficiency measures Development of renewable energy Improvements in transport system efficiency
1.5TECH	Net-zero	Relies more heavily on the deployment of biomass associated with significant amounts of carbon capture and storage (BECCS) Energy efficiency measures Development of renewable energy Improvements in transport system efficiency
1.5LIFE	Net-zero	Less carbon intensive diets Sharing economy in transport Limiting growth in air transport demand Rational use of energy demand for heating and cooling.

6.2.1 Greenhouse gas emissions mitigation

The total GHG emissions in 2030 in the LTS Baseline scenario is estimated at -48% compared to 1990 levels (-46% without considering LULUCF) and -64% in 2050 (-62%, respectively). The GHG target announced in the EU's INDC of -40% is thus overachieved for all the scenarios proposed. The GECO2019 Reference scenario also reaches comparable values: -48% for 2030 and -62% for 2050.

In 2050 most LTS scenarios reductions exceed 80% compared to 1990 (85-89%), with the 1.5°C scenarios reaching net-zero. The GECO2019 2°C scenarios achieve reductions of 84-85%, thus being most comparable with the six "2°C-compatible" LTS scenarios (**Figure 56**).

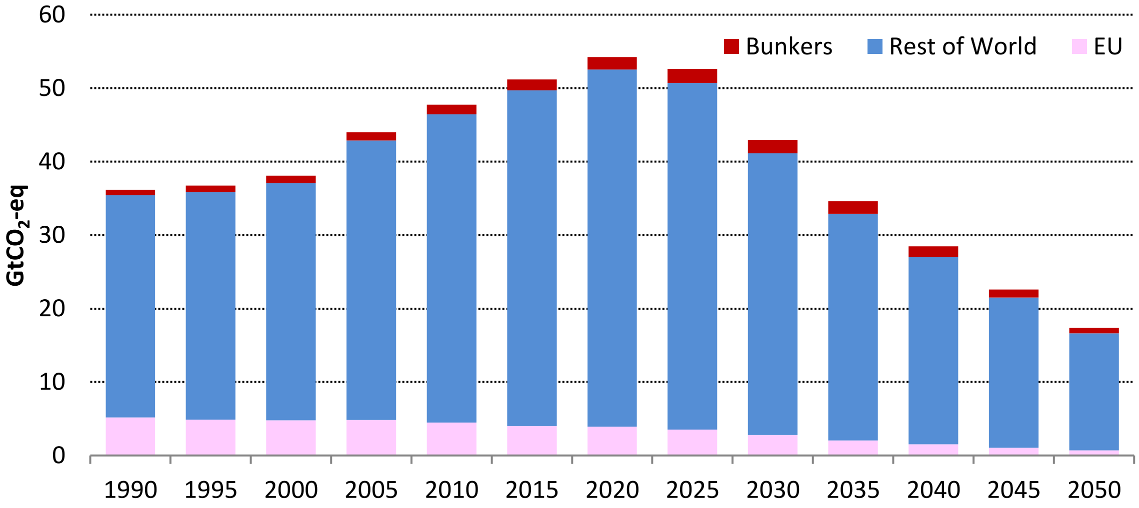
Figure 56: Total GHG emissions, EU



Note: Differences in 2015 essentially come from energy CO_2 (LTS: 3531 $MtCO_2$; POLES-JRC: 3298 $MtCO_2$).

In the global context of a 2°C scenario, the decrease in EU emissions is accompanied by a peak and decrease of emissions in other world regions. The EU's share in global emissions decreases from 13.9% in 1990 to 6.9% in 2015, then to 2.9% in 2050, in the 2°C-Medium scenario (see **Figure 57**).

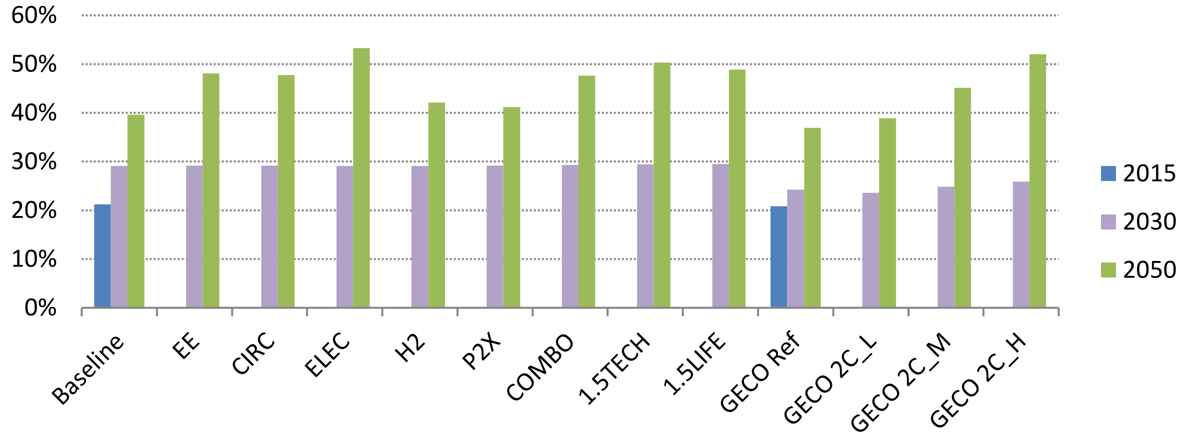
Figure 57: EU and World total GHG emissions, 2°C scenario



6.2.2 Electrification in EU: the total picture

Across Europe the share of electricity in final energy demand continues to grow, displacing mainly oil and gas uses. In 2030 share of electricity in final energy demand reaches values around 30% for all the scenarios, in 2050 the electricity share despite the scenario continues to grow, reaching values above 40% for almost all the scenarios (see **Figure 58**).

Figure 58: Share of electricity in final energy consumption, EU

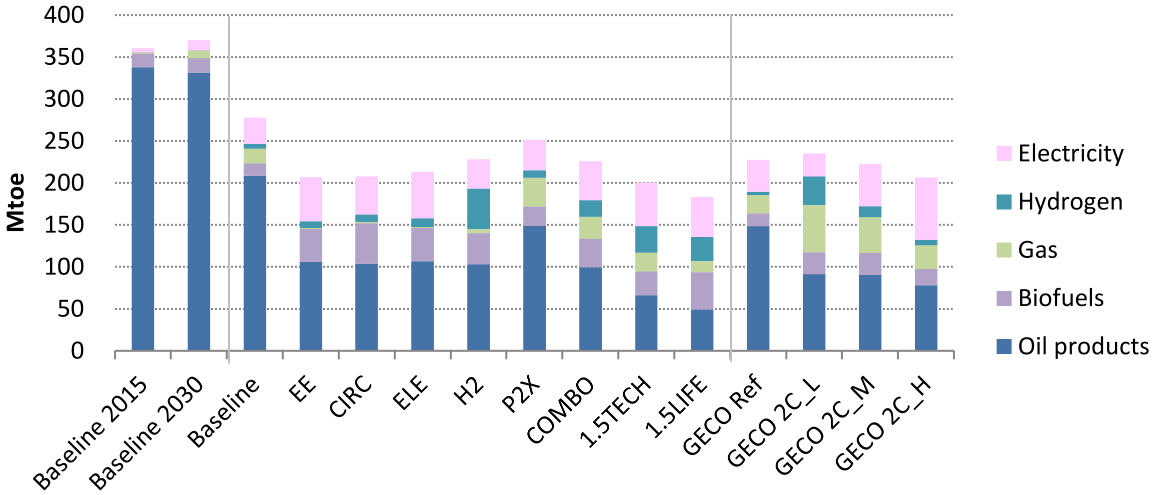


6.2.3 Electrification in EU: Transport

Transport represents around a third of the final energy consumption in the EU. Oil products make up the dominant fuel for the transport sector (with a 94% share in 2015); projections show a gradual drop in the importance of oil and a diversification of the fuel mix (see **Figure 59**).

Reducing GHG emissions in the transport sector requires actions on overall vehicles efficiency, promoting low- and zero-emissions vehicles, promoting the deployment of refuelling (or recharging) infrastructure as well as promoting the transport system efficiency.

Figure 59: Fuel consumed in the transport sector in 2050, EU



Note: Include international aviation. In the LTS scenarios, methanol and ethanol consumption (<0.04% of total) has been aggregated with oil products.

Road transport is the mode where electrification is most suitable, particularly in the segment of light-duty vehicles (passenger cars and vans) and 2-wheelers (bikes), but also for busses. Electric vehicles with batteries represent a promising option, with fast developments being foreseen. However, large scale roll out of recharging infrastructure is a prerequisite.

The electrification of road transport, defined as electricity consumption as a share of total final energy consumption, is presented in **Figure 60**. While that share is still low in 2030 in all scenarios (2.1% in GECO Reference, as much as 5.9% in GECO 2C_H), by 2050 there is a large differentiation. The GECO Reference scenario reaches a higher electrification than the LTS Baseline, and the high electrification 2°C scenario (2C_H) reaches a higher electrification than the other LTS scenarios.

Figure 60: Share of electricity in road transport final energy consumption, EU

6.2.4 Electrification in EU: Buildings

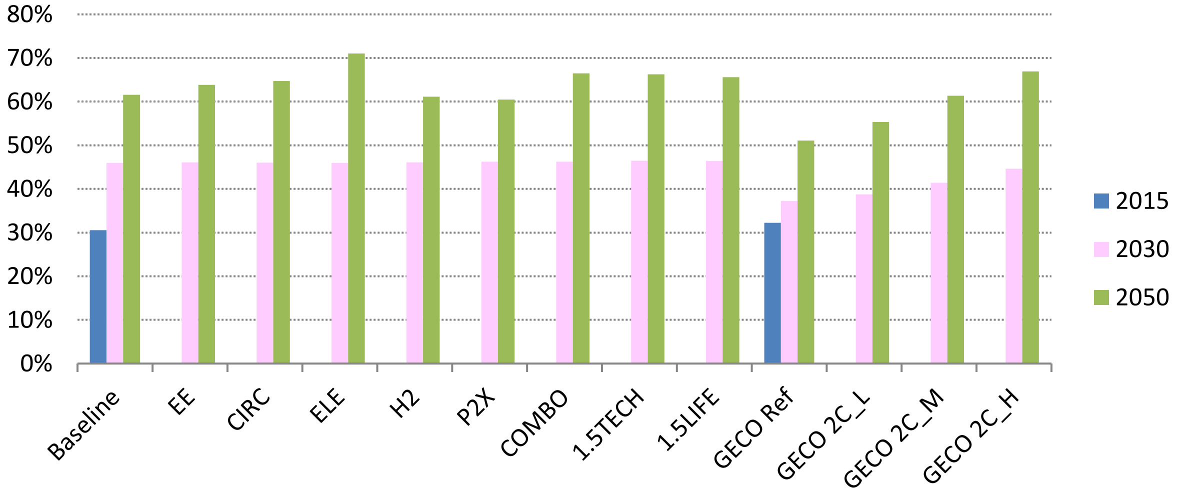
Buildings (defined here as the residential, services and agriculture sectors) currently represent the highest share of final energy consumption in the EU. Energy consumption in buildings serves multiples purposes: heating & cooling, operation of appliances, water heating and cooking.

Even though the majority of energy needs are still covered by fossil fuels (54% in 2015), there are powerful drivers for reducing energy demand in buildings: first by the better isolation of the building shell, thus reducing useful energy needs for space heating and cooling; and second by the uptake of efficient and low-carbon energy-consuming equipment (i.e. heat pumps, which have a high final-to-useful energy ratio). Indeed, the large majority of energy consumption serves heating and cooling uses (86% in 2015) and is often fuelled by gas (space heating, water heating) and oil products (heating).

Currently only 0.4-1.2% of the building stock is renovated each year. As with the LTS scenarios, the GECO scenarios include assumptions on increasing the renovation rate to as much as 3% per year in order to reduce energy consumption.

The resulting electrification in buildings, defined as electricity consumption as a share of total final energy consumption, is presented in **gure 61**. The LTS scenarios generally reach higher electrification in 2030 than the GECO scenarios. Electrification in 2050 ranges from 57% to 66% in the GECO 2°C scenarios (52% in GECO Reference), compared to 60% to 71% in the LTS scenarios.

Figure 61: Share of electricity in buildings final energy consumption, EU



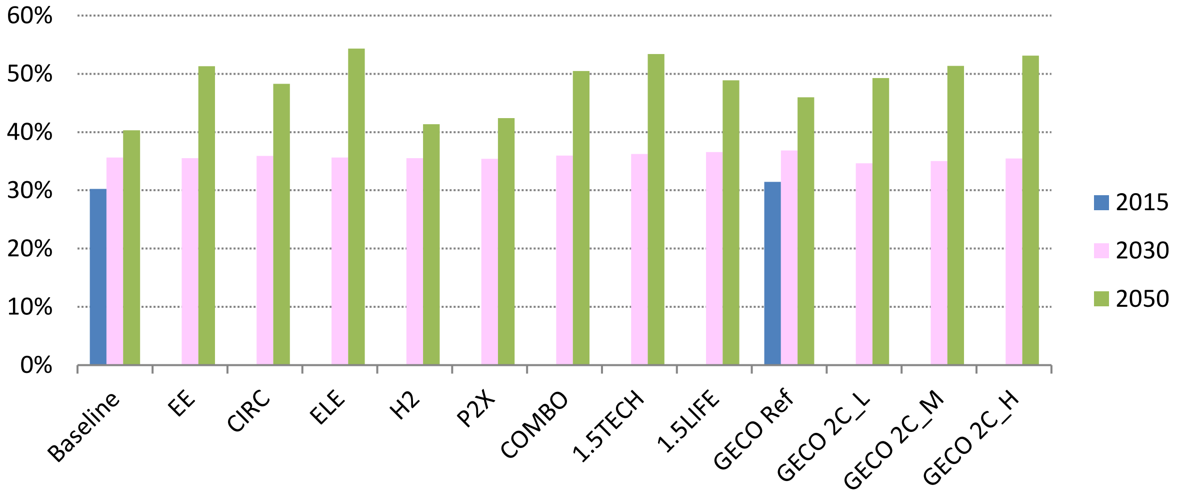
6.2.5 Electrification in EU: Industry

A large part of GHG reductions achieved up to date in industry is a result of energy efficiency improvements. In order to reduce emissions further and more deeply, especially to align with the EU's 2050 ambition, major changes need to be made in the way industry consumes energy and produces its products.

Further energy use and process optimisation, for instance through the reduction of heat losses, recovery and re-use of heat released by processes (e.g. in gaseous effluents) are all achievable. Further overall efficiency could be achieved by linking heat recovery to district heating systems for buildings. However, such efforts on their own would seem insufficient to achieve the long term GHG reduction goals, with more efforts needed to decarbonise the fuel mix of the energy consumed in industry.

Electrification of certain processes is a promising emission abatement option. Electrification in industry, defined as electricity consumption as a share of total final energy consumption, is presented in **Figure 62**. Electrification increases are gradual in the LTS Baseline and more ambitious in the GECO Reference. Overall, GECO mitigation scenarios appear to be more ambitious, reaching 52%-55% in 2050, versus 41%-54% in the LTS mitigation scenarios.

Figure 62: Share of electricity in industry final energy consumption, EU



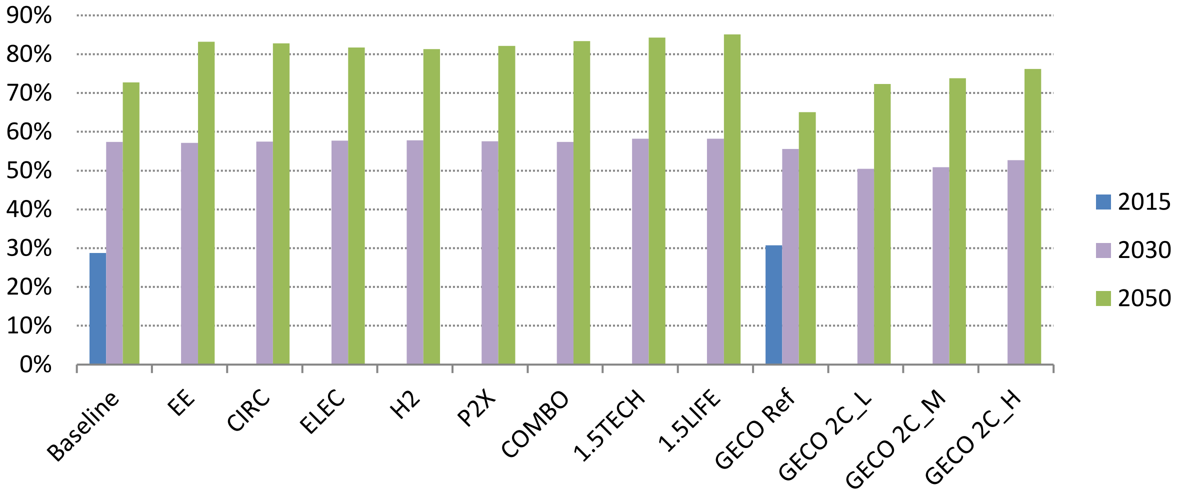
Note: Figures do not include non-energy uses of fuels (uses as raw materials).

6.2.6 Electrification effects in EU: Power generation

Decarbonising power production while at the same time electrifying EU final energy consumption will be essential for creating a GHG-neutral and energy-efficient economy. EU power sector emissions have been decreasing and the share of renewables in power generation has been increasing since before 1990. This is to be extended further in the future, aiming to provide a very low-carbon electricity supply across Europe by 2050.

The share of renewables in the EU power generation is presented in **Figure 63**. Projections are in agreement on the achievement of the 2030 objective. Overall, projections in 2050 differ, with LTS scenarios having a higher penetration of renewables than GECO scenarios, notably presenting a higher penetration of wind power.

Figure 63: Share of renewables in power generation, EU

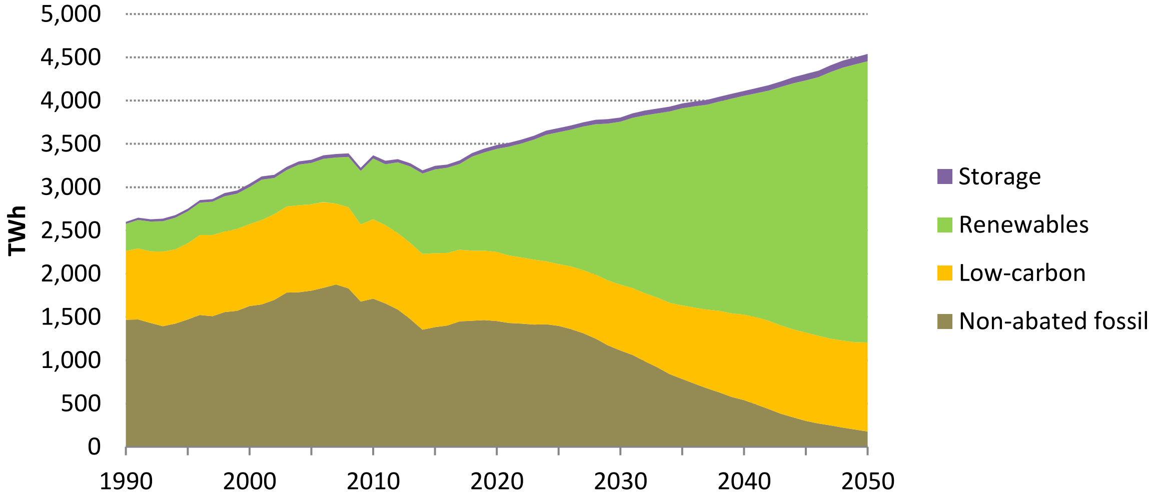


The European power sector has made the most important steps towards decarbonisation with the closure of most inefficient thermal generation, the growth of renewables, the contribution of nuclear and the announced phase-out of coal power plants from many Member States.

Further developments include better interconnection between grids in order to achieve a unified EU-wide electricity market. Connecting markets through appropriate infrastructure and cross border trading rules allowed significant increases liquidity and security of supply significantly. Such developments go hand in hand with the capability to integrate an increasing share of variable renewable generation in the grid.

Power generation becomes more reliant on renewables (**Figure 64**). The role of storage becomes more notable, with its share in total power generation doubling between 2015 and 2050 to 2.2%.

Figure 64: Power generation mix, EU, 2°C-Medium scenario



Note: Low-carbon consist of fossil fuels with CCS and nuclear. Hydro pumped storage is accounted in storage. Hydrogen fuel cells are accounted in storage.

7 Regional energy system impacts of electrification: focus on China

7.1 Climate-related policy actions in China

As the largest developing country, China is a country with a huge population, complex climate and vulnerable eco-environment, and one of the most vulnerable countries to the adverse impacts of climate change. China has attached great importance to the issue of global climate change, set up national, local or relevant departmental (industrial) organizations and institutions to address climate change, and issued a series of policies ranging from comprehensive national strategies to sector regulations and plans. From the climate change mitigation perspective, China issued policies including adjusting the industrial structure, optimizing the energy system, conserving energy and improving energy efficiency, controlling GHG emissions from non-energy activities and increasing carbon sinks to control its greenhouse gas emissions. To adapt to climate change, China released policies to improve the capacity of adapting to climate change in agriculture, water resources, forestry, ocean, meteorology, disaster prevention, etc.

As the theme of this year's GECO report is electrification, the following discussion in this chapter will focus on China's energy and electrification related policies. It should be noted that industrial restructuring policy, controlling emissions from non-energy activities, increasing carbon sinks and adapting to climate change are also the focus of China's response to climate change.

Table 5: Overview of the Chinese policies discussed in this section

Policy domain	Policy	Issued year	Government department
Overarching Climate Policy	National Plan on Climate Change (2014-2020)	2014	NDRC
	Nationally Determined Contribution (NDC)	2015	
Optimizing Energy Supply	Energy Development Strategy Action Plan (2014-2020)	2014	State Council
	13th Five Year Plan for Energy Development	2016	NDRC, NEA
	13th Five Year Plan for Natural Gas Development	2016	NDRC
	13th Five Year Plan for Renewable Energy Development (2016-2020)	2016	NDRC
	13th Five Year Plan for Electricity Development	2016	NDRC, NEA
	Energy Supply and Consumption Revolution Strategy (2016-2030)	2016	NDRC
	Opinions on Comprehensively Enhancing Ecological and Environmental Protection and Resolutely Winning the Tough Battle for Prevention and Control of Pollution	2018	CPC Central Committee, State Council
	Opinions of the CPC Central Committee and the State Council on further deepening the reform of the electric power system	2015	CPC Central Committee, State Council
	Notice on Piloting Spot Market	2019	NDRC, NEA
	Notice on Establishing a Mandatory Renewable Electricity Consumption Mechanism	2019	NDRC, NEA
Conserving Energy and	Opinions on Promoting Electric Power Substitution	2016	NDRC, NEA, MoF, MEP, MoHURD,

Improving Energy Efficiency			MIIT, MOT, CAAC
	13th Five Year Energy Saving and Emissions Reduction Work Plan	2016	State Council
	Plan for the Development of Building Energy Conservation and Green Buildings during the 13th Five Year Plan Period	2017	MoHURD
	Special Plan for Scientific and Technological Innovation in Housing and Urban-Rural Development during the 13th Five Year Plan Period	2017	MoHURD
	Implementation Plan for the Promotion of Ecological Civilization in Transport	2017	MOT
	Opinions on Comprehensively and Profoundly Promoting the Development of Green Transport	2019	MOT
	Energy Conservation and Emission Reduction Plan in Civil Aviation for the 13th Five Year Plan Period	2017	CAAC
	Mid- and Long-Term Development Plan for the Automobile Industry	2017	MIIT, NDRC, MOST
	Notice on Preferential Vehicle and Vessel Tax Policies for Energy-Saving and New-Energy Vehicles and Vessels	2018	MoF, STA, MIIT, MOT
	Passenger Cars Corporate Average Fuel Consumption and New Energy Vehicle Credit Regulation	2017	MIIT, MoF, GACC, MOFCOM, AQSIQ
	Notice on Further Perfecting the Policy of Financial Subsidies for the Promotion and Application of New Energy Vehicles	2019	MoF, MIIT, MOST, NDRC
	Catalogue of National Key Energy Conservation and Low-Carbon Technologies for Promotion	2018	NDRC
National Carbon Emission Trading Market	Scheme for the Construction of the National Carbon Emission Trading Market (for the Power Generation Industry)	2017	NDRC

7.1.1 Overarching Climate Policy

In September 2014, China released the **National Plan on Climate Change (2014-2020)**. The plan identified the principles, policy direction and key tasks and raised targets for climate action by 2020, including to cut carbon intensity (carbon emissions per unit of GDP) by 40-45% from its 2005 level, to increase the percentage of non-fossil energy in primary energy consumption to 15% and to increase the proportion of forest area and stock volume by 40 million ha and 1.3 billion m^3 from their respective 2005 levels.

For the post-2020 period, China has put forward its **Nationally Determined Contribution (NDC)** on June 30, 2015, setting the targets for 2030. As its NDC targets, China promised to achieve the peaking of carbon dioxide emissions around 2030, and making best efforts to peak early. By 2030, the CO_2 emissions per unit of GDP should fall by 60% to 65% compared with the 2005 level. By 2030, non-fossil energy should account for about 20% of primary energy consumption, and the amount of forest reserves should be increased by about 4.5 billion m^3 by 2030, compared with 2005. In addition, it also promised to continue to actively tackle climate change, form mechanisms and capabilities for effectively resisting climate change risks in key sectors such as agriculture, forestry, energy and water resources, as well as in fragile regions such as cities, coastal areas, and ecosystems; and gradually improve forecasting and disaster prevention systems.

Table 6. Overarching climate targets and progress from latest statistics

	2018	2020	2030
CO_2 Intensity Compared with 2005 Level	-45.8%	-40-45%	-60-65%
Share of Non-fossil Energy in Primary Energy	14.3%	15%	20%
Forest Area Compared with 2005 Level	45.09 million ha	40 million ha	-
Forest Stock Value Compared with 2005 Level	5.140 billion m^3	1.3 billion m^3	4.5 billion m^3

Note: Electricity generated from nuclear and primary renewables (wind, solar) is converted into primary energy (tons of coal-equivalent) using the average efficiency of coal power plants in China. In this report where POLES-JRC modelling results are presented, electricity generated from nuclear and primary renewables (wind, solar) is directly considered as primary energy.

7.1.2 Optimizing Energy Supply

Along with rapid economic growth, China's total primary energy consumption experienced a fast increase in the past decades, becoming the largest energy consumer in the world. In 2014, emissions from the energy sector accounted for 77.7 percent of national total GHG emissions[27]. Therefore, controlling the energy consumption and decarbonizing the energy system is of great importance for China in mitigating climate change and achieving its NDC target. To control total energy and coal consumption, in 2014, China released the **Energy Development Strategy Action Plan (2014-2020)**, including targets of controlling the total primary energy consumption at about 4.8 billion tons of standard coal equivalent (tce), and the total coal consumption at about 4.2 billion tons by 2020. In 2016, China's **13th Five Year Plan for Energy Development** set targets of the total primary energy consumption to be less than 5 billion tce, the coal consumption to be less than 4.1 billion tons, and the share of coal consumption in total energy consumption to be less than 58% by 2020 compared with 64% in 2015. For 2030, China's Energy Supply and Consumption Revolution Strategy (2016-2030) outlines the goal that primary energy consumption should be controlled within 6 billion tce.

In addition, policies targeting key air pollution also include coal control as one of the instruments. In 2018, the Central Committee of the Communist Party of China and the State Council issued **Opinions on Comprehensively Enhancing Ecological and Environmental Protection and Resolutely Winning the Tough Battle for Prevention and Control of Pollution**, requesting to continue to exercise control over total coal consumption in key regions, and reduce coal consumption by 10% from 2015 to 2020 in Beijing, Tianjin, Hebei, Shandong, Henan, and the Pearl River Delta and by 5% in Shanghai, Jiangsu, Zhejiang, Anhui, and the Fen-Wei Plain.

In 2018, China's total primary energy consumption was 4.64 billion tons of standard coal, and the total coal consumption was 3.9 billion tons, for the first time below 60 percent of the total, about 10 percent points below the level in 2010.

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(27) The People's Republic of China Second Biennial Update Report on Climate Change

Table 7. Energy consumption control targets and progress from latest statistics

	2018	2020 target (from 2014 Energy Development Strategy Action Plan)	2020 target (from 2016 13th Five Year Plan for Energy Development)	2030 target
Total Primary Energy Consumption (billion tons of standard coal)	4.64[28]	4.8	5.0	6.0
Total Primary Coal Consumption (billion tons of coal)	3.9[29]	4.2	4.1	-
Share of Coal in Total Primary Energy Consumption	59%[30]	-	58%	-

Note: Electricity generated from nuclear and primary renewables (hydro, wind, solar) is converted into primary energy (tons of coal-equivalent) using the average efficiency of coal power plants in China. In this report where POLES-JRC modelling results are presented, electricity generated from nuclear and primary renewables (hydro, wind, solar) is directly considered as primary energy.

In improving coal-fired power plants efficiency, the **Energy Supply and Consumption Revolution Strategy (2016-2030)** sets the heat rate of power supply in existing coal power plants to be lower than 310 grammes of coal equivalent per kWh (gce/kWh), and heat rate of new-built power plants would go down to 300 gce/kWh by 2020. By 2030, the share of coal used for power generation will continue to increase with a declining share of coal used in other final energy consumption sectors; especially to phase out scattered coal use in rural area, the average coal consumption per kWh electricity of coal-fired power plants will be further reduced, and coal-fired plants with ultra-low pollutant emissions will account for more than 80% of the total coal fired power plants.

For natural gas development, the Energy Development Strategy Action Plan (2014-2020) and the **13th Five Year Plan for Natural Gas Development** put forward the goal that natural gas in primary energy consumption should be increased to about 10% by 2020. In China's Energy Supply and Consumption Revolution Strategy (2016-2030), the goal is stated that natural gas should account for more than 15% of the mix by 2030.

Table 8. Natural gas consumption target and progress from latest statistics

	2018	2020	2030
Share of Natural Gas in Energy Mix	7.8%[31]	10%	15%

To develop non-fossil energy, the Energy Development Strategy Action Plan (2014-2020) set the goals for year 2020, including:

- non-fossil energy will account for 15% of primary energy consumption；
- installed capacity of hydro power will reach about 350 GW;
- installed capacity of wind power will reach about 200 GW;
- installed capacity of solar power will reach about 100 GW; and
- the utilization of geothermal will reach about 50 million tce.

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(28) National Bureau of Statistics of China http://www.stats.gov.cn/tjsj/zxfb/201902/t20190228_1651265.html

(29) Calculated based on National Bureau of Statistics of China http://www.stats.gov.cn/tjsj/zxfb/201902/t20190228_1651265.html and 2018 China energy statistical yearbook

(30) National Bureau of Statistics of China http://www.stats.gov.cn/tjsj/zxfb/201902/t20190228_1651265.html

(31) National Bureau of Statistics of China, http://www.stats.gov.cn/tjsj/zxfb/201907/t20190718_1677011.html

The **13th Five Year Plan for Renewable Energy Development (2016-2020)** and **13th Five Year Plan for Electricity Development**, adopted in 2016, outlined targets for renewable energy and nuclear energy until 2020, which include:

- increase the share of non-fossil energy in total primary energy consumption to 15% by 2020 and to 20% by 2030, as set previously;
- increase installed renewable power capacity to 680 GW by 2020, and renewable electricity generation to 1900 TWh, accounting for 27% of total electricity generation;
- increase installed hydro capacity to 340 GW (excluding pump storage);
- increase installed wind capacity to 210 GW;
- increase installed solar capacity to 110 GW;
- increase installed biomass capacity to 15 GW;
- increase installed nuclear power plant capacity to 58 GW, and another 30 GW under construction;
- lead renewable energy technology innovation; and
- resolve renewable power curtailment issues.

For 2030, China's Energy Supply and Consumption Revolution Strategy (2016-2030) set a goal of increasing the share of non-fossil electricity in total electricity generation to 50%.

Table 9. Non-fossil energy targets in power generation and progress from latest statistics

Year	2018	2020	2030
Total Installed Renewable Capacity (GW)	728[32]	680	-
Share of Renewable Electricity in Total Electricity	26.7%[33]	27%	-
Share of Non-fossil in Total Installed Capacity	40.6%[34]	39%	50%
Share of Non-fossil Electricity in Total Electricity	30.9%[35]	31%	-
Installed Hydro Capacity (GW)	352[36]	340	-
Installed Wind Capacity (GW)	184[37]	210	-
Installed Solar Capacity (GW)	174[38]	110	-
Installed Biomass Capacity (GW)	17.81[39]	15	-
Installed nuclear power plant (GW)	44.66[40]	58	-

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(32) http://www.gov.cn/xinwen/2019-01/28/content_5361939.htm#1

(33) http://www.gov.cn/xinwen/2019-01/28/content_5361939.htm#1

(34) Calculated based on http://www.gov.cn/xinwen/2019-01/28/content_5361939.htm#1

(35) Calculated based on http://www.gov.cn/xinwen/2019-01/28/content_5361939.htm#1

(36) http://www.gov.cn/xinwen/2019-01/28/content_5361939.htm#1

(37) http://www.gov.cn/xinwen/2019-01/28/content_5361939.htm#1

(38) http://www.gov.cn/xinwen/2019-01/28/content_5361939.htm#1

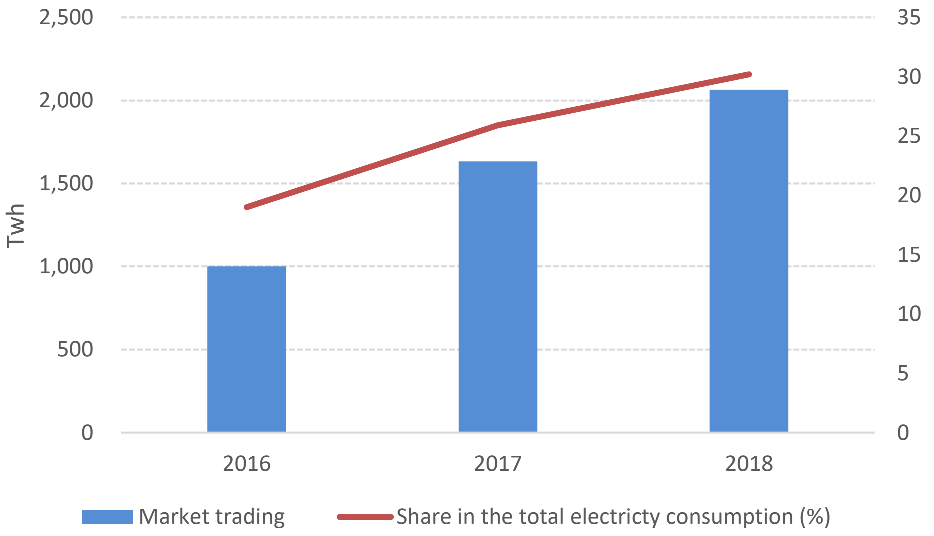
(39) http://www.gov.cn/xinwen/2019-01/28/content_5361939.htm#1

(40) http://www.cec.org.cn/d/file/guihuayutongji/tongjxinxi/niandushuju/2019-01-22/4fedb4c956f6059c5998913b10a6233a.pdf

The latest data shows that China's total installed renewable energy capacity, installed hydropower, solar and biomass capacity already respectively achieved 2020 targets at least two years ahead of schedule. Although it has maintained momentum in terms of installed capacity, renewable energy curtailment is still an issue, as the increasing use of variable renewable energy raises the challenge of integration into the current power system. In 2018, China's renewable energy power generation reached 1.87 trillion kWh, but in the same year, the renewable energy curtailment added up to more than 100 billion kWh equal to around 5.4% of the total renewable electricity generation.[41] [42] Improving the utilization of renewable energy has become a key issue for China to effectively use renewable energy.

In October 2015, China issued **Opinions of the CPC Central Committee and the State Council on further deepening the reform of the electric power system**, launching a new round of market reform, main objectives include building market-based energy pricing mechanism through competition, reducing energy consumption, improving energy efficiency, and protecting the environment. The 2015 reform foresees the orderly withdrawal of the administrative allocation system, with mid-to long-term market as a crucial step towards a market-based system. In 2016-2018, the electricity trading via mid- to long-term markets increased to 2065 TWh, representing 30.2% of total electricity consumption (**Figure 65**). The spot market plays a fundamental role in market-based electricity systems, as a valid approach to integrate high shares of variable renewable energy, while avoiding curtailment[43]. In August 2019, China released the **Notice on Piloting Spot Market**, selecting Guangdong, Shanxi, Gansu, West Inner Mongolia, Zhejiang, Shandong, Fujian, and Sichuan as the pilots to start spot market operation.

Figure 65 Electricity trade on mid- to long-term markets, China



In addition to a market-based mechanism, China released the **Renewable Energy Consumption Obligation Policy: Notice on Establishing a Mandatory Renewable Electricity Consumption Mechanism** in May 2019 to promote the renewable energy consumption, which set provincial renewable power consumption and non-hydro renewable power consumption quotas, the minimum percentages of renewables (hydro and non-hydro) in overall power consumption.

China has been active in the deployment of wind and solar power generation capacity. The manufacturing costs have been declined along with technological innovations. In 2018, the average costs for onshore wind and solar were 7,100 yuan/W, and 5,500 yuan/W, respectively.[44] With the cost reduction of renewable energy, projects can be economically viable without additional subsidies. In areas with abundant solar or wind resources, lower construction costs and good investment and market conditions, the levelized cost of electricity (LCOE) for solar and wind power are equal to or less than the LCOE for a coal fired power plant,

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(41) http://www.xinhuanet.com/fortune/2019-06/05/c_1124583606.htm
(42) http://www.gov.cn/xinwen/2019-01/28/content_5361939.htm#1
(43) IEA, China power system transformation.
(44) http://www.xinhuanet.com/fortune/2019-06/27/c_1124679482.htm

achieving cost parity with coal without subsidies.45 Historically, government subsidies drove the renewable energy installation, but recently, China's renewable energy policy is transitioning to reducing and phasing out subsidies and encouraging subsidy-free renewable energy projects to develop advanced and high-efficiency technologies and lower renewable energy costs. From 2009 to 2018, the feed-in-tariffs (FiT) for onshore wind power declined from 0.51-0.61 yuan/kWh to 0.4-0.57 yuan/kWh. The feed-in tariffs for utility solar power declined from 1-1.15 yuan/kWh to 0.5-0.7 yuan/kWh from 2011 to 2018. With these developments, wind and solar power are planned to be operating at grid parity at the beginning of 14th Five Year Plan period (2021-2025).[46] From the consumption perspective, subsidy-free (grid parity) renewable power could lower the electricity rate, and increase the share of clean energy consumption. In the meanwhile, the viability of subsidy-free electricity could also accelerate renewable energy companies' technology innovation and further lower the generation costs of renewable energy on the supply side.

7.1.3 Conserving Energy and Improving Energy Efficiency

Electric power substitution for coal, gas and oil in final sectors is an approach to promote utilization of electricity, improve air quality and reduce carbon emissions. In 2014, the Energy Development Strategy Action Plan (2014-2020) proposed to accelerate the replacement of scattered coal with electric energy. After this, many ministries have taken actions in industry, buildings and transport. In 2016, China set a goal of increasing the share of electricity in final energy consumption to 27% in 2020 and replacing around 450 TWh of non-electric energy with electricity by 2020 in the 13th Five Year Plan for Electricity Development. In 2016, the **Opinions on Promoting Electric Power Substitution** was released with a focus on replacing coal and oil consumption with electric power in the areas of residential heating, industrial and agricultural production, transportation, and power supply and consumption. From 2015 to 2017, the share of electricity in total final energy consumption increased from 21.3% to 23.2% (in calorie equivalent). Specifically, the electricity share in industry, buildings and transport sectors increased from 23% to 24.6%, 25% to 26.9%, and 4.0% to 4.4%, respectively. During this time frame, electricity consumption per capita increased from 4,231 kWh/year to 4,676 kWh/year. In 2018, the total electric power substitution for coal, gas and oil was 155.7 TWh, in which the industry sector accounted for 62.2%, the power sector accounted for 17.2%, the transport sector accounted for 8.4% and residential heating accounted for 7.4%.

Advancing the energy-efficient and green development in the building sector. In 2016, the **13th Five Year Energy Saving and Emissions Reduction Work Plan** announced that by 2020, the share of urban green buildings in the new buildings will be improved to 50%, energy-saving renovations for more than 500 million square meters will be completed, energy-saving renovation in areas with heating during the winter in Northern China should be basically achieved, and energy-saving renovations for more than 100 million square meters of the public building will be completed. In 2017, China issued the **Plan for the Development of Building Energy Conservation and Green Buildings during the 13th Five Year Plan Period** and the **Special Plan for Scientific and Technological Innovation in Housing and Urban-Rural Development during the 13th Five Year Plan Period**, with the aim to push forward the green development in buildings.

To advancing energy conservation and green development in transport, **the 13th Five year Energy Saving and Emissions Reduction Work Plan** announced targets for 2016-2020:

- Reducing energy consumption of railway transport by 5% from 4.71 tce/million ton·km to 4.47 tce/million ton·km;
- reducing energy use of civil aviation by 4% from 0.433 kgce/ton·km to 0.415 kgce/ton·km;
- reducing the energy consumption per unit transport by vessel by 6%; and
- reducing the energy consumption per unit transport by commercial vehicles by 6.5%.

In addition, China issued series of policies to support the energy saving and emissions reduction in transport sectors including the **Implementation Plan for the Promotion of Ecological Civilization in Transport**, the **Opinions on Comprehensively and Profoundly Promoting the Development of Green Transport**, **Energy Conservation and Emission Reduction Plan in Civil Aviation for the 13th Five Year Plan Period**.

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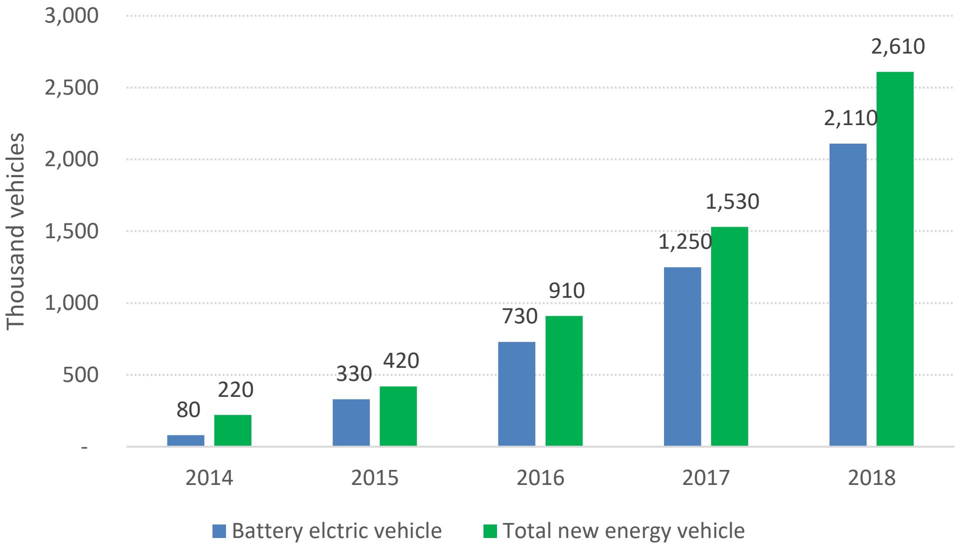
(45) http://www.ndrc.gov.cn/zcfb/zcfbtz/201901/t20190109_925398.html

(46) http://www.nea.gov.cn/2019-01/10/c_137733708.htm

To improve fuel efficiency and promoting new energy vehicles[47], China set the goals in **Energy Saving and New Energy Automotive Industry Development Plan 2012-2020** in 2012. According to the plan, by 2020, the average fuel efficiency of new passenger vehicles will drop to 5.0 l/100km, the fuel consumption of energy-saving vehicles will drop to 4.5 l/100km, commercial vehicles will be close to the international advanced level, and the national VI emission standards will be implemented. The targets were extended to 2025 in the **Mid- and Long-Term Development Plan for the Automobile Industry** released in 2017. This plan foresees the average fuel consumption of new passenger vehicles to drop to 4.0 l/100km in 2025, commercial vehicles will reach the international leading level. For promoting new energy vehicles, China announced targets for 2020, the annual production of new energy vehicles shall reach 2 million, and the stock of new energy vehicles shall achieve 5 million, and by 2025, new energy vehicles will account for more than 20% of vehicle sales. In addition, support policies also include EV quotas for vehicle manufacturers and importers, manufacturing subsidies, tax exemptions, government procurement, and support for the construction of electric vehicle charging stations. Many provincial governments also support electric vehicles, with preferential access to license plates and other incentives. In addition, the **Notice on Preferential Tax Policies for Energy-Saving and New-Energy Vehicles and Vessels** was released to promote the adoption of energy-efficient vehicles and vessels through halving the tax. The **Passenger Cars Corporate Average Fuel Consumption and New Energy Vehicle Credit Regulation** (dual-credit policy) was enacted in 2017 to stimulate fuel-efficient and electrification technologies in China's passenger vehicle market.[48] In 2018, although the sales of total vehicles in China experienced a 2.8% decrease, the sales of total new energy vehicles was 1.25 million, increasing by 61.7% from 2017, with about 0.986 million of battery electric vehicles. By the end of 2018, the stock of new energy vehicles was 2.61 million accounting for 1.1% of the total, increased by 70% from 2017, of which the electric vehicles accounted for 2.11 million, up to 81.1% of the total.[49] In the meanwhile, the electric vehicle charging infrastructures played a significant role in promoting electric vehicles. According to the statistics, by 2018 the number of total public and private electric vehicle charging stations reached 0.777 million. In 2018, the new built electric vehicle charging stations was 0.331 million units, and the ratio of the newly sold newly energy vehicles to newly added charging stations was 4:1.

Figure 66 Stock of total new energy vehicles in China from 2014-2018



Note: new energy vehicles include battery electric vehicle, plug-in hybrid electric vehicle, and fuel cell vehicles.

The introduction of new energy vehicles at the beginning stage was relying on government subsidies. With the rapid expansion of the market, challenges such as manufacturing enterprises' excessive dependence on

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(47) According to Energy saving and new energy vehicle industry development plan, the types of new energy vehicle include battery electric vehicle, plug-in hybrid electric vehicle, and fuel cell vehicles; both for passenger cars and commercial vehicles.

(48) https://ideas.repec.org/a/eee/enepol/v121y2018icp597-610.html

(49) Ministry of Public Security of the People's Republic of China

subsidies, and overcapacities emerged. In order to promote high-quality development of new energy vehicles and foster technological progress, China adjusts the subsidies by taking into account factors such as the technology progress and cost reduction, improvements of the electric range or battery energy density and energy efficiency. In March 2019, the **Notice on Further Perfecting the Policy of Financial Subsidies for the Promotion and Application of New Energy Vehicles** further reduces the new energy vehicle subsidies in the 2019, with an average decline of 50% across vehicle types compared to the rates of 2018, plans to phase out all subsidies by the end of 2020, and cancels local subsidies for new energy vehicles, switching to supporting charging infrastructure, and strengthening non-financial policies.

To promote energy conservation technologies and products, in February 2018, China released the **Catalogue of National Key Energy Conservation and Low-Carbon Technologies for Promotion** (2017 Edition, Energy Conservation Section), with 260 key energy conservation technologies in 13 industries including coal, electric power, steel, nonferrous metals, petroleum and petrochemical, chemical engineering and building materials.

To promote supply side structural reform and lower electricity prices and fees, China's economic policy framework reserves a key role. The purpose of this policy is to deleverage and eliminate excess capacity and to improve the quality of economic growth. Alleviating the taxes and fees burden on enterprises is one of the aspects of the reform, and a series of policies were released, targeting lowering the electricity prices and fees. As a result, in 2018, the electricity prices for general industrial and commercial businesses were 10.11% lower compared to the prices before the policy, which were 0.7018 yuan/kWh and 0.7807 yuan/kWh, respectively. The national total electricity cost savings reached 125.8 billion yuan. In 2019, the Chinese government announced to deepen market-oriented reforms in the electric power sector, overhaul surcharges on electricity prices, lower electricity costs in manufacturing, and cut the average electricity price for general industrial and commercial businesses by additional 10%.

7.1.4 Construction of the National Carbon Emission Trading Market

Since 2013, China has implemented seven provincial and city level pilots for Emissions Trading Scheme. In December 2017, China released the **Scheme for the Construction of the National Carbon Emission Trading Market (for the Power Generation Industry)**, marking the official establishment of a national carbon emission trading system. It requested to start from the power generation sector. Active efforts were also made to develop the administration measures of carbon emissions reporting, administration measures of the carbon emission trading, and technical guideline for the distribution of quotas in power generation sector, and other supporting regulations and technical specifications.

7.2 Energy transformation pathways by sectors in China

This section explores the role of electrification in China's energy transformation with a reference scenario from POLES-JRC (*GECO2019 Reference*, built with a global model and taking into account current policies, see **Annex 1**) and two 2°C scenarios from POLES-JRC (*GECO2019 2°C-Medium*, built with a global model and where mitigation is driven by a carbon price, see **Annex 1**) and from PECE (*2°C*, built with a national model)[50].

The PECE model was co-developed by NCSC and the Renmin University of China (RUC). PECE is an integrated energy system model, and consists of three coupled sub- models: a bottom-up technology sub-model of energy supply and consumption of an individual country (PECE- ES); a socio-economic sub-model based on a production function approach (PECE-SE); and a quantitative energy service demand sub-model (PECE-ESD). The model was developed using the General Algebraic Modelling System (GAMS) and was designed for comprehensive, dynamic, nonlinear optimization problems in the energy and climate policy fields. The China 2°C scenario is defined to be in line with the objective to limit global warming to well-below 2°C by limiting cumulative Chinese CO_2 emissions in the 2010-2050 period to the medium level well within the range projected by a number of global models[51] for cost-optimal scenarios assuming a global carbon budget of 1000 Gt CO_2, considered equivalent to likely below 2 °C.

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(50) Differences in the data presented for historical years might arise from the source data used (derived from the China Energy Statistical Yearbooks for PECE, derived from Enerdata and IEA for POLES-JRC).

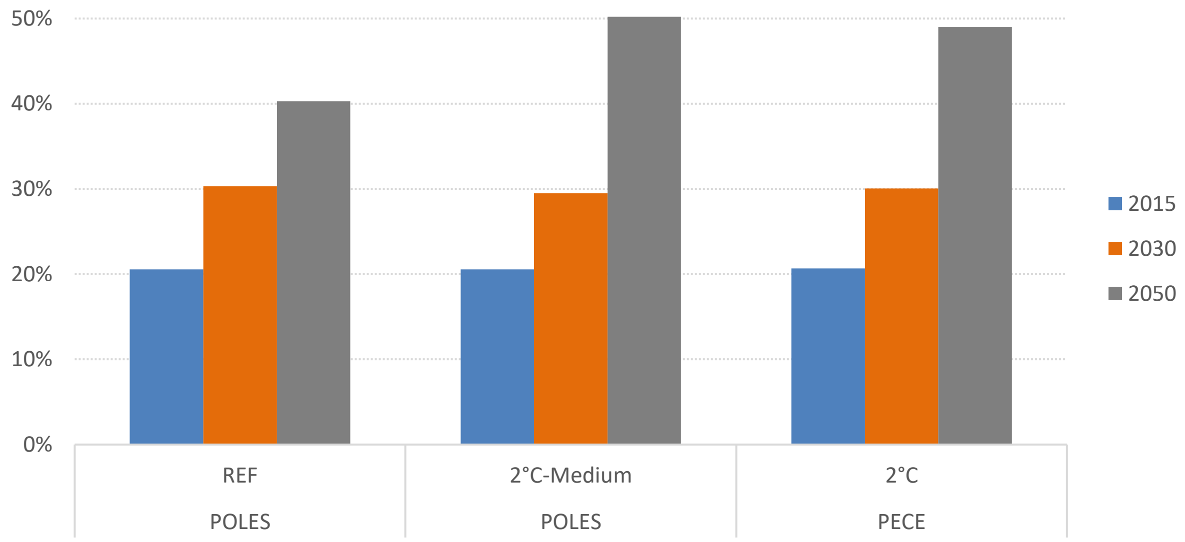
(51) The range of China cumulative CO_2 emissions in the 2010-2050 period from global models is [170-423] Gt in the 1000 Gt global carbon budget scenario. (McCollum, et al., 2018)

7.2.1 Electrification in China: the whole picture

Electrification is one of the key areas in China's energy transformation with a target of 27% in final energy consumption for 2020, which requires rapid electrification in industry, transportation and building sectors. Substituting coal consumption in industrial process and residential heating, cooking and other final energy uses is one of main contributors to China's electrification. As shown in previous section, from 2015-2017, the share of electricity in total final energy consumption increased from 21.3% to 23.2%. The share of electricity in final energy consumption is expected to grow even without any additional policy (reference scenario).

As presented in **Figure 67**, in the Reference scenario, the electricity share in total final energy consumption increases from 21% to 30% in 2030 and 40% in 2050. In the 2°C scenarios, the electricity share in total final energy consumption in 2030 is about same level as in the Reference scenario, while in 2050 it is about 49% for PECE and 50% for POLES-JRC.

Figure 67: Share of electricity in final energy consumption, China



7.2.2 Electrification in China: Transport

China has been making efforts in developing and implementing clean transport policies, including improving fuel standards, encouraging public transport, and supporting new energy vehicles. Though the new energy vehicles developed rapidly in recent years, the energy consumption of electric vehicles still accounts for a small share (0.2% in 2018) of total electricity consumption[52] and the share of electricity in transport is at a lower stage (2% in 2015). Promoting battery innovations, the deployment of charging infrastructure and policies such as phase out conventional vehicles in the long-term could accelerate the electrification of transport.

As presented in **Figure 68**, in reference scenario, the share of electricity in transport sector gradually increases to 3% in 2030 with 1 percentage point increase compared with 2015 and reaches 10% in 2050. In the 2°C scenarios, the share of electricity in transport sector in 2030 is estimated at 5% by POLES-JRC, and 4% by PECE, and in 2050 the share increases to 24% in PECE and 16% in POLES-JRC.

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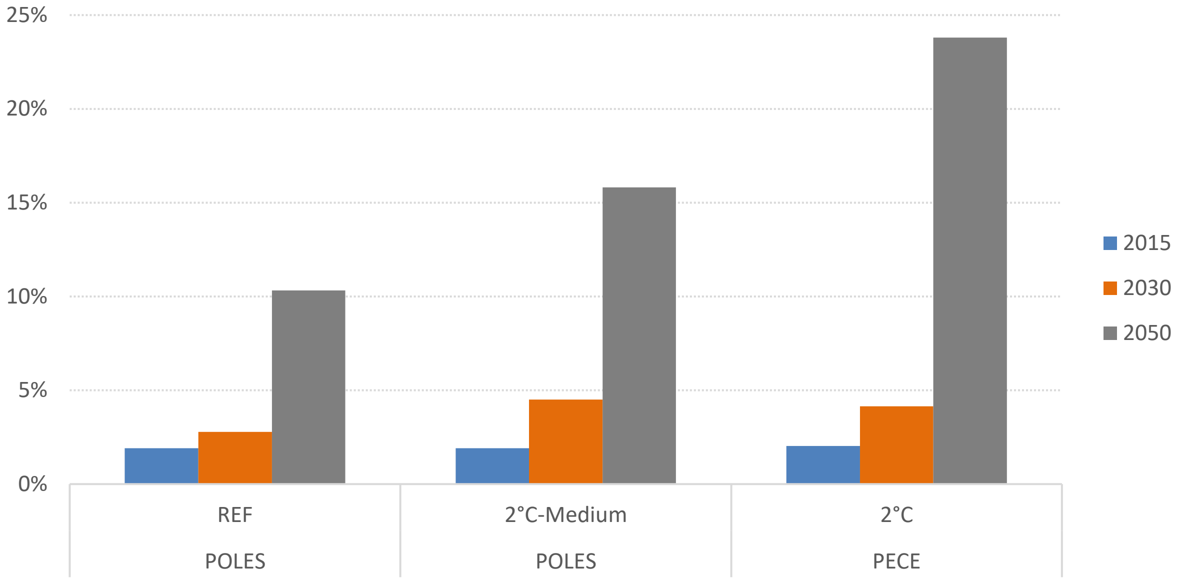
(52) https://www.chinadialogue.net/article/show/single/ch/11466-China-s-plan-to-electrify-its-economy

Figure 68: Share of electricity in transport, China

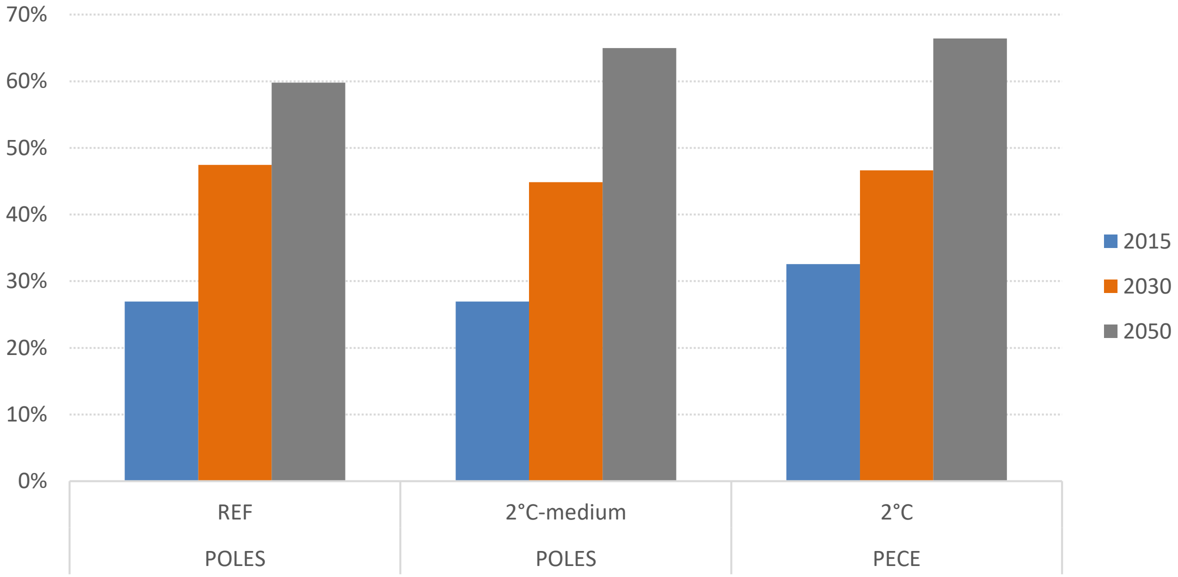


7.2.3 Electrification in China: Buildings

The building sector is currently the second largest sector in China's final energy consumption, after the industry sector, and the share in total final energy consumption has continued to increase in recent years accompanied by the rapid urbanization. At present, coal consumption is the main energy source for the building sector in rural area, while natural gas is the main source in urban area. In recent years, China actively promotes technologies such as decentralized electric heating, electric boilers, and heat pumps to increase the electrification rate in the building sector.

As presented in **Figure 69** in the POLES-JRC Reference scenario, the share of electricity reaches 49% in 2030 and 61% in 2050. In the 2°C scenarios, it achieves around 46% in POLES-JRC and 47% in PECE in 2030 and increases to about 66% in both in 2050.

Figure 69: Share of electricity in buildings, China

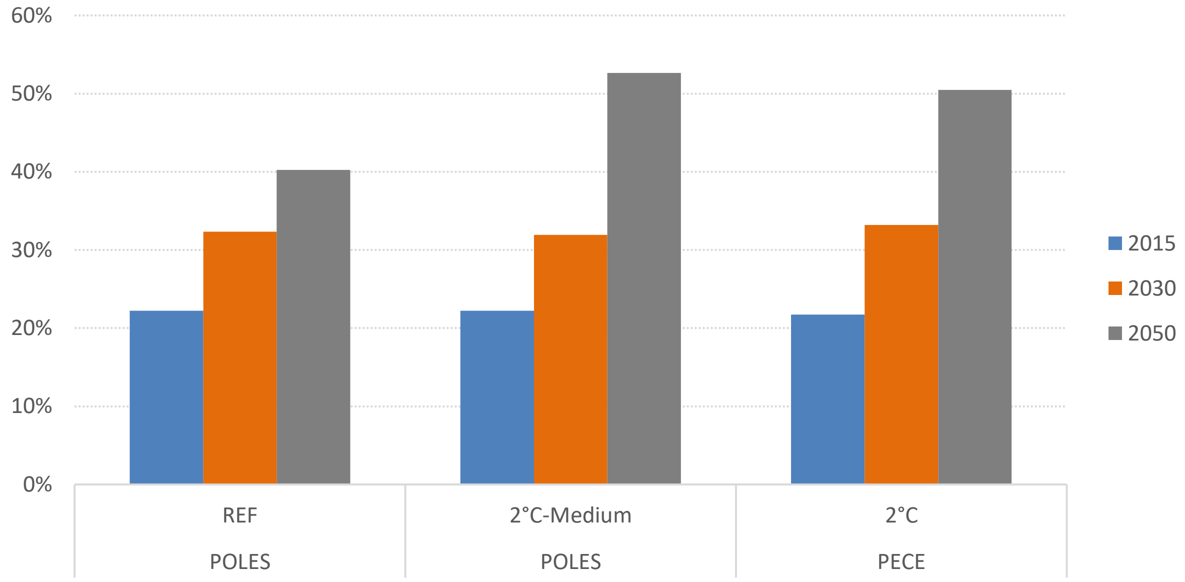


7.2.4 Electrification in China: Industry

The industry sector takes the largest share of China's final energy consumption, accounting for around two-thirds of total final consumption and final electricity consumption. Electrification of the industrial sector is an important part of China's energy conservation and emissions reduction. In 2018, the total electric power substitution for fossil fuel in industry sector reached 96.8 TWh accounting for 62.2% of the total electric power substitution.

In 2°C scenarios, China's industry sector electrification develops rapidly in 2030-2050, compared with the reference scenario. As presented in **Figure 70**, the share of electrification in industry sector increases from 22% in 2015 to 31% by POLES-JRC and 33% by PECE in 2030, and to 53% by POLES-JRC and 56% by PECE in 2050. The potential of substituting fossil energy with electricity in the industry sector would be further released.

Figure 70 Share of electricity in industry, China

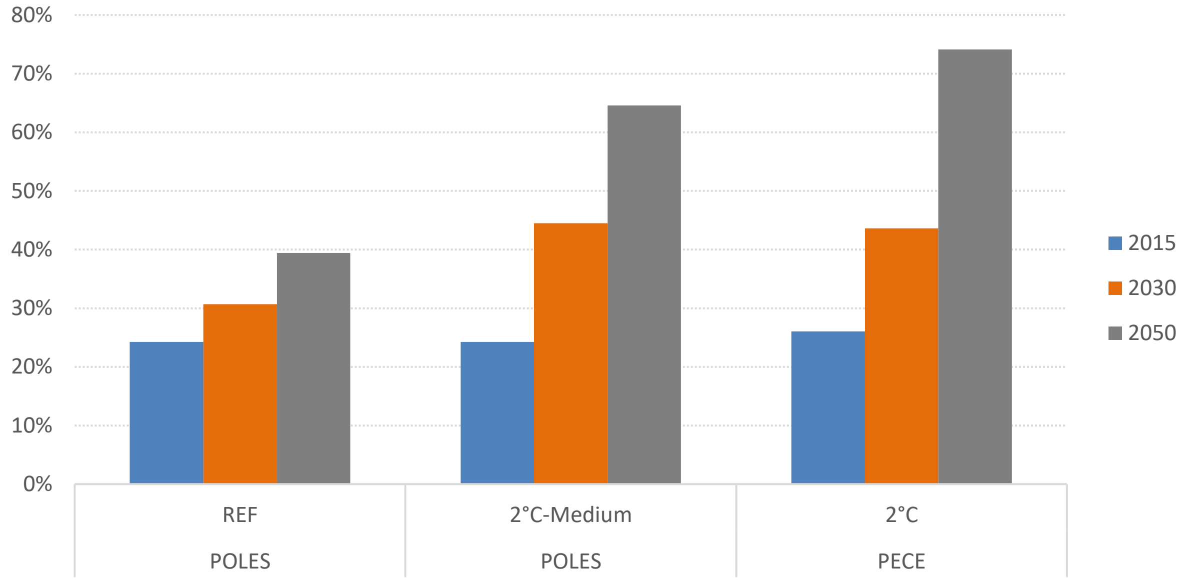


7.2.5 Electrification in China: Power Sector

The decarbonization of the power sector is essential for achieving China's low-emissions development. To this end, China has adopted measures to develop non-fossil energy, improve the efficiency of power generation to reduce carbon dioxide emissions from the power sector. In 2018, China's renewable energy installed capacity reached 729.68GW, accounting for 38% of the total generation capacity, which increased by 15.1 percentage points relative to 2005; renewable energy power generation reached 1867 TWh, accounting for 27% of the total power generation, with an increase of 10.6 percentage points relative to 2005; and carbon dioxide emissions per unit of thermal power generation across the country decreased by 19% compared to 2005 level.

With growing penetration of technologies such as electric heating, electric boilers, electric vehicles, electrified railway, and new added power demand from Information and Communication Technology (ICT) and other sectors, China's electricity consumption will further increase to 1.7 times as of 2015 in 2030 and 2.6 times in 2050.

Figure 71 Share of renewables sources in electricity generation, China



To fulfil growing electricity demand and reduce carbon emissions, continuous improvement in power generation efficiency, phasing out outdated and inefficient power generation capacity, development of CCUS and non-fossil power generation capacity as well as supporting policies are of great importance. As shown in **Figure 71**, in 2°C scenarios, the share of renewable in electricity generation reaches 44% by PECE and 47% by POLES-JRC in 2030, and 68% by POLES-JRC and 74% by PECE in 2050. For the non-renewable electricity generation, PECE's 2°C scenario projects the low-carbon energy gradually replaces non-abated fossil energy after 2030 and accounts for most of the non-renewable electricity generation in 2050, while the POLES-JRC's 2°C-Medium scenario projects the non-abated fossil energy and low-carbon remains around 10% and 30% of the total electricity generation, respectively, in 2050.

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List of abbreviations and definitions

BECCS: Bio-Energy combined with Carbon Capture and Sequestration

BEV: Battery electric vehicle

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

CCS: Carbon Capture and Sequestration

CDD: Cooling Degree-Days

CGE: Computable General Equilibrium model

COM: Communication from the European Commission

COP: Conference of the Parties

DAC: Direct Air CO_2 Capture

DACCS: Direct Air CO_2 Capture and Sequestration

EC: European Commission

EFC: Energy Foundation China

ETS: Emission Trading Scheme

EU: European Union as of December 2019 (including the United Kingdom)

EV: Electric Vehicle

GDP: Gross Domestic Product

GECO: Global Energy & Climate Outlook

GHG: Greenhouse Gases

GLOBIOM: The Global Biosphere Management Model

GEM-E3: General Equilibrium Model for Economy-Energy-Environment

GTAP: Global Trade Analysis Project

GWP: 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

LTS: Long Term Strategy

LULUCF: Land Use, Land Use Change and Forestry

NDC: Nationally Determined Contribution

NCSC: National Centre for Climate Change Strategy and International Cooperation

NREL: US National Renewables Energy Laboratory

OECD: Organisation of Economic Co-operation and Development

PECE: Planner for Energy and Climate Economics, model used by NCSC

PFC: Perfluorocarbons

POP: Population

p.p.: percentage point

PPP: Purchasing Power Parity

POLES-JRC: Prospective Outlook on Long-term Energy Systems, model version used in the JRC

ppm: part per millions

PV: Photovoltaics

R/P: Ratio Reserves by Production

RES: Renewable Energy

UN: United Nations

UNFCCC: United Nations Framework Convention on Climate Change

USGS: US Geological Survey

WEC: World Energy Council

WMO: World Meteorological Organisation

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Annex 1: Policies considered

The scenario presented in this report builds on past work (Kitous, et al., 2017) (Keramidas, et al., 2018). A full list of the policies considered in the GECO 2019 Reference and medium 2°C scenarios 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-JRC model documentation (Després, Keramidas, Schmitz, Kitous, & Schade, 2018)). Country-specific patterns in technology choices are replicated in the beginning of the simulation with weighting factors that are relaxed over time.

Projections also include policies at different time horizons. Policies were implemented in a number of ways, modifying model parameters that were relevant for the implementation perimeter of each policy considered: sectoral carbon price, feed-in tariff, subsidy, energy tax, etc.

The Reference scenario includes adopted energy and climate policies in world countries unit June 2019.

The tables below summarize the energy, GHG and air pollution policies considered in the Reference scenario.

Table 10. Energy policies in the Reference scenario

UN Party	Technology	Metric	Target year	Objective	GECO2019 Reference	Source
Europe						
EU	Renewables	Share in gross final demand	2020	20%	Reached	European Commission , DG Energy
EU	Renewables	Share in gross final demand	2030	32%	Reached	European Commission , DG Energy
EU	Renewable fuels	Share in transport demand	2020	10%	Not reached	European Commission , DG Energy
EU	Renewable fuels	Share in transport demand	2030	14%	Not reached	European Commission , DG Energy
EU	Private vehicles emissions	New cars emissions, in g/km	2021	95	Reached	European Commission , DG Energy
EU	Private vehicles emissions	New cars emissions, in g/km, vs 2021	2030	-37.5%	Reached	European Commission , DG Energy
EU	Heavy vehicles emissions	Stock emissions, in g/km, vs 2021	2030	-30%	Reached	European Commission , DG Energy
EU	Buildings	New construction from 2021	2021	Near-zero energy buildings	Reached	European Commission , DG Energy
EU	Energy demand	% reduction vs. BAU	2020	-20%	Reached	European Commission , DG Energy
EU	Energy demand	% reduction vs. BAU	2030	-32.5%	Reached	European Commission , DG Energy
EU	Nuclear power generation	Phase-out			Reached	BEL: 2030; DEU: 2025; NLD: 2035

EU	Coal power generation	Phase-out (does not apply to IGCC, CCS)			Reached	AUT: 2025; BEL: 2015; DNK: 2030; FIN: 2030; FRA: 2022; DEU: 2038; IRL: 2025; ITA: 2025; NLD: 2029; PRT: 2030; SWE: 2022; UK: 2025
EU	Nuclear power generation	Phase-out (does not apply to IGCC, CCS)			Reached	BEL: 2030; DEU: 2025
EU	Nuclear power generation	No construction			Reached	AUT, CYP, DNK, EST, GRC, HRV, IRL, ITA, LUX, LVA, MLT, PRT
Switzerland	Renewables	Share in primary demand	2020	24%	Reached	Energy Strategy 2050
North America						
Canada	Private vehicles emissions	Emissions, in g/km	2025	88	Reached	Canadian Environmental Protection Act
Canada	Renewables	Share in transport demand		2% for biodiesel (2011 onwards); 5% for bioethanol (2011 onwards)	Reached	Environmental Protection Act (2008)
Canada	Coal power generation	Phase-out (does not apply to IGCC, CCS)			Reached	2030
Mexico	Non-fossil	Share in power production	2021	30%	Not reached	Energy Transition Law 2015
Mexico	Non-fossil	Share in power production	2024	35%	Not reached	Energy Transition Law 2015

USA	Wind, Solar, Geothermal	Power production	2020 vs. 2012	Doubling	Reached	White House
USA	Private vehicles emissions	Consumption, miles/gal	2020	54.5	Not reached	US EPA
USA	Renewables	Production target	2022	Renewable fuel blended in transport: 36 billion gallons	Not reached	Renewable fuel standard (2015)
Central & South America						
Argentina	Renewables (excluding large hydro)	Share in power production	2025	20%	Not reached	RenovAr, 2016
Argentina	Renewables	Share in transport demand	2016	12%	Not reached	Biofuels Law (2016)
Brazil	Renewables	Share in primary energy	2022	41%	Reached	Decenal Energy Expansion Plan (2014)
Brazil	Renewables	Share in primary energy	2024	45%	Reached	Decenal Energy Expansion Plan (2014)
Brazil	Renewables (excluding large hydro)	Share in power production	2020	16%	Reached	National Plan on Climate Change (2008)
Brazil		Capacity targets	2024	Biomass: 18 GW Hydro: 117 GW + small hydro 8 GW Nuclear: 3	Reached	Decenal Energy Expansion Plan (2014)

				GW Solar: 7 GW Wind: 24 GW		
Brazil	Renewables	Share in transport demand		10% for biodiesel (2019 onwards); 25% for bioethanol (2015 onwards)	Reached	National Biodiesel Programme (2005); Ethanol Blending Mandate (1993)
Chile	Renewables (excluding large hydro)	Share in power production	2020	12%	Reached	Non-Conventional Renewable Energy Law (2013)
Chile	Renewables (excluding large hydro)	Share in power production	2025	20%	Reached	Non-Conventional Renewable Energy Law (2013)
Chile	Renewables (including large hydro)	Share in power production	2030	60%	Reached	Energy Plan 2050 (2016)
Chile	Renewables (including large hydro)	Share in power production	2050	70%	Reached	Energy Plan 2050 (2016)
Chile	Energy demand	% reduction vs. 2011	2020	-20%	Not reached	Energy Efficiency Action Plan (2012)
Chile	Electric vehicles deployment	Share in passenger fleet	2050	40%	Reached	Electromobility Strategy (2017)
Pacific						

Australia	Renewables	Share in power production	2020	25%	Not reached	Australian Government, Department of Environment (2010)
Australia	Renewables	Share in power production	2030	50%	Not reached	Australian Government, Department of Environment (2010)
Japan	Renewables	Share in power production	2020	13.5%	Reached	
Japan	Renewables	Share in power production	2030	22%-24%	Reached	
Japan	Nuclear	Capacity targets	2025	34 GW	Reached	
Japan	Renewables	Capacity targets	2020	Biomass: 5.5 GW Solar: 28 GW Wind: 6 GW	Reached	Ministry of Economics, Trade and Industry
Japan	Private vehicles emissions	Consumption, km/l	2020	20.3 (from 16.8 in 2015)	Reached	Top Runner Programme (1999)
New Zealand	Renewables	Share in power production	2025	90%	Reached	New Zealand Energy Efficiency and Conservation Strategy 2011-2016
S.Korea	Renewables	Share in primary demand	2020	5%	Reached	4th Basic Plan on New and Renewable Energies (2014)
S.Korea	Renewables	Share in primary demand	2030	9.7%	Reached	4th Basic Plan on New and Renewable Energies (2014)
S.Korea	Renewables	Share in primary demand	2035	11%	Reached	4th Basic Plan on New and Renewable Energies (2014)
S.Korea	Renewables	Share in power production	2024	10%	Reached	7th Basic Plan for Long-term Electricity Supply and Demand (2014)
S.Korea	Renewables	Share in power production	2029	11.7%	Reached	7th Basic Plan for Long-term Electricity Supply and Demand (2014)

S.Korea	Renewables	Share in power production	2035	13.4%	Reached	7th Basic Plan for Long-term Electricity Supply and Demand (2014)
S.Korea	Private vehicles emissions	Emissions, in g/km	2020	97 (from 140 in 2015)	Reached	Fuel efficiency standard (2005)
S.Korea	Renewables	Share in transport demand	2018	Biodiesel: 3% of diesel from 2018 onwards	Reached	Renewable fuel standard (2013)
Asia						
China	Non-fossil	Share in primary demand	2020	15%	Reached[53]	Copenhagen Accord (UNFCCC, 2009)
China	Renewables	Capacity targets	2020	Hydro (excl pumped storage): 340 GW Solar: 110 GW Wind: 210 GW Biomass: 15 GW	Reached	Energy Development Strategy Action Plan (2014-2020)
China	Nuclear	Capacity targets	2020	58 GW	Not reached	Energy Development Strategy Action Plan (2014-2020)
China	Nuclear	Capacity targets	2030	150 GW	Not reached	Energy Development Strategy Action Plan (2014-2020)

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(53) To calculate this target, the Chinese statistical methodology was used: electricity generated from nuclear and primary renewables (hydro, wind, solar) is converted into primary energy (tons of coal-equivalent) using the average efficiency of coal power plants in China.

China	Total energy	Cap	2020	5.0 Gtce	Not reached	13th Five Year Plan (2016-2020)
China	Coal	Cap	2020	4.1 Gtons	Reached	13th Five Year Plan for Energy Development (2016-2020)
China	Gas	Share in primary energy	2020	10%	Not reached[54]	Energy Development Strategy Action Plan (2014-2020)
China	Renewables	Production target	2020	Biodiesel: 2 Mt; Bioethanol: 10 Mt	Not reached	Energy Development Strategy Action Plan (2014-2020)
India	Renewables	Capacity targets	2022	Biomass: 10 GW Solar: 100 GW Wind: 60 GW Small hydro: 5 GW	Solar: Not reached	India's Union Budget 2015-2016
India	Renewables	Capacity targets	2027	Total renewables: 227 GW	Not reached	National Electricity Plan (2018)
India	Electric vehicles deployment	Share in car stock	2030	30%	Not reached	Electric vehicle target (2018)
Indonesia	Renewables	Share in transport demand	2025	15%	Not reached	Biofuel targets (2013)
Indonesia	Renewables	Share in primary demand	2025	15%-23%	Reached	Renewable energy targets (2014)
Indonesia	Low-carbon	Share in power generation	2025	23%	Not reached	National Electricity Plan (2018)

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(54) To calculate this target, the Chinese statistical methodology was used: electricity generated from nuclear and primary renewables (hydro, wind, solar) is converted into primary energy (tons of coal-equivalent) using the average efficiency of coal power plants in China.

Malaysia	Renewables (excluding large hydro)	Share in power capacities	2020	10%	Not reached	National Renewable Energy Policy and Action Plan (2010)
Malaysia	Renewables	Capacity targets	2020	Biomass: 0.8 GW Hydro (small): 0.5 GW Solar PV: 0.2 GW	Reached	National Renewable Energy Policy and Action Plan (2010)
Thailand	Renewables	Share in primary demand	2021	25%	Not reached	Alternative Energy Development Plan (2015-36) (2015)
Thailand	Renewables	Share in primary demand	2036	30%	Not reached	Alternative Energy Development Plan (2015-36) (2015)
Thailand	Renewables	Share in power production	2036	20%	Reached	Power Development Plan (2015-36) (2015)
Thailand	Renewables	Share in transport demand	2036	35%	Not reached	Alternative Energy Development Plan (2015-36) (2015)
Thailand	Energy demand	% reduction of energy intensity vs BAU of 2010	2036	-30%	Reached	Energy Efficiency Plan (2015-36) (2015)
Vietnam	Renewables	Share in primary demand	2020	5%	Reached	National Energy Development Strategy 2020 (2013)
Vietnam	Renewables	Share in power production	2020	4.5%	Reached	Power Development Plan 2011-2020 (2013)
CIS						
Russia	Renewables (excluding large hydro)	Share in power production	2020	2.5%	Not reached	Renewable energy targets (2013)

Russia	Renewables	Capacity targets	2020	Wind: 3.6 GW Solar: 1.52 GW Small hydro: 75 MW	Not reached	Renewable energy targets (2013)
Russia	Energy demand	% reduction of energy intensity vs 2007	2020	-40%	Not reached	Energy intensity targets (2008)
Russia	Energy demand	% reduction of residential heat consumption vs 2014	2030	-20%	Not reached	Strategy for building materials (2016)
Ukraine	Renewables	Share in final consumption	2020	11%	Reached	National Action Plan for Renewable Energy (2014)
Ukraine	Renewables	Share in transport demand	2020	10% (5% by 2014-2015; 7% by 2016)	Not reached	Law on Alternative Liquid and Gaseous Fuels (2012)
Ukraine	Renewables	Capacity targets	2020	Biomass: 1 GW Hydro: 5.4 GW Solar: 2.3 GW Wind: 2.3 GW	Reached	National Action Plan for Renewable Energy (2014)
Ukraine	Renewables	Share in power generation	2035	Renewables (excl hydro): 25% Hydro: 13%	Not reached	Energy Strategy (2017)
Ukraine	Nuclear	Share in power generation	2035	50%	Not reached	Energy Strategy (2017)
Middle East						
Turkey	Energy demand	% reduction of energy	2023	-14% = 23.9 Mtoe of	Reached	Energy Efficiency Action Plan (2018)

		consumption vs BAU		savings		
Turkey	Renewables	Share in gross final energy consumption	2023	20.5%	Reached	National Renewable Energy Action Plan (2014)
Turkey		Capacity targets	2023	Hydro: 34 GW Solar: 5 GW Wind: 20 GW Biomass: 1 GW Geothermal: 1 GW	Reached	National Renewable Energy Action Plan (2014)
Turkey	Renewables	Share in power production	2023	13% to 30%	Reached (high-end)	Energy Strategy Plan 2010-2014 (2011)
Saudi Arabia	Renewables	Capacity targets	2023	9.5 GW	Not reached	Vision 2030 (2016)
Africa						
Egypt	Renewables	Share in power production	2020	20%	Not reached	Egypt Regional Center for Renewable Energy and Efficency
Egypt	Wind	Share in power production	2020	12%	Not reached	Egypt Regional Center for Renewable Energy and Efficency
South Africa	Renewables	Capacity targets	2030	Solar: 9.4 GW Wind: 8.5 GW	Reached	Integrated Resource Plan (2010, updated 2013)
South Africa	Renewables	Share in transport demand	2015	2%-10% for bio-ethanol; >5% for biodiesel; for 2015 onwards	Not reached	Biofuels Industrial Strategy (2007)

Table 11. GHG policies in the Reference scenario

UN Party	GHG coverage	Sectoral coverage	Metric	Base year	Target year	Objective	BAU emissions at Target year (Mt)	GECO2019 Reference	Source
Europe									
EU	All GHGs	All excl LULUCF	Emissions	1990	2020	-20%		Reached	EU 2020 Climate and Energy Package (European Commission, 2008)
EU	All GHGs	All excl LULUCF	Emissions	1990	2030	-40%		Reached	EU 2030 Climate and Energy Framework (European Commission, 2014)
EU	All GHGs	ETS sectors	Emissions	2005	2020	-21%		Reached	EU 2020 Climate and Energy Package (European Commission, 2008) + 2021-2050 cap linear reduction factor of -1.74%/year
EU	All GHGs	ETS sectors	Emissions	2005	2030	-43%		Reached	EU 2030 Climate and Energy Framework (European Commission, 2014) + 2021-2050 cap linear reduction factor of -2.2%/year
EU	CO_2	Road transport	Emissions	2005	2030	-23%		Reached	European Commission , DG Energy
EU	HFCs	All	Emissions	2012	2019-2036	-10% to -85% over time		Reached	Kigali Amendment to the Montreal Protocol
Norway	All GHGs	All	Emissions	1990	2020	-30%		Not reached (follows EU ETS price)	National Communication 6 (UNFCCC, 2014)

Switzerland	All GHGs	All	Emissions	1990	2020	-20%		Not reached (follows EU ETS price)	National Communication 6 (UNFCCC, 2014)
North America									
Canada	All GHGs	All	Emissions	2005	2020	-17%		Reached	Copenhagen Accord (UNFCCC, 2009)
Canada	CO_2	Power generation from coal	Emissions	2015	2030	420 gCO2/kWh		Not reached	Reduction of CO2 Emissions from Coal-fired Generation of Electricity (2018)
Canada	CO_2	Power generation from gas	Emissions	2015	2019	420 gCO2/kWh		Reached	Reduction of CO2 Emissions from Natural Gas-fired Generation of Electricity (2019)
Canada	All GHGs	All	Carbon price	n/a	n/a	20 C$/tCO2 from 2019 to 50 C$/tCO2 in 2022		Implemented	GHG Pollution Pricing Act (2018)
Mexico	All GHGs	All	Emissions	2020 (BAU)	2020	-30%	890	Not reached (conditional)	Copenhagen Accord (UNFCCC, 2009); National Communication 4 (UNFCCC, 2009)
USA	All GHGs	All	Intensity of GDP	2005	2020	-17%		Reached	Climate Action Report (US Department of State, 2014) / National Communication 6 (UNFCCC, 2014)
USA	All GHGs	Power generation	Emissions	2005	2030	-32%		Not implemented, but reached	Clean Power Plan (2014) (scrapped 2016)
USA	CH_4	Oil & gas production	Emissions	2012	2025	-45%		Not reached	
Central &									

South America									
Argentina	CO_2	Energy system	Carbon price	n/a	n/a	10 $/tCO2 from 2018 onwards		Implemented	Carbon tax act (2018)
Brazil	All GHGs	All	Emissions	2020 (BAU)	2020	-36.1% to -38.9%	2704	Reached	Copenhagen Accord (UNFCCC, 2009); National Communication 2 (UNFCCC, 2010)
Chile	All GHGs	All excl LULUCF	Emissions	2020 (BAU)	2020	-20%	144	Reached	Copenhagen Accord (UNFCCC, 2009); BAU from MAPS-Chile project (2012)
Pacific									
Australia	All GHGs	All	Emissions	2000	2020	-5% (conditional: up to -25%)		Not reached (unconditional)	National Communication 6 (UNFCCC, 2013)
Australia	CO_2	Power generation	Emissions	2005	2030	-26%		Reached	National Energy Guarantee Plan (2018) (scrapped 2018)
Japan	All GHGs	All	Emissions	2005	2020	-3.8%		Reached	Ministry of the Environment (COP19, 2013)
New Zealand	All GHGs	All	Emissions	1990	2020	-5% (conditional: -10% to -20%)		Not reached (unconditional)	Copenhagen Accord (UNFCCC, 2009); National Communication 6 (UNFCCC, 2013)

South Korea	All GHGs	All excl LULUCF	Emissions	2020 (BAU)	2020	-30%	776	Not implemented - target superceded by more recent 2030-only policy	Copenhagen Accord (UNFCCC, 2009); National Communication 3 (UNFCCC, 2012); Green Grown Act (2016)
Asia									
China	CO_2	All excl LULUCF	Intensity of GDP	2005	2020	-40% to -45%		Reached (high-end)	Copenhagen Accord (UNFCCC, 2009)
China	CO_2	Industry	Intensity of VA	2015	2025	-40%		Reached	Made in China 2025 (2013)
India	GHG	All excl agriculture	Intensity of GDP	2005	2020	-20% to -25%		Reached (high-end)	Copenhagen Accord (UNFCCC, 2009)
Indonesia	CO_2	Energy, LULUCF	Emissions	2020 (BAU)	2020	-26%	1000	Reached	Copenhagen Accord (UNFCCC, 2009); National Communication 2 (UNFCCC, 2012)
Malaysia	All GHGs	All	Intensity of GDP	2005	2020	-40%		Reached	National Communication 2 (UNFCCC, 2011)
Thailand	All GHGs	Energy, transport	Emissions	2020 (BAU)	2020	-7% to -20%	499	Reached (low-end)	Copenhagen Accord (UNFCCC, 2009); Development trajectory (ADBI, 2012)
CIS									
Kazakhstan	All GHGs	All	Emissions	1990	2020	-15%		Not reached	Copenhagen Accord (UNFCCC, 2009)
Russia	All GHGs	All	Emissions	1990	2020	-15% to -25%		Reached (high-end)	Copenhagen Accord (UNFCCC, 2009)
Ukraine	All GHGs	All	Emissions	1990	2020	-20%		Reached	Copenhagen Accord (UNFCCC, 2009)

Ukraine	CO_2	Energy	Carbon intensity of fuel use	2010	2035	-20% (-5% by 2020; -10% by 2025; -15% by 2030)		Reached	National Renewable Energy Action Plan 2020 (2014)
Africa									
South Africa	All GHGs	All	Emissions	2020 (BAU)	2020	-34%	800	Not reached	Copenhagen Accord (UNFCCC, 2009); National Communication 2 (UNFCCC, 2011)
South Africa	All GHGs	All	Carbon price	n/a	n/a	120 Rand/tCO2 from 2019 then 600 Rand/tCO2 from 2023		Implemented	Carbon Tax Bill (2019)

Table 12. Air pollution policies in the Reference scenario

UN Party	Gas coverage	Sectoral coverage	Metric	Base year	Target year	Objective	GECO2019 Reference	Source
EU	SO_2	All land-based, anthropogenic	Emissions	2005	2030	-79%	Reached	NEC Directive
EU	NO_x	All land-based, anthropogenic	Emissions	2005	2030	-63%	Reached	NEC Directive
EU	VOC	All land-based, anthropogenic	Emissions	2005	2030	-40%	Reached	NEC Directive
EU	PM2.5	All land-based, anthropogenic	Emissions	2005	2030	-49%	Reached	NEC Directive
EU	NH_3	All land-based, anthropogenic	Emissions	2005	2030	-19%	Reached	NEC Directive
China	NOx	Road transport	Emissions		2023	China 6b	Reached	

India	NOx	Road transport	Emissions	2020	India 6	Reached	

The 2°C scenarios presented in this report go into deeper emissions cuts compared to the mitigation achieved with the policies in the Reference scenario. On top of the abovementioned, the scenarios implemented the following modelled policies in order to achieve the desired global warming target:

- Emission objectives announced in the Copenhagen Pledges (2020), INDCs and NDCs (conditional and unconditional) are reached or exceeded; carbon prices are at least their level necessary to reach the INDC/NDC level of emissions (2025-2035). For a complete list see GECO 2017 (Kitous, et al., 2017).
- Maritime freight: the IMO objective for 2050 (-50% emissions vs 2008) is reached.
- HFCs: the objectives described in the Kigali amendment are reached.
- Fossil fuel subsidies, direct or indirect (final user price compared to the international import price), are phased out by 2030.

The above are reached with the following modelling measures:

2°C and 1.5°C scenarios measures:

- Emissions objectives are reached via the implementation of a carbon price, distinguished by country (see below).
- To reflect fossil fuel subsidies phase-out, final user prices (before the implementation of the carbon price) are brought to at least the level of the country's international import price by 2030, across all countries.
- Buildings: increased rate of renewal of the stock and of renovation of existing surfaces (dependent on carbon price); new and renovated surfaces move closer to best-available practices in terms of insulation (country-dependent on the basis of HDD, CDD and energy and carbon prices).
- Transport: gradual development of refuelling infrastructure and consumer acceptance over time for electric vehicles and fuel cells, accelerated compared to the Reference scenario.

Treatment of Reference scenario measures:

- Countries are only subject to the carbon price and the measures described above. The implementation of the sector-specific policies in the Reference scenario was removed in the 2°C and 1.5°C scenarios.

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 specialized sectoral model (55).

All other sectors of the economy are subject to the same carbon price.

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 13**, with 100% representing a "leading" carbon price that increases over time; other sectoral measures followed a similar regional distinction, where relevant.

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(55) The projections for agriculture and land use metrics in this report were done by soft-linking the specialized model GLOBIOM-G4M (IIASA, 2017) with the energy system model POLES-JRC.

Table 13. Carbon price differentiation in the GECO 2019 scenarios

Income in 2030 (USD (2015) per capita)	Countries	2020	2030	2050 and beyond
> 30,000	EU, 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 Medium America and Caribbean, Rest of Pacific, Rest of South Asia, Rest of South-East Asia, Rest of Sub-Saharan Africa, Vietnam	20%	67%	100%

European Union as of December 2019 (including the United Kingdom)

Annex 2: Description Energy/GHG model POLES-JRC

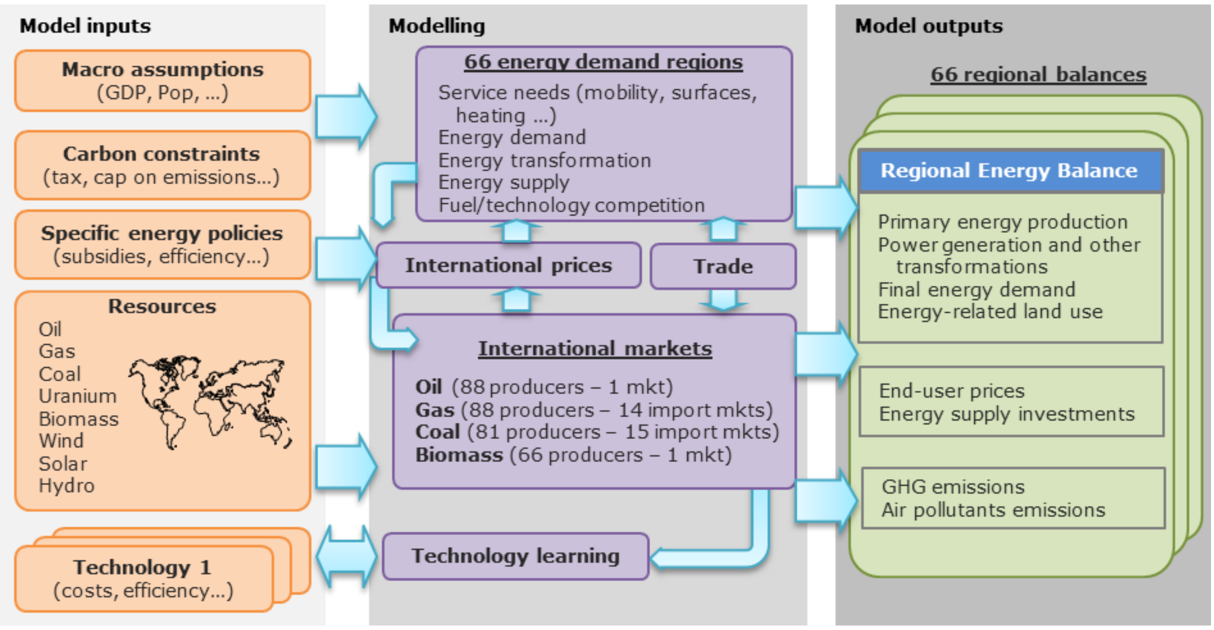
For a fuller description of the model, see (Després, Keramidas, Schmitz, Kitous, & Schade, 2018).

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 72**).

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 POLES-JRC 2019 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 model version, historical data sets, parameterisation, and/or policies considered.

Figure 72. 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.

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.

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.

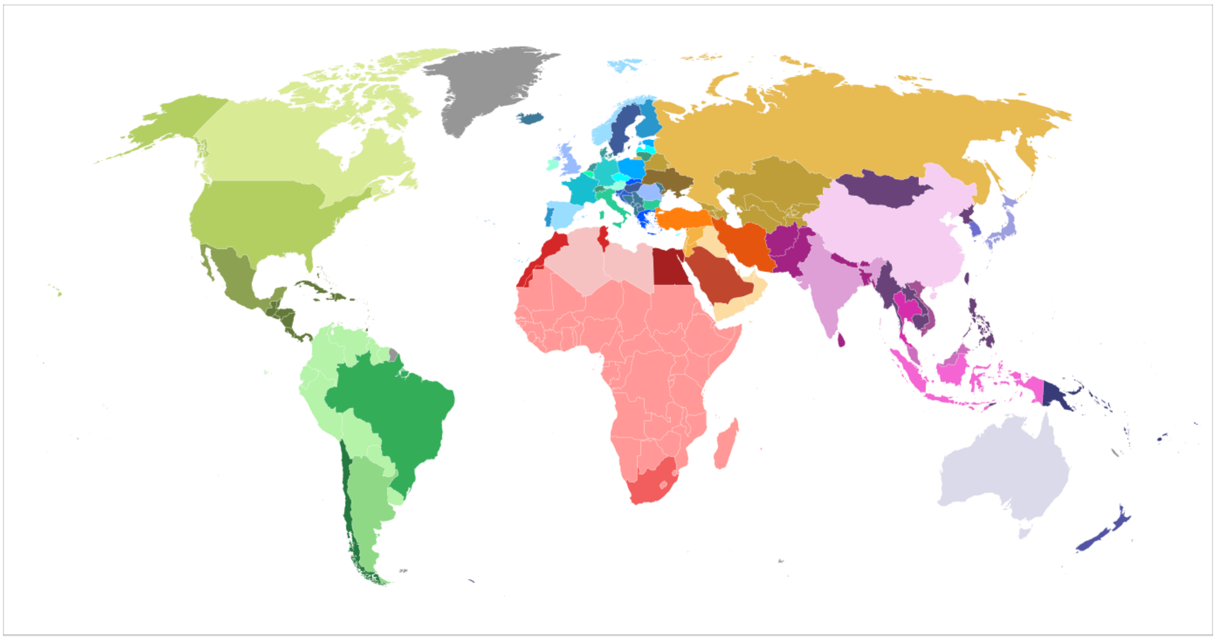
GHG emissions

CO2 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 73**, Table 14, Table 15), to which international bunkers (air and maritime) are added.

Figure 73. POLES-JRC model regional detail map (for energy balances)



Source: POLES-JRC model

Table 14. List of 54 individual countries represented in POLES-JRC (for energy balances)

Non-EU individual countries	EU 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, European Union as of December 2019 (including the United Kingdom)

Table 15. Country mapping for the 12 regions in POLES-JRC (for energy balances)

Rest Central America

Bahamas
Barbados
Belize
Bermuda
Costa Rica
Cuba
Dominica
Dominican Republic
El Salvador
Grenada
Guatemala
Haiti
Honduras
Jamaica
Nicaragua
NL Antilles and Aruba
Panama
Sao Tome and Principe
St Lucia
St Vincent & Grenadines
Trinidad and Tobago

Rest South America

Bolivia
Colombia
Ecuador
Guyana
Paraguay
Peru
Suriname
Uruguay
Venezuela

Rest Balkans

Albania
Bosnia-Herzegovina
Kosovo
Macedonia
Moldova
Montenegro
Serbia

Rest CIS

Armenia
Azerbaijan
Belarus
Georgia
Kazakhstan
Kyrgyz Rep.
Tajikistan
Turkmenistan
Uzbekistan

Mediterranean Middle East

Israel
Jordan
Lebanon
Syria

Rest of Persian Gulf

Bahrain
Iraq
Kuwait
Oman
Qatar
United Arab Emirates
Yemen

Morocco & Tunisia

Morocco
Tunisia

Algeria & Libya

Algeria
Libya

Rest Sub-Saharan Africa

Angola
Benin
Botswana

Rest Sub-Saharan Africa (continued)

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
Senegal
Sierra Leone
Somalia
Sudan
Swaziland
Tanzania
Togo
Uganda
Zambia

Rest South Asia

Afghanistan
Bangladesh
Bhutan
Maldives
Nepal
Pakistan
Seychelles
Sri Lanka

Rest South East Asia

Brunei
Cambodia
Lao PDR
Mongolia
Myanmar
North Korea
Philippines
Singapore
Taiwan

Rest Pacific

Fiji Islands
Kiribati
Papua New Guinea
Samoa (Western)
Solomon Islands
Tonga
Vanuatu

Source: POLES-JRC model.

Data sources

Table 16. POLES-JRC model historical data and projections

Series		Historical data	GECO Projections
Population		Europop (Eurostat, 2018) ; (Lutz, Goujon, KC, Stonawski, & Stilianakis, 2018)	
GDP, growth		(World Bank, 2019); (International Monetary Fund, 2019)	GDP/cap as Ageing Report 2018 (European Commission, 2018) x Europop; (OECD, Long-term baseline projections, No. 95 (Edition 2014), 2014) and (OECD, Long-term baseline projections, No. 103, 2018)
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, Rystad, 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-G4M model
	Other GHG Non-Annex 1 (excl.	EDGAR	POLES-JRC model, GLOBIOM-G4M model

	LULUCF)		
	LULUCF Non-Annex 1	National inventories, FAO	POLES-JRC model, GLOBIOM-G4M 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: JRC, WEC, IEA, TECHPOL database	

Annex 3: Description of JRC-GEM-E3

The Computable General Equilibrium (CGE) model JRC-GEM-E3 (Capros, et al., 2013), 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 all Kyoto greenhouse gases. Furthermore, existing tax structures and unemployment mechanisms are incorporated. The version of the model used here is global (see **Table 17**) and covers all industrial sectors, disaggregated into 33 sectors, of which there are 10 electricity-generating technology sectors.

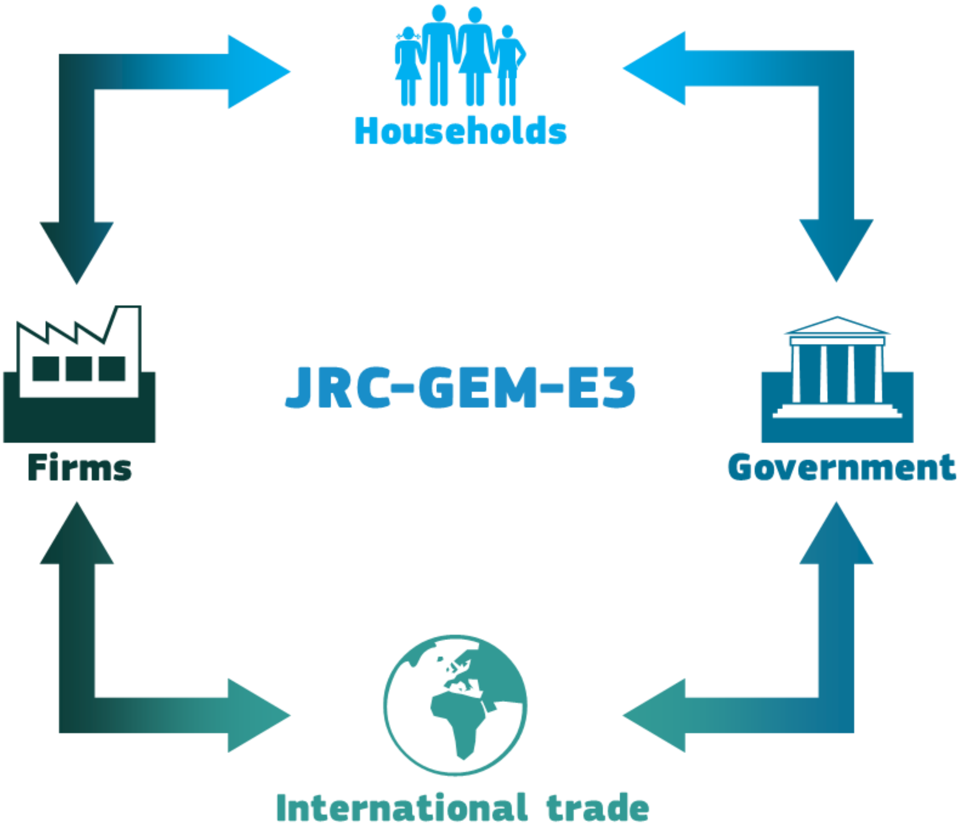
Table 17. Regional aggregation of the JRC-GEM-E3 model

Regions in the JRC-GEM-E3 model	Abbreviation
European Union	EU
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: JRC-GEM-E3 model, European Union as of December 2019 (including the United Kingdom)

The JRC-GEM-E3 model is a recursive dynamic CGE model representing the interactions between three types of agents: households, firms and governments. Household behaviour derives from the maximisation of a Stone-Geary (Linear Expenditure System) utility function. Unemployment can be 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.

Figure 74: Schematic representation of the JRC-GEM-E3 model



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, in particular achieving an integration of energy balances from PRIMES for the EU and POLES-JRC for non-EU regions (see (Rey Los Santos, et al., 2018) and (Wojtowicz, et al., 2019). The main data sources for the model version used in GECO 2019 include

- The input-output tables and the data on bilateral trade flows are derived from the Global Trade Analysis Project (GTAP) 9 database (Aguiar, Narayanan, & McDougall, 2016).
- GDP growth rates are assumed to be the same as in the PRIMES and POLES-JRC models for the EU and non-EU regions, respectively. The GDP assumptions of POLES-JRC are described in **Annex 5**.
- The 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.
- Energy and emission data using energy balances from PRIMES (for EU) and POLES-JRC (for non-EU regions).

The alignment with energy balances implies that the emission levels of greenhouse gases (totals and by sector) and the shares of electricity generation technologies are harmonised with the reference in the POLES-JRC and PRIMES models. For the EU, the Baseline is consistent with the 2018 reference of the PRIMES model that was used in the European Commission Communication COM (2018) 773 as well as corresponding in-depth analysis. In contrast to the GECO 2018 report, where the baseline assumed that (non-EU) countries and regions would achieve their NDC targets, the reference scenario in GECO 2019 follows the POLES-JRC Reference, in which regions might fail to achieve their NDC commitments (see **Annex 1** for details).

In the 2°C scenario, GHG emissions are reduced in line with the reductions in the POLES-JRC model. Regional emission trading systems the lead to an endogenous carbon price necessary to achieve the reduction targets. Emission allowances are auctioned in the EU power sector and are allocated freely elsewhere. In the sectors covered by the current EU emission trading scheme, it is assumed that firms maximise their output rather than pricing in the opportunity cost of the freely allocated emission permits (profit maximization).

In addition, structural change in key sectors of the decarbonisation is taken from the energy system models PRIMES and POLES-JRC. To better represent the large changes in the electricity and transport sectors, the generation mix as well as decarbonisation in household fuel use are taken exogenously into JRC-GEM-E3. In addition, to model the effects of electrification in the transport sector, a number of modifications have been implemented to this version of the JRC-GEM-E3 model (see below). Finally, non-CO_2 emissions and process emissions can be reduced in the model based on end-of-pipe abatement technologies calibrated to bottom-up information (Weitzel, Saveyn, & Vandyck, 2019).

Transport electrification related model development

Within the JRC project “Societal impacts of disruptive mobility scenarios” (SIMOD), the macroeconomic impacts of road transport electrification are examined using the macroeconomic model JRC-GEM-E3. Relative to previous versions of the model, the manufacturing of vehicles is now specifically represented. Further, the manufacturing of vehicles was split into manufacturing of conventional vehicles and electric vehicles. The cost structure of the new sector (intermediate inputs + factors of production) is derived by modifying the cost structure of the EU 28 average vehicle manufacturing sector as represented by the GTAP database (Aguiar, Narayanan, & McDougall, 2016). When translating cost information to the GTAP dataset, it was assumed that the cost of the battery is assigned as purchase from the Other Equipment Goods sector, and reduction in self-supplied inputs is introduced to reflect the fact that no internal combustion engine is needed the cost structure for the conventional and EV sectors are shown in **Box 3** in the main text. Country-dependent tax rates from GTAP for conventional vehicles are assumed the same for EVs; labour and capital input shares are assumed equivalent to the EU average of conventional manufacturing and all countries have the same structure based on EU average assumptions. In addition, to initialise trade shares, all countries are assumed to have the same trade structure for EVs and for conventional vehicles.

Households gradually move away from conventional vehicles towards purchasing vehicles in the new EV sector (through adjusting the consumption matrix, adjusting the coefficients representing the “purchase of vehicles” consumption category).

New investment matrices are introduced for the three transport sectors (land, water, and air), to reflect their higher reliance of vehicle manufacturing than others (previously all sectors had same identical investment vectors). This is based on an EU average from available Eurostat data.

In GECO 2019, the model is used to explore the impact of electrifying road transport, decomposing the total effect into several individual effects.

Stock effect: For household, exogenous adjustments are made in the consumption matrix, parameterised by the share of electric vehicles in new sales of cars, taken from energy system models (PRIMES and POLES-JRC). For firms, the shares of conventional vehicles in investment supply is adjusted over time to shift towards EVs in line with exogenous projections from energy system models.

Learning-by doing for batteries: Learning induced cost reductions for battery inputs to the EV manufacturing sector are implemented through an exogenous improvement in the productivity of "Other equipment Goods" (including batteries) in the production of electric vehicles. This productivity improvement is parameterised so that the input cost reduces to match the battery cost reduction trajectories assumed in PRIMES and very similar to POLES-JRC. The learning rate is varied in the high, medium and low electrification scenarios in line with the GECO scenario design.

Reduced maintenance requirements: For households, reduced maintenance requirements are implemented as an exogenous improvements in the productivity of non-fuel inputs to consumption category 9 (Operation of personal transport equipment), which mostly consist of market services (providing maintenance and repair), chemicals (e.g. fluids) and motor parts. For other vehicles, the change is captured as a productivity improvement on 16% of the input of market services to land transport, where the 16% represent the services that are related to repairs of vehicles. The reduction of the maintenance is estimated to be 30% compared to conventional vehicles and is explained in **Box 4**, which references in **Table 18**.

Table 18: Cost saving in maintenance attributable to BEVs according to main literature sources

Authors (year)	Maintenance costs estimations/ assumptions (% BEVs lower than ICEVs)	Geographical Coverage	Type of vehicles
(Moon & Lee, 2019)	50%	Korea	PC
(van Velzen, Annema, van de Kaa, & van Wee, 2019)	50%	The Netherlands	PC
(Palmer, Tate, Wadud, & Nellthorp, 2018)	23% J; 30% C; 24% T; 23% UK The % differences were calculated based on the nominal values provided in the paper.	Japan (J); California (C); Texas (T); United Kingdom (UK)	PC
(Weldon, Morrissey, & O'Mahony, 2018)	18%	Ireland	PC and LCV
(Logtenberg, Pawley, & Saxifrage, 2018)	47%	Canada	PC
(Danielis, Giansoldati, & Rotaris, 2018)	30% or 35% based on the values identified in literature	Italy	PC
(Letmathe & Suares, 2017)	25-31% Small Vehicles 30-35% Medium Vehicles Class (depending on the Annual vehicle mileage)	Germany	PC
(Hoekstra, Vijayashankar, & Linesh, 2017)	70%	The Netherlands	PC
(Mitropoulos, Prevedouros, & Kopelias, 2017)	30%	USA	PC
(Kleiner & Friedrich, 2017)	33% (40 ton long- haulage) 46% (12 ton urban)	Germany	HDV
(Bubeck, Tomaschek, & Fahl, 2016)	25%	Germany	PC
(Madina, Zamora, & Zabala, 2016)	65% The % differences was calculated based on the nominal values provided in the paper.	Spain Germany	PC
(Taefi, et al., 2014)	20-30%	Germany and UK	LCV
(Rusich & Danielis, 2015)	50%	Italy	PC
(Gnann, Plötz, Funke, & Wietschel, 2014)	19% Small; 17% Medium; 16% Large and LCV The % differences were calculated based on the nominal values provided in the paper	Germany	PC and LCV
(Lebeau, Lebeau, Macharis, & Mierlo, 2013)	35%	Belgium	PC
(Macharis, Lebeau, Mierlo, & Lebeau, 2013)	50%	Belgium - Brussels-Capital Region	LCV
(Davis & Figliozzi, 2013)	50% The % difference was calculated based on the nominal values used in the paper	USA	HDV
(Lee, Thomas, & Brown, 2013)	50%- 75%	USA	HDV
(Propfe, Redelbach, Santini, & Friedrich, 2012)	19% The % difference was calculated based on the nominal values provided in the paper	Germany	PC
(Egbue & Long, 2012)	25%	USA	PC

	The % difference was calculated based on the nominal values provided in the paper		
(Feng & Figliozzi, 2012)	50%	USA	HDV
(Delucchi & Lipman, 2001)	24% The % difference was calculated based on the nominal values provided in the paper	USA	PC

Fuel consumption: For households, the consumption matrix is adjusted to exogenously impose the fuel mix in for households' "Operation of personal transport equipment" category, to be consistent with the same energy scenario used in the fleet. As the efficiency of electric vehicles is higher than for conventional vehicles (i.e. more miles can be driven per kWh of electricity than per kWh of gasoline or diesel), the consumption matrix coefficients are complemented with productivity increases. For the land transport sector, the fuel mix is adjusted through Leontief coefficients, while the overall reduction in consumption is implemented through an productivity coefficient for energy consumption.

Note that the modelling of electric vehicles has some caveats, mainly due to data uncertainty. The current modelling does not take into account investments needed to set up a charging infrastructure as cost estimates are not precise and hard to scale up. Along the same line, part of the existing infrastructure of gas stations would become obsolete, which is also not modelled. In addition, as explained above, transportation in a CGE model is typically represented differently than in the energy system models. We capture changes in transport demand by households and in the commercial transportation sector, but do not capture changes in transport by other sectors as these are not purchased over the market and not reported separately. While we observe the purchases of oil productions into these sectors, it would require further work to separate these flows according to their uses.

Annex 4: Socio economic assumptions

The population assumptions follow Europop (Eurostat, 2018) for EU and JRC-IIASA projections (Lutz, Goujon, KC, Stonawski, & Stilianakis, 2018) for the rest of the world.

The GDP projections follow EC (The 2018 Ageing Report), IMF (World Economic Outlook) and the OECD (CIRCLE project).

Table 19: GDP assumptions apply to POLES-JRC energy and GHG projections

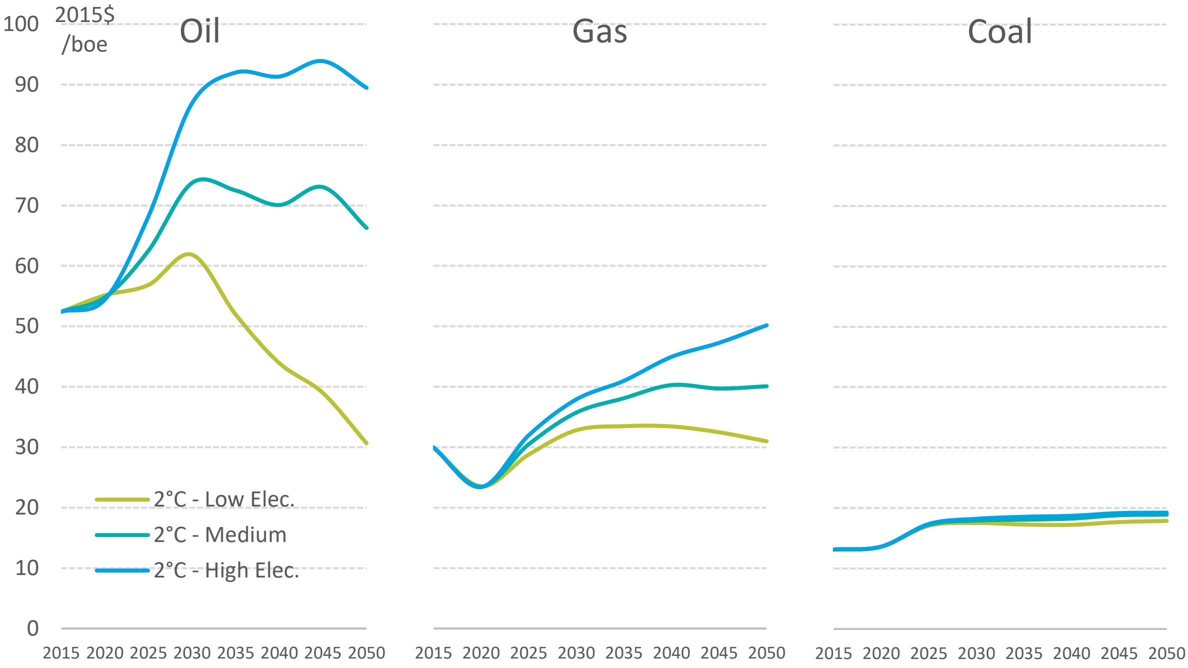
Data sources	Historical (-2017/2018)	2018/2019-2024	2025-2030	2031-2060	2061-2070	2071-2100
EU	World Bank Oct-2019	GDP/capita as in Ageing Report 2018 x Europop population				GDP/capita growth as 2060-2070 in Ageing Report 2018 x Europop population
Large non-EU	World Bank Oct-2019	IMF Oct-2019	(intrapolation)	OECD Jul-2018	GDP/capita growth as 2050-2060	
Rest of World	World Bank Oct-2019	IMF Oct-2019	(intrapolation)	OECD CIRCLE 2014	GDP/capita growth as 2050-2060	

Sources: (European Commission, 2018), (Eurostat, 2018), (World Bank, 2019), (International Monetary Fund, 2019), (OECD, Long-term baseline projections, No. 103, 2018), (OECD, Long-term baseline projections, No. 95 (Edition 2014), 2014)

Annex 5: Techno-economic assumptions

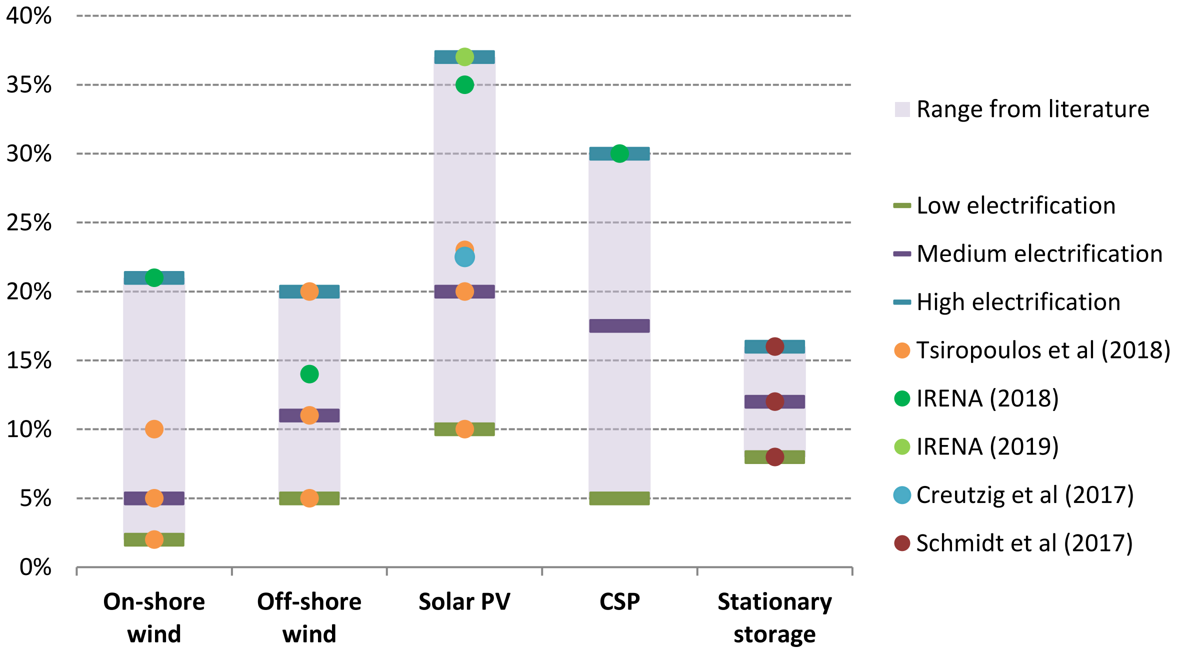
Fossil fuel prices in the 2°C sensitivities are to be compared with **Figure 75.**

Figure 75. Fossil fuel prices in the 2°C sensitivities



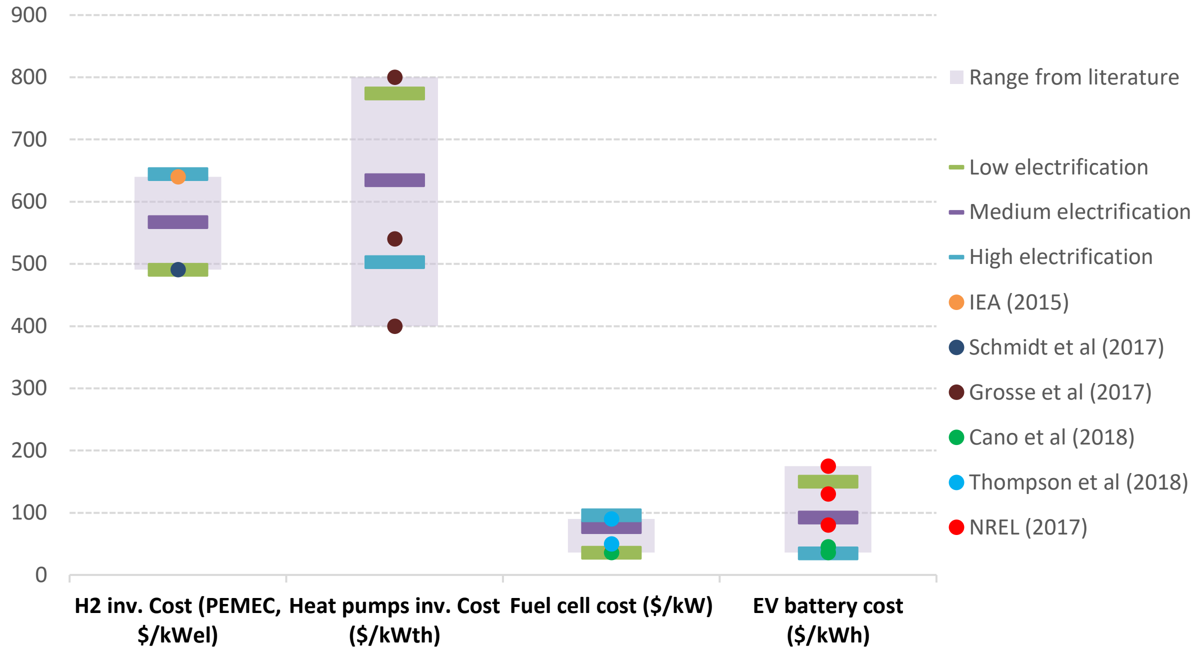
For key technologies used as a basis for the sensitivities conducted in this report (see **Table 1**), assumptions are compared with literature in **Figure 76** (learning rates) and **Figure 78** (exogenous costs).

Figure 76. Comparison of learning rates used in this study with literature



Sources: (Schmidt, Hawkes, Gambhir, & Staffell, 2017), (Tsiropoulos, Tarvydas, & Zucker, 2018), (IRENA, 2018), (IRENA, 2019), (Creutzig, et al., 2017)

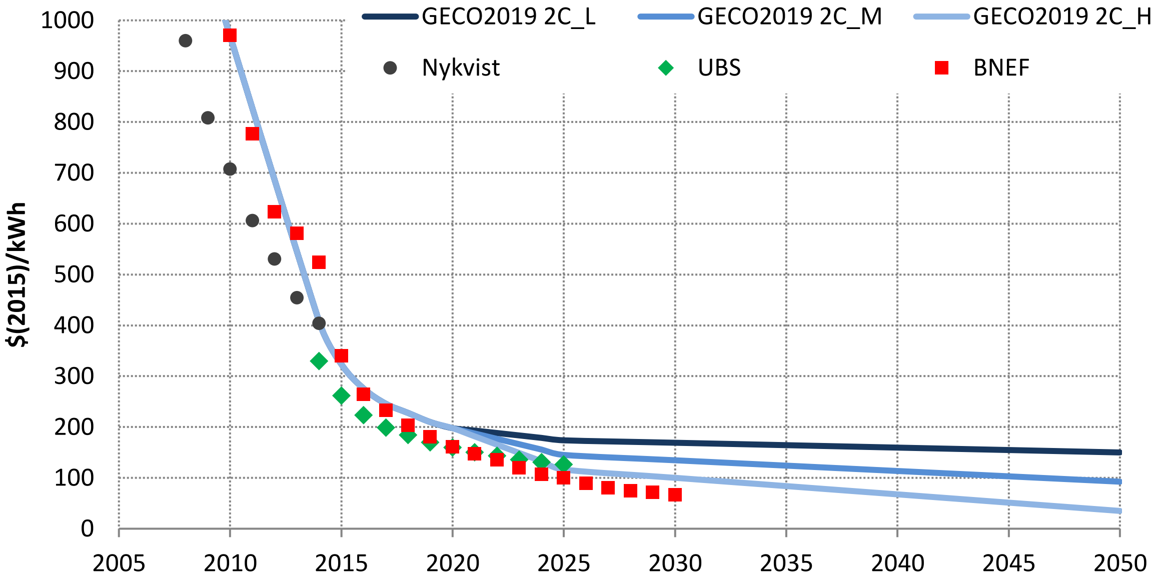
Figure 77. Comparison of costs used in this study with literature



Sources: (Cano, et al., 2018), (Grosse, Christopher, Stefan, Geyer, & Robbi, 2017), (IEA, 2015), (Jadun, et al., 2017), (Schmidt, Hawkes, Gambhir, & Staffell, 2017), (Thompson, et al., 2018)

Battery costs are inserted exogenously; there is no endogenous learning in the modelling. Battery electric and plug-in hybrid vehicles assume a 70 kWh and 20 kWh battery, respectively. The battery goes from making up about a quarter of the purchase cost of a battery LDV in 2020 to a sixth in the 2040s.

Figure 78: Battery costs for road vehicles



Source: Nykvist & Nilsson (March 2015)[56], UBS (May 2017)[57], BNEF (July 2017)[58]

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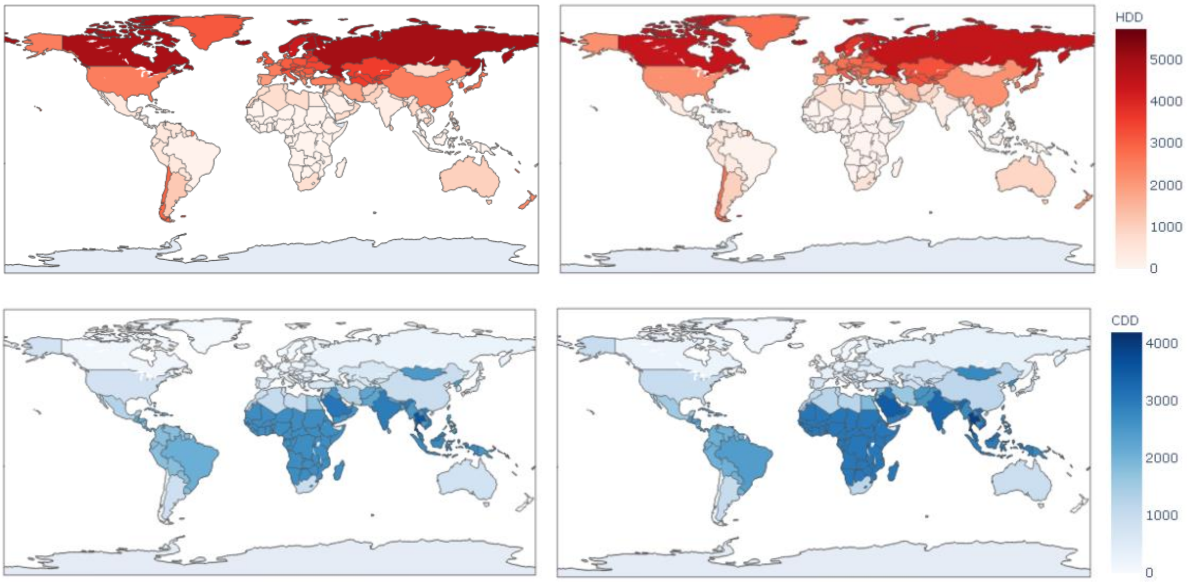
(56) Nykvist, B. & Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles. Nature Climate Change, 23 3, Volume 5, p. 329.

(57) https://neo.ubs.com/shared/d1wkuDlEbYPjF/

The effects of climate on energy needs for heating and cooling are captured through the use of respectively "heating degree days" (HDD) and "cooling degree days" (CDD). Degree-days are the summation of temperature differences from a human comfort level over time. They capture both extremity and duration of outdoor temperatures. HDD and CDD are measured in “degree-days” below (HDD) or above (CDD) a temperature set point (here: 18°C). The HDD and CDD are calculated for each geographical cell for which daily temperature is provided. HDDs and CDDs used in this report are from (Kitous & Després, 2018) and are presented in **Figure 79**. To reflect the effects of evolving climate change over time on the energy system, different values were used depending on the scenario considered: dataset related to an RCP 8.5 trajectory for the Reference/NDC scenarios and an RCP 4.5 trajectory the for the 2°C/1.5°C scenarios.

Figure 79. Heating degree-days (top) and Cooling degree-days (bottom) in 2015 (left) and 2050 (right) for the 2°C scenarios



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(58) https://about.bnef.com/blog/lithium-ion-battery-costs-squeezed-margins-new-business-models/

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