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Global Energy and Climate Outlook 2022: Energy trade in a decarbonised world

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Abstract

This edition of the Global Energy and Climate Outlook (GECO 2022) presents an updated view on the implications of energy and climate policies around the world. Current climate policy pledges and targets imply a rapid decline in greenhouse gas emissions, but there remains both an implementation gap in adopting policies aligned with countries' mid-term Nationally Determined Contributions and Long-Term Strategies, and a collective ambition gap in reducing emissions to reach the Paris Agreement targets of limit global warming to well below 2°C and pursue efforts to 1.5°C. This report provides insight into the structural evolution of energy trade in a decarbonising world in the coming decades.

Meeting the 1.5°C target set out in the Paris Agreement requires a rapid shift to low-carbon energy systems, which implies a strong decrease in total volumes of fossil fuel trade, partially offset by an increase in alternative forms of energy trade, such as biomass and low-carbon hydrogen. With a greater share of energy produced domestically, the decarbonisation effort results increased energy self-sufficiency. We examine the role of hydrogen specifically: the share of hydrogen and of derived fuels in total global final energy consumption remain low by 2050 (7% and 5%, respectively). International hydrogen trade is limited (6-11% of hydrogen demand), with most trade taking place via pipeline from neighbouring regions. The trade of hydrogen-derived liquid fuels is more pronounced (up to 25% of these fuels' demand) and takes place over longer distances by ship. Embodied energy trade remains an important element in a decarbonised global economy, while shifting away from embodied fossil fuels towards embodied low-carbon electricity.

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The energy and greenhouse gas (GHG) emissions modelling was carried out by Florian Fosse, Kimon Keramidas, Burkhard Schade, Andreas Schmitz.

The economic modelling was led by Rafael Garaffa, Jose Ordonez, Toon Vandyck and Matthias Weitzel.

Visuals and infographics included in this report were developed by Esperanza Moreno Cruz, Estrella Vaca Campayo. The GECO website was developed by Bruno Cattaneo and Julia Garcia Lopez.

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GECO 2022 is dedicated to the memory of our late colleague and outstanding energy economist Nikos Kouvaritakis. Nikos' efforts contributed to the modelling foundations on which we continue to build today.

Executive Summary

This edition of the Global Energy and Climate Outlook (GECO) presents an updated view on the implications of energy and climate policies around the world. Since the previous edition, post-pandemic economic developments and Russia's invasion of Ukraine have caused turmoil in international energy markets. With a timely focus on the future of (direct and embodied) energy trade, the report aims to look beyond short-term turbulence and provide insight into the structural evolution of energy trade in a decarbonising world in the coming decades.

Policy context

Disruptions to energy supply in the wake of the Russian invasion of the Ukraine, and resulting increases in international energy prices, have shifted energy security up in the list of policy priorities. Governments are facing unexpected inflation rates, resulting from the war-induced energy supply shock and exacerbated by years of loose monetary policy and the post-pandemic consumption outburst. The confluence of these circumstances is regionally worsened by external dependency on energy imports (EU, Asia), food (Africa) or intermediate supplies.

Geopolitical tensions urge governments to reconsider energy import channels and strategic trade policies. The role of liquefied natural gas (LNG) is rising, and competition for LNG has seen typical contract times shifted from years to days. This has also affected global power markets due to the crucial role that gas-fired power plants have in many countries. Price volatility has also increased, and as a consequence, investment decisions may suffer from the additional uncertainty created. In order to restore the price predictability needed to carry out a well-ordered energy transition, stable and reliable energy import flows are sought as a key element of international trade policies.

Against this unstable framework, climate policy is set to reduce fossil fuel import dependence, while creating opportunities for low-carbon energy trade. Traditional energy trade channels will be replaced by new ones. In the urgent need to reduce emissions globally, attention has returned to the possibility of hydrogen as an energy carrier to replace fossil fuels. Many countries have announced hydrogen strategies, but so far only a few have announced actual policies to incentivise increased hydrogen demand or supply, partly because there is significant uncertainty about the role that hydrogen and it's derivative fuels can play in global energy markets.

The renewable potentials in different world areas will crucially determine the pattern of these new flows, as well as will the evolution of demand for industry, services, transport and households across the globe. The combination of renewable potentials and availability of prime, raw materials may in the mid- to long-term induce also a substantial relocation of energy-intensive activities, although this is an aspect that has not been specifically tackled in this GECO edition.

The report explores the interactions between energy trade and climate policy, building on the latest updates of Nationally Determined Contributions (NDC), Long-Term Strategies (LTS) and Net-Zero Targets submitted or announced in the context of the United Nations Framework Convention on Climate Change (UNFCCC).

Key conclusions

Meeting the 1.5°C target set out in the Paris Agreement requires a rapid shift to energy systems dominated by renewable sources. Along with energy efficiency improvements, far-reaching electrification of end-use drives down total volumes of fossil fuel trade. The increase in alternative forms of energy trade, such as biomass and low-carbon hydrogen, make up for only part of the declining fossil fuel trade, and a greater share of energy produced domestically increases global energy self-sufficiency as the world decarbonises. Ambitious global climate policies therefore induce a declining trend of total volumes of energy trade, introduce shifts in geographical energy trade patterns, and reduce energy import dependency.

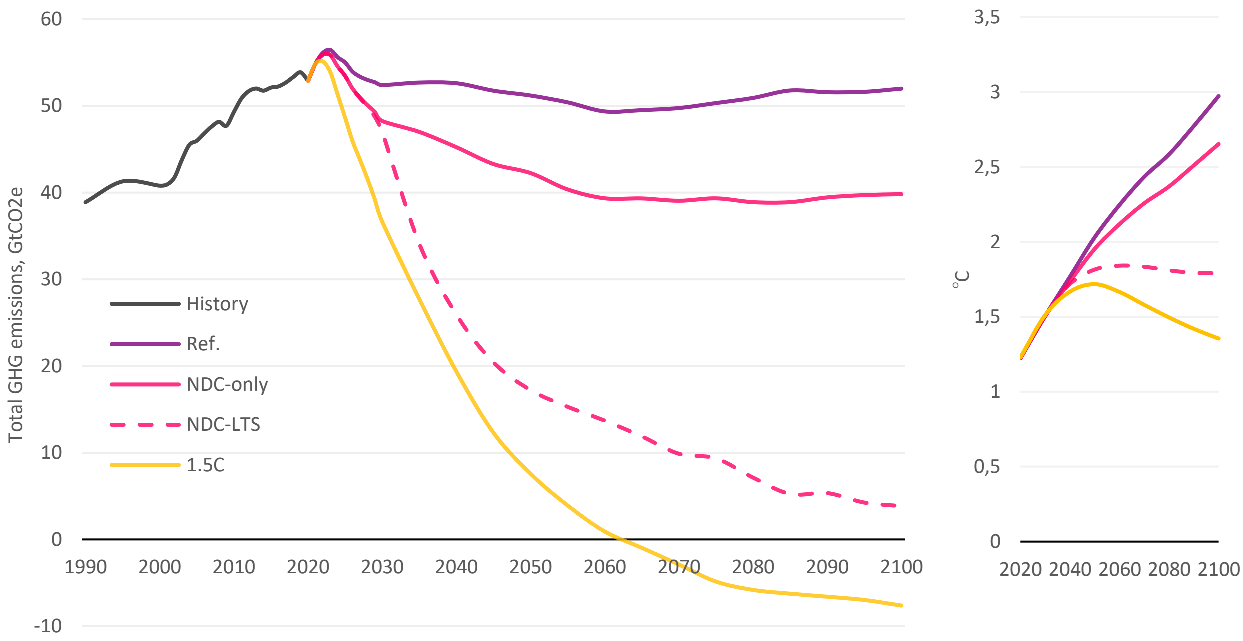
Policymakers' goals of improving energy security and reducing emissions appear to have overlapping solutions: increasing renewables use and electrification to reduce emissions also results in reduced imports of fossil fuels and increases the share of domestic energy production in many countries.

Besides direct imports and exports of fuels, energy is also used to produce products that are then traded globally. The amount of energy that is embodied in the international exchange of goods and services is of a similar magnitude to the amount of energy that is directly traded as energy fuels. Also, their evolution from today to 2050 in the 1.5°C Scenario is similar, with the total volume of embodied energy declining, and with embedded non-fossil electricity trade taking an increasing share. Global trade of goods and products rises while the economy grows and decouples from emissions, illustrating that globalisation can go hand in hand with decarbonisation.

Main findings

Current climate policy pledges and targets imply a rapid decline in greenhouse gas emissions, but implementation and ambition gaps remain. Global emissions are still not on track to deliver on the temperature targets of the Paris Agreement. Both the Reference Scenario which captures the current policy settings, and the NDC-LTS Scenario which captures the current announced climate targets globally, fall short of limiting temperature rise to 1.5°C. However, some progress has been made in the previous year. Policy action in major regions and continued cost reductions and deployment of low-emission technologies in the past year limit the temperature increase to 3.0°C by the end of the century in the Reference Scenario, the temperature increase was projected to be closer to 3.2°C in the corresponding pathway in GECO 2021.

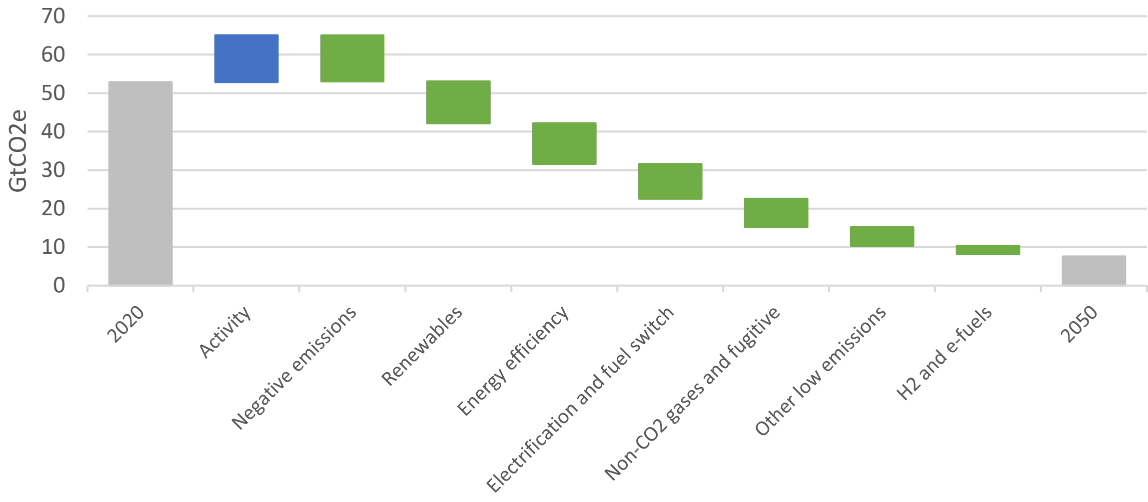
Figure 1. Global emissions and global mean temperature change, by scenario



Source: POLES-JRC model; MAGICC online

The 1.5°C Scenario outlines a cost-efficient pathway for limiting global temperature rise to 1.5°C by the end of the century. Figure 2 shows the importance of major decarbonisation policy areas, providing direction for policymakers to focus their efforts. The major policy levers in the coming decade are an accelerated deployment of renewables, continuous improvements in energy efficiency, and the electrification of as many end-uses as possible. Equally important, but more so after 2030 is the mobilisation of negative emissions technologies and options, largely in the land sector. In addition, there is significant policymaker and private sector interest in the role that hydrogen can play in a decarbonised world. The 1.5°C Scenario sees hydrogen and derivate fuels playing a small role in the overall energy mix, however they are very important in certain subsectors.

Figure 2. Global emission reductions from 2020 to 2050, 1.5°C Scenario



Source: POLES-JRC model

The 1.5°C Scenario requires a rapid phase out of coal. Correspondingly, the direct and embodied international trade of coal declines by about 70% and 80%, respectively, from volumes observed today over the next two decades. Under currently implemented climate and energy policies, on the contrary, direct coal trade volumes steadily increase while embodied coal trade remains roughly constant. This striking divergence indicates a misalignment of projected trade flows with global climate ambitions. Oil trade volumes already decline over time in the Reference Scenario as transport electrifies, but the speed of this decline more than doubles in the 1.5°C scenario. Global fossil gas trade increases over time in the Reference Scenario, despite the phase out of EU-Russia gas trade. In the 1.5°C scenario, global trade of fossil gas increases in the short run, only to drop substantially thereafter.

At the same time, ambitious climate policy creates potential for emerging trade flows of low-carbon energy carriers, such as solid biomass, liquid biofuels, hydrogen and e-fuels. Combined, international trade in these energy carriers does not compensate for falling fossil fuel trade volumes. In monetary terms, however, the results suggest that increasing trade in low-carbon energy carriers can bring the value of global energy trade to levels similar to those observed in recent years.

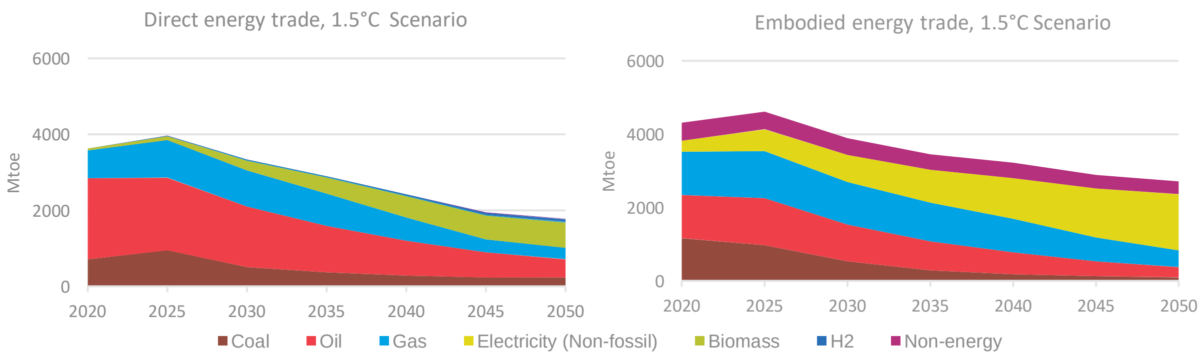
Global demand for hydrogen is largest in China, India and the United States. In the 1.5°C Scenario hydrogen is used mostly in transport, both used directly in hydrogen fuel cell vehicles (mostly in trucks) and indirectly as an input to the production of e-fuels (also used as transport fuels in road, aviation and maritime, as well as mixed with fossil gas in industry). A relatively minor share of hydrogen goes to steelmaking and decreasing volumes go to non-energy uses, primarily as demand in the refinery sector decreases with the decrease in oil demand in the 1.5°C Scenario.

Green hydrogen reaches half of global hydrogen production in 2050 in the 1.5°C Scenario. With limited CCS deployment and green hydrogen still relatively expensive in the mid-term, the 1.5°C Scenario sees nuclear-based hydrogen production playing an important role, reaching one-third in 2050. Nuclear-based hydrogen production takes a larger share in countries with more limited renewables resources. Finally, hydrogen made from fossil fuels fitted with CCS and gas pyrolysis accounts for 13% in 2050.

On the supply side, the 1.5°C Scenario provides a very clear picture: the bulk of hydrogen demand is met by domestic production, whereas only a small share is imported mostly from neighbouring regions. That picture is relaxed somewhat for e-fuels: as the transport costs are much lower than for hydrogen, it becomes economically viable to produce e-fuels in the best locations and ship them to the demand point. This results in one-quarter of e-fuels demand being met by imports in 2050.

Currently, the magnitude of direct energy trade and indirect energy trade embodied in the trade of goods and services are of similar magnitude. More than 60 % of embodied energy trade occurs in traded products of energy intensive and other manufacturing industries. While the energy intensity of traded goods is projected to substantially decrease in the 1.5°C Scenario, rising trade flows under a growing economy lead to a more gradual decline of embodied energy in trade under ambitious climate policy. However, the composition of energy embodied in trade changes substantially. Fossil fuels embodied in trade, most importantly coal, are projected to rapidly decline towards 2050. While electricity is only playing a marginal role for direct energy trade, the strong shift towards electrification substantially increases the share low carbon electricity in embodied energy trade.

Figure 3. Direct and embodied energy trade of all fuels, 1.5°C Scenario



Source: POLES-JRC and JRC-GEM-E3 models

Related and future JRC work

The Global Energy and Climate Outlook (GECO) is published annually since 2015. It contributes to the JRC work in the UNFCCC policy process and the IPCC Assessment Reports.

Quick guide

After an introduction describing the motivation and scope of the GECO this year, Section 2 provides details on the climate policy scenarios, Section 3 presents key results for emissions and energy systems on the global level. Section 4 takes a deep dive into the emerging energy carriers that are relevant in the context of international trade, particularly hydrogen and liquid e-fuels. Section 5 describes the future of direct and embodied energy trade under different climate policy pathways.

1 Introduction

Geopolitical events of 2022 have resulted in significant turmoil in European and global markets, leading to major policy action that has greatly altered the short-term and long-term outlooks, particularly concerning the trade of energy.

It is in this context that GECO 2022 takes a focus on the new landscape for energy trade and how it changes with increasing global efforts to decarbonise. Including updated modelling for hydrogen and e-fuels demand, supply and trade, GECO 2022 investigates the increasing role of low-emission fuels trade as that of fossil fuels diminishes in the transition to a decarbonised world.

International trade has increased strongly over the last decades, especially for manufactured goods. This increase has led to a substantial amount of global energy crossing borders not as an energy carrier, but being embodied in products. Next to the direct trade of energy carriers, GECO 2022 therefore sheds light on the trade of energy and emissions embodied in goods and services as the world decarbonises.

Several authoritative reports[1] have recently addressed the increasingly promoted role that hydrogen and other synthetic fuels could play in reaching climate targets, however much uncertainty remains in this relatively new field of analysis[2]. This is important to note for optimal policy-making, given that the crucial integration of renewables and electrification for decarbonisation is presently well understood.

This year, the global energy and climate policy updates concern a relatively minor number of countries compared to last year's GECO. The latest emissions pledges found in the Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs) announced by all world countries are included in the modelling.

Brazil (43% to 50% emissions reduction), South Korea (35% to 40%) and Australia (26-28% to 43%) are major emitters that have announced updated NDC emission targets over the past year. Outside of the NDC submission process, major policy action to address other concerns also accelerates decarbonisation. The European Commission announced the RePowerEU Plan[3] with its focus on reducing fossil fuel imports, which reinforces the long-term decarbonisation pathway of the EU. Likewise, the Inflation Reduction Act in the United States will have a significant impact on investments that lower the reliance on fossil fuels and therefore will substantially reduce future GHG emissions. Large emerging economies such as Indonesia, Vietnam and South Africa have concluded Just Energy Transition Agreements with industrialised nations, committing to limiting the expansion of coal use for power generation in years ahead.

GECO 2022 first investigates how recent policies, updated energy prices and technology cost evolutions impact global energy and emissions projections, and associated temperature increases in three scenarios (Section 3). Then we provide a deep-dive into hydrogen and e-fuel demand and supply (Section 4). Finally, we investigate the international trade of all energy fuels as well as the energy embodied in traded goods in Section 5.

[1] https://www.irena.org/publications/2022/May/Global-hydrogen-trade-Cost; https://www.iea.org/reports/global-hydrogen-review-2022
[2] https://www.nature.com/articles/d41586-022-03693-6
[3] European Commission COM(2022) 230 RePowerEU Plan

2 Scenarios and definitions

GECO 2022 was produced based on results from the partial equilibrium global energy model POLES-JRC and the general equilibrium model JRC-GEM-E3 that covers the interactions between the global economy, the energy system and the environment. A description of the POLES-JRC model used in GECO 2022 can be found in Annex 2, and the JRC-GEM-E3 model description is in Annex 3. In addition, detail on socio-economic assumptions and fossil fuel prices can be found in Annex 5.

This section provides a description of the assumptions made for the projections presented in this report. The following scenarios were modelled:

Reference: this scenario corresponds to a world where existing policies related to energy supply and demand policies and targets, as well as legislated GHG policies and targets that are backed by supporting energy-sector policies, are enacted. No additional policies are considered compared to what had been legislated as of June 2022. Exogenous macroeconomic projections (GDP and population), with endogenously calculated energy prices and technological development specific to the POLES-JRC model, combine with the effect of enacted policies resulting in projections of the energy system and GHG emissions. As a consequence, this scenario may differ from energy and emissions projections from official national sources and international organisations. See Annex 1 for the list of policies considered.

This scenario does not aim to reach stated policies or targets that have not been translated into law and accompanied by concrete action plans.

NDC-LTS: this scenario considers the policies of NDCs in the medium term and the LTSs in the longer term. This scenario assumes that the objectives in the NDCs (including conditional objectives) are reached in their relevant target year (2030 in most cases). To this end, carbon values and other regulatory instruments are put in place on top of the existing, legislated measures of the Reference Scenario. Beyond 2030, the objectives of the countries' LTS, where they exist, are pursued; if the country has not announced an LTS, it is assumed that no additional decarbonisation effort is made, and carbon values, if any, are kept constant to their 2030 level. This scenario includes the net zero targets announced by many countries. See Annex 1 for a list of NDC and LTS objectives included in this scenario. The NDC-LTS scenario also considers decarbonisation proposals related to international aviation and maritime transportation sectors (international bunker fuels).

An **NDC-Only case** was also modelled, where the effect of the LTSs was removed from the NDC-LTS scenario in order to quantify the impact of each mechanism; carbon prices of the NDC-LTS scenario, if any, were kept constant after 2030 in the NDC-Only case.

1.5°C: A decarbonisation scenario designed to limit global temperature increase to 1.5°C Scenario. The scenario was designed with a global carbon budget over 2020-2100 (cumulated net CO_2 emissions) of approximately 400 $GtCO_2$, resulting in a 50% probability of not exceeding the 1.5°C temperature limit in 2100[4,5].

A single global carbon price for all regions is used in this scenario, starting immediately (2022) and strongly increasing. Bottom-up policy drivers (such as capacity targets) from the NDC-LTS scenario are not included here, as this scenario is constructed based on the policy settings of the Reference Scenario. The global carbon price is the sole additional policy driver in this scenario. This scenario is therefore a stylised representations of an economically-efficient pathway to the temperature targets, as the uniform global carbon price ensures that emissions are reduced where abatement costs are lowest. This scenario does not consider financial transfers between countries to implement mitigation measures. The use of negative emissions technologies, including the land use sinks, is considerable (21 $GtCO_2$/year in 2100); CO_2 capture from combustion and CO_2 direct air capture technologies are made available progressively beyond 2030 (<5 $GtCO_2$/year in 2050). The mobilisation of biomass as an energy resource is relatively limited (remaining below 200 EJ/year for all years), in order to reflect the use of only sustainably-grown biomass[6]. Within the above economic and technological constraints, the overshoot of the temperature target was kept low (at slightly above 1.7°C in

[4] Characterised as a scenario between categories C1 (Below 1.5°C with no or limited overshoot) and C2 (Below 1.5°C with high overshoot) of IPCC AR6 WGIII Table 3.2 (IPCC, 2022).

[5] Global mean surface temperatures obtained with the online tool liveMAGICC, based on GHG and air pollutant emissions projections from POLES-JRC: http://live.magicc.org/

[6] There appears to be a moderate agreement in the literature for the potential of biomass for energy use of about 200 EJ/year, and a higher level of agreement for the more conventional figure of 90 EJ/year (Creutzig, F. et al., 2015).

2050 in the 1.5°C Scenario[7]).

Box 1. Definitions and taxonomy used in this report

In this report hydrogen demand refers to hydrogen used as a fuel for energy use and non-energy applications, such as hydrogen used as feedstock for ammonia production.

E-fuels refers to fuels obtained from power-to-gas and power-to-liquid processes, in which hydrogen and CO_2 are converted to gaseous or liquid hydrocarbon fuels through methanation or the Fischer-Tropsch process. In both cases the CO_2 is sourced from direct air capture powered by renewables. E-fuels are renewable fuels of non-biological origin (RFNBO).

Hydrogen demand as feedstock (pure hydrogen for the production of ammonia and other industrial applications) appears in "Non-energy uses" in the balances, except for hydrogen demand in steelmaking which appears in industry energy demand. Hydrogen uses mixed with other gases (such as methanol) are not considered. Energy inputs for the production of hydrogen, for both energy and non-energy uses, appear in "Other energy transformation and losses" in the balances.

Hydrogen demand as industrial feedstock is included in total hydrogen demand (section 4.1).

Ammonia demand as an energy fuel is only included in international maritime bunkers grouped together with e-fuels.

Domestic e-fuel production can be both gaseous and liquid fuels; however the international trade of e-fuels is exclusively liquid fuels.

Internationally traded e-fuels can only be produced from renewables ("green hydrogen").

Biomethane is produced from biomass and agricultural wastes, and the inputs of which are accounted for in primary energy as biomass. Biomethane is then mixed together with fossil gas for final users and appears as gas in final energy demand.

CO2 emissions from agriculture, land use, land use change and forestry (AFOLU) follow the latest historical data submitted to UNFCCC (data was available for all Annex I countries and select non-Annex I countries; final year differs depending on the country). Changes in the AFOLU emissions projections follow the same logic as previous GECO reports (based on data provided by the GLOBIOM-G4M models). For the reporting at the global level, CO2 AFOLU emissions were harmonized following the same methodology used in IPCC AR6 WGIII (offset to match 2015 emissions of CMIP6, convergence to native projections in 2150) (IPCC, 2021).

At all times, monetary values ($) are constant US dollars of 2015.

[7] Obtained with the online tool liveMAGICC, based on GHG and air pollutant emissions projections from POLES-JRC: http://live.magicc.org/

Box 2. Differences with GECO 2021

The POLES-JRC model has been updated with the latest historical data. Technologies costs were updated with recent literature. Fuel/technology preference factors were revised to reflect the updated data. Current and announced policies especially in G20 countries were reviewed and updated. The carbon price in the 1.5°C scenario was revised to reflect a gradual effort over the century; the carbon price trajectory follows a sigmoid curve with an inflection point in 2040. Notable upgrades in the modelling include: allowing for international trade of hydrogen and e-fuels (see Annex 4); in-depth revision of steel and cement sectors; inclusion of heat pumps and electrification potentials in industry; stock-flow approach for energy-consuming equipment in all final demand sectors.

Objectives and schedules by country put forth in the Kigali Amendment of the Montreal Protocol for the phasing down of HFCs are included in the Reference Scenario, not only in the NDC-LTS scenario.

GECO projections differ from national modelling exercises in the NDCs, mostly due to different key macroeconomic assumptions and consequently energy demand growth, but also operating patterns of the power sector. This can lead to some sectoral targets in an NDC not being reached in the NDC-LTS scenario; however, effort has been made to achieve the most important targets regarding renewables and emissions reductions.

3 Global results: supply and demand, technology mix, emissions

3.1 Greenhouse gas emissions and temperature change

In the Reference Scenario, emissions reach a plateau for the coming decades at around 48 $GtCO_2$-eq, as continued fossil fuels use and non-CO_2 emissions growth offsets growth in renewables. The Reference Scenario sees a global temperature increase of 3.0°C above pre-industrial levels at a 50% probability in 2100[8,9].

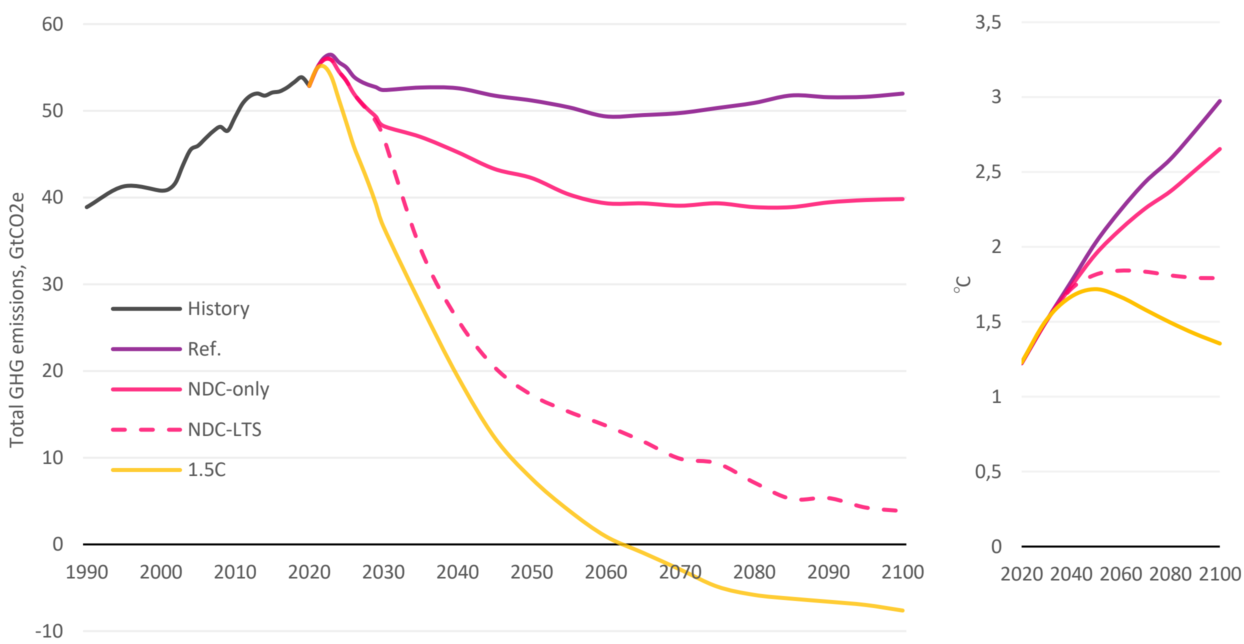
GECO 2021 projected a plateau in emissions from 2035, GECO 2022 sees the plateau occurring already in the current decade, and a lower long-term temperature increase of 3°C. These differences are brought about by multiple factors: decelerated macroeconomic projections, stronger climate policies in select markets, stronger expectations for the market-based deployment of key low-carbon end-use technologies (electric vehicles, heat pumps in buildings and industry).

Over 190 countries have submitted Nationally Determined Contributions (NDCs) as of October 2022, which when modelled as the NDC-Only case result in a reduction of 4.1 $GtCO_2$-eq in 2030 compared to the Reference Scenario, and limit the global temperature increase to 2.7°C at the end of the century.

The addition of the submitted and announced Long-Term Strategies (LTSs) to the NDC-Only case shows that the combined pledges result in the NDC-LTS Scenario reaching 17.4 $GtCO_2$-eq in 2050, a 66% decrease compared to the Reference Scenario. The NDC-LTS limits the global temperature increase to 1.8°C. There have been a relatively minor number of additional NDCs and LTSs announced since those included in GECO 2021.

The 1.5°C Scenario sees further emission reductions resulting in global net zero emissions being reached in 2065, with global net negative emissions after that date. In addition, the 1.5°C Scenario sees the temperature peak at 1.7°C around 2050. Achieving net zero emissions in our scenario design requires negative emission technologies and options, namely BECCS, DAC and LULUCF. In 2100 there are 26.0 Gt of residual emissions that are offset by 30.9 Gt of negative emissions.

Figure 4. Global emissions and global mean temperature change, by scenario



Source: POLES-JRC model

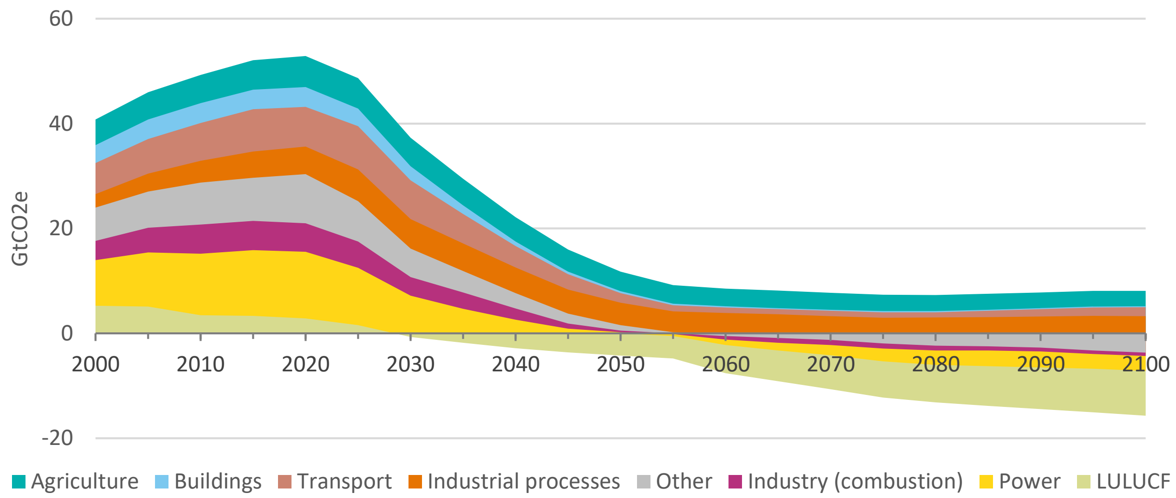
8 MAGICC (http://live.magicc.org/) and FAIR (https://gmd.copernicus.org/articles/14/3007/2021/gmd-14-3007-2021.html)

9 All temperature references in GECO 2022 refer to a global mean surface temperature increase compared to pre-industrial levels at a 50% probability.

In the 1.5°C Scenario, the power generation sector, the largest emitting sector today, decarbonises quickly in the coming decades, and reaches net zero emissions in 2052, in spite of the almost three-fold increase in generation by 2050.

On the demand side, energy efficiency combined with electrification offsets fossil fuel consumption at different speeds depending on the technology substitution mechanisms and the characteristics of the energy-using processes within each sector. The building sector switches from fossil fuels (mainly fossil gas) to electricity, and decarbonises based on relatively mature technologies like heat pumps and thermal insulation. Industry sees a significant fuel switch potential realised in the 1.5°C Scenario towards electrification which, combined with the deployment of CCS, results in fuel combustion-related emissions reaching net zero in 2053. The transport sector sees rapid decarbonisation from 2030 to 2050 as EVs, and to a lesser extent HFCVs, reduce fossil fuel demand. Residual emissions remain in 2050, particularly in the agriculture and transportation sectors.

Figure 5. Global emissions, by sector, 1.5°C Scenario



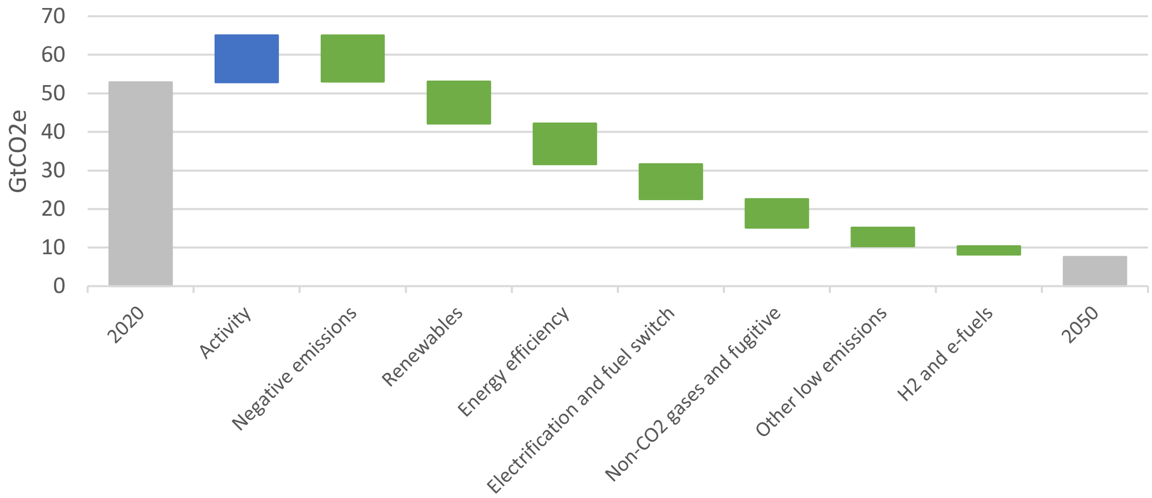
Source: POLES-JRC model

Figure 6 shows the pathway from today to 2050 in the 1.5°C Scenario, grouped into major policy areas, providing direction for policymakers to focus their efforts. Renewables take the largest role, encompassed by the well understood goal of deploying solar and wind capacities as quickly as possible.

Followed by energy efficiency and electrification, which go hand in hand, as electrifying end-uses leads to an increase in energy efficiency since technologies that deliver services via electricity are generally significantly more energy efficient than the equivalent fossil fuel powered technology. Effort here is focussed on replacing fossil gas in buildings with electricity in the coming decade, further accelerating the penetration of EVs into transport, and the electrification on industrial processes, which accelerates after 2030.

Finally, an equally important decarbonisation lever as those discussed above, but differentiated by its importance growing towards the end of the projection period, is that of negative emissions, which includes BECCS, DACS and LULUCF. This requires both further technological development, but also importantly, the global spread of markets and governance structures that facilitate the efficient and economically attractive realisation of these emissions reductions.

Figure 6. Global emission reductions from 2020 to 2050, 1.5°C Scenario



Source: POLES-JRC model

Figure 7 shows the global cumulative emissions between 2020 and 2070 by source, as well as LULUCF emissions and emission sinks, and resulting net cumulative emissions. The right-hand side presents CO2 emission budgets from 2020 onwards from the IPCC (2022) for several global temperature stabilisation targets and different levels of probability.

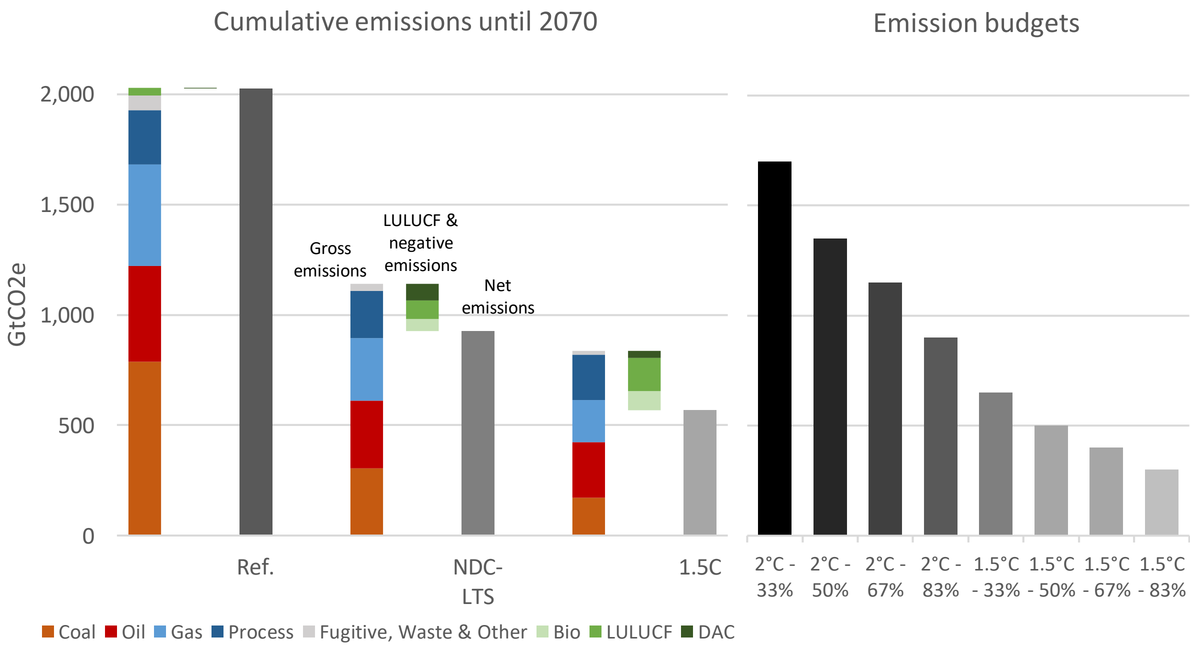
Emission budgets can be linked to a resulting temperature stabilisation target, given the near-linear relationship between cumulative net CO2 emissions and the resulting global warming (IPCC 2022). In GECO 2022, the 1.5°C Scenario achieves net-zero CO2 emissions, early in the 2050-2060 decade, (which corresponds to the time it reaches its temperature peak), and continues with net-negative CO2 emissions thereafter. For the NDC-LTS scenario, global net-zero CO2 emissions are reached in 2075. The cumulative emissions to 2070 for these two scenarios can thus be approximately compared to the emission budgets and probabilities illustrated in the right-hand side of Figure 7.

The Reference Scenario projects global net cumulative emissions between 2020 and 2070 to reach over 2000 Gt. This cumulative emission level comfortably exceeds the remaining carbon budget for a 2°C increase above pre-industrial levels. Coal is the single largest source of cumulative emissions, close to 780 Gt, followed by gas (460 Gt), oil (430 Gt) and industrial process emissions (245 Gt). Fugitive emissions (70 Gt) and LULUCF (35 Gt) represent smaller shares in total cumulative emissions. Negative emission technologies, in particular direct air capture (DAC), are projected to play a negligible role the Reference Scenario, removing close to 4 Gt towards 2070.

Both the NDC-LTS Scenario and the 1.5°C Scenario see lower cumulative emissions in the 2020-2070 period. The NDC-LTS scenario is projected to result in gross cumulative emissions of 1150 Gt by 2070. Negative emissions are projected to remove 220 Gt from the atmosphere, resulting in net cumulative emissions close to 930 Gt. By 2070, the 1.5°C Scenario projects resulting gross cumulative emissions close to 840 Gt, negative emissions of 270 Gt, and resulting net cumulative emissions of 570 Gt. Net global cumulative emissions continue to decrease towards end of the century, to 500 Gt, in order to reach the 1.5°C temperature stabilisation target with a probability of 50%.

In the 1.5° Scenario, cumulative coal emissions see an 80% reduction compared to the Reference Scenario, followed by gas (60% reduction) and oil (40% reduction). Cumulative industrial process emissions are projected to see a 20% reduction, reflecting the need for carbon capture and storage facilities to achieve reductions in net industrial process emissions.

Figure 7. Global cumulative emissions between 2020 and 2050 (left) and carbon budgets and probabilities of temperature stabilisation (right)



Source: POLES-JRC model (left) and IPCC (2022) (right)

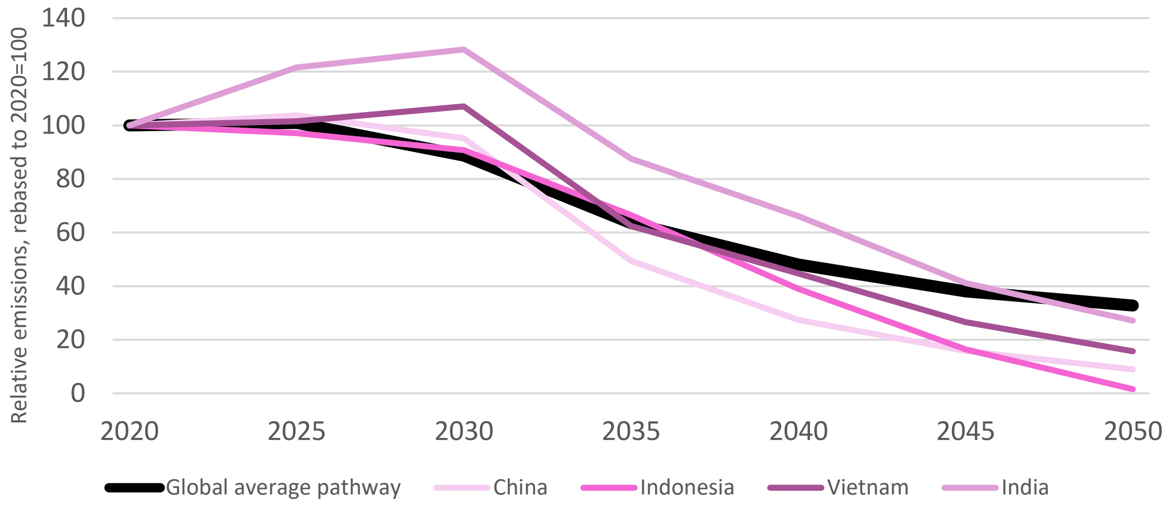
3.2 Balancing NDC Pledges and long-term decarbonisation

The question of efficiently balancing cost-optimal achievement of long-term decarbonisation goals and continued economic development in the short term can be addressed by examining the relationship between current emissions, a country's NDC target, and the pathway to net-zero emissions. On the one hand, allowing increasing emissions in the coming decade could help to soften the cost of mitigation on economic growth in this period. On the other hand, continued emissions growth in the next decade leads to the requirement for extremely rapid (and possibly more costly) emission reductions post-2030.

The following graph highlights countries with an NDC target that requires very rapid post-2030 emissions reductions. In the graph the 2020 emissions for these selected countries have been rebased to 100. These large emitting countries have an NDC emission reduction target that allows increased emissions in the coming decade; thereafter they have to achieve very rapid emission reductions in order to move towards a net-zero target. Raising the ambition of the NDC with further emission reductions by 2030 would lead to a slower rate of emissions reductions in the 2030-2040 period, and result in overall lower cost emission reductions between today and 2050.

In addition, extremely rapid emissions reductions could face constraints not captured in our modelling, such as the availability of financing emissions reductions at this speed, and issues around managing such a rapid decarbonisation from the perspective of social and industrial transitions (Brutschin et al, 2021).

Figure 8. Total emissions for selected countries vs global average pathway, NDC-LTS Scenario



Source: POLES-JRC model

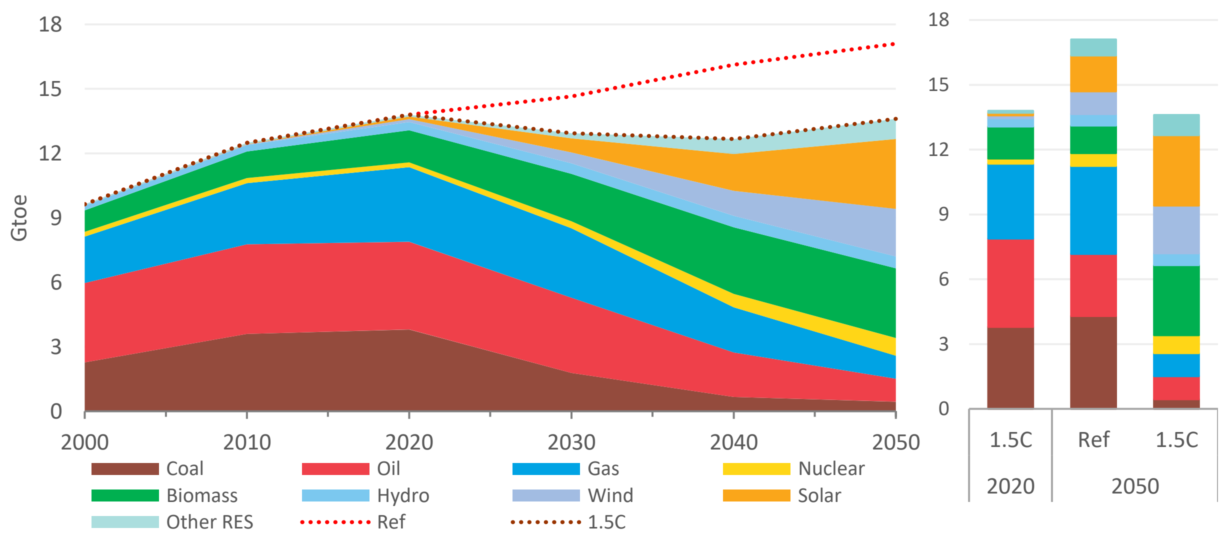
3.3 Energy Supply

3.3.1 Total Primary Energy Supply

In the Reference Scenario, total energy needs continue to grow at a sustained pace, reaching 17.1 Gtoe in 2050 from 13.8 Gtoe in 2020. Most energy in 2050 is supplied by fossil fuels (66%), with nuclear and renewables increasing their share respectively to 3% and 31%.

The decarbonisation required in the 1.5°C Scenario entails a rapid reduction in energy demand from fossil fuels, firstly in the most CO_2-intensive fuel, coal, which all but disappears from global supply by 2040 reaching a share in the energy mix of just 5%. Oil and fossil gas both see significant supply reductions through the 2030-2050 period, their share shrinking to a mere of 8% for oil and 8% for fossil gas in total supply by 2050. Biomass supply more than doubles from 2020 to 2050, while non-biomass renewables increase over 9-fold between 2020 and 2050, resulting in share of 16% for wind and 24% for solar in the global primary mix by 2050.

Figure 9. Global total primary energy supply, by fuel, Reference and 1.5°C Scenarios



Source: POLES-JRC model

3.3.2 Power Generation

The global power sector is the largest source of global GHG emissions. Its transformation in the coming decades in the 1.5°C Scenario plays a key role in the decarbonisation of the global economy. Beyond the reduction of direct GHG emissions, low-carbon electricity is essential in the decarbonisation of the transport, industrial and buildings sector via the electrification of end-uses.

To date, the global power sector is dominated by fossil fuels. Approximately 60% of global electricity generation in 2020 came from coal and gas-fired power plants. Hydroelectricity (16%) was the largest source of low-carbon electricity, followed by nuclear power (10%). Wind turbines and solar PV have seen a strong expansion in recent years, increasing their share in global electricity generation from close to zero in the year 2000 to 6% and 4% by 2020, respectively. In individual countries, the growth rates and levels reached for wind and solar can be substantially higher. This expansion was driven by a decisive decrease in the technology costs and the financing landscape of solar PV and wind power plants, as well as the existence of supporting policies. As technology costs continue to decrease for wind and solar, all scenarios in GECO 2022 project considerable capacity additions of renewable energy technologies in the years ahead.

However, in the Reference Scenario and to a lesser extent in the NDC scenario, fossil fuel capacity additions are projected to persist in many countries of the Global South for decades to come. This is mostly brought about by the planned expansion of coal- and gas-fired power capacities in emerging economies.

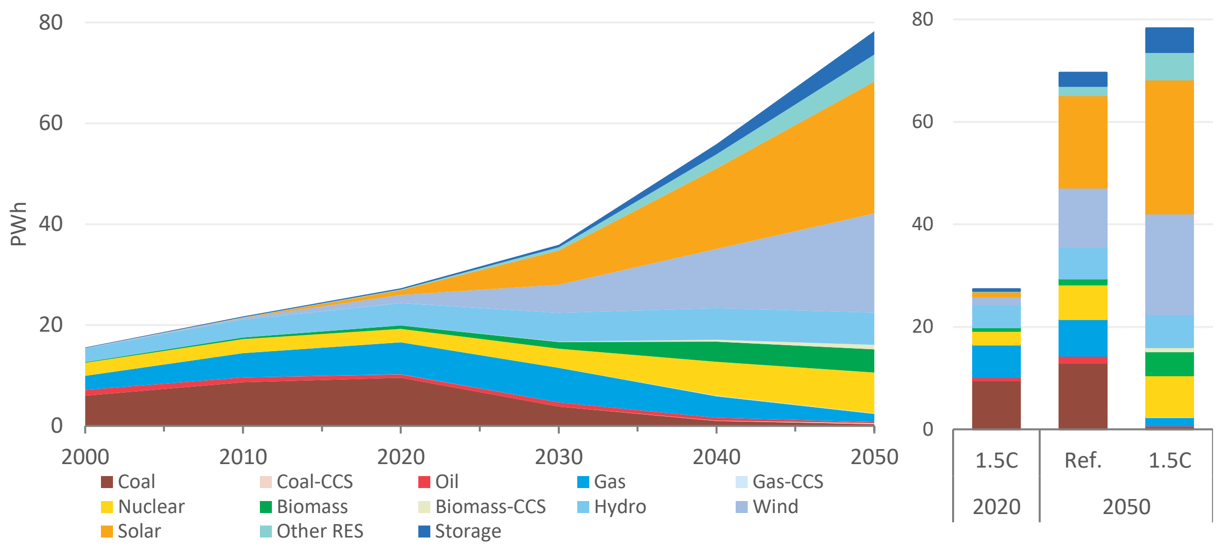
Across all scenarios, the global power generation sector is projected to be dominated by a strong and sustained expansion of solar PV and wind power generation in decades to come. In the 1.5°C Scenario, solar PV increases its share in global generation to 19% in 2030 and 33% by 2050. Wind power increases its share to 16% by 2030 and 25% from in 2050. The installed capacity of wind power reaches 8,400 GW in 2050, a 10-fold increase compared to today. Solar reaches over 22,000 GW in 2050, representing a 26-fold increase from current levels.

Translating the expansion of solar PV and wind power to yearly capacity additions outlines the massive requirement for solar PV and wind power manufacturing facilities, as well as financial resources required to finance these capital intensive investments in a 1.5°C compatible trajectory. Global solar PV net capacity additions grow from an average of 70 GW per year between 2020 and 2030 to 450 GW and more than 800 GW per year in the 2020-2030 and 2030-2050 timeframes, respectively. Global wind net capacity additions required in a 1.5°C trajectory are 170 GW per year between 2020 and 2030, and close to 300 GW per year between 2030 and 2050. This compares to historical wind yearly net capacity additions of 55GW per year in the 2010-2020 timeframe.

Nuclear power is the third largest source of generation in 2050, providing 10% of total generation, and seeing a 3-fold increase in installed capacity from today to 2050, reaching 1,100 GW. Power plants fitted with CCS provide only 2.6% of generation in 2050, reflecting a projected lack of competitiveness of CCS as compared to low carbon alternatives across the projection timeframe and scenarios. Gas fired power generation gradually reduces towards 2050, and coal generation is almost completely phased out by 2050.

Coal-fired power plants represent the single largest source of GHG emissions, given coal's high carbon content (approximately double that of fossil gas). In the 2000-2020 decades, installed coal capacity for power generation increased strongly, reaching 2300 GW in 2020 from 1200 GW in 2000. Most of this development has taken place in developing Asia, in particular in China and India. Yet, the renaissance of coal has taken place in a number of emerging economies, such as Indonesia, Vietnam or South Africa (Steckel et al,2015),(Edenhofer et al, 2018). As outlined in Figure 7, just the construction and operation of coal-fired power plants in the Reference Scenario of this Outlook alone would consume the carbon budget for a 1.5°C temperature stabilisation target.

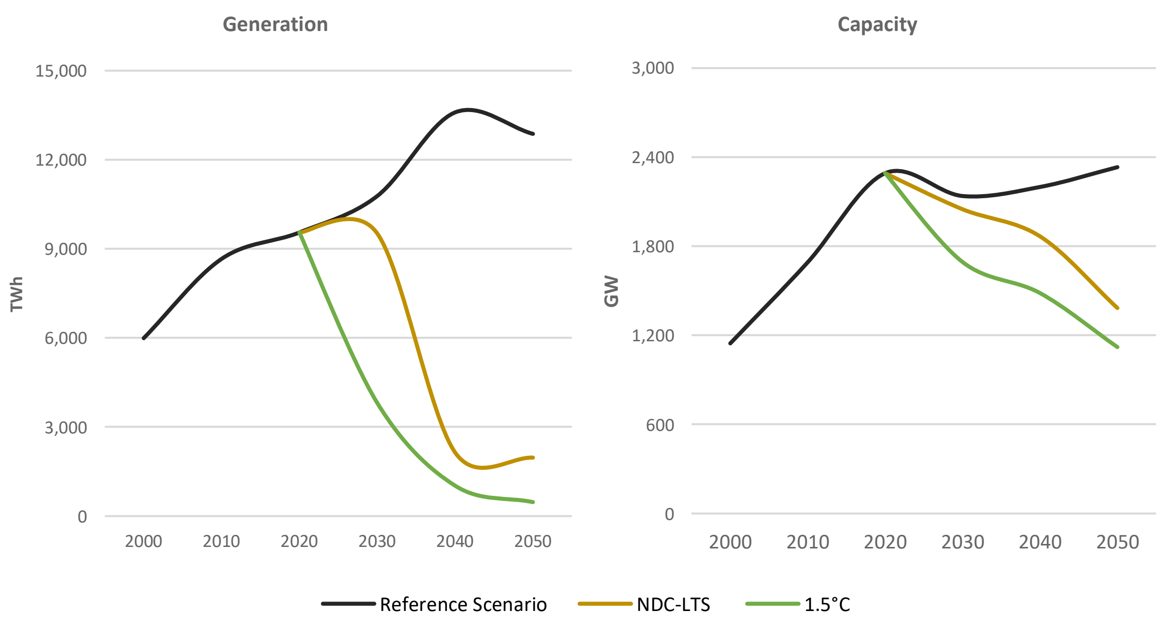
Figure 10. Global power generation, by technology, Reference and 1.5°C Scenarios



Source: POLES-JRC model

Figure 11 shows the projected generation and capacity of coal-fired power plants in the three main scenarios considered in this outlook. The Reference Scenario projects coal electricity generation to increase rapidly in the next two decades, peaking in the 2040s at around 14,000 TWh globally. The NDC-LTS scenario shows a continuous expansion of coal power generation until the 2030s, and a rapid decrease between 2030 and 2040. The 1.5°C scenario sees an immediate decrease in coal use for power generation, at a sustained rate of -12 % per year. In terms of capacity, the three scenarios in this Outlook project a peak in installed capacities in 2020. The Reference Scenario sees a decrease and subsequent increase after 2030, reaching the current level of installed capacities by mid-century. Both the NDC and 1.5° Scenarios see a steady decrease in coal capacities, yet at a slower pace than generation, implying that coal-fired power plants would be running at lower capacity factors in years ahead.

Figure 11. Global coal power generation and capacity, by scenario



Source: POLES-JRC model

The enormous gap between the current trajectory, towards an increased use of coal, and the immediate reduction of coal use at unprecedented speed to attain a 1.5°C temperature stabilization target, brings about the question of the regions and drivers of this coal expansion. Figure 12 shows the coal net capacity additions in the Reference Scenario for the 2020, 2030 and 2040 decades. It groups countries and regions modelled in this outlook according to their coal expansion pattern in years ahead into three different groups:

Established coal users are projected to have the largest net coal capacity additions in the 2020-2030 decade, if unrestrained. This country group comprises India, China as well as Vietnam and Indonesia[10]. These countries are projected to continue their coal capacity expansion trajectory, adding some 112 GW of coal-fired power plants in the 2020s and 97 GW in the 2030s. In 2040, India, Vietnam and Indonesia are projected to expand net coal capacities by some 60 GW combined, while China is projected to reduce net coal capacities by 90 GW. The coal expansion in this country group is driven by different structural factors. In China, electricity demand growth is determined by a strong growth in manufacturing industries, the rising income level, as well as the electrification of final demand, in particular in the transport sector. Vietnam´s electricity demand growth is strongly pushed by a rapid growth in industrial production. India´s and Indonesia´s demand growth is driven by both increasing industrial activity and growing populations.

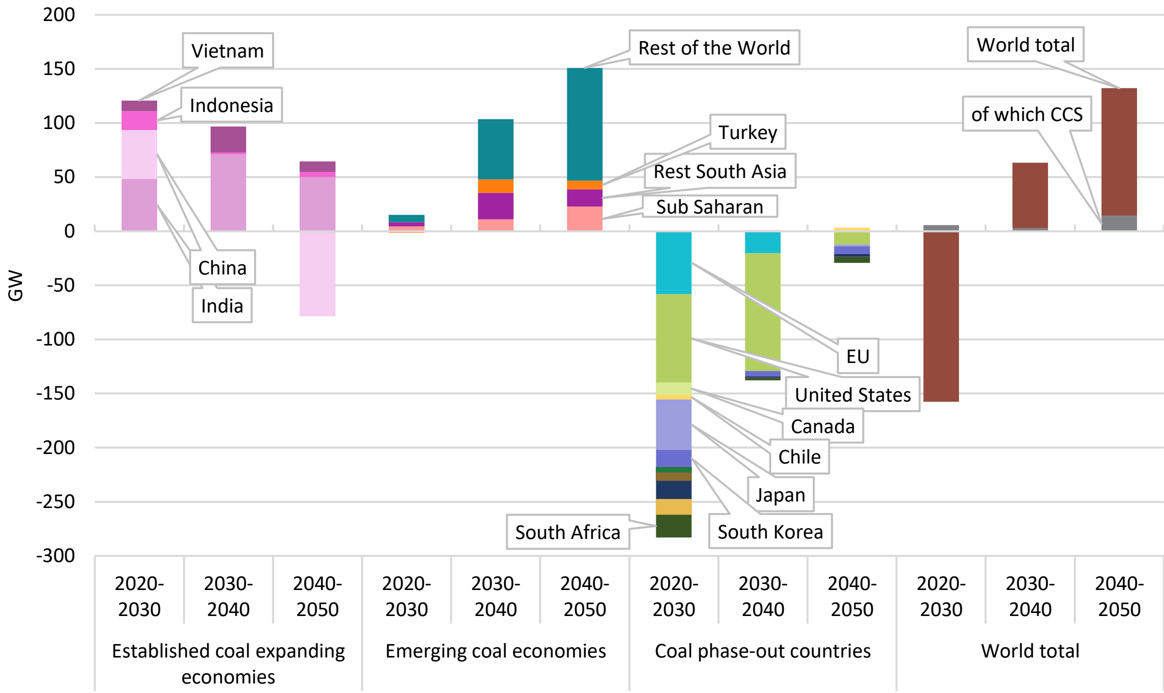
Emerging coal economies are projected to have strong net coal capacity additions in the 2030s and 2040s decade, with 105 GW and 150 GW in each respective timeframe. This country group is comprised by developing countries and emerging economies. In particular, Sub-Saharan African countries such as Nigeria and Angola, South Asian countries such as Bangladesh and Pakistan, and other expanding economies such as Egypt and Turkey. The coal expansion in this country group is driven by a strong population growth and a simultaneous increase in the income level, leading to a strongly rising demand for electricity.

Coal phase-out countries are projected to have strong reductions in coal capacities in years ahead. This country group is projected to experience a combined capacity reduction of 280 GW in the 2020s, 140 GW in the 2030s and some 25 GW of reductions in the 2040s. This group is comprised of developed countries from different regions, including the EU, USA, Canada, Japan, South Korea and Chile, and countries that have planned to phase out coal such as South Africa (which detailed its coal phase-out plant within its Just Energy Transition Partnership, JETP). The coal reduction in this group is driven by stronger climate policies, the higher competitiveness of locally produced gas in the US, and the higher competitiveness of capital-intensive renewable energy technologies given overall lower financing costs in highly developed countries.

Globally, the Reference Scenario projects a decrease in net coal capacities by 146 GW in the 2020s, and additions of 63 GW and 132 GW in the 2030s and 2040s decade. The reductions in coal use of highly developed countries are projected to be offset by the expansion of coal use in established coal economies, as well as a number of developing economies worldwide. With about 2300 GW of installed coal capacities as of 2020, coal electricity generation and emissions in the Reference Scenario are projected to remain nearly unchanged towards the middle of the century.

[10] Most recently, Indonesia and Vietnam concluded Just Energy Transition Partnerships with industrialised nations. These agreements are considered in the NDC Scenario of this outlook. The Reference Scenario reflects the unconstrained development of coal in these countries, following the countries' power sector expansion plans. For South Africa, the Just Energy Transition Agreement is considered already in the Reference scenario, reflecting its detailed coal phase-out plan.

Figure 12. Net capacity additions of coal, by decade, Reference Scenario



Source: POLES-JRC model

3.4 Final Energy Demand

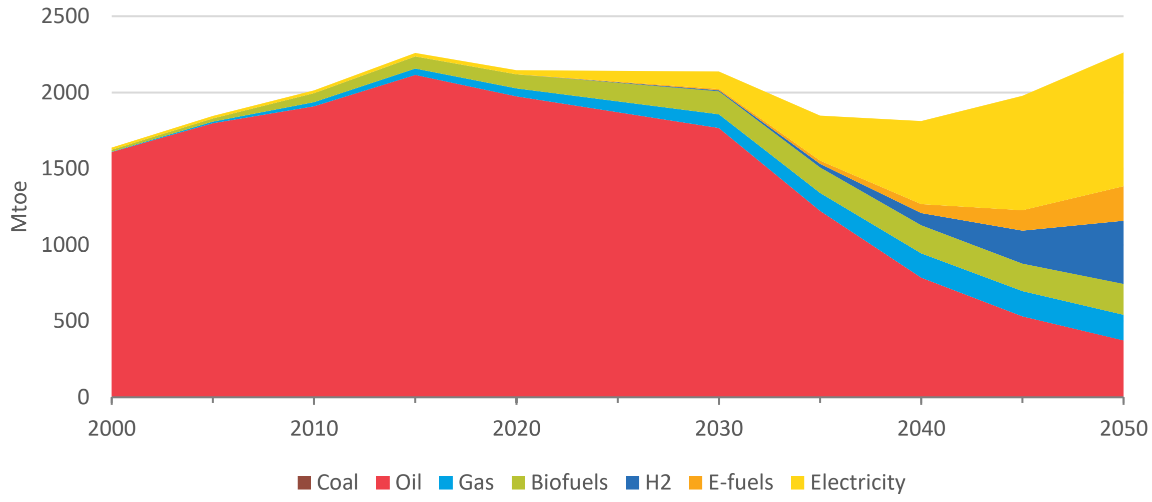
3.4.1 Transport

Recent battery electric vehicles (EVs) sales data show that they are becoming a mainstream purchase decision in an increasing number of markets. EV sales were 86%, 72% and 43% respectively in Norway, Iceland and Sweden in 2021 (IEA, 2022).

In the coming decade electrification begins to slow overall transport energy demand in the 1.5°C Scenario due to the significantly higher efficiency of EVs compared to internal combustion engines, where the resulting decrease in oil consumption is roughly three times larger than the increase in electricity. In the 1.5°C Scenario it takes until after 2030 to see zero-emission vehicles represent a sufficiently large share of the fleet, which leads to a significant reduction in oil demand, resulting in total transport demand in 2040 being lower than today.

Post-2040 sees both electrification and hydrogen take an increasing share of transport demand, and e-fuels play an increasing role in niche markets such as aviation and maritime transport. Post 2040 transport demand once again increases, but over three quarters of demand is met by low-emission fuels.

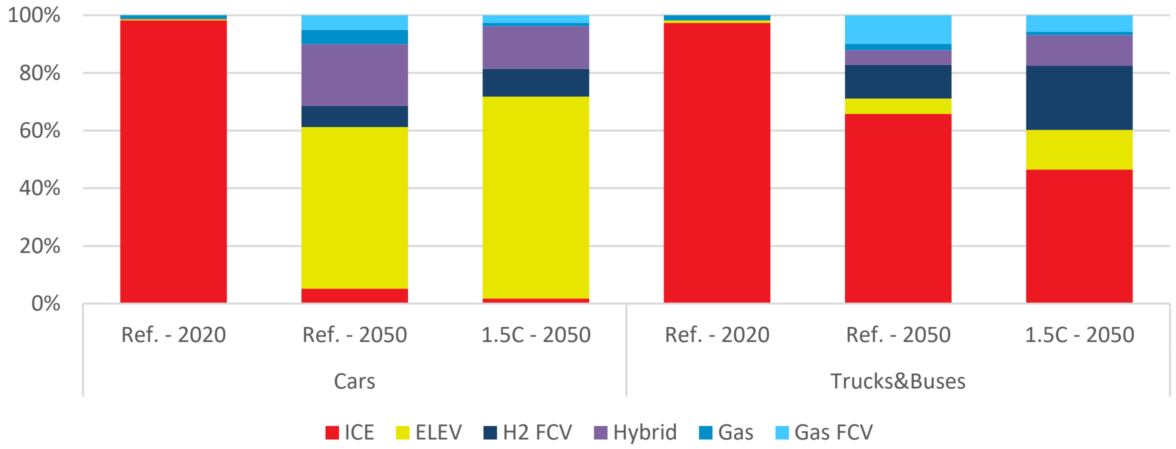
Figure 13. Global transport sector energy demand, by fuel, 1.5°C Scenario



Source: POLES-JRC model

Internal combustion engine (ICE) vehicles come to represent just 2% and 46% of cars and heavy duty vehicles (HDVs) by 2050, respectively. Those vehicles consume oil products as well as other liquids, such as biofuels and e-fuels; by 2050, oil products come to represent just a third of liquid fuels in road transport.

Figure 14. Shares of road transport technologies in the global stock, 1.5°C Scenario

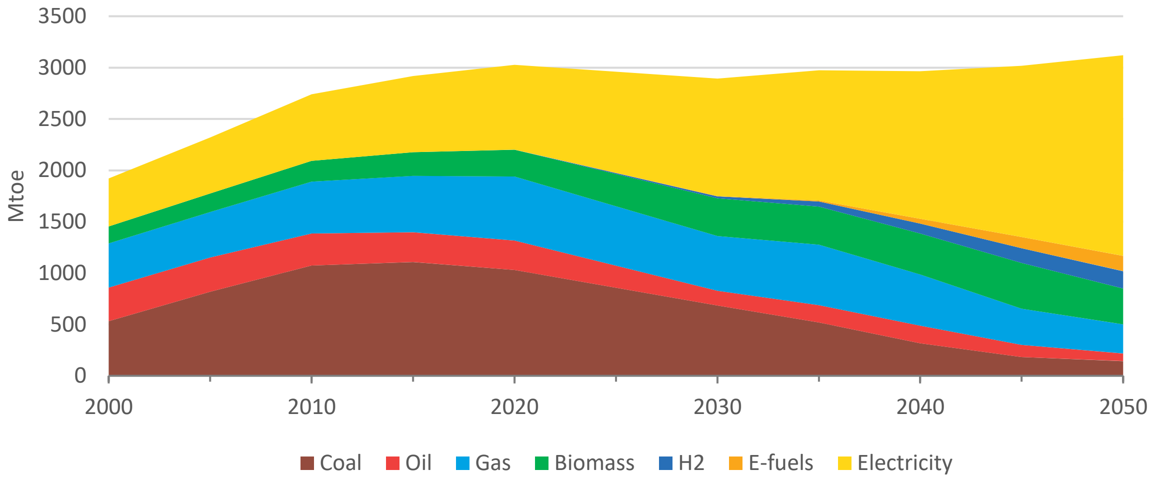


Source: POLES-JRC model

3.4.2 Industry

The 1.5°C Scenario sees the realisation of a significant potential to electrify industrial processes via industrial heat pumps, resistance heaters and electric kilns and furnaces, driven by favourable economics including both fossil fuels and carbon permits increases. Although industry electrification advances significantly in the 1.5°C Scenario, it is far from complete: 54% of total industrial energy demand (including feedstocks) is met by electricity in 2050, with biomass meeting 10%, and oil, mostly as feedstocks, meeting 14%, followed by gas (10%) and hydrogen (5%). All industrial sectors are electrified, with non-energy intensive sectors presenting the higher share (to 80% in 2050), but with the energy-intensive sectors of chemicals, non-metallic minerals and steel also increasing their electrification share significantly (to 44% collectively).

Figure 15. Global industry sector energy demand, by fuel, 1.5°C Scenario



Source: POLES-JRC model

In order for this electrification rate to be achieved, considerable investments need to be made in the optimisation and deployment of industrial production processes accommodating electricity-consuming equipment. The use of electricity leads to decreased reliance on fossil fuels and associated infrastructure, and, accordingly, a decreased reliance on decarbonisation technologies that are either unproven or that carry significant trade-offs at large scale, such as CCS and lignocellulosic biomass.

3.4.3 Buildings

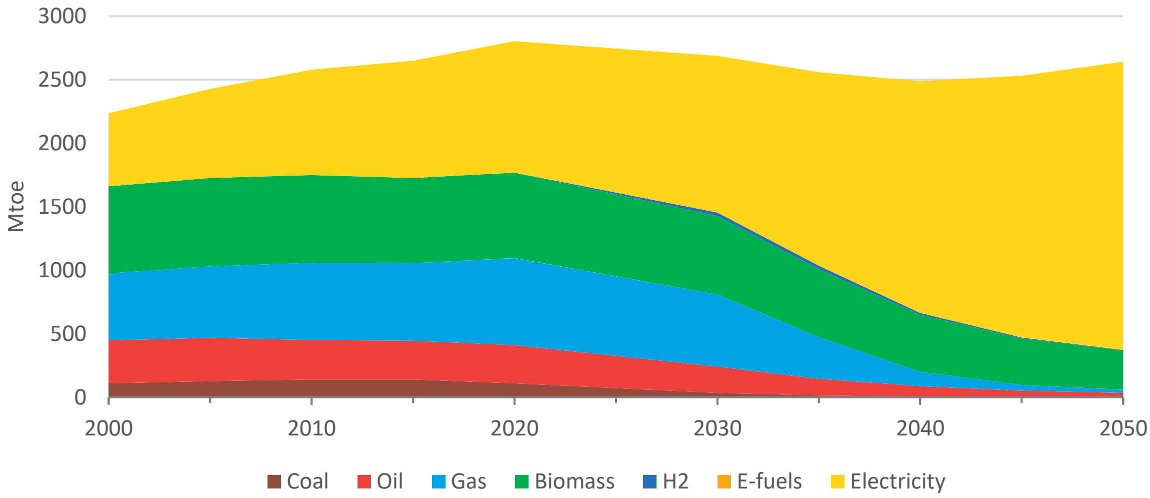
Global energy demand of buildings is projected to grow at a much lower speed than its main drivers (economic growth and demographic dynamics) thanks to substantial improvements on energy efficiency and thermal insulation. The dominant trend for the building sector as it decarbonises in the 1.5°C Scenario is that of energy efficiency and fuel switching from all fuels towards electricity. Electrical heating (mostly with heat pumps) is projected to replace oil and gas boilers in developed countries and countries with cooler climates; electrical heating and electrical cooking is projected to replace traditional biomass and liquefied petroleum gas (LPG) in developing countries. These electrification processes also boost overall energy efficiency gains in the global building sector.

Heat pumps for space heating and cooling in buildings show considerable growth, led by a strong market in the EU (some 20-30% of the global heat pumps market in the 2020-2030 decade), making them a key technology in the electrification of final energy demand and the decarbonisation of the energy system. Air-to-air heat pumps transfer heat from the outside air to air in the interior of buildings or vice-versa, driven by electricity. As heat pumps are adopted, a growing amount of energy for buildings is provided by ambient air[11]; indeed, in the 1.5°C Scenario, ambient air provides about twice the energy compared to the electricity and other energy fuels used in buildings for space heating and cooling globally in 2050.

The growth in buildings energy demand is also driven by space cooling needs, in particular in warmer climates, and increasing air conditioning equipment rates. Electricity demand for space cooling grows by a factor of 2.3 over 2020-2050 globally. This electricity use, with a demand profile well correlated to hours of sunshine, can be coupled well with PV panels installed on residential and commercial rooftops; indeed, in the 1.5°C Scenario, electricity provided by building-integrated PV satisfies some 20% of buildings total electricity demand globally by 2050, compared to an estimated 3% today.

[11] Energy from ambient air is not included in the statistics presented in this report.

Figure 16. Global buildings sector energy demand, by fuel, 1.5°C Scenario



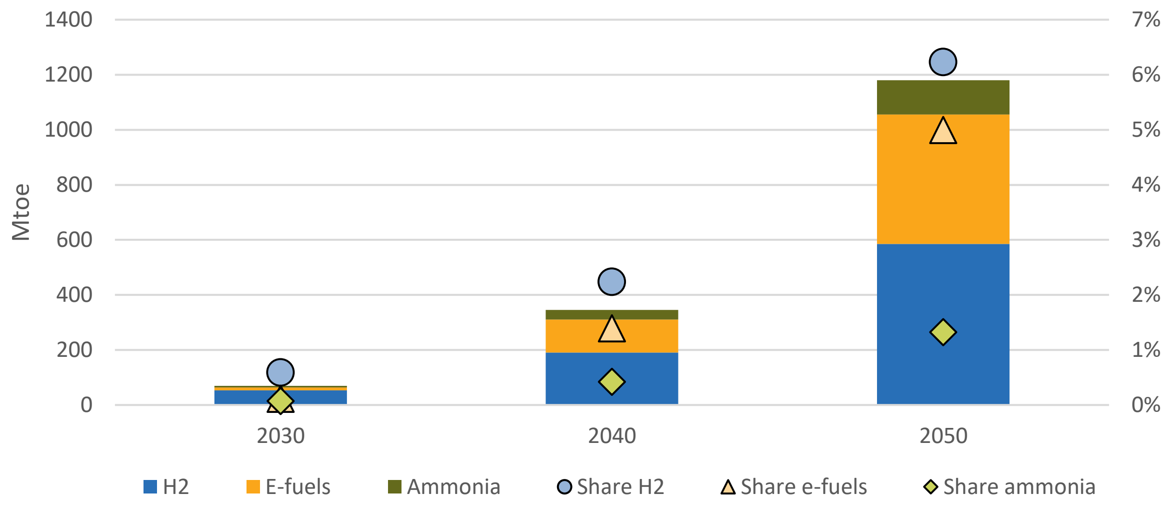
Source: POLES-JRC model

4 Hydrogen and e-fuels demand and supply in a decarbonised world

4.1 Hydrogen and e-fuels demand in the 1.5°C Scenario

As the world decarbonises in the 1.5°C Scenario, there is an increasing number of applications that see the use of hydrogen and e-fuels as the lowest cost option. However, their share in total final energy consumption remains low even in the 1.5°C Scenario, where hydrogen and e-fuels account for 8% and 4% of global demand, respectively.

Figure 17. Global hydrogen and e-fuel demand and shares in final energy consumption, 1.5°C Scenario

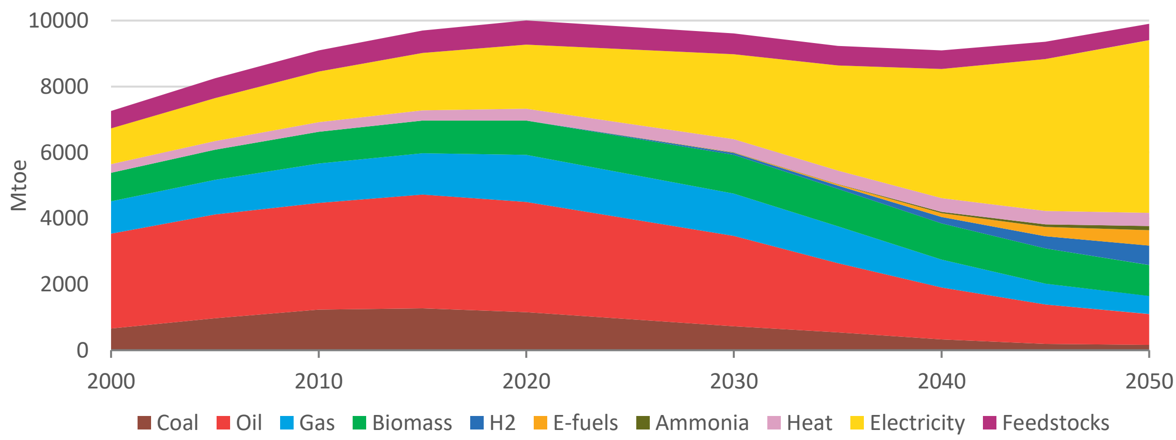


Source: POLES-JRC model

The main fuel in final energy consumption changes from oil to electricity in 2030. Electricity increases its share from 22% today to 60% in 2050 as decarbonisation drives electrification in end-use applications. Comparatively, hydrogen and e-fuels play a minor role. Direct electrification therefore plays a more important role in decarbonisation than the indirect electrification via the use of hydrogen.

However, the contribution of hydrogen and hydrogenated fuels is very important, as they are low-carbon energy carriers in market segments where other energy carriers cannot provide the energy service that is required: steelmaking and heavy transport.

Figure 18. Global final energy consumption, including feedstocks, by fuel, 1.5°C Scenario

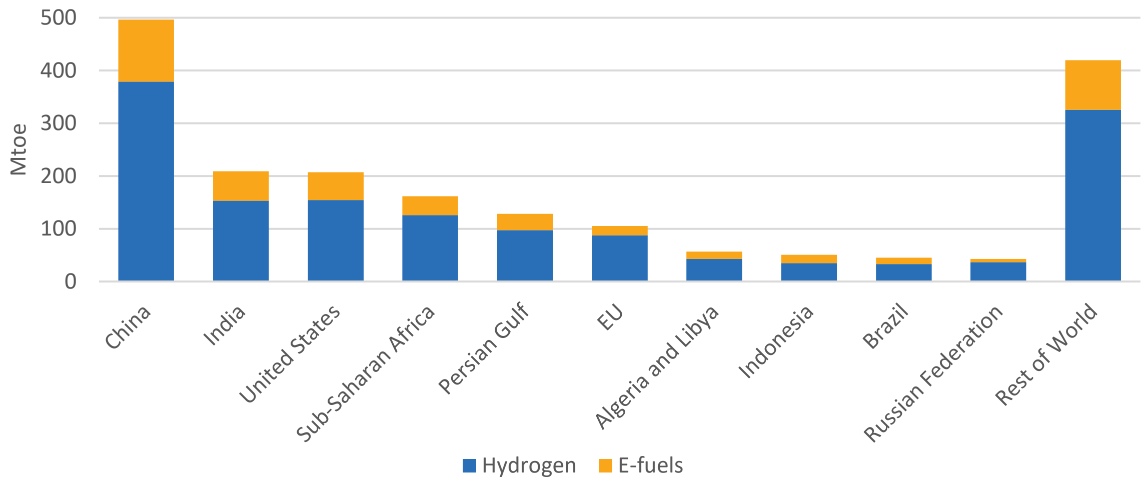


Source: POLES-JRC model

4.1.1 Hydrogen and e-fuels demand by country

Globally, hydrogen and e-fuels demand is dominated by China in the 1.5°C Scenario, accounting for 24% of global demand in 2050. The top 3 countries, China, India and the US, account for 45% of global demand. Other large economies account for a relatively small share of global demand; the EU accounts for 6%, and Brazil, Russia, and Mexico account for 2% each.

Figure 19. Global hydrogen and e-fuel demand in 2050, 1.5°C Scenario



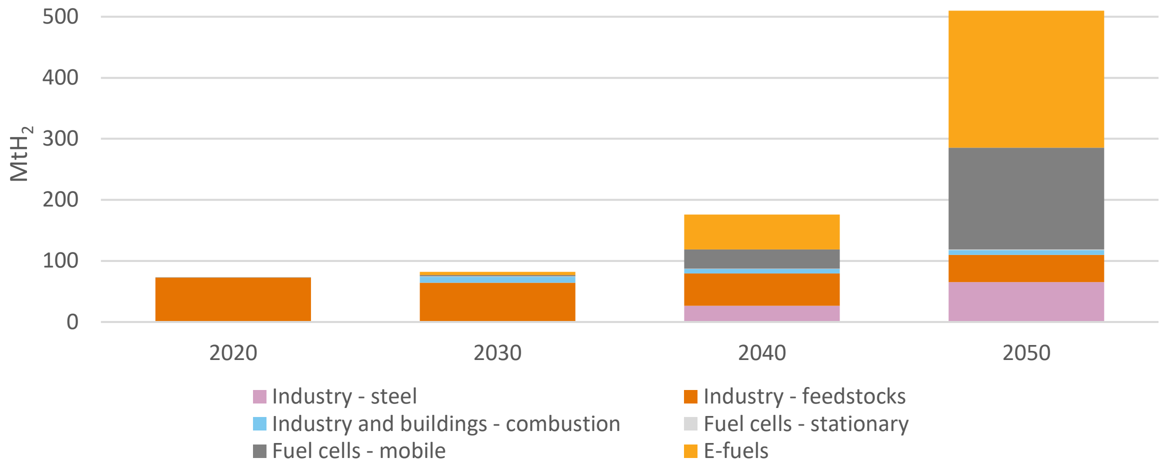
Source: POLES-JRC model

4.1.2 Hydrogen and e-fuels demand in all sectors

Hydrogen is used mostly in transport in 2050 in the 1.5°C Scenario, evenly split across direct use or indirect use (as input to e-fuels production), accounting for 78% of total hydrogen demand. A relatively minor share of total hydrogen demand goes to the iron and steel industry (12%). Decreasing volumes are used as feedstock in other industrial processes[12], primarily in the refinery sector which decreases as overall oil demand also decreases in the 1.5°C Scenario. The use of hydrogen as a combustion fuel in both buildings and industry accounts for 1% of total hydrogen demand, as electrification of these end-uses mostly provides a lower-cost option.

[12] For industry feedstocks, only hydrogen used in its pure form is considered in this report. Hydrogen mixed with other species (such as methanol) are not considered.

Figure 20. Global hydrogen demand, by sector and use, 1.5°C Scenario



Source: POLES-JRC model

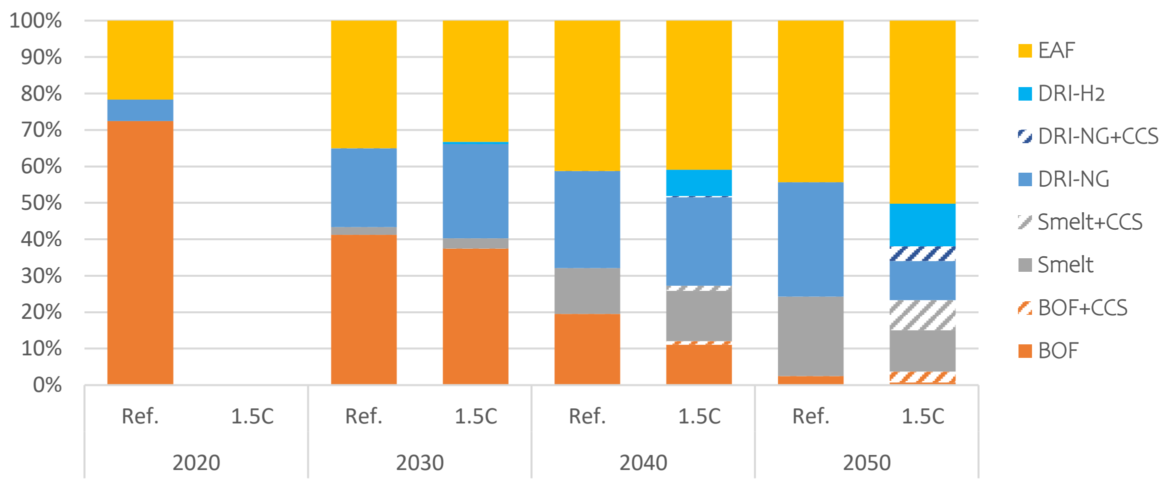
4.1.3 Hydrogen demand in industry

In the 1.5°C Scenario in 2050, the biggest use of hydrogen in industry is as a chemical feedstock in the petrochemical industry (non-energy use), followed by its use as an energy carrier to provide process heat, then by its use as a reducing agent in steelmaking.

As of 2018 (IEA, 2018), as a chemical feedstock, hydrogen in its pure form was mainly used as an intermediate product in ammonia production and in oil refineries (to remove sulphur from crude and for hydrocracking); in the 1.5°C Scenario both of these uses are set to stabilise or decrease with a more targeted use of nitrogen fertilisers in agriculture and with the move away from oil in all modes of transport due to electrification and alternative liquids (direct energy use of hydrogen in fuel cell vehicles in road transport does, however, increase).

Hydrogen demand in the iron and steel sector is only a small share of overall demand in a 1.5°C Scenario as the switch to steelmaking processes that use hydrogen is one option among several to decarbonise the iron and steel sector. The 1.5°C Scenario sees an increase in global demand for steel products, from 1.89 Gt in 2020 to 3.57 Gt in 2050. On the supply side, the 1.5°C Scenario sees a diversification of steelmaking technologies, with initially an increased role for electric arc furnace production with the increase availability of scrap for recycled steel. Beyond 2030, direct smelting technology starts taking a larger role; it is still a nascent technology today. CCS does not play a large role until after 2040, subject to acceptability and infrastructure limitations that also apply to CCS in other sectors. Direct reduction using fossil gas also gains market share, as a proven technology that has lower emissions than the currently predominant basic oxygen furnace; direct reduction using hydrogen is comparatively costlier and only enters the market in a significant way beyond 2035 in the 1.5°C Scenario. Direct reduction using hydrogen is responsible for 12% of steel tons produced globally by 2050 in the 1.5°C Scenario; while non-negligible, it is only the third largest steelmaking option, after the electric arc furnace and the sum of the CCS options.

Figure 21. Global steel production, by technology, Reference and 1.5°C Scenarios



Note: BOF: basic oxygen furnace; Smelt: smelting reduction; DRI: direct reduction using natural gas (DRI-NG) or hydrogen (DRI-H2) followed by electric arc furnace; CCS: carbon capture and storage; EAF: electric arc furnace.

Source: POLES-JRC model

Hydrogen is also used as an energy vector in all industrial sectors, blended with fossil gas, based on a cost competition. Hydrogen content in that gas mix reaches an average of 9% globally in 2050 in the 1.5°C Scenario, close to the limit imposed by distribution pipelines embrittlement (12% in energy terms). In addition, in approximately the same quantities as hydrogen to 2050, gaseous e-fuels are used in industry as a direct substitute to fossil methane; by 2050, about half of methane consumed in industry is e-fuels, globally.

4.1.4 Hydrogen and e-fuels demand in transport

Hydrogen and e-fuels are used in the road transport, aviation and maritime sectors. In road transport, as seen in Figure 14, HFCVs come to represent 10% and 28% of the cars and heavy duty vehicles (HDVs) fleet by 2050 in the 1.5°C Scenario, respectively. Hydrogen is more competitive than electricity in some heavy vehicles segments due to its higher energy density. Liquid e-fuels replace about 40% of the oil consumption for cars and HDVs. In addition, gaseous e-fuels reach a share of more than 60% of gas consumption in road transport.

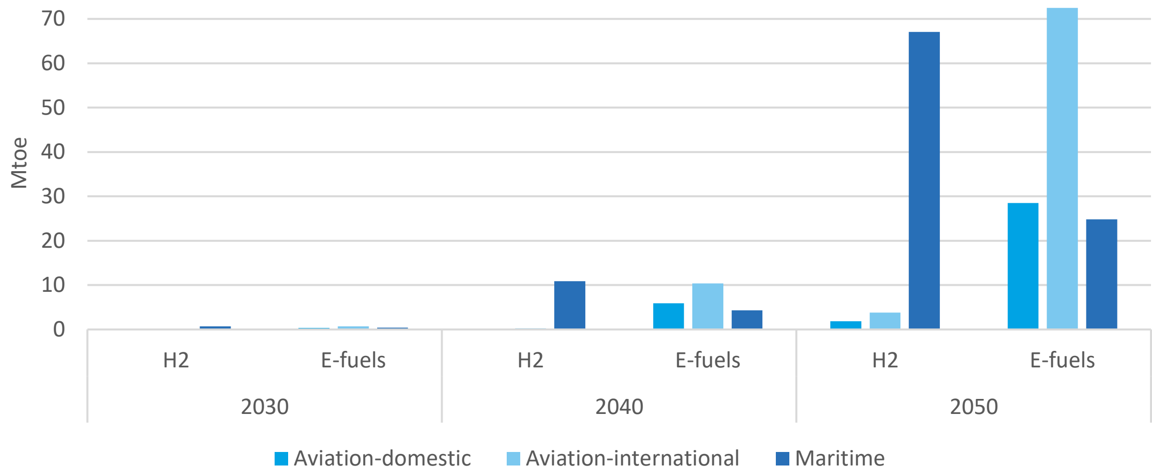
In the long-haul trucking, the long distances result in large battery requirements, which are heavy and costly; hydrogen storage and the fuel cell stack are comparatively more economically attractive. However, there are some shorter distance segments in heavy vehicles transport, and there have been recent developments from large truck manufacturers that point towards the large-scale adoption of EVs for heavy vehicles as well.[13]

One of the major emission reduction levers in the aviation sector is drop-in e-fuels, where the benefits of compatibility with existing engines and infrastructure outweighs their higher cost, resulting in strong demand for e-fuels in aviation. In the maritime sector, hydrogen-based ammonia (classified as an e-fuel in our nomenclature) as a fuel becomes a major decarbonisation route towards 2050. However, there are concerns over the full lifecycle impact of increased ammonia use in shipping on emissions (Wolfram et al, 2022).

In 2030 in the 1.5°C Scenario, hydrogen and e-fuels hardly play a role, their share of total demand being in the fractions of a percent, as decarbonisation in the next decade is achieved via energy efficiency rather than fuel switching. As the decarbonisation effort increases, the shares increase towards 2050, reaching 1.5% for hydrogen and 30% for e-fuels in aviation and 18.5% and 6.8% in maritime.

[13] https://www.scania.com/group/en/home/newsroom/press-releases/press-release-detail-page.html/4286998-scania-introduces-electric-trucks-for-regional-long-haul; https://insideevs.com/news/610390/volvo-trucks-starts-production-heavy-electric/

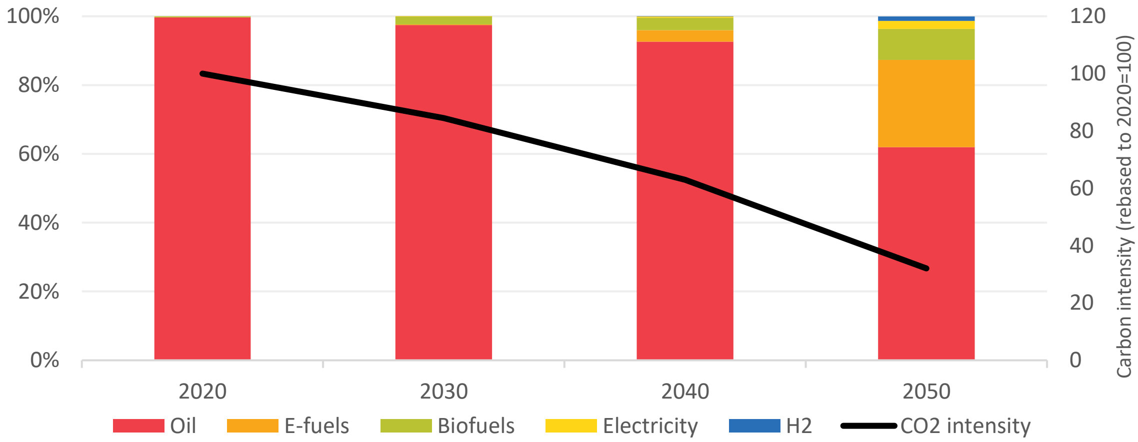
Figure 22. Global hydrogen and liquid e-fuel demand in aviation and maritime, 1.5°C Scenario



Source: POLES-JRC model

International aviation sees strong demand growth from today to 2030, with continued emissions growth due to most demand being met by oil through to 2030. From 2030-2040 the impact of increased efficiency slows overall growth. In the 2040-2050 decade, reduced costs of alternatives see them take a larger share and reduce emissions, led by e-fuels. Direct use of hydrogen in international aviation remains limited. The emissions intensity, measured in emissions per pkm or per tkm, drops by 68% between 2020[14] and 2050 in the 1.5°C Scenario.

Figure 23.Global international aviation consumption, by fuel (left axis) and emission intensity (right axis), 1.5°C Scenario

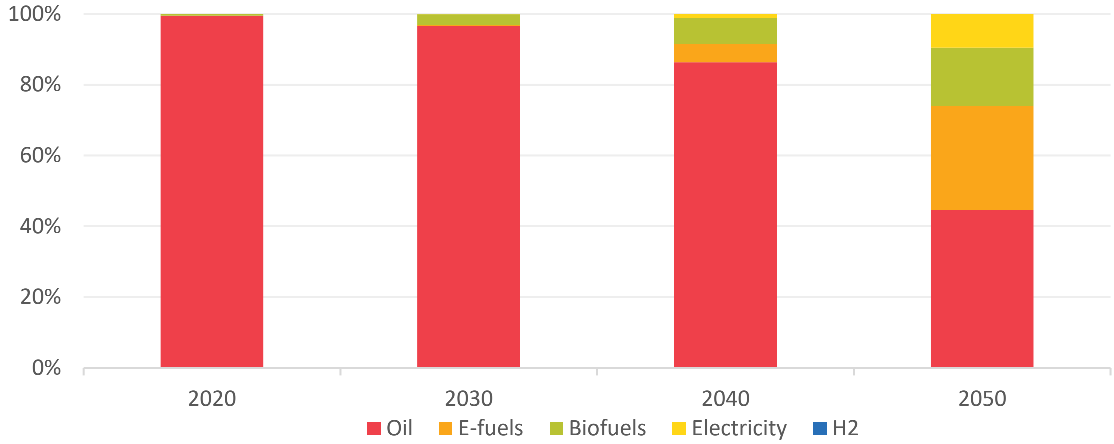


Source: POLES-JRC model

Domestic aviation, which accounted for 41% of global aviation demand in 2019, sees similar growth patterns to that of international aviation in the 1.5°C Scenario. The main decarbonisation levers are higher efficiency and fuel switching, mostly to e-fuels and biofuels. Electric planes play a smaller role overall, and here the distances impact the technology choice, where the shorter distances of domestic travel see electric planes take a larger share; whereas hydrogen planes do not enter domestic aviation markets.

[14] Aviation demand in 2020 was impacted by altered travel patterns due to the Covid restrictions, however when the reductions from 2020 to 2050 are measured in emissions intensity the comparison remains appropriate.

Figure 24. Global domestic aviation consumption, by fuel, 1.5°C Scenario

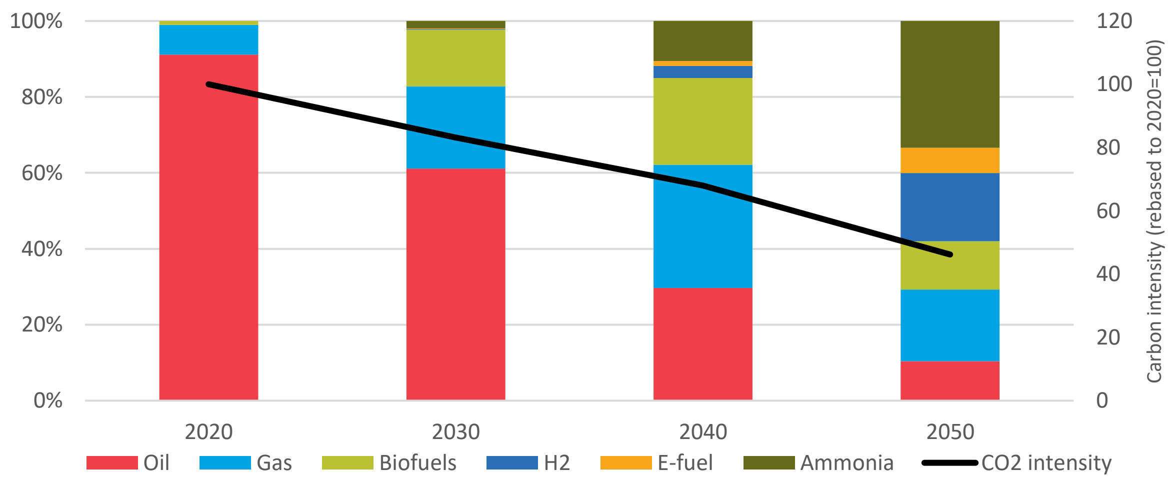


Source: POLES-JRC model

The global aviation fleet remains heavily dominated by conventional engines in 2050 in the 1.5°C Scenario, accounting for 94% of the global fleet. Liquid fuels (oil products, biofuels and e-fuels) remain the most suitable energy carriers.

Global international maritime demand sees more easily achievable decarbonisation options than aviation, as ammonia, hydrogen and liquid e-fuels all take large shares compared to oil products by 2050 in the 1.5°C Scenario. Ammonia gains the highest market share due to lower production costs than liquid e-fuels and lower investment costs than hydrogen. This reduces oil and fossil gas demand to account for 29% of the energy mix by 2050. Fossil gas is used as an emission reduction option over the next two decades but sees its share decrease in the longer term in the strong push to decarbonisation.

Figure 25. Global maritime consumption, by fuel (left axis), and emission intensity (right axis), 1.5°C Scenario



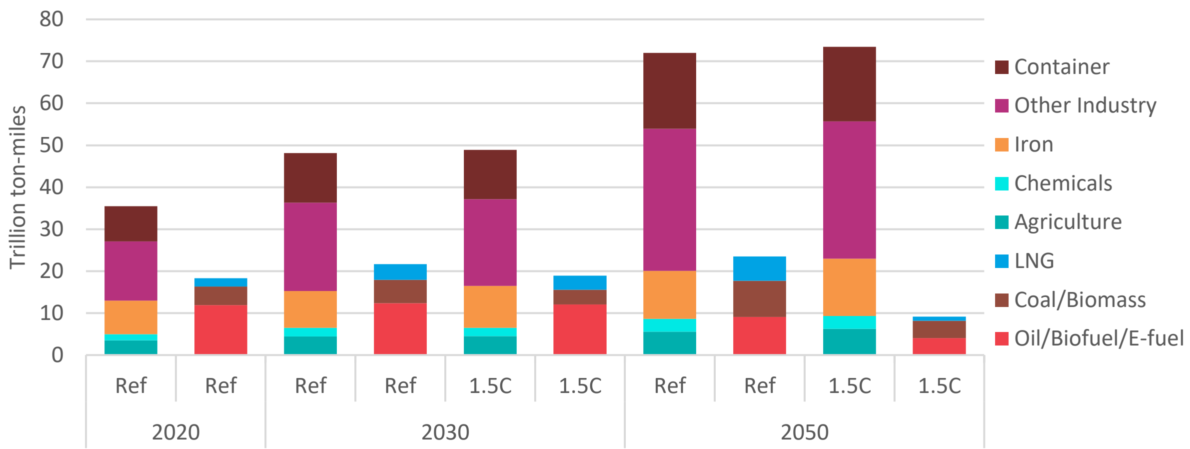
Source: POLES-JRC model

The global international shipping fleet gradually shifts away from oil-powered engines as it decarbonises in the 1.5°C Scenario, as new technologies enter the fleet. Until 2030 the share of ships being able to use gas as fuel increases, while at the same time ammonia-powered engines enter the market, followed by an increasing share of hydrogen-powered engines. As a result of changes in the fuel mix, GHG emissions of international maritime transport decrease by more than 54% compared to 2008, slightly exceeding the IMO target.

The decarbonisation effort in the 1.5°C Scenario leads to changes in the mix of shipped goods, mostly led by the reduction in the trade of fuels used for energy, most of which are fossil fuels. Energy fuels accounted 34% of total maritime transport cargo in 2020; this is reduced to 11% in the 1.5°C Scenario.

While the trade of non-energy commodities increases over time and does not differ between scenarios, changes of trade patterns emerge for energy commodities. Overall trade of energy commodities decreases in the 1.5°C Scenario, led by the reduction in the trade of fossil fuels, which is only compensated to a small extent by the increase of biomass, biofuels and e-fuels. Altogether, energy fuels accounted 34% of total maritime transport cargo in 2020; this is reduced to 11% in the 1.5°C Scenario.

Figure 26. Maritime transport demand, by non-energy and energy commodity, Reference and 1.5°C Scenarios



Source: POLES-JRC model

4.2 Hydrogen and e-fuels supply in the 1.5°C Scenario

4.2.1 Hydrogen supply

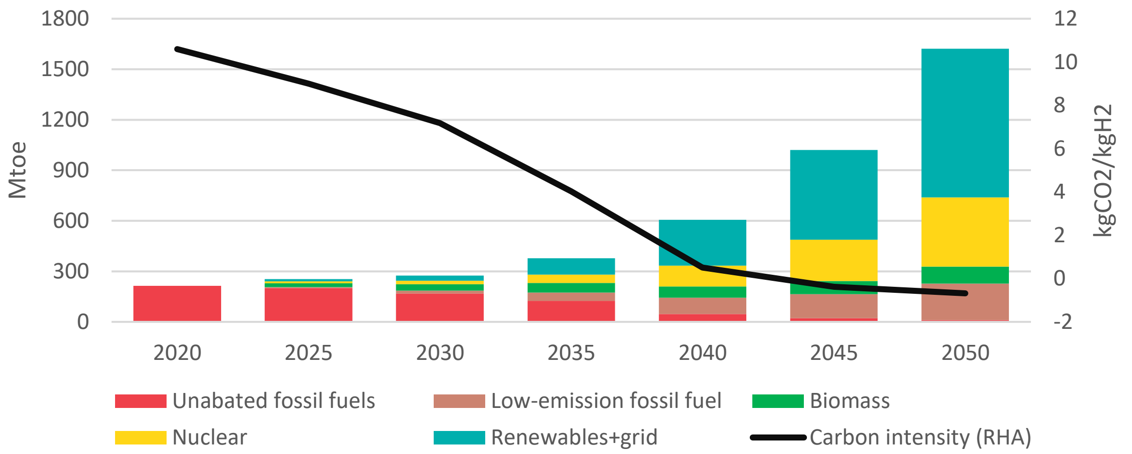
Many hydrogen supply pathways emerge in a decarbonised 1.5°C Scenario, depending on domestic factors, renewable resource availability, CCS storage availability, and existing industries and infrastructure.

Production pathways are grouped into unabated fossil fuels (steam methane reforming, coal gasification), low-emission fossil fuel (the former with CCS, as well as gas pyrolysis), biomass (gasification and pyrolysis), nuclear (low and high temperature electrolysis) and renewables and grid (electrolysis with dedicated wind and solar capacities, and use of grid electricity during hours of oversupply).

Green hydrogen (electrolysis with renewables) reaches 54% of total global hydrogen production in 2050. Due to limited CCS deployment and the fact that green hydrogen is still relatively expensive to produce in the mid-term, nuclear-based hydrogen production plays an important role, reaching 25% in 2050. Hydrogen production using electricity from dedicated nuclear power plants offers a pathway to domestic low-emission hydrogen production for countries with relatively poorer renewables and CCS infrastructure resources. Blue hydrogen made from fossil fuels fitted with CCS accounts for 13% in 2050.

Hydrogen production becomes carbon-negative in 2050 as the emissions from the remaining 1% of production that comes from unabated fossil fuel production are offset by the emissions of the 4% of global production coming from BECCS, accounted as negative emissions.

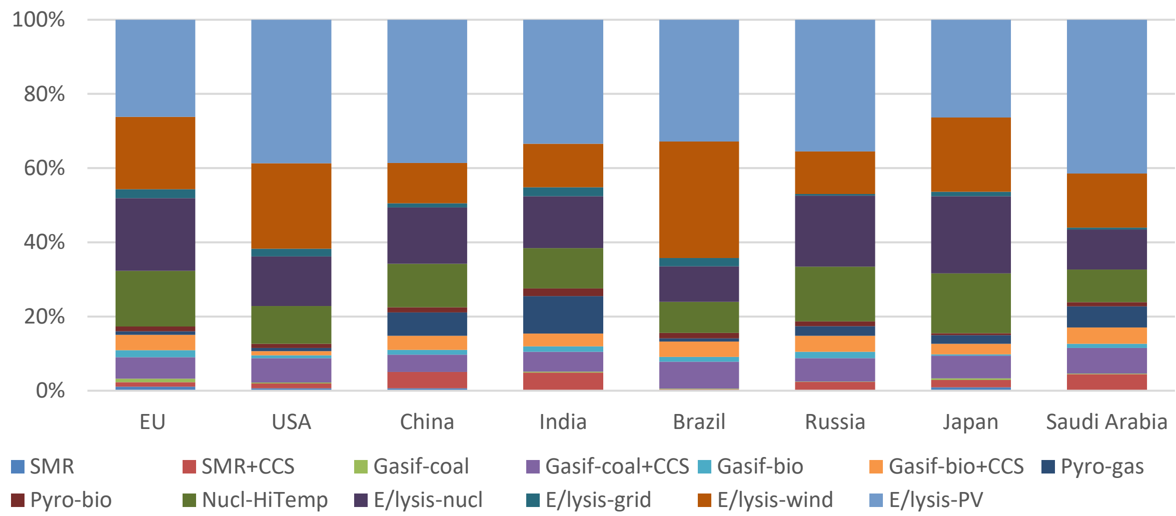
Figure 27. Global hydrogen production, by technology, 1.5°C Scenario



Source: POLES-JRC model

Regional differences play a large role in the hydrogen production mix across countries. Most notably, the share coming from renewables in a country like Brazil is significantly larger than in relatively renewables-constrained Japan, where a larger role is taken by nuclear.

Figure 28. Shares of hydrogen production in selected countries in 2050, by technology, 1.5°C Scenario



Source: POLES-JRC model

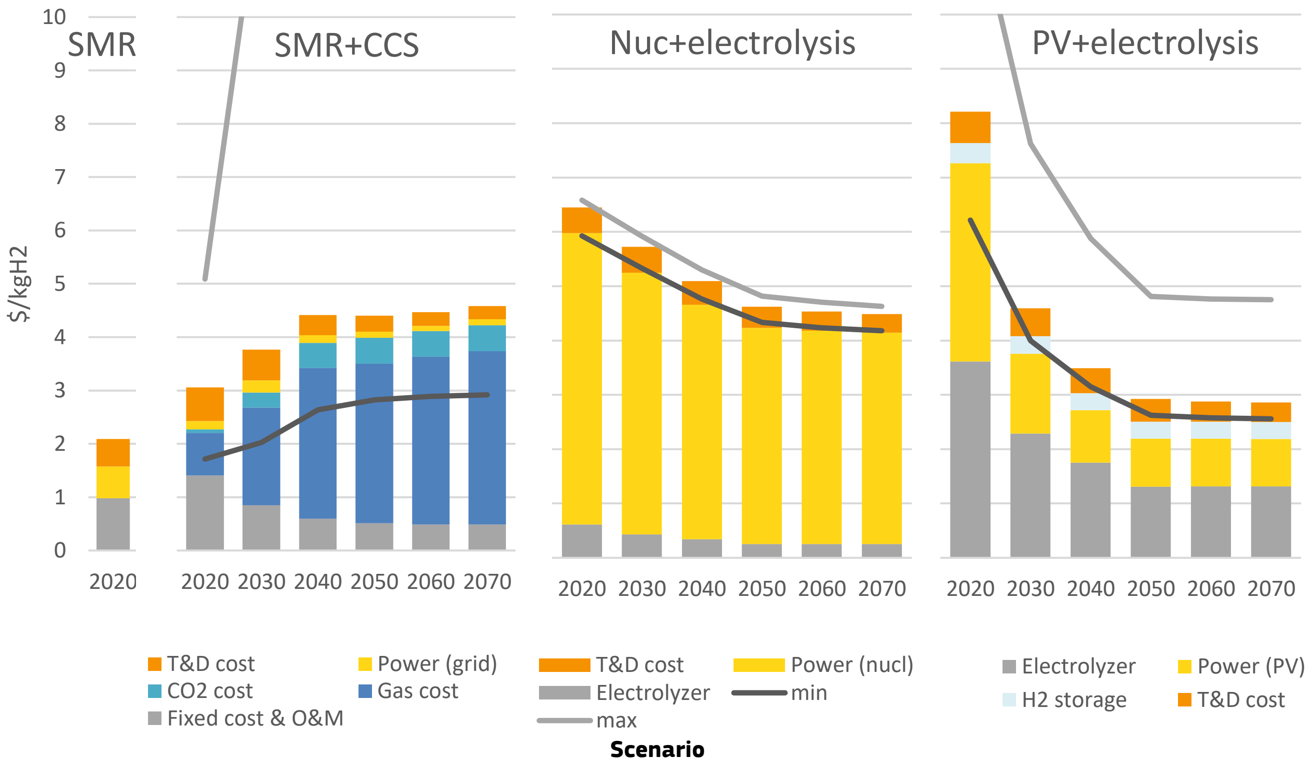
The hydrogen production mix is a result of a cost-based competition between many options. As of 2020, the dominant hydrogen production technology (taking into account pure hydrogen produced as an industrial feedstock) is steam methane reforming (SMR), followed by coal gasification in select markets such as China; taking into account the emissions in the production step, hydrogen would be a carbon-intensive fuel.

In the 1.5°C Scenario, the fossil gas price increase and climate policy in the form of a price on carbon emissions results in a loss of competitiveness of the fossil fuel-based production pathways. Retrofitting CCS on existing production capacities with steam methane reforming (SMR+CCS) is an option for reducing emissions, albeit with an efficiency penalty; however, not 100% of the emissions can be captured, resulting in an increasing production cost of blue hydrogen as well. In addition, apart from the cost dimension, CCS technologies are also subject to additional availability constraints related to the construction of the necessary CO_2 transport and storage infrastructure; this limits the deployment of SMR+CCS in the first decades of the projection. As a consequence, comparatively costlier technologies such as low- and high-temperature electrolysis using nuclear power gain market share. Electrolysis using grid electricity at times of intermittent renewables over-supply is projected to play a limited role, given the large amounts of hydrogen that need to be produced, capacities of renewables fully dedicated to hydrogen production need to be installed.

While currently among the costlier pathways, hydrogen production with low-temperature electrolysis using stand-alone wind or solar PV power is projected to become the dominant hydrogen source globally by mid-century. These "green hydrogen" technologies benefit from cost decreases in the electrolyser as well as in the wind and solar electricity that powers the electrolyser. Electrolyser costs decrease from an estimated 1130 $/kW in 2020 to 480 $/kW in 2050; and utility-scale PV from 620 $/kW$_{el}$ in 2020 to 300 $/kW$_{el}$ in 2050. The green hydrogen production costs then vary across countries depending on the renewables endowment of each country (wind operating hours, full solar irradiation hours); in addition, a hydrogen storage cost is added to reflect the need to accommodate fluctuating production from intermittent renewable technologies, as compared to SMR which can operate continuously.

As a result of this technological learning and thanks to the implementation of the climate policy, green hydrogen progressively becomes cost-competitive in an increasing number of markets and in the longer term (2030 and beyond). This technological learning and electrolyser installations require significant policy support for RD&D investments and market deployment.

Figure 29. Hydrogen production costs for selected technologies, global mean, minimum and maximum, 1.5°C



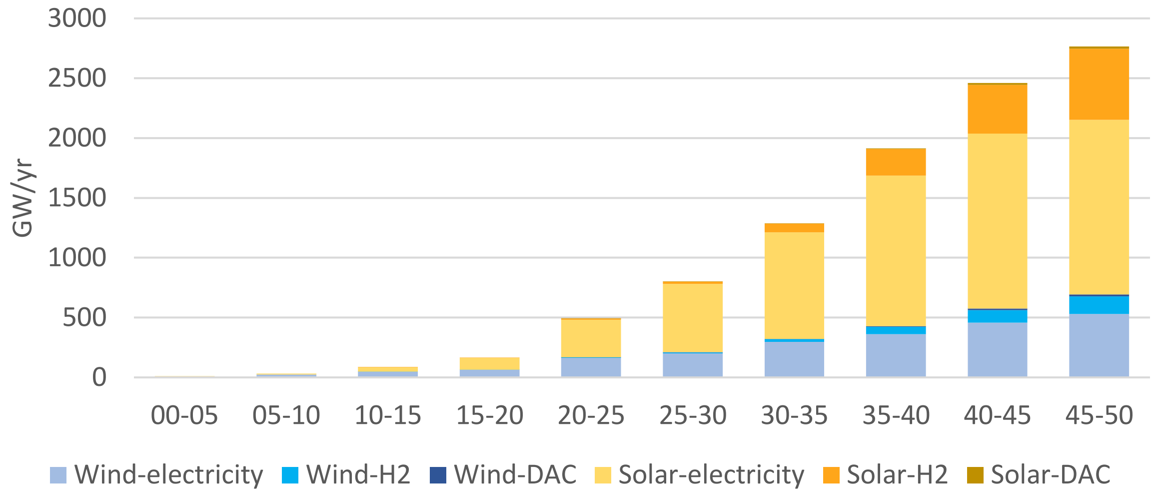
Source: POLES-JRC model

4.2.2 Hydrogen supply vs capacity

As demand for hydrogen and hydrogen-based e-fuels increases and hydrogen production becomes lower-carbon, an increasingly large share of low-emissions electricity production goes towards hydrogen production. 38% of global nuclear capacity is used to produce hydrogen in 2050; that figure is 18% for solar and 13% for wind. In addition, 2% and 1% of wind and solar capacities, respectively, are dedicated to direct air capture of CO_2 (three quarters of which is used to produce e-fuels, leaving a quarter that is actually stored underground). The rest of nuclear, wind and solar capacities are used to produce electricity for final demand sectors.

This considerable growth of wind and solar capacities will present several challenges, among which administrative (e.g. the awarding of land permits), and supply chain (manufacturing and transport of wind turbines and solar panels, their connection to the grid where relevant) are the most challenging. The global annual installation rate of wind and solar, all uses combined, is projected to increase significantly compared to recent history, from around 200 GW/yr over 2015-2020 to more than ten times as much by 2040. On top of installations for electricity generation, which is challenging in and of themselves, by 2050, a quarter of new wind and solar installations are dedicated to producing hydrogen and capturing CO_2 from the air in the 1.5°C Scenario.

Figure 30. Share of wind and solar accessible potential used in 2050*, 1.5°C Scenario

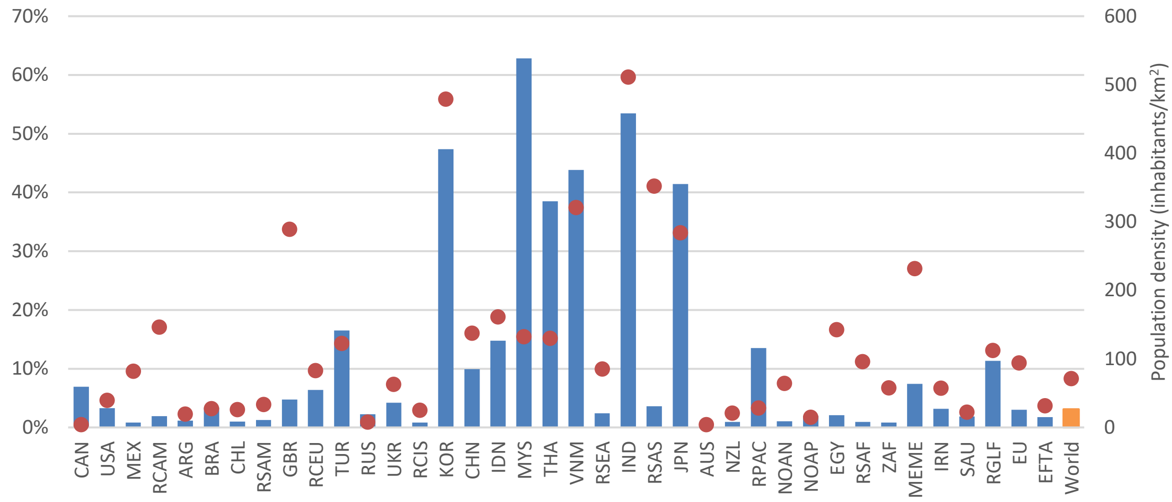


Source: POLES-JRC model

However, while an increasing share of electricity production capacity is used for producing hydrogen and capturing CO_2 in direct air capture, the technical and economic potential for renewable energy far exceeds the required amounts in 2050 in the 1.5°C Scenario. After excluding areas that are used for other purposes[15] the world uses only 3.1% of this accessible potential in 2050, and no individual country or region individually modelled reaches its potential limits of renewable production throughout the projection period.

[15] Exclusion factors applied to account for great distances from population centres and electric grids; for densely populated areas; for unsuitable surfaces such as forests. The POLES-JRC model represents surfaces for wind and solar by wind classes and irradiation, allowing a "renewable resource cost curve" to inform RE costs and construction.

Figure 31. Share of accessible renewable potential used in 2050, 1.5°C Scenario



Note: includes solar PV, onshore wind and offshore wind, after exclusions.

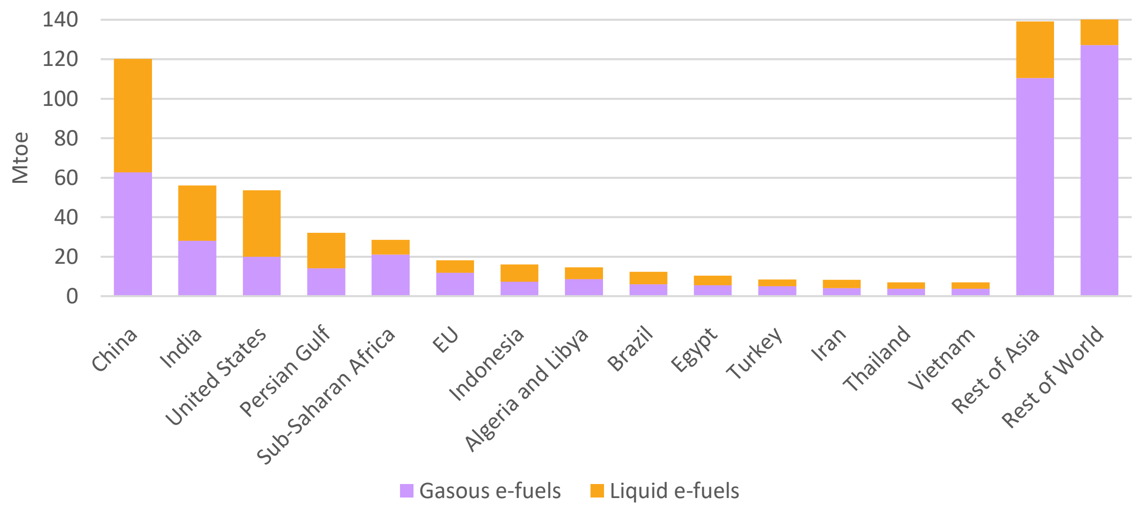
Source: POLES-JRC model

4.2.3 E-fuels supply

China is the main e-fuels producer in 2050 in the 1.5°C Scenario, followed by India and the United States, which together account for almost half of global production.

53% of global e-fuel production is gaseous e-fuels, produced from hydrogen via the methanation process. Gaseous e-fuels are blended with fossil gas and other sources of methane (biomethane, methane from waste, captured methane from oil and gas wells that would have otherwise been vented or flared, and captured methane from coal mines). Gaseous e-fuels are used as a blended gas and are only used for domestic consumption.

Figure 32. E-fuels production in 2050, 1.5°C Scenario

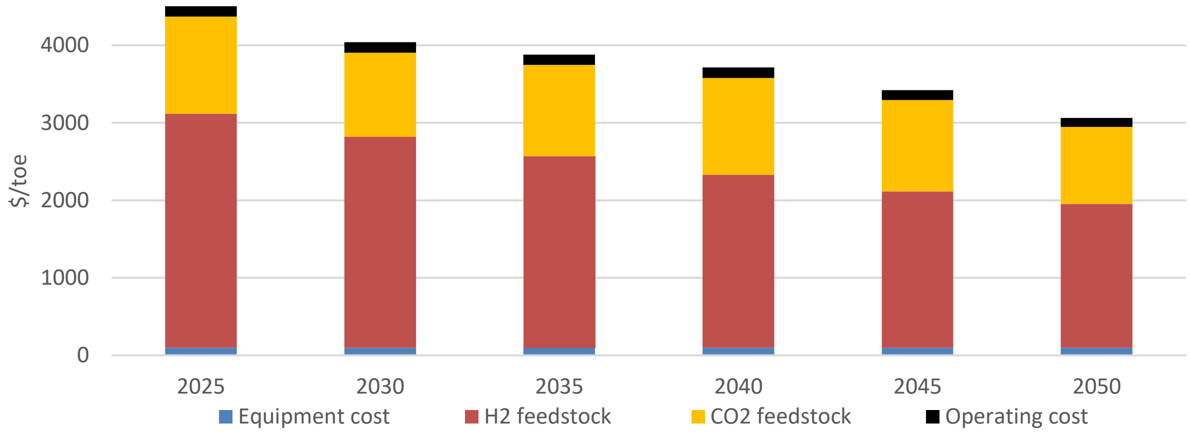


Source: POLES-JRC model

Liquid e-fuels are used only in the transport sector as drop-in fuels. Liquid e-fuels are produced from hydrogen via the fischer-tropsch process. The modelling framework allows for the trade of liquid-efuels between regions. The largest costs of liquid e-fuels production are the feedstocks: hydrogen and CO_2. Hydrogen costs decline through the projection period as outlines in Section 4.2.1. Carbon-dioxide costs also decrease through the projection period. The CO_2 used in liquid-efuels comes exclusively from direct air capture powered by renewables; as renewables costs decrease, the cost to capture the CO_2 decreases as well.

Throughout the time horizon, approximately two-thirds of liquid e-fuel costs are hydrogen and one-third CO_2.

Figure 33. Global average liquid e-fuel production cost breakdown, 2025-2050, 1.5°C Scenario



Source: POLES-JRC model

5 Energy trade in a decarbonised world

Energy resources are unevenly distributed across the world, some regions dispose of large, low-cost fossil fuel reserves, while others have limited or no domestic supply. As a result, international trade of fossil fuels plays an important role in the global economy. As the distribution of renewable energy sources differs to that of fossil fuels, a shift towards net zero emissions energy systems has the potential to reshape the geopolitical energy landscape.

In addition to the direct trade of fuels, the global economy relies on significant international trade of goods and services. Over the past decades, global trade in goods has grown about 50% faster than GDP (Bekkers et al, 2020) as part of the overall trend of globalisation. The production of goods and services typically uses energy as an input in the production process. As such, a country can export energy directly, or use the energy as an input to produce raw materials, intermediate and final products, and then export these products. In this case, the energy used in production of the goods is exported indirectly, as it is embodied in the export of the product.

This section provides an in-depth presentation of the current state of direct and embodied energy trade, and a perspective of how energy trade is projected to develop in a decarbonised world. Section 5.1 presents an overview of overall direct and embodied energy trade trends. Section 5.2 explores the direct trade of energy by fuel, while section 5.3 presents an overview of embodied energy trade.

5.1 Overall trends

5.1.1 Historical perspective

Figure 34 presents a snapshot of direct energy trade in 2015, illustrating traded energy carriers, as well as importing and exporting regions. Figure 35 presents a detailed snapshot of embodied energy trade for the same year, illustrating embodied fuels in traded products, outlining which products embodying energy are traded, and presenting the corresponding large exporting and importing regions.[16]

As for 2015, direct energy trade across world regions represented close to 4600 Mtoe. Embodied energy trade represented close to 3650 Mtoe, putting embodied and direct energy trade in the same order of magnitude, and representing roughly 35-30% of global primary energy supply in the same year, respectively.[17]

Fossil fuels represent the totality of global direct energy trade in the JRC-GEM-E3 modelling framework in 2015. Oil represents close to 60% of total directly traded energy in 2015, followed by gas (25%) and coal (15%). Fossil fuels also represent approximately 85% of global embodied energy trade, with oil and coal having a share close to 30%, and gas 25%, of total embodied energy trade. Energy embodied in chemical feedstocks and other goods utilising fossil fuels as non-energy uses, e.g. oil and gas use for plastics or ammonia and fertiliser production, represent close to 10%. Electricity embodied in goods and services other than that produced by coal, oil and gas-fired power plants, represents 5%.

Coal embodied in trade is mainly embodied in manufactured industries (50%) and energy intensive industries (30%). Oil embodied in trade is embodied in transport services (37%)[18], manufacturing industries (34%) and energy intensive industries (14%). Gas embodied in trade is embodied in manufacturing industries (36%), energy intensive industries (26%) and in fossil fuel production (20%). Electricity is largely embodied in traded industrial goods, both in energy intensive (30%) and non-energy intensive, manufacturing industries (45%).

Products of manufacturing and energy-intensive industries, represent the bulk (66%) of embodied energy in trade. Transport services (16%) are also important, while the energy embodied in fossil fuels (11%) reflects the energy-intensive extraction, processing and transportation of fossil energy carriers. Agricultural goods, services and electricity combined represent the smallest share, comprising only 7% of total embodied energy.

Regions also differ greatly with regard to their direct and embodied trade of energy. The Middle East is by far the largest exporter of fossil fuels, followed by Russia, African countries, as well as North and South American countries. Highly developed regions lacking a sizable domestic production of fossil fuels to meet their energy demand; Europe as well as Japan and South Korea combined, are the largest importers of fossil fuels. China

[16] Excluding intra-regional trade.

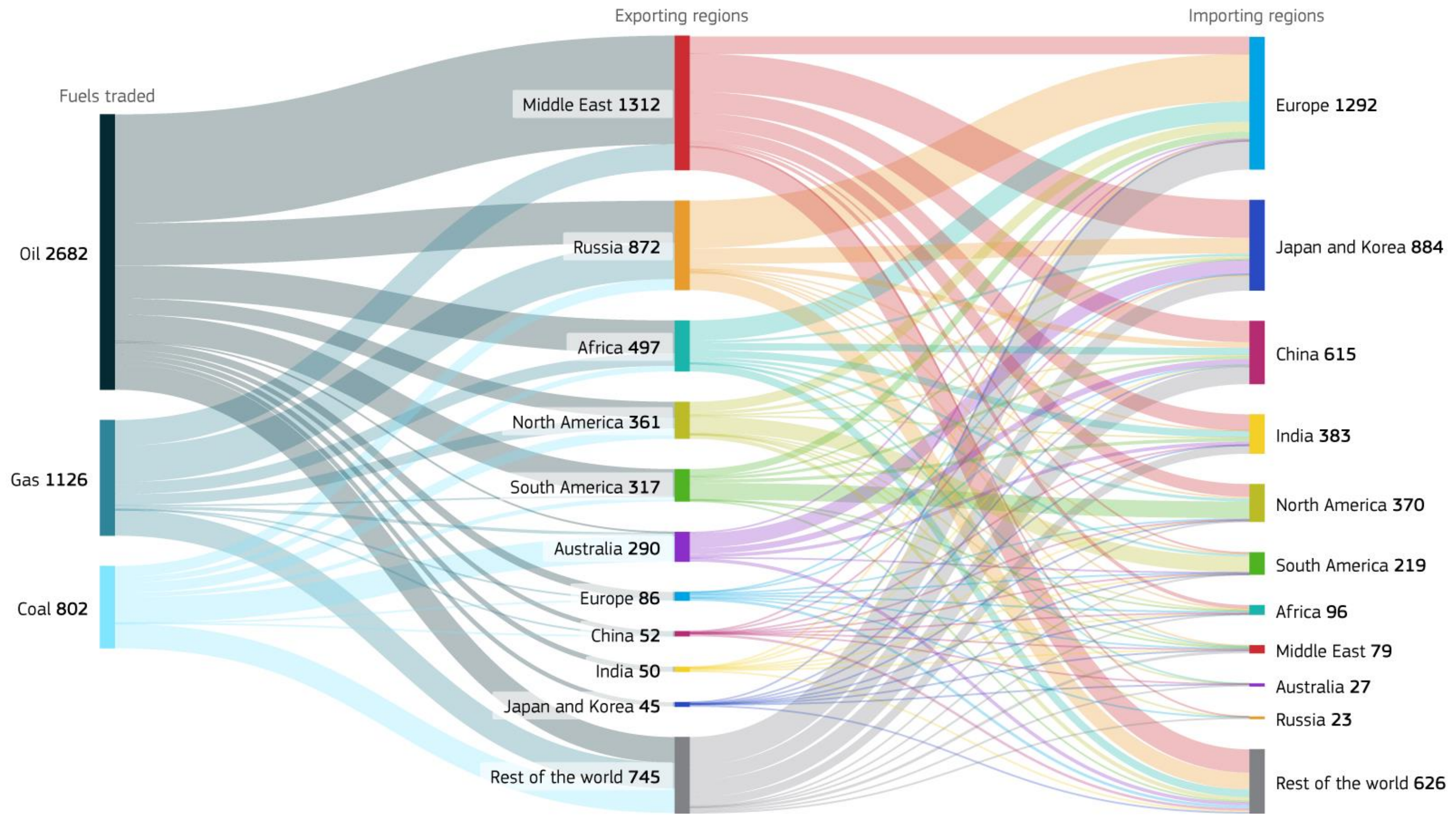
[17] All figures refer to energy units. Embodied emissions may be counted more than once, if a product is crossing international borders more than once during its production process.

[18] Transport includes international transport services which are accounted as internationally traded.

and India, as most populous countries globally, and as strongly expanding economies, also rank across the largest importers of fossil fuels.

Embodied energy is determined by the trade of goods and services across regions. Consequently, embodied energy flows are determined by trade patterns, with China ranking as largest exporter of embodied energy, followed by Europe, North America, Japan and South Korea (Figure 35). Notably, exporters of fossil fuels are also large exporters of embodied energy. This includes energy embodied in fossil fuel energy carriers, reflecting the energy required to extract and transport oil, coal and gas, as opposed to the direct energy content of these energy carriers. However, these countries also have embodied energy in industry exports – economies with cheap fossil energy may have specialized in energy intensive production, and often the energy intensity of any given sector is higher than the world average as incentives for efficient energy use are low.

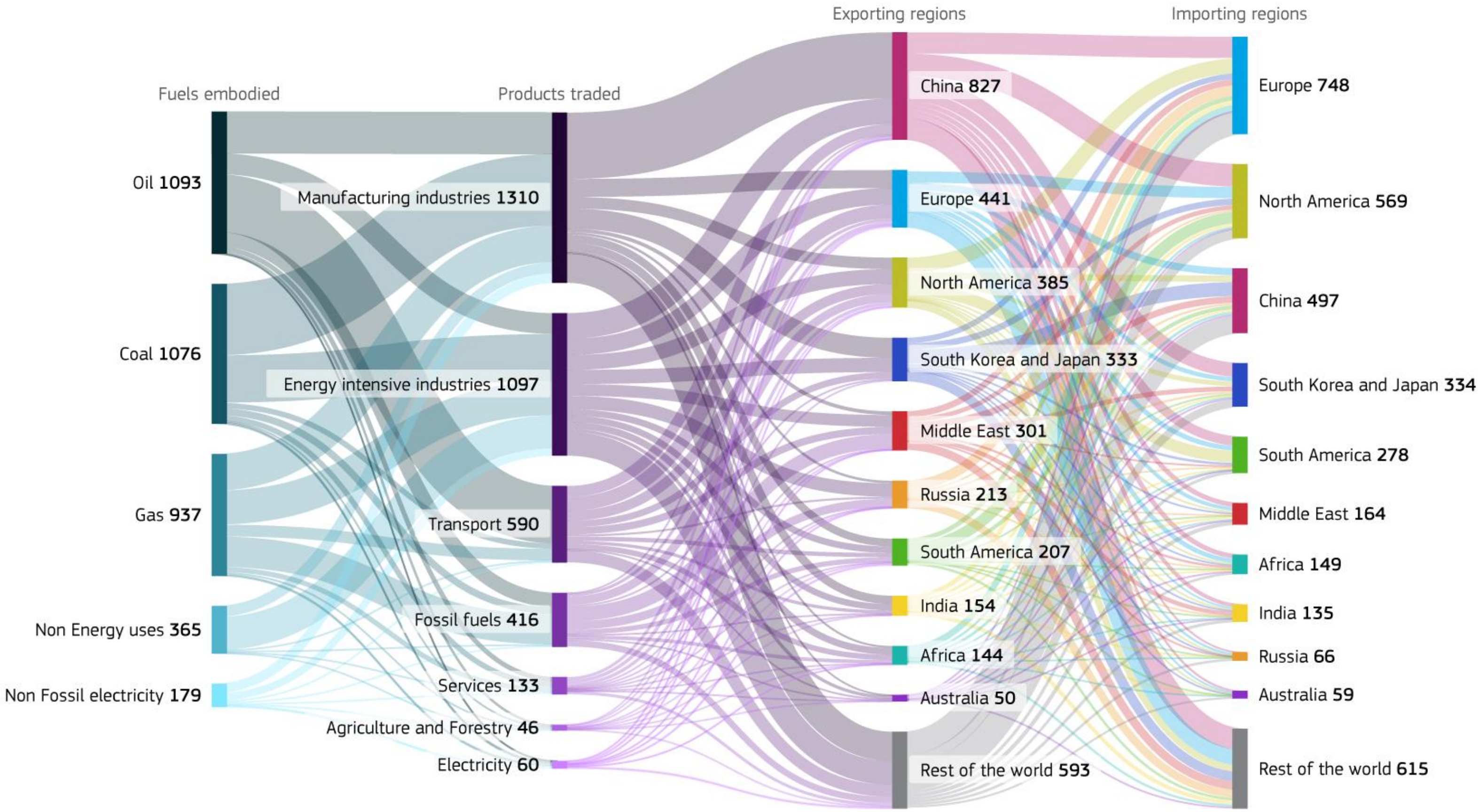
Figure 34. Global direct energy trade for oil, gas and coal in 2015 (Mtoe)[19]



Source: JRC-GEM-E3 model

[19] Excluding (intra) trade flows within regions. Discrepancies in totals due to rounding may occur.

Figure 35. Global embodied energy trade in 2015 (Mtoe)[20]



Source: JRC-GEM-E3 model

[20] Excluding (intra) trade flows within regions. Discrepancies in totals due to rounding may occur.

5.1.2 Scenario results

The projection of direct and embodied energy trade in the different scenarios see a changing landscape for energy trade in years to come (Figure 36).

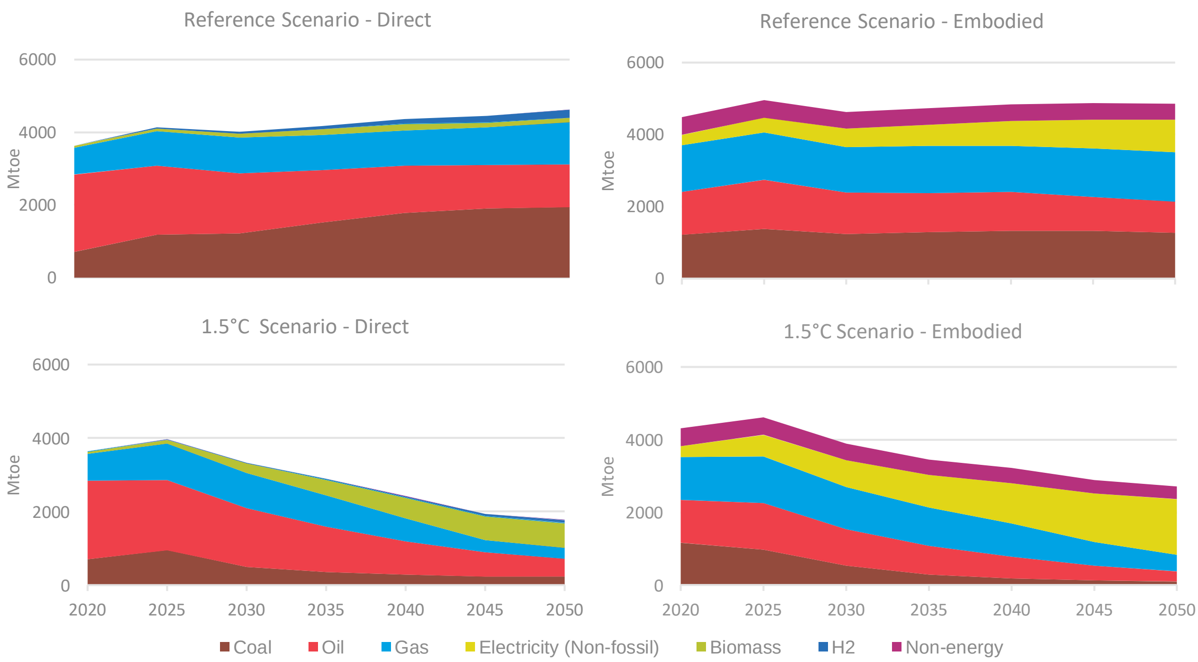
In the Reference Scenario, direct energy trade increases by one third from 2020 values, reaching 6000 Mtoe by 2050. Gas represents most of this increase, followed by an increase in traded coal, reflecting the increased use of gas for industrial production and coal for electricity generation. The direct trade of hydrogen and e-fuels remains negligible, as compared to fossil fuel trade during the projection period. The share of traded biomass increases to reach 7% of total direct energy trade by 2030 and then stabilises at 5% in 2050.

The Reference Scenario projects embodied energy to remain at a similar level as of 2020, with an increase in the share of embodied non-fossil electricity, reaching 18% of total embodied energy in trade by mid of the century.

In the 1.5°C Scenario, direct trade in fossil fuels decreases sharply over the coming decades as the world decarbonises. The 80% decrease in fossil fuel trade from 2020 levels is partially offset by an increase in direct biomass trade (mostly as modern biomass used in power generation), which reaches 37% of total direct energy trade in 2050. Even in the 1.5°C Scenario, H2 and liquid e-fuels represent a small share of energy global trade, accounting for 8% and 3% respectively in 2050.

Similarly, in a 1.5°C Scenario, the total embodied energy in goods and services is projected to decrease by about third from 2020 values. This reduction is driven by an 80% reduction of embodied energy from fossil fuels in trade, and partially offset by an increase in embodied low carbon electricity, which reaches 63% of embodied energy in trade by mid-century.

Figure 36. Direct and embodied energy trade of all fuels, Reference and 1.5°C Scenarios

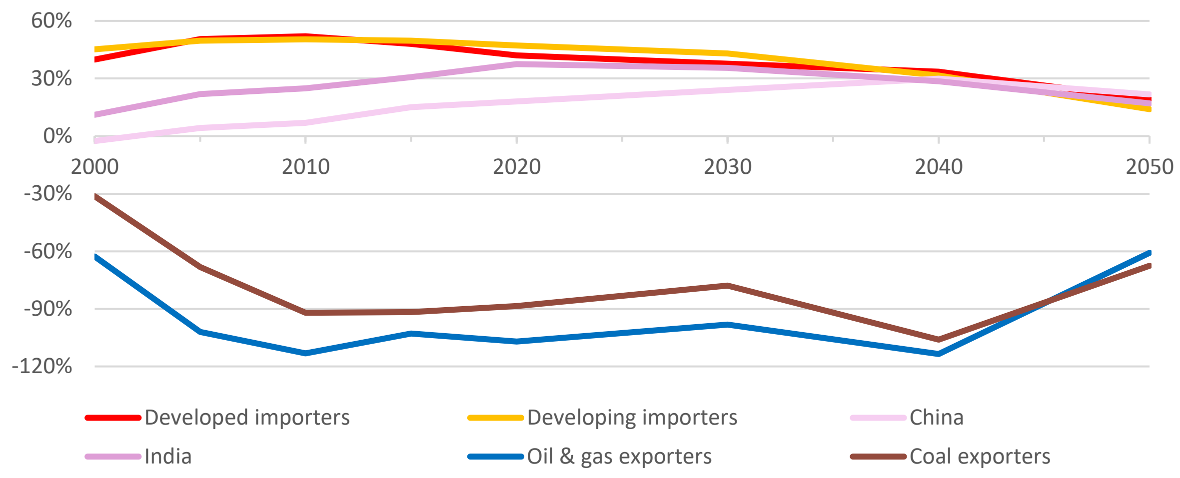


Source: POLES-JRC and JRC-GEM-E3 models

All net importing regions, and large individual importers see the share of total energy demand met by imports decreasing in the 1.5°C Scenario. Developed importers decrease from 42% today to 19% in 2050, and developing importers decrease from 47% today to 14% of imports by 2050.

An exception is China, whose significant dependence on domestic coal supply today sees it transition to importing more gas and biomass in order to decarbonise in the 1.5°C. The reduced imports of fossil fuels sees these two groups of oil and gas exporters and coal exporters greatly reduce their exports towards 2050.

Figure 37. Share of total demand met by net imports, by country grouping, 1.5°C Scenario

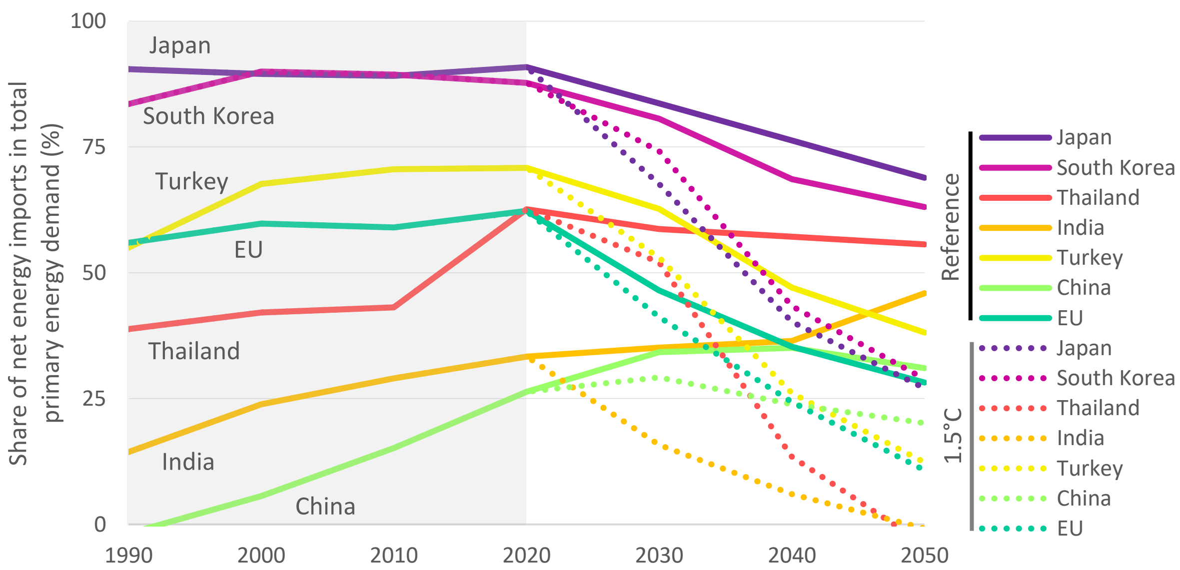


Note: Countries with negative shares are net exporters.

Source: POLES-JRC model

In several countries, the share of energy imports in total primary energy demand has been rising in previous decades, indicating stronger reliance on imports and associated energy security concerns. The penetration of renewables represents a domestic energy source which limits or reverses increasing import dependency. This effect is already apparent in the Reference Scenario, although the further uptake of renewables is not guaranteed to outpace overall energy demand. For example, in the case of India, results indicate that the share of energy imports in total primary energy demand continues to rise over time under current policies. In the 1.5°C Scenario energy import dependency declines rapidly over the coming decades in countries that are currently major energy importers, signalling the potential of climate action to enhance energy security. For some Asian countries, such as Japan and South Korea, the share of net energy imports in total primary energy demand falls from nearly 90% today to below 30% by mid-century in the 1.5°C Scenario. Correspondingly, the transition to climate neutrality strengthens the economic resilience to fossil fuel price fluctuations.

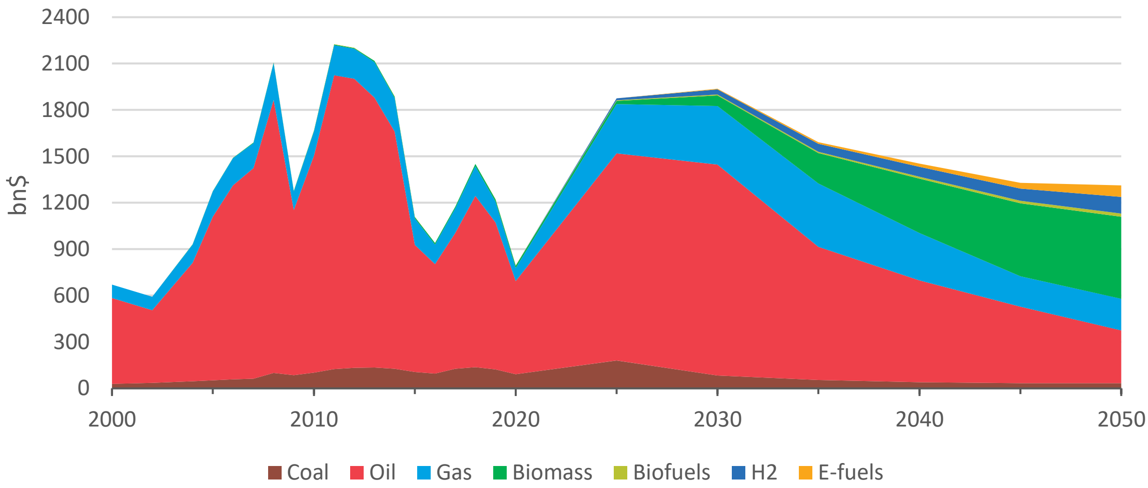
Figure 38. Direct energy import dependency of selected countries, Reference and 1.5°C Scenarios



Source: POLES-JRC model

In addition to the decline in traded fossil fuel quantities, the value of direct energy trade decreases as fossil fuel trade decreases in the 1.5°C Scenario. However, as global hydrogen demand and trade accelerates post-2040, the value of the increasing hydrogen trade market partially offsets the decreasing value of fossil fuel trade as the costs of hydrogen and e-fuels are greater than those of the diminishing fossil fuels.

Figure 39. Monetary value of global direct energy trade, 1.5°C Scenario



Source: POLES-JRC model

5.2 Direct energy trade

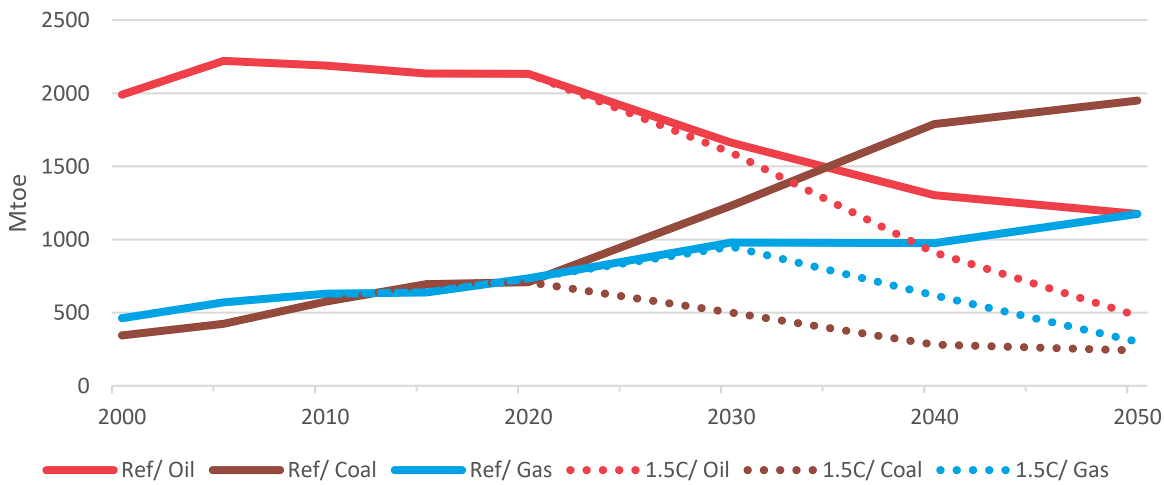
5.2.1 Fossil fuels

Trade declines for all fossil fuels in the 1.5°C Scenario, but the changes are not uniform across them. Coal trade suffers the most from the decarbonisation effort, with global volumes of traded coal reduced by 88% in the 1.5°C Scenario compared to the Reference Scenario in 2050. Oil trade is reduced by 59% and fossil gas by 74%.

As the rapid switch away from coal is largely under way during the current decade in the 1.5°C Scenario, there is a limited fuel switch and fossil gas trade is higher in 2030 in the 1.5°C Scenario than in the Reference Scenario. However, this is short-lived as decarbonisation continues at pace in the 1.5°C Scenario and therefore trade in fossil gas decreases towards 2040 and 2050.

Of note, global oil trade also decreases in the Reference Scenario in the coming decades, largely driven by the decrease of demand with the electrification of road transport.

Figure 40. Fossil fuel trade, Reference and 1.5°C Scenarios

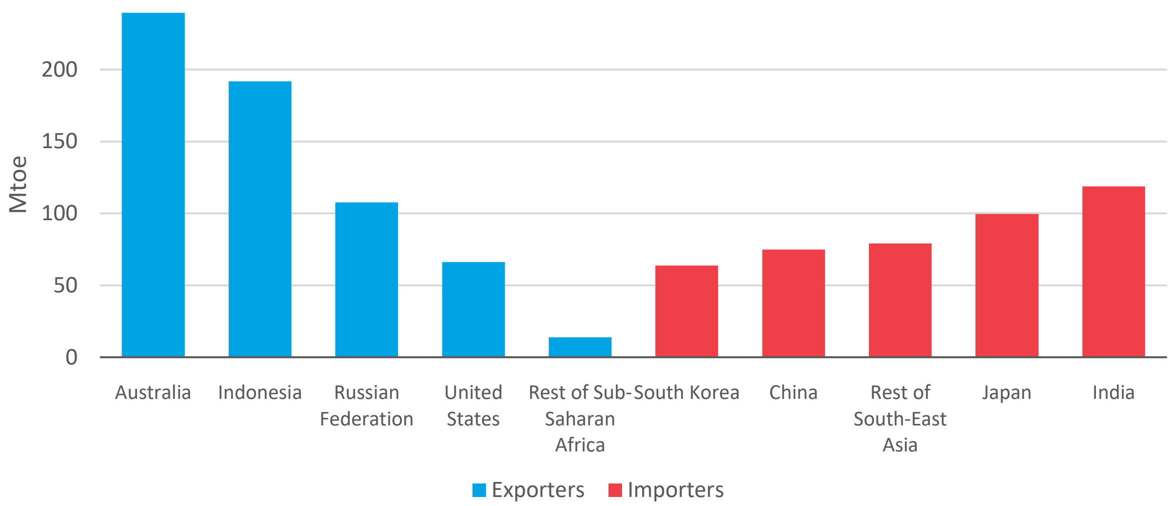


Source: POLES-JRC model

Decarbonisation leads to significant changes in trade flows by 2050, where in general larger importers reduce their imports of fossil fuels, and large exporters reduce their exports. Regarding coal, Indonesian exports reduce by 86% (this equates to $28 trillion less in 2050) and Australian exports by 95% ($34 trillion) in 2050 compared to 2020, while Chinese coal imports reduce by 45% ($11 trillion), and Japan's by 95% ($14 trillion) in 2050 compared to 2020.

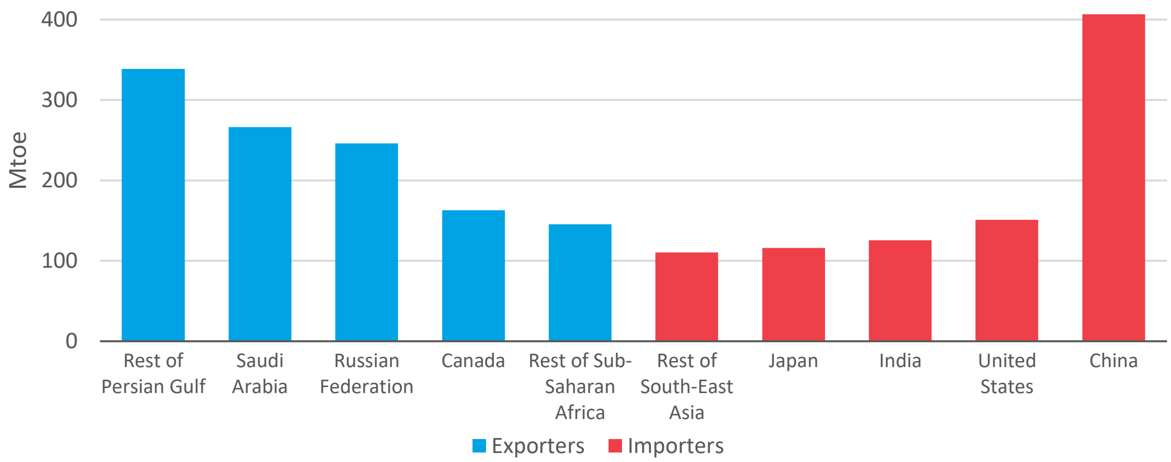
For oil, the Rest of Gulf region reduces exports by 62% ($450 trillion) and Russia by 68% ($183 trillion) in 2050 compared to today, while China's oil imports reduce by 74% ($303 trillion) and the EU's by 89% ($251 trillion). For fossil gas, the largest impact comes from the change in Russian exports to the EU, which follow the RePowerEU Plan and drop to zero by 2027.

Figure 41. Top 5 largest import and export reductions of coal, 1.5°C Scenario



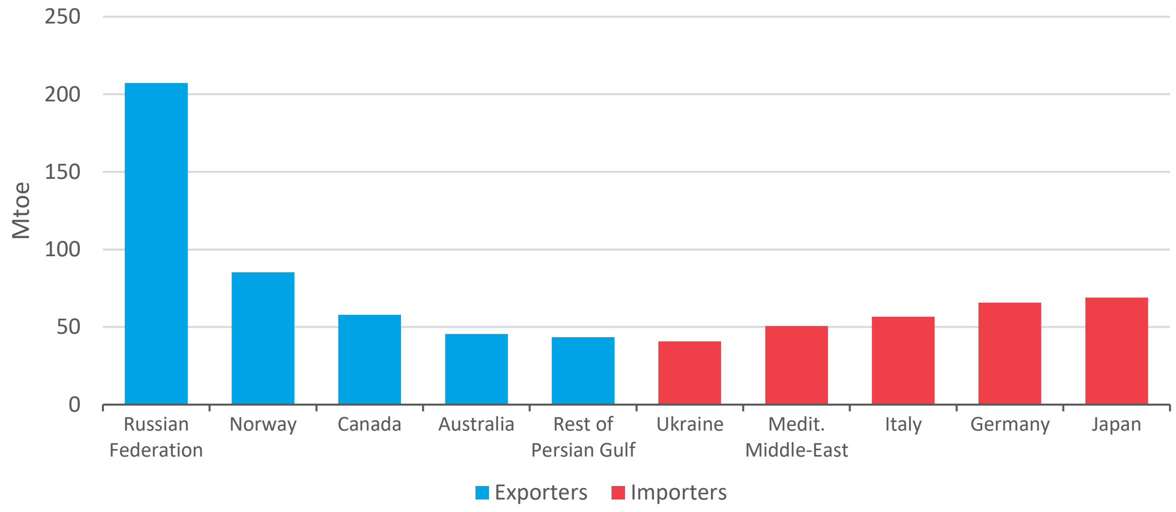
Source: POLES-JRC model

Figure 42. Top 5 largest import and export reductions of oil, 1.5°C Scenario



Source: POLES-JRC model

Figure 43. Top 5 largest import and export reductions of gas, 1.5°C Scenario



Source: POLES-JRC model

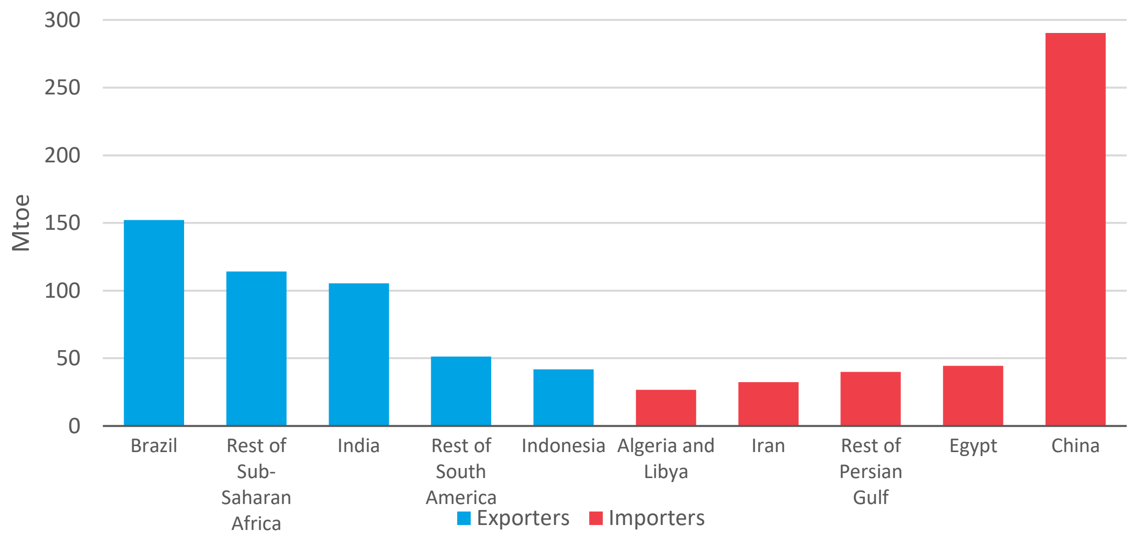
5.2.2 Biomass and biofuels

The trade of solid biomass increases significantly in the 1.5°C Scenario, as the pace of decarbonisation required sees all available low-carbon options employed. Traditional biomass (wood collected mainly for cooking purposes in rural areas) is sourced domestically; only modern biomass is traded internationally.

China increases biomass imports as it decarbonises, accounting for 45% of global biomass imports in 2050 in the 1.5°C Scenario. All other countries and regions individually account for less than 7%.

Brazil (20%), Rest of Sub-Saharan Africa (17%) and India (16%) are the largest exporters of biomass in 2050, all other exporters account for 7% or less.

Figure 44. Top 5 global biomass importers and exporters in 2050, 1.5°C Scenario

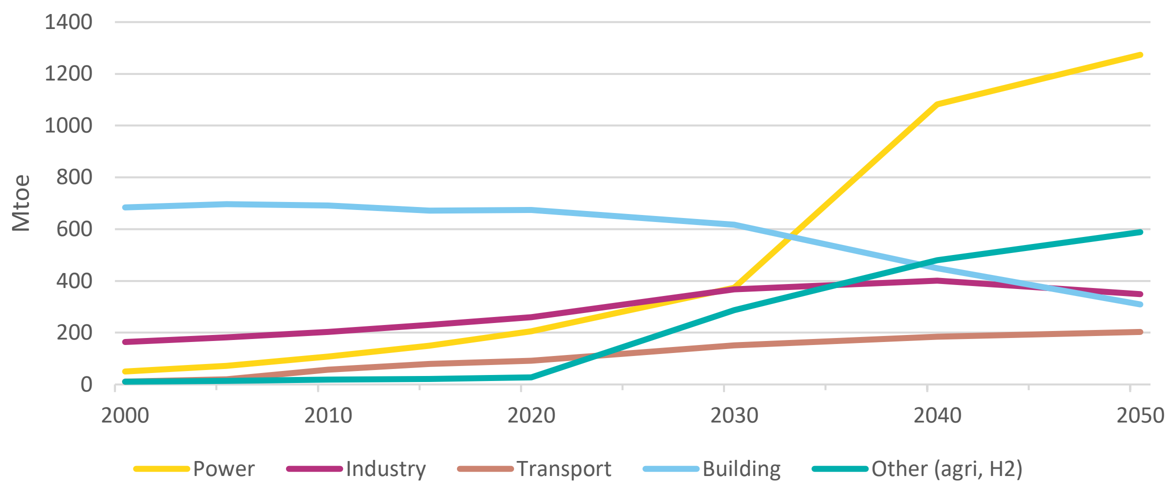


Source: POLES-JRC model

What drives increasing biomass trade is increasing biomass demand in the 1.5°C Scenario. Below we see that the buildings sector is the only sector that sees a reduction in biomass demand; traditional biomass used in developing countries is reduced as they are increasingly connected to the electricity grid, and modern biomass-based fuels, e.g. wood pellets, are also substituted by electric heating solutions. This decrease is offset by increases in all other sectors, led by power generation, where biomass is increasingly used to replace fossil fuels and provide a low-emissions dispatchable technology to manage renewables integration.

Biomass use also increases in industry, as it replaces fossil fuels, and in transport via second-generation biofuels. Overall biomass demand in 2050 in the 1.5°C Scenario is more than double that of today. In many regions demand exceeds domestic biomass supply and leads to increased demand for biomass imports.

Figure 45. Global biomass demand, by sector, 1.5°C Scenario



Note: demand in transport refers to liquids derived from biomass (1st and 2nd generation biofuels); demand in all other sectors refers to solid biomass.

Source: POLES-JRC model

Liquid biofuels trade accounts for 1% of direct energy trade in 2050 in the 1.5°C Scenario, which reflects the relatively small share that biofuels represent in total final energy consumption, accounting for 3% in 2050. Of total biofuel supply, only 9% is met by trade, as the bulk is produced domestically.

5.2.3 Hydrogen

Only certain types of hydrogen trade are allowed within our modelling framework (namely green[21] and low-carbon[22]), to ensure that only the hydrogen that is a low-carbon fuel that can displace higher-carbon carriers is traded. Hydrogen is traded to respond to demand of both energy and non-energy uses.

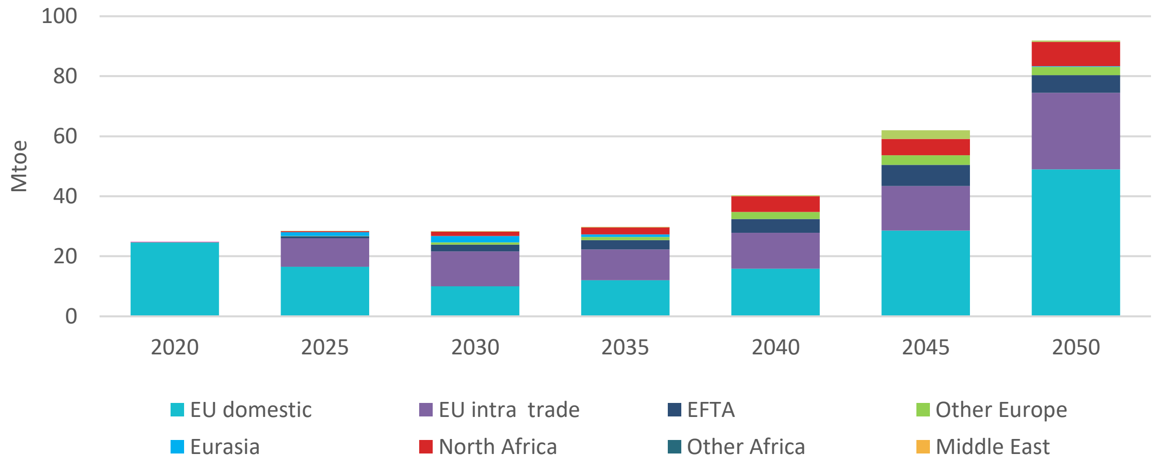
In the 1.5°C Scenario the bulk of hydrogen demand is met by domestic production, and of the small share that is traded most arrives via pipeline. In 2030, 10% of global hydrogen demand is met by imports, and while the global hydrogen trade market increases over time, decreasing production costs see a decreasing share of demand met by imports, reaching 6% in 2050. Indeed, the cost penalty for pipeline transport or shipping is too large to overcome the cost benefit of lower cost hydrogen production in better resource locations.

The bulk of hydrogen trade is via pipeline between neighbouring regions, with only 1% of all trade in 2030 and 12% of all trade in 2050 by ship in the 1.5°C Scenario.

The share of domestically produced and consumed hydrogen in EU countries is around 83% in 2050, of which 28% is traded between EU countries. 17% of EU demand is met by imports outside of the EU. Major imports to the EU originate from Switzerland and Norway (together 6%) and from Rest of Balkans (3%) and from Northern Africa (7%). To a large extent hydrogen is imported via pipelines.

[21] Green hydrogen includes PV, onshore wind and offshore wind based electrolysis.
[22] Low-carbon hydrogen includes nuclear-based electrolysis, gas and biomass pyrolysis, steam methane reforming with CCS, coal gasification with CCS, biomass gasification and biomass gasification with CCS.

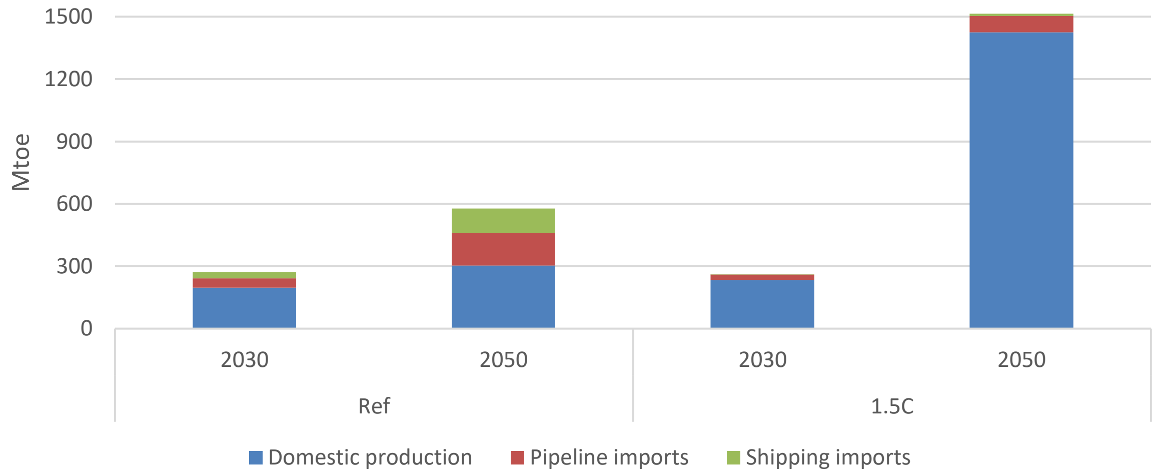
Figure 46. Domestic production and imports of hydrogen in the EU27, 1.5°C Scenario



Source: POLES-JRC model

In the Reference Scenario, the share of hydrogen supply that comes from imports globally is 48% in 2050. As total global demand for hydrogen is lower in the Reference Scenario compared to the 1.5°C Scenario, costs of both renewable electricity and electrolysers are higher due to fewer cost reductions from fewer deployments, leading to greater hydrogen cost differentials between regions and therefore more trade. The lower hydrogen production costs in the 1.5°C Scenario lead to less trade, as the cost differentials between regions are reduced and rarely offset transport costs.

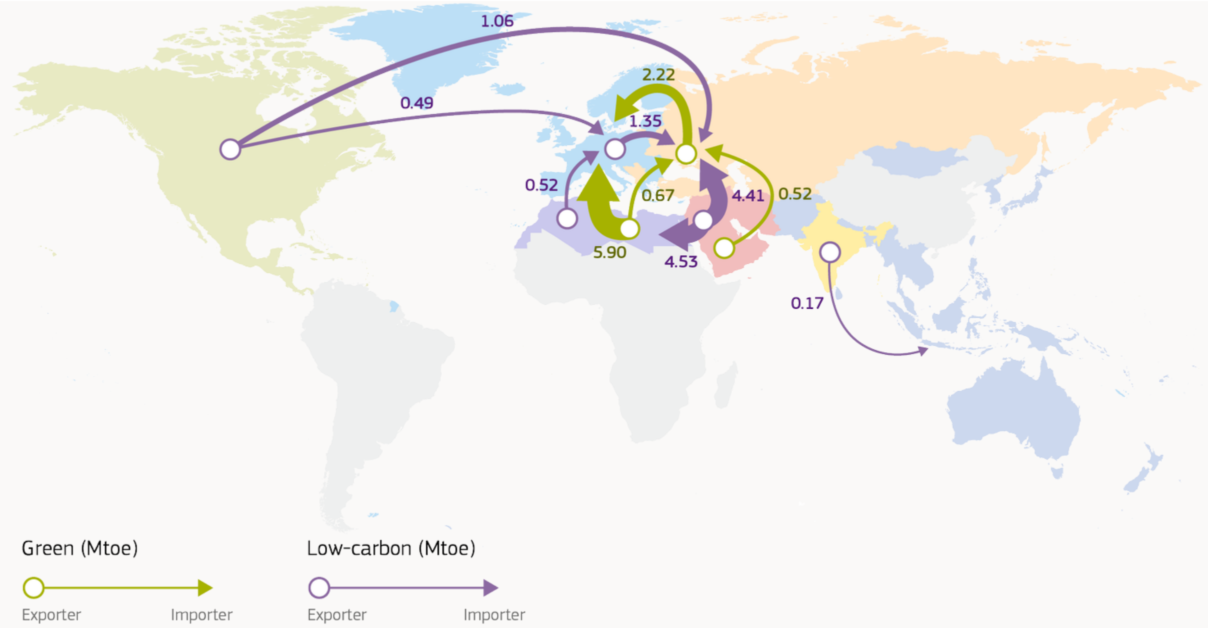
Figure 47. Global hydrogen supply by source, Reference and 1.5°C Scenarios



Source: POLES-JRC model

In 2050, 39% of global hydrogen trade is green hydrogen, with the dominant trade flows of green hydrogen going from North Africa and the Balkans to the EU via pipeline. 61% of hydrogen trade is in low-carbon hydrogen, with the main flows from the Middle East to countries around the Black Sea via pipeline.

Figure 48. Map of green and low-carbon hydrogen trade, by aggregated region in 2050, 1.5°C Scenario[23]



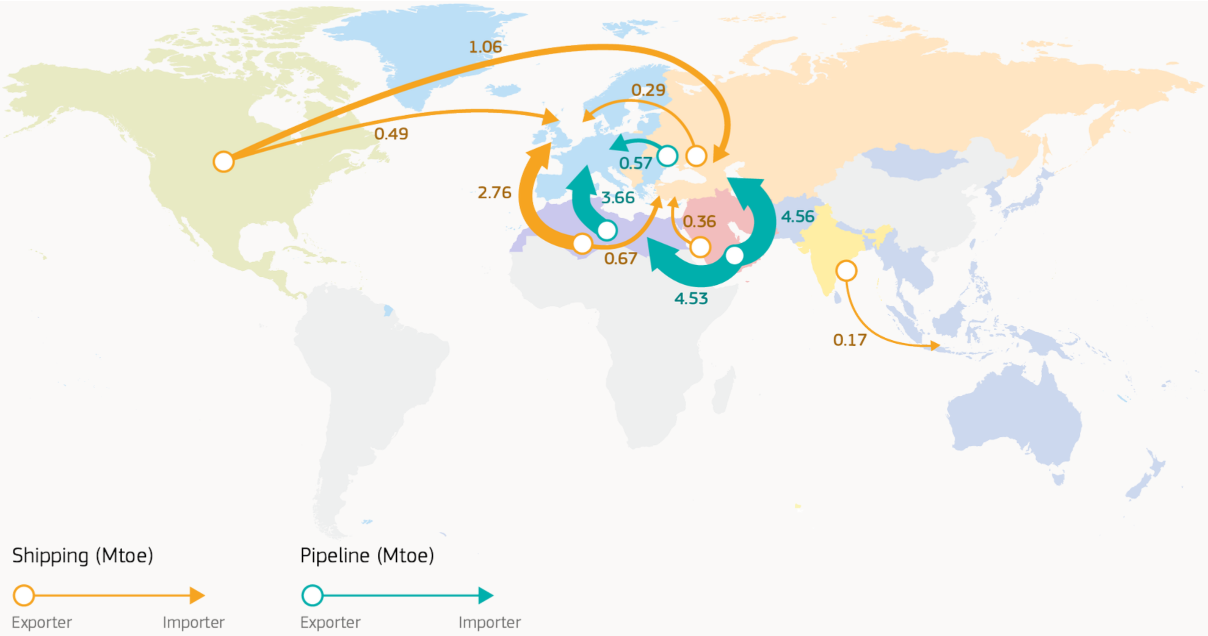
Note: apart from policies reducing direct energy trade between the EU and Russia, the analysis assumes a return to non-sanctioned trade flows between Russia and the rest of the world in the long term.

Source: POLES-JRC model

Onshore and offshore pipelines handle most global hydrogen trade, as such most global hydrogen trade occurs between neighbouring countries or over relatively short distances, i.e. across the Mediterranean Sea. When shipping trade does occur, it is generally over larger distances, i.e. from North America and North Africa to Northern Europe.

[23] Results reported in graphs and text relate to trade between all the regions in the POLES-JRC model. Trade flows shown in maps represent net trade between 10 global regions, and therefore eliminates some interregional trade that is reported in the graphs and text.

Figure 49. Map of global hydrogen trade by aggregated region in 2050, via pipeline and ship, 1.5°C Scenario

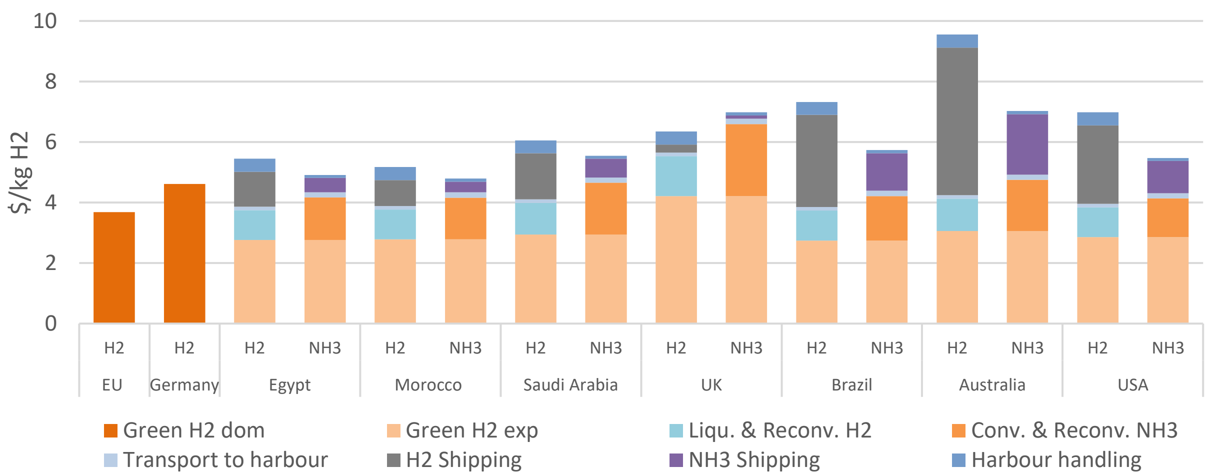


Note: apart from policies reducing direct energy trade between the EU and Russia, the analysis assumes a return to non-sanctioned trade flows between Russia and the rest of the world in the long term.

Source: POLES-JRC model

A comparison of EU domestic green hydrogen production costs in 2050 compared to potential imports via ship shows the many costs elements involved in the transporting of hydrogen. Liquefaction of hydrogen for transport and the conversion and reconversion of hydrogen to and from ammonia make shipping less attractive, even for relatively short distances, such as Egypt to Europe.

Figure 50. Comparison of domestic vs imported hydrogen costs via shipping for the EU in 2050, 1.5°C Scenario

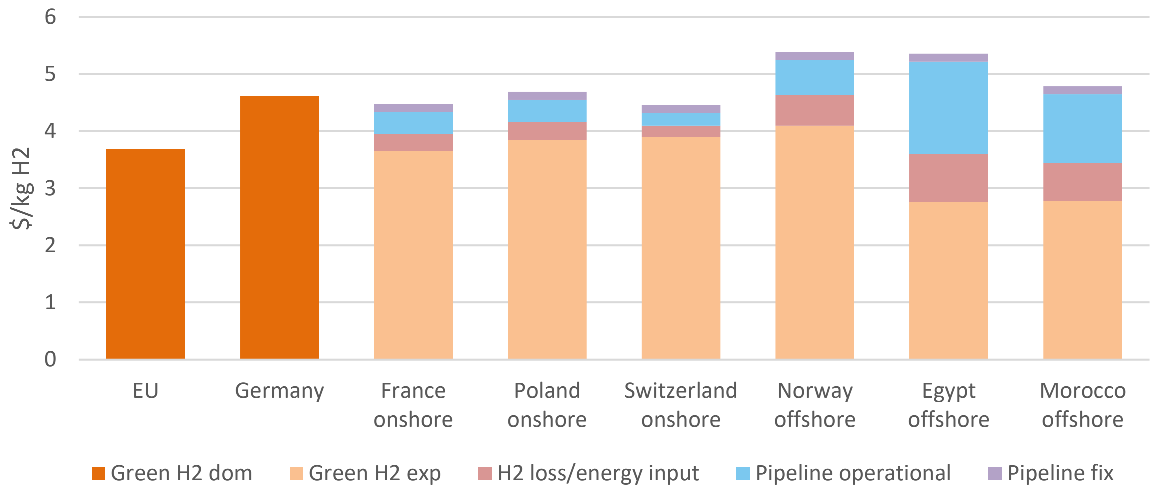


Note: EU Green H2 dom is average for all EU Member States. All importing costs are for imports to Germany. Pipelines refer to pipelines dedicated for hydrogen transport; their construction cost is amortised in the fixed cost.

Source: POLES-JRC model

However EU domestic green hydrogen production price in 2050 in the 1.5°C Scenario is comparable to the cost of imports coming via pipeline from North Africa.

Figure 51. Comparison of domestic vs imported hydrogen costs via pipeline for the EU in 2050, 1.5°C Scenario



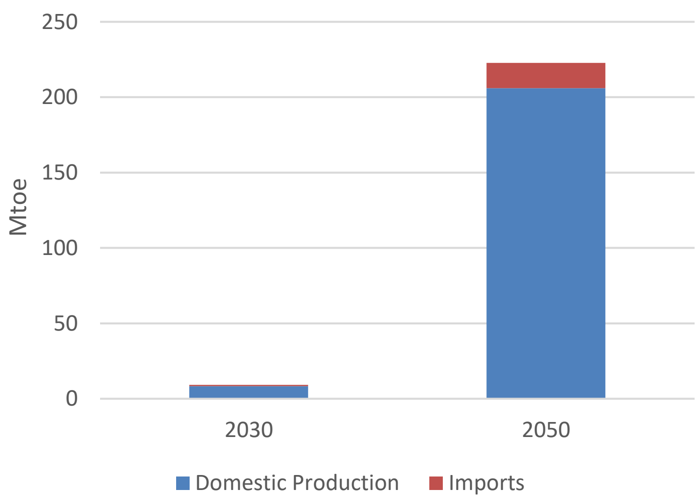
Note: EU Green H2 dom is average for all EU Member States. All importing costs are for imports to Germany.

Source: POLES-JRC model

5.2.4 Liquid e-fuels

As the transport costs for liquid e-fuels are much lower than for hydrogen, it becomes more economically viable to produce e-fuels in the best locations and ship them to the demand point. This results in a higher share of e-fuel supply being met by trade: 9% in 2030 and 7% in 2050. Although the share of trade is substantially higher for e-fuels than for hydrogen, the majority of exports/imports take place within regions.

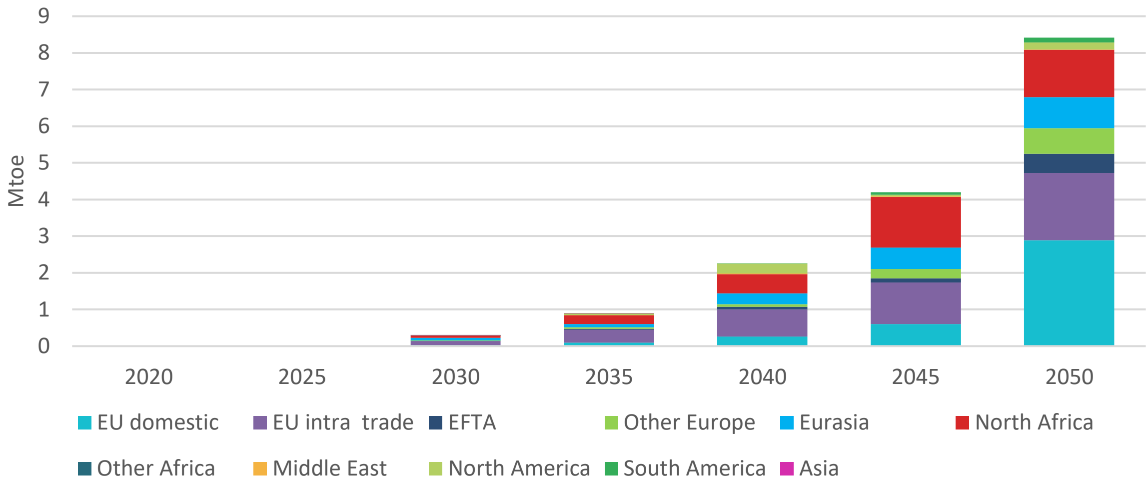
Figure 52. Global e-fuel supply, by source, 1.5°C Scenario



Source: POLES-JRC model

Regarding the EU, the amount of domestically produced and consumed e-fuels plus the intra-EU trade reaches 54% of demand in 2050 (compared to 83% for hydrogen). Major imports of e-fuels to the EU originate from the EFTA countries (7%), from Rest of Central Europe (8%), from Eurasia (10%) and from Northern Africa (16%). Minor trade flows for EU originate as well from North and Central America by ship.

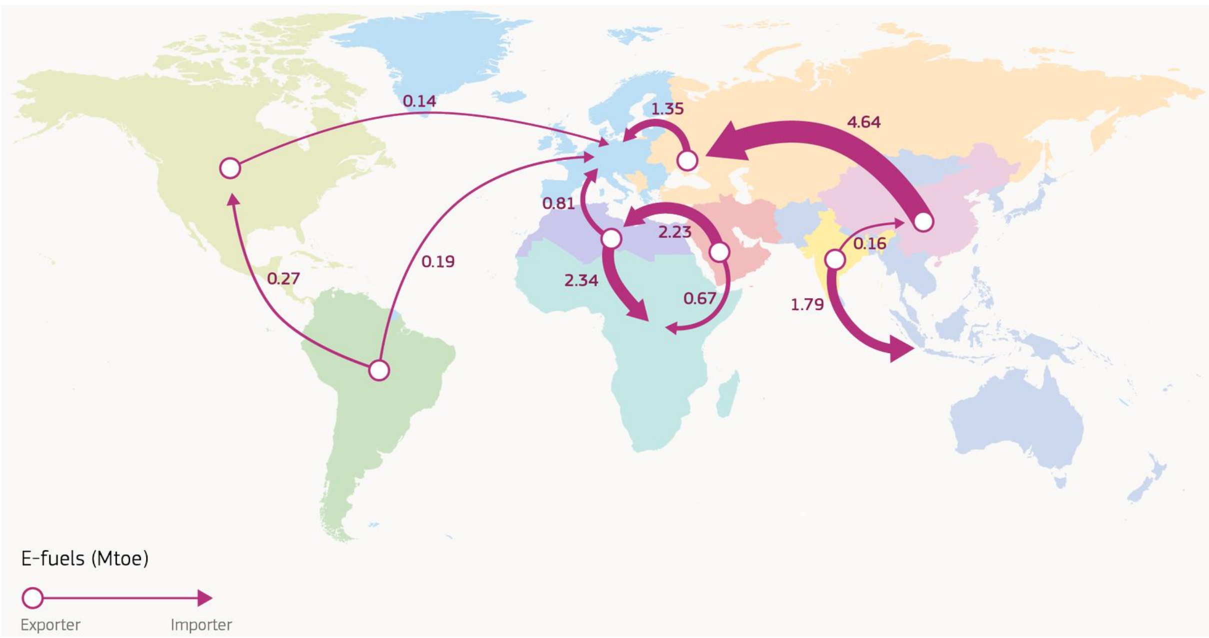
Figure 53. Domestic production and imports of liquid e-fuels in the EU27, 1.5°C Scenario



Source: POLES-JRC model

China and India, with their vast renewables resources, become large exporters of e-fuels, mostly supplying other Asian countries and Eurasia. Likewise, the Middle East and North Africa supply Europe and the rest of Africa. In the 1.5°C Scenario, we see longer trade distances for e-fuels than for hydrogen, e.g. Sub-Saharan Africa and South East Asia become importing regions, while both of these regions are mostly self-reliant in hydrogen by 2050.

Figure 54. Map of global liquid e-fuel trade, by aggregated region in 2050, 1.5°C Scenario

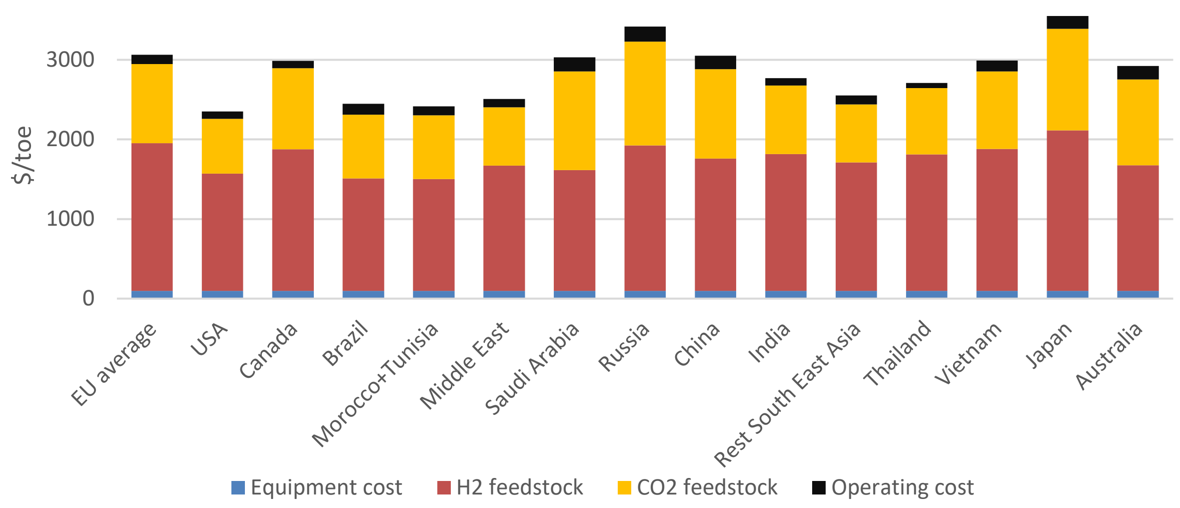


Note: apart from policies reducing direct energy trade between the EU and Russia, the analysis assumes a return to non-sanctioned trade flows between Russia and the rest of the world in the long term.

Source: POLES-JRC model

Larger cost differences across countries in e-fuels production costs compared to the corresponding hydrogen production costs lead to increased trade flows of e-fuels compared to hydrogen. E-fuel production costs depend largely on domestic green hydrogen costs and CO_2 supply costs, where CO_2 is taken from direct air capture (DAC) powered by renewables. Hence e-fuels costs are largely a reflection of renewables costs.

Figure 55. E-fuel production costs in selected countries/regions in 2050, 1.5°C Scenario

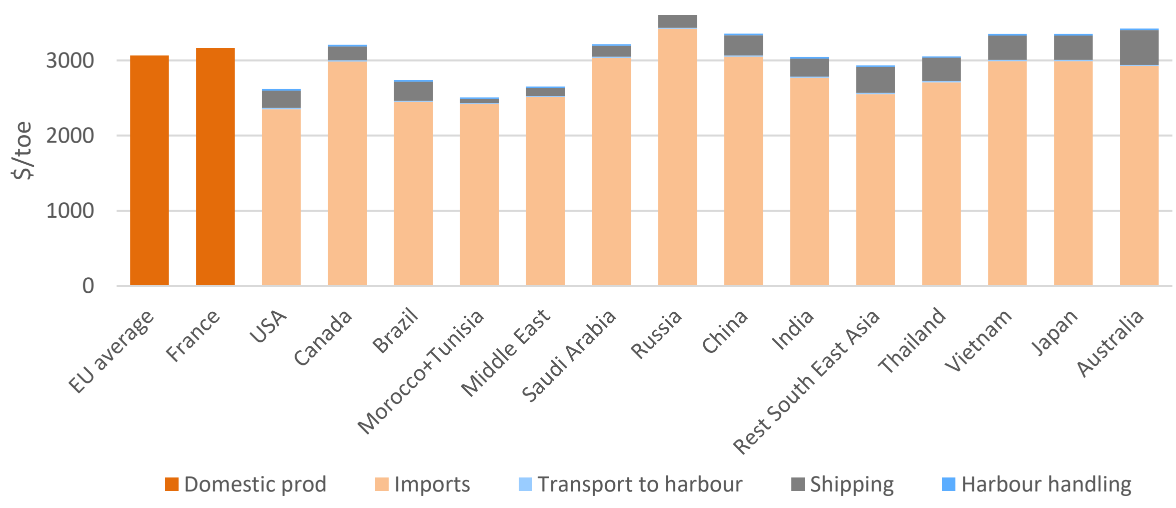


Note: operating cost refers to the cost of electricity used to run the liquefaction process.

Source: POLES-JRC model

Production cost differentials of e-fuels can be quite high, e.g. production cost of e-fuels in Germany are almost 50% more expensive than in India. By contrast, transport costs for liquid e-fuels are relatively small compared to transport cost of hydrogen, as such they have a lower impact on the cost of delivered e-fuels, and therefore overall trade volumes. As transport cost for pipelines are even smaller than those for shipping transport, e-fuel transport is dominated by transport via pipelines.

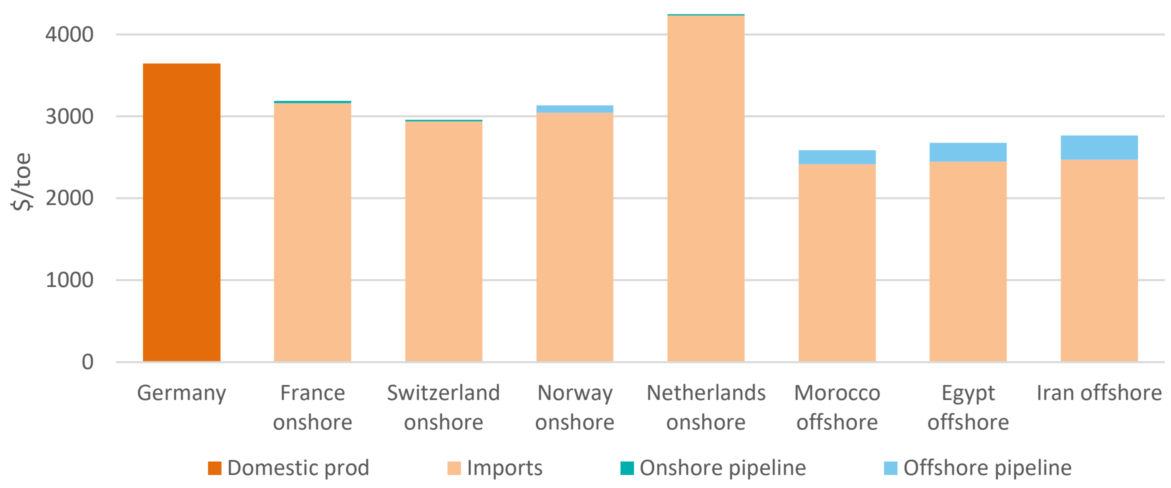
Figure 56. Comparison of liquid e-fuel domestic vs import by ship for EU in 2050, 1.5°C Scenario



Note: EU average is the average of for all EU Member States. All importing costs are for imports to France. Pipelines refer to pipelines dedicated for hydrogen transport; their construction cost is amortised in the fixed cost.

Source: POLES-JRC model

Figure 57. Comparison of liquid e-fuel domestic vs import by pipeline for EU in 2050, 1.5°C Scenario



Note: All importing costs are for imports to Germany.

Source: POLES-JRC model

5.3 Embodied energy

As outlined in section 5.1, embodied energy trade plays an important role in the world economy. This section first provides an overview of the fuels embodied and products traded in a 1.5°C decarbonising world. It then discusses the development of embodied energy in trade across the scenarios, presenting how energy and emissions evolve over time and for different regions.

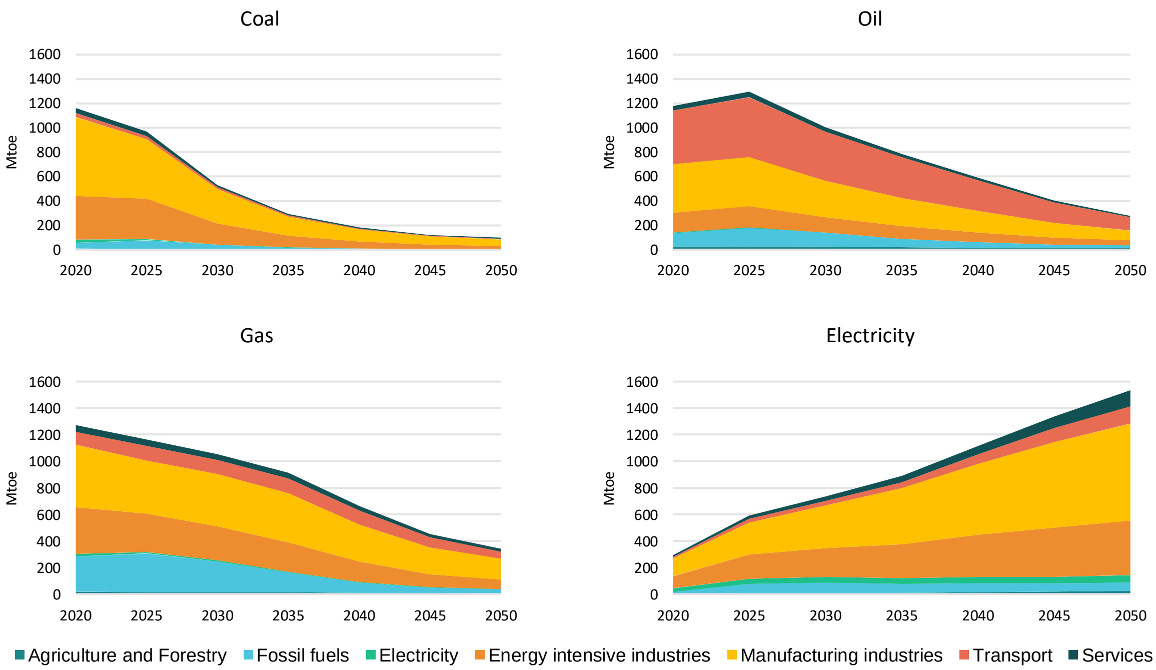
5.3.1 Fuels and products

The Reference Scenario projects the shares of fuels to remain nearly unchanged towards mid of the century, with exception of a 7% decrease in the share of oil embodied in trade. The share of low carbon electricity is also projected to increase by the same amount, to reach a share of 16% of total embodied energy in goods and services by 2050. Likewise, the reference scenario projects no fundamental change in the share of product categories over time.

In the 1.5°C Scenario, the total embodied energy in goods and services is projected to decrease by about one third from 2020 values. Embodied energy from fossil fuels in trade contracts from 3700 Mtoe in 2020 to approx. 800 Mtoe by 2050. At the same time, embodied low carbon electricity is projected to substantially increase, growing from 300 Mtoe to 2000 Mtoe by 2050,

Figure 58 presents the development of embodied energy by products in the 1.5°C Scenario for coal, oil gas and electricity, outlining the strong decrease in fossil fuels and the simultaneous increase in low-carbon electricity embodied in trade. Embodied coal in trade shows the strongest reduction among all fuels in a 1.5°C Scenario, reaching 120 Mtoe by 2050, a 90% reduction from 1200 Mtoe by 2020. Embodied oil and gas in trade decrease considerably, albeit remaining at a level of 300 Mtoe and 390 Mtoe by 2050.

Figure 58. Embodied energy in trade, by fuel, 1.5°C Scenario



Source: JRC-GEM-E3 model

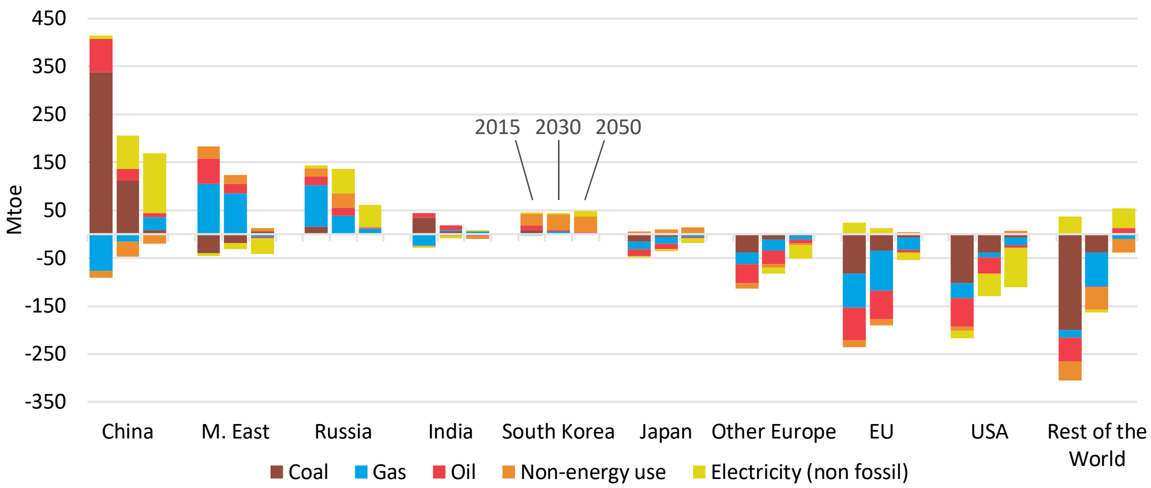
5.3.2 Fuels and regions

As of 2015, China (830 Mtoe) was the largest exporter of embodied energy excluding intra-regional trade flows, followed by Europe (430 Mtoe), North America (380 Mtoe) and East Asia (330 Mtoe). The largest importing regions were Europe (750 Mtoe), North America (560 Mtoe), China (500 Mtoe) and East Asia (330 Mtoe) (see Figure 35). Note that intra-regional trade is particularly substantial in Europe (622 Mtoe) given the close integration of the European market.

Fossil fuel producing regions, such as the Middle East and Russia, also represent a substantial share of embodied energy in trade, reflecting the energy intensive process of producing and transporting fossil fuels – and thus the embodied energy and not the energy content of these energy carriers.

The share of embodied non-fossil electricity in traded goods and services is projected to differ strongly across regions. Visualising how regional patterns of embodied energy trade are projected to evolve, Figure 59 illustrates the evolution of embodied net energy trade by fuel and region for the years 2015, 2030 and 2050 in the 1.5°C Scenario. China is projected to become the largest net exporters of non-fossil electricity embodied in goods and services by 2030. The US is projected to become the largest net importer of non-fossil electricity by 2030. The EU is projected to be a small net exporter of embodied energy by 2030, before becoming a net importer. Other highly developed regions, such as Japan or South Korea, are projected to remain with comparatively smaller net imports and exports of embodied energy.

Figure 59: Net exports of embodied energy by fuels in the 1.5°C Scenario in 2015, 2030 and 2050



Note: Positive values for each fuel represent net exports, while negative values reflect net imports.

Source: JRC-GEM-E3 model

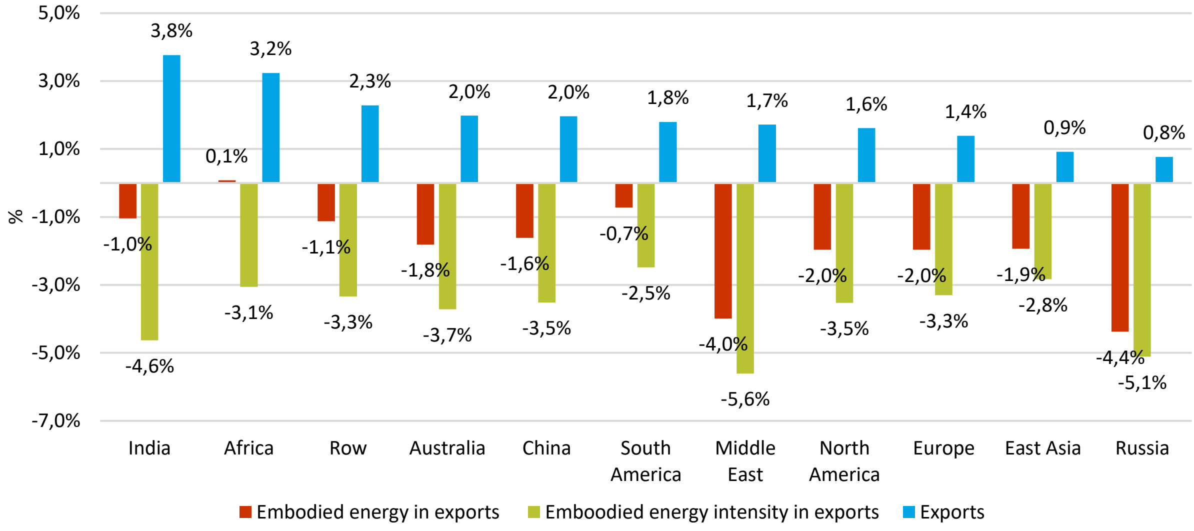
The development of embodied energy can be further disentangled in its underlying drivers, the development of trade over time, as well as the energy intensity of traded products and services. Figure 60 shows the average annual growth rate of energy embodied in exports, which can be decomposed into the change in exports volumes and the change of the embodied energy intensity of exports. The figure indicates how these drivers are changing in different regions in the 1.5°C Scenario.

In an expanding global economy, all regions are projected to experience a growth in exports. However, when comparing the 1.5°C Scenario to the Reference Scenario, we observe globally a small decrease of trade over time (around -1%), due to lower trade of (fossil) energy goods, reduced overall economic activity as climate policy comes with a small macroeconomic cost, and increased cost of (international) shipping as carbon pricing is also applied to the corresponding sectors. Emerging and developing economies are projected to grow at a faster pace, with India and Africa growing their exports at an annual rate of 3.8% and 3.2%, respectively.

As the world decarbonises, the energy intensity of products and services traded in a 1.5°C decarbonisation trajectory is projected to decrease in all regions. Fossil fuel exporting regions are projected to see the strongest decrease in the energy intensity of traded products, with annual growth rates of -5.6% and -5.1% for exports of the Middle East and Russia, respectively.

The development of embodied energy in trade can be interpreted as the combination of the change in export composition and energy intensity of those exports. The stronger decline in the energy intensity of exports compensates the growing trade in an expanding economy. As a result, all regions but Africa are projected to experience a decline in the trade of embodied energy. The decline in embodied energy trade is most pronounced in regions with a slow growth in exports and a strong decline in their energy intensity, such as fossil fuel exporting regions. Conversely, regions with a strong growth in exports and a small decrease in energy intensity of exports, such as Africa or South America, will experience the slowest decrease in the trade of embodied energy.

Figure 60. Compounded average annual growth rate between 2020 and 2050 for energy embodied in exports, embodied energy intensity of exports, and export volumes for different regions, 1.5°C Scenario



Source: JRC-GEM-E3 model

5.3.3 Trade and emissions

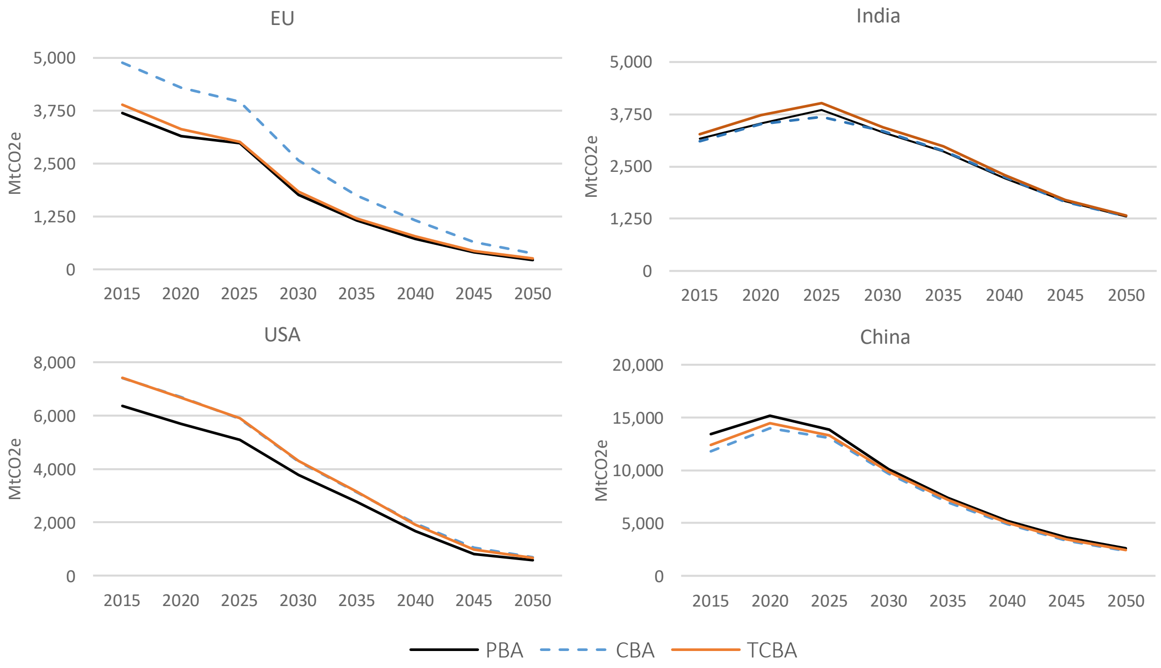
Figure 61 shows the evolution of GHG emissions for the largest emitters globally, China, USA, EU and India in the timeframe 2015-2050 in the 1.5°C Scenario. Emissions shown in the figure are assigned to regions based on a production-based accounting (PBA) and consumption-based accounting (CBA), as well as technology-adjusted consumption-based accounting (TCBA). While PBA assigns emissions to a country or region where they are emitted during production in line with UNFCCC inventories, CBA assigns emissions where the final product is consumed, considering emissions along the entire value chain[24]. The difference between PBA and CBA is often referred to as the balance of emissions embodied in trade, with PBA being commonly referred to as "territorial" emissions. Emissions under CBA are thus emissions from PBA, adjusting for the net embodied emissions in trade. TCBA accounts for differences in technology of export sectors to adjust the CBA metric. Under TCBA, export-related emissions are subtracted based on the average carbon intensity for the relevant sector on the world market, rather than the domestic average, under the assumption that a similar good would have been produced at the average emissions intensity on the world market for that sector (Kander et al, 2015). This metric thus assigns lower emissions to a country under CBA when its exports are cleaner than the world average, after accounting for sectoral differences in the composition of exports. As we do not allocate emissions from land use and land use change as well as emission removals from direct air capture to individual sectors, these emissions are accounted for in the country that they occur in under all approaches.

As for 2020, the EU and the United States are net importers of CO_2 emissions, and correspondingly show higher emissions under a CBA than a PBA assignment. China and India show an inverse pattern, being net exporters of emissions. In line with a 1.5°C decarbonisation trajectory, emissions decline to net zero in all regions towards mid-century. As decarbonisation advances, the gap between territorial emissions and consumption-based emissions (both in CBA and TCBA) is reduced. This trend is observed both for net importing and net exporting regions (EU and USA, India and China, respectively), reflecting the decarbonisation of producing sectors and the increasing share of non-fossil electricity embodied in goods and services.

Overall, a decarbonisation of the global economy towards mid-century requires all countries and regions to reduce emissions at a rapid pace. While both consumption and production-based emissions in the EU and USA have been declining at least since 2015, emissions in China decline prior to 2025 and in India prior to 2030 decade in the 1.5°C scenario.

[24] Final demand includes investment purchases. There are methods to allocate embodied energy and emissions from investment goods to capital in future periods (e.g., Chen et al., 2022), as the fixed capital used in production (for instance, machinery) also contributes to the embodied energy of the final output, but we do not adjust that in the current analysis.

Figure 61. GHG emissions assigned to major emitters by production, consumption and technology-adjusted consumption accounting in the timeframe 2015-2050 in the 1.5°C Scenario.



Source: JRC-GEM-E3 model

6 Conclusions

The 2022 edition of the Global Energy and Climate Outlook focused on the future of (direct and embodied) energy trade, especially in the context of a projected worldwide effort for economy-wide decarbonisation. In particular, we examined the role of the emerging energy vectors hydrogen and e-fuels in the energy mix and in energy trade.

The current and expected status of adopted policies, market prices and technology costs point towards a stabilisation of global emissions globally. Major policies announced in 2022, combined with increasing deployments of low-emissions technologies, notably in renewables and electric vehicles, lead to the projected temperature increase in the Reference Scenario being 3°C by the end of the century.

Current climate policy pledges and targets imply a rapid decline in greenhouse gas emissions, but implementation and ambition gaps remain. The NDC-LTS Scenario sees a temperature increase of 1.8°C at the end of the century.

Evidently, both the Reference Scenario results and the NDC-LTS Scenarios show that both current policies and announced actions and targets continue to fall short of limiting the global temperature increase to 1.5°C either in the medium term (overshoot) and in the long-term (stabilisation in 2100).

Major action is still required. In our 1.5°C Scenario, the coming decade must be centred on fossil-fuel phase out, increased deployment of renewables and electrification of the bulk of final demand. The energy system undergoes a major restructuring, with fossil fuels reducing their collective share in the global primary energy mix to 21% by 2050, while solar, biomass and wind become the dominant forms of primary energy supply.

Domestic renewables deployment and electrification reduce the demand of fossil fuels, which in turn reduces the need to trade fossil fuels. This trend sees most regions reducing their reliance on imported energy, leading to a global increase in energy self-sufficiency.

There is significant policymaker and private sector interest in the role that hydrogen can play in a decarbonised world. Hydrogen and hydrogenated e-fuels are important decarbonisation levers in a limited number of sectors. Given their high cost, large investments in RD&D still need to materialise immediately and in the mid-term in order for their deployment in large quantities to occur, mostly post-2040.

Green hydrogen, produced from electrolysers powered by solar and wind, provides the largest share of hydrogen production in 2050 in the 1.5°C Scenario. However, the interplay of renewable resources, gas resources, CCS deployment and nuclear industry result in some countries in a role for nuclear-based hydrogen production and production from fossil-fuels with abatement (CCS) or pyrolysis.

Hydrogen trade accounts for a limited amount to hydrogen supply in all world regions (11% globally). The cost of producing hydrogen decreases over time. Hydrogen transport costs account for an increasing share of total delivered hydrogen costs; as a consequence, the lowest cost hydrogen becomes increasingly produced domestically rather than being imported. Imported hydrogen accounts for a small share of total hydrogen supply in 2050 in the 1.5°C Scenario, and of that small share most arrives from neighbouring countries. The transport costs for e-fuels being much lower than for hydrogen, it becomes economically viable to produce e-fuels in the best locations and ship them to the demand point, resulting in one-quarter of e-fuels demand being met by imports in 2050.

In the 1.5°C Scenario, the trade of energy embodied in goods and services decreases less than direct energy trade does, reflecting the expansion of the global economy and higher trade volumes in years ahead. Embodied energy in traded goods largely consists of embodied low-carbon electricity, reflecting the shift towards renewable electricity in the global power sector and the electrification of manufacturing industries.

This report contributes to a growing literature on how globalisation, in the form of increasing trade of goods and products, can go hand in hand with a growing global economy as it decarbonises.

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List of abbreviations and definitions

AFOLU	Agriculture, forestry and land-use
BAU	Business as usual
BECCS	Bio-Energy combined with Carbon Capture and Sequestration
BEV	Battery electric vehicle
CCS	Carbon Capture and Sequestration
CDD	Cooling Degree-Days
CGE	Computable General Equilibrium model
CH4	Methane
CO_2	Carbon dioxide
COM	Communication from the European Commission
COP	Conference of the Parties
DACCS	Direct Air CO_2 Capture and Sequestration
EC	European Commission
ETS	Emission Trading Scheme
EU	European Union as of November 2019 (27 Member States)
EV	Electric Vehicle
GDP	Gross Domestic Product
GECO	Global Energy & Climate Outlook
GHG	Greenhouse Gases
GLOBIOM	The Global Biosphere Management Model
GTAP	Global Trade Analysis Project
GWP	Global Warming Potential
HFCs	Hydrofluorocarbons
IATA	International air transport association
ICAO	International Civil Aviation Organization
ICE	Internal Combustion Engine
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IFC	International Finance Corporation, World Bank Group
ILO	International Labour Organisation
IMF	International Monetary Fund
IMO	International Maritime Organisation
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

MRIO Multi-regional input-output (table)

N2O Nitrous oxide

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

O&G Oil and Gas

PFCs Perfluorocarbons

PIRAMID Platform to Integrate, Reconcile and Align Model-based Input-output Data

POP Population

PPP Purchasing Power Parity

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

ppm part per millions

R/P Ratio Reserves by Production

RES Renewable Energy

SDS Sustainable development scenario from IEA

SF6 Sulphur hexafluoride

TC Transport changes

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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Annexes

Annex 1: Policies considered

The Scenarios presented in this report build on past work: GECO 2020 (Keramidas, et al., 2021) and GECO 2021 (Keramidas, et al., 2021). The Reference scenario builds from the GECO 2021 Current Policies scenario. A full list of the policies considered in the GECO 2022 Reference scenario can be found below.

The NDC-LTS scenario includes the policies of the Reference scenario as well as additional policies presented in the tables below.

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.[25]

The 1.5°C scenario has the same carbon price for all countries and all sectors; it consists in a sigmoid curve with an inflection point in 2040. The 1.5°C scenario has the Reference scenario as a starting point; the country-level policies of the NDC-LTS were removed from the 1.5°C scenario, in order to subject all countries to a homogeneous policy driver. This allows to compare country-level pathways that include national policies with the "economically-efficient" pathways of the carbon price scenarios.

The following tables summarize all the policies considered to build the emissions pathways in the Reference and NDC-LTS scenarios. We assume that all the major policies are implemented, however some country-related policies may be missing or only partially represented because of several causes:

- They may be announced but not be ratified: e.g. Argentina and South Africa carbon neutrality objectives.
- The policy might lack sufficient information to be represented: e.g. certain mitigation measures in NDCs where emissions without measures are not informed or where the effect is not quantified.
- The POLES-JRC model is not able to take them into account for different reasons: e.g. specific land-related or agriculture-related measures.

For POLES-JRC regions that are country aggregates, the Reference pathway is derived purely from the modelling without additional policies. The NDC-LTS pathway necessitated aggregation work. First, the component countries' NDCs were accounted as volumes of emissions; then, the sum of emissions was converted into a growth (or decrease) target compared to a historical base year (UNFCCC inventories and WRI (World Resources Institute, 2021) were used to translate countries' base years into a single base year); this growth target was used to calibrate POLES-JRC model results for that region.

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

Table 1: Reference Scenario – Energy-related policies

Region	Sector	GHG	Subsector	Target	Base year	Target year	Objective	Source
Europe								
EU	Transport		New passenger vehicles	Emissions reduction	2015	2021	-26.9%	European Commission, DG Energy
EU	Transport		New passenger vehicles	Emissions reduction	2021	2025	-15.0%	European Commission, DG Energy
EU	Transport		New passenger vehicles	Emissions reduction	2021	2030	-37.5%	European Commission, DG Energy
EU	Transport		New heavy vehicles	Emissions reduction	2019-2020	2025	-15%	European Commission, DG Energy
EU	Transport		New heavy vehicles	Emissions reduction	2019-2020	2030	-30%	European Commission, DG Energy
EU	Energy		Gross final demand	Share of renewables		2030	45%	European Commission, RePowerEU Plan (2022)
EU	Energy		Biomethane	Biomethane production (bcm)		2030	35	European Commission, RePowerEU Plan (2022)
EU	Energy		Hydrogen	Hydrogen demand (Mt)		2030	16.2 (not reached)	European Commission, RePowerEU Plan (2022)
EU	Power		Primary energy demand	Primary energy (Mtoe)		2030	980	European Commission, RePowerEU Plan (2022)
EU	Power		Final energy demand	Final energy (Mtoe)		2030	750	European Commission, RePowerEU Plan (2022)
EU	Power		Solar	Capacity (GW)		2030	600	European Commission, RePowerEU Plan (2022)
EU	Energy		Fossil gas imports from Russia	Phase-out		2027	0	European Commission, RePowerEU Plan (2022)
EU	Transport		Transport demand	Share of renewable fuels		2030	29%	European Commission, DG Energy
North America								
Canada	Power		Power production	Share of renewables		2030	90%	Pan-Canadian Framework on Clean Growth and Climate Change (2017)
Canada	Power		Power production	Traditional coal-fired plants reduction		2030	30%	Pan-Canadian Framework on Clean Growth and Climate Change (2017)

Canada	Transport	Transport demand	Share of renewable fuels	2012	2030	7%	Canadian Environmental Protection Act (2008)
Canada	Transport	New passenger vehicles	Emissions reduction	2017	2025	-34%	Adapted from Canadian Environmental Protection Act (2008)
Canada	Transport	New passenger vehicles	Zero emissions vehicles share		2025	20%	Zero emissions vehicle infrastructure program (2019)
Canada	Transport	New passenger vehicles	Zero emissions vehicles share		2030	60%	Zero emissions vehicle infrastructure program (2019)
Canada	Transport	New passenger vehicles	Zero emissions vehicles share		2035	100%	Zero emissions vehicle infrastructure program (2019)
Mexico	Power	Power production	Share of renewables (including large hydro and nuclear)		2024	35%	Energy Transition Law (2015)
United States	Power	Power production	Share of renewables		2030	26%	Fusing subnational with national (Hultman, et al., 2020)
United States	Power	Power production	Share of nuclear		2030	17%	Fusing subnational with national (Hultman, et al., 2020)
United States	Power	Power production	Share of coal		2030	16%	Fusing subnational with national (Hultman, et al., 2020)
United States	Transport	Transport demand	Electric vehicles and PHEV sales ('000)		2020-2030	13,500	Fusing subnational with national (Hultman, et al., 2020)
United States	Transport	New passenger vehicles	Emissions reduction	2017	2025	-21.9%	Adapted from EPA GHG standard (2012)
Central & South America							
Argentina	Power	Power production	Share of renewables (including large hydro)		2023	18%	RenovAr (2016)
Argentina	Power	Power production	Share of renewables (including large hydro)		2025	20%	RenovAr (2016)
Brazil	Energy	Primary energy demand	Share of renewables (including biofuels)		2031	48%	Decenal Energy Expansion Plan (2031)
Brazil	Power	Power production	Share of renewables (including biofuels)		2031	85%	Decenal Energy Expansion Plan (2031)
Brazil	Power	Power capacity	Hydro (GW)		2031	107	Decenal Energy Expansion Plan (2031)
Brazil	Power	Power capacity	Small hydro (GW)		2031	10	Decenal Energy Expansion Plan (2031)
Brazil	Power	Power capacity	Nuclear (GW)		2031	4	Decenal Energy Expansion Plan (2031)

Brazil	Power	Power capacity	Biomass (GW)		2031	16	Decenal Energy Expansion Plan (2031)
Brazil	Power	Power capacity	Wind (GW)		2031	30	Decenal Energy Expansion Plan (2031)
Brazil	Power	Power capacity	Solar (GW)		2031	10	Decenal Energy Expansion Plan (2031)
Brazil	Transport	Transport demand	Share of biodiesel		from 2020	15%	National Biodiesel Programme (2005)
Brazil	Transport	Transport demand	Share of bioethanol		from 2020	27%	Ethanol Blending Mandate (1993)
Chile	Energy	Final energy demand	Energy efficiency	2019	2030	-10%	Ley de Eficiencia Energética (2021)
Chile	Power	Power production	Share of renewables (including large hydro)		2035	60%	Energy Plan 2050 (2016)
Chile	Power	Power production	Share of renewables (including large hydro)		2050	70%	Energy Plan 2050 (2016)
Chile	Power	Power capacity	Coal capacities reduction	2021	2025	-65%	Ley de Eficiencia Energética (2021)
Chile	Power	Power capacity	Coal phase-out		2040		Just Transition Strategy for the Energy Sector (2021)
Chile	Transport	Electric vehicles	Share in cars fleet		2050	40%	Electromobility Strategy (2017)
Pacific							
Australia	Economy	Energy productivity of the economy	Productivity increase	2015	2030	40%	National Energy Productivity Plan 2015-2030 (2015)
Australia	Power	Power production	Share of renewables		2030	42%	States legislation aggregation
Japan	Power	Power production	Share of renewables		2030	24%	NDC (2015)
Japan	Power	Power capacity	Coal phase-out		2050		Ministry of Economy, Trade and Industry (2021)
Japan	Transport	Passenger vehicles	Fleet consumption (km/L)	2016	2030	-32.4%	Adapted from fuel economy standards (2019)
Japan	Transport	Heavy vehicles	Fleet consumption (km/L)	2015	2025	-13-14%	Adapted from fuel economy standards (2019)
New Zealand	Power	Power production	Share of renewables		2025	90%	New Zealand Energy Efficiency and Conservation Strategy 2011-2016
South Korea	Energy	Electricity demand	Reduction vs BAU	BAU	2029	-14.3%	7th Basic Plan for Long-term Electricity Supply and Demand (2014)

South Korea	Power	Power production	Share of renewables	2024	10%	7th Basic Plan for Long-term Electricity Supply and Demand (2014)
South Korea	Power	Power production	Share of renewables	2030	20.8%	Renewable Energy 3020 of Korea (2017)
South Korea	Power	Power production	Share of renewables	2040	30-35%	Third Energy Master Plan (2019)
South Korea	Power	Power production	Share of LNG	2030	23.3%	Ninth Electricity Plan
South Korea	Power	Power production	Share of coal	2030	25.0%	Ninth Electricity Plan
South Korea	Power	Power production	Share of nuclear	2030	29.9%	Ninth Electricity Plan
South Korea	Power	Power capacity	Renewables (GW)	2025	42.7	Green New Deal (2020)
South Korea	Power	Power capacity	Renewables (GW)	2040	129	Third Energy Master Plan (2019)
South Korea	Transport	Electric vehicles	Number in cars fleet ('000)	2025	1,130	Green New Deal (2020)
South Korea	Transport	Electric vehicles	Number in cars fleet ('000)	2030	3,000	2nd Basic Plan for Climate Change Response (2019)
South Korea	Transport	H2 vehicles	Number in cars fleet ('000)	2025	200	Green New Deal (2020)
South Korea	Transport	H2 vehicles	Number in cars fleet ('000)	2030	850	2nd Basic Plan for Climate Change Response (2019)
Indonesia	Energy	Primary energy demand	Share of renewables	2025	23%	Government Regulation No. 79/2014 on Indonesia National Energy Policy (2014)
Indonesia	Energy	Primary energy demand	Share of renewables	2050	31%	Government Regulation No. 79/2014 on Indonesia National Energy Policy (2014)
Indonesia	Energy	Primary energy demand	Share of oil	2025	25%	Government Regulation No. 79/2014 on Indonesia National Energy Policy (2014)
Indonesia	Energy	Primary energy demand	Share of oil	2050	20%	Government Regulation No. 79/2014 on Indonesia National Energy Policy (2014)
Indonesia	Energy	Primary energy demand	Share of coal	2025	30%	Government Regulation No. 79/2014 on Indonesia National Energy Policy (2014)
Indonesia	Energy	Primary energy demand	Share of coal	2050	25%	Government Regulation No. 79/2014 on Indonesia National Energy Policy (2014)

Indonesia	Energy	Primary energy demand	Share of gas		2025	22%	Government Regulation No. 79/2014 on Indonesia National Energy Policy (2014)
Indonesia	Energy	Primary energy demand	Share of gas		2050	24%	Government Regulation No. 79/2014 on Indonesia National Energy Policy (2014)
Indonesia	Power	Power production	Share of low-carbon		2025	23%	National Electricity Plan (2018)
Indonesia	Power	Power capacity	Coal (GW)		2030	54	RUPTL 2021-2030
Indonesia	Power	Power capacity	Solar PV (GW)		2030	5	RUPTL 2021-2030
Indonesia	Power	Power capacity	Geothermal (GW)		2030	6	RUPTL 2021-2030
Indonesia	Power	Power capacity	Hydro (GW)		2030	13	RUPTL 2021-2030
Indonesia	Transport	Electric vehicles	Number in cars fleet ('000)		2030	2,000	6th ASEAN Energy Outlook - Presidential Regulation 55/2019
Asia							
China	Energy	Primary energy demand	Share of non-fossil		2025	20%	Energy Development Strategy Action Plan (2014-2020) (2014)
China	Energy	Primary energy demand	Energy intensity reduction	2020	2025	-14%	Energy Development Strategy Action Plan (2014-2020) (2014)
China	Power	Power capacity	Nuclear (GW)		2025	70	Energy Development Strategy Action Plan (2014-2020) (2014)
China	Transport	New passenger vehicles	Fuel consumption reduction	2020	2025	-20%	Phase V standards (2019)
China	Transport	New passenger vehicles	Share of BEV, PHEV and Fuel Cells Vehicles in sales		2025	25%	New Energy Vehicle development plan (2020)
India	Power	Power capacity	Biomass (GW)		2022	10	India's Union Budget 2015-2016
India	Power	Power capacity	Solar (GW)		2022	100	India's Union Budget 2015-2016
India	Power	Power capacity	Wind (GW)		2022	60	India's Union Budget 2015-2016
India	Power	Power capacity	Small hydro (GW)		2022	5	India's Union Budget 2015-2016
Thailand	Energy	Primary energy demand	Reduction of energy intensity	2010	2036	-30%	Energy Efficiency Plan (2015)
Thailand	Energy	Primary energy demand	Share of renewables		2036	30%	Alternative Energy Development Plan (2015)
Thailand	Energy	Final energy demand	Demand reduction	2018	2036	-6%	Alternative Energy and Power Development Plan (2018)
Thailand	Energy	Final energy demand	Share of renewables		2036	30%	Alternative Energy and Power Development Plan (2018)

Thailand	Energy	Heat generation	Share of renewables		2036	35%	Alternative Energy and Power Development Plan (2018)
Thailand	Power	Power production	Share of renewables		2036	20%	Power Development Plan (2015)
Thailand	Power	Power production	Share of coal		2036	12%	Alternative Energy and Power Development Plan (2018)
Thailand	Power	Power production	Share of gas		2036	53%	Alternative Energy and Power Development Plan (2018)
Thailand	Transport	Transport demand	Share of renewables		2036	35%	Alternative Energy and Power Development Plan (2018)
Malaysia	Power	Power capacity	Share of renewables		2025	20%	National Renewable Energy Policy (2009)
Vietnam	Power	Power production	Share of renewables		2030	15-20%	National Energy Development Strategy (2021)
Vietnam	Power	Power production	Share of renewables		2045	25-30%	National Energy Development Strategy (2021)
Vietnam	Power	Power capacity	Coal (GW)		2030	31	Just Energy Transition Partnership (2022)
Vietnam	Power	Power capacity	Additional coal	2021	2035	30	Power Development Plan 8 (2021)
Vietnam	Power	Power capacity	Additional gas	2021	2030	12	Power Development Plan 8 (2021)
Vietnam	Power	Power capacity	Additional gas	2021	2045	34	Power Development Plan 8 (2021)
CIS							
Russia	Power	Power production	Share of renewables		2024	20%	Resolution of the Government No. 1-r of 8 January 2009
Russia	Power	Power capacity	Renewables (excluding hydro) (GW)		2025	5.4	Capacity Supply Agreement for Renewable Energy Sources (CSA-RES) 1.0
Russia	Power	Power capacity	Additional solar (GW)	2025	2035	2.2	Adapted from the new program of contracts for the supply of capacity (DPM) (2019)
Russia	Power	Power capacity	Additional wind (GW)	2025	2035	3	Adapted from the new program of contracts for the supply of capacity (DPM) (2019)
Russia	Power	Power capacity	Additional small Hydro (GW)	2025	2035	0.17 (not reached)	Adapted from the new program of contracts for the supply of capacity (DPM) (2019)

Russia	Buildings	Residential heat consumption	Consumption reduction	2014	2030	-20% (not reached)	Strategy for building materials (2016)
Ukraine	Power	Power production	Share of renewables (including hydro)		2035	25%	Energy Strategy (2017)
Ukraine	Power	Power production	Share of nuclear		2035	50%	Energy Strategy (2017)
Middle East							
Turkey	Energy	Primary energy demand	Demand reduction	2017	2023	-14.0%	Energy Efficiency Action Plan (2018)
Turkey	Energy	Final energy consumption	Share of renewables		2023	20.5%	National Renewable Energy Action Plan (2014)
Turkey	Power	Power production	Share of renewables		2023	38.8%	Energy Strategy Plan 2010-2014 (2011)
Turkey	Power	Power capacity	Hydro (GW)		2023	34	National Renewable Energy Action Plan (2014)
Turkey	Power	Power capacity	Solar (GW)		2023	5	National Renewable Energy Action Plan (2014)
Turkey	Power	Power capacity	Wind (GW)		2023	20	National Renewable Energy Action Plan (2014)
Turkey	Power	Power capacity	Biomass (GW)		2023	1	National Renewable Energy Action Plan (2014)
Turkey	Power	Power capacity	Geothermal (GW)		2023	1	National Renewable Energy Action Plan (2014)
Saudi Arabia	Energy	Primary energy demand	Share of renewables		2030	10% (not reached)	Energy markets mechanism (2012)
Saudi Arabia	Energy	Electricity	Electricity intensity reduction	2005	2030	-30%	Vision 2030 (2016)
Saudi Arabia	Energy	Electricity	Energy efficiency increase	2005	2030	30%	National Energy Efficiency program (2013)
Saudi Arabia	Power	Power capacity	Renewables (GW)		2023	27.3 (not reached)	Vision 2030 (2016)
Saudi Arabia	Power	Power capacity	Renewables (GW)		2030	59	Vision 2030 (2016)
Saudi Arabia	Power	Power capacity	Wind (GW)		2030	16	Vision 2030 (2016)
Saudi Arabia	Power	Power capacity	PV (GW)		2030	40	Vision 2030 (2016)
Saudi Arabia	Power	Power capacity	CSP (GW)		2030	3	Vision 2030 (2016)
Saudi Arabia	Power	Power capacity	Nuclear (GW)		2030	3	Vision 2030 (2016)
Africa							

South Africa	Power	Power capacity	Solar (GW)		2030	9	Integrated Resource Plan (2010, updated 2013)
South Africa	Power	Power capacity	Wind (GW)		2030	9	Integrated Resource Plan (2010, updated 2013)
South Africa	Power	Power capacity	Coal remaining (GW)		2022	32	Integrated Resource Plan (2010, updated 2013)
South Africa	Power	Power capacity	Coal remaining (GW)		2030	27	Integrated Resource Plan (2010, updated 2013)
South Africa	Power	Power capacity	Coal remaining (GW)		2050	3	Integrated Resource Plan (2010, updated 2013)
South Africa	Power	Power capacity	Additional renewables (GW)	2012	2020	5	Renewable Energy Independent Power Producer Procurement Programme (REI4P)
South Africa	Buildings	Final energy demand	Consumption reduction	2015	2030	-33% (not reached)	Post-2015 National Energy Efficiency Strategy

Table 2: Reference Scenario – GHG-related policies

Region	Sector	GHG	Subsector	Target	Base year	Target year	Objective	Source
Europe								
EU	Transport	All GHG	Transport	% reduction in 2050 vs 1990	1990	2050	-60%	European Strategy for low-emission mobility
EU	Transport	CO2	Road transport	% reduction in 2030 vs 2005	2005	2030	-23%	European Commission, DG Energy
EU	All excl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 1990	1990	2030	-55%	Fit for 55 (2021)
EU	ETS sectors	All GHG	Emissions reduction	% reduction in 2030 vs 2005	2005	2030	-61%	European Commission, DG Energy
EU	ETS sectors	All GHG	Emissions reduction	% reduction in 2050 vs 2005	2005	2050	-73%	European Commission, DG Energy
EU	Non-ETS sectors	All GHG	Emissions reduction	% reduction in 2030 vs 2005	2005	2030	-40%	European Commission, DG Energy
EU	Transport	All GHG	GHG intensity reduction	% reduction in 2030 vs 2022	2022	2030	-13%	European Commission, DG Energy
EU	LULUCF	All GHG	LULUCF	Emissions budget (MtCO2eq)		2030	310	European Commission, DG Energy
Pacific								
Australia	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2005	2005	2030	-28%	NDC (2021)
North America								
United States	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2005	2005	2030	-40%	Rhodium Group (2022)
United States	Power	All GHG	Power production	% reduction in 2030 vs 2005	2005	2030	-70%	Resources For the Future (2022)
United States	Oil & Gas	CH4	Oil & gas production	% reduction in 2025 vs 2012	2012	2025	-45%	Environmental Protection Agency (EPA) (2016)
Central & South America								
Pacific								
Japan	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2013	2013	2030	-26%	NDC (2015)
Japan	All incl LULUCF	F-gases	Emissions reduction	% reduction in 2030 vs 2013 (HFC, PFC, SF6, NF3)	2013	2030	-25.1% (not reached)	NDC (2015)
Asia								
China	Industry	CO2	CO2 emissions per unit of industrial added value	Carbon intensity reduction	2015	2025	-40%	14th Five-Year Plan (2021)

Vietnam	Energy	All GHG	Emissions reduction	% reduction vs BAU	BAU	2030	-15%	National Renewable Energy Action Plan 2020 (2014)
Vietnam	Energy	All GHG	Emissions reduction	% reduction vs BAU	BAU	2045	-20%	National Renewable Energy Action Plan 2020 (2014)
CIS								
Ukraine	Energy	CO2	Fuel use	Carbon intensity reduction	2010	2025	-10%	National Renewable Energy Action Plan 2020 (2014)
Ukraine	Energy	CO2	Fuel use	Carbon intensity reduction	2010	2030	-15%	National Renewable Energy Action Plan 2020 (2014)
Ukraine	Energy	CO2	Fuel use	Carbon intensity reduction	2010	2035	-20%	National Renewable Energy Action Plan 2020 (2014)
Africa								
South Africa	Power	CO2	Power production	Emissions budget (MtCO2eq)		2025	275	Integrated Resource Plan (2019)

Table 3: NDC-LTS Scenario – Energy-related policies

Region	Sector	GHG	Subsector	Target	Base year	Target year	Objective	Source
Europe								
EU	Power		Power production	Nuclear phase-out for some countries				Countries commitment
EU	Power		Power production	No more construction of nuclear plants				Countries commitment
EU	Power		Power production	Coal phase-out (does not apply to IGCC, CCS)				Countries commitment
United Kingdom	Power		Power production	Coal phase-out (does not apply to IGCC, CCS)				Countries commitment
North America								
Central & South America								
Brazil	Energy		Primary energy demand	Share of renewables (including large hydro)		2030	45%	NDC (2016)
Brazil	Energy		Primary energy demand	Share of renewables (excluding large hydro)		2030	33%	NDC (2016)
Brazil	Energy		Primary energy demand	Share of biomass		2030	18%	NDC (2016)
Brazil	Power		Power production	Share of renewables (excluding large hydro)		2030	23%	NDC (2016)
Brazil	Transport		Transport demand	Share of biodiesel		2023	15%	Government announcement (2022)
Pacific								
South Korea	Power		Power production	Nuclear: no further extensions, no new reactors		2050	0	Third Energy Master Plan (2019)
South Korea	Power		Power production	Coal: drastically reduced		2050	0	Third Energy Master Plan (2019)
Asia								
China	Energy		Primary energy demand	Share of non-fossil		2030	25%	NDC (2021)
China	Power		Power capacity	Wind and solar (GW)		2030	1.2	NDC (2021)
India	Power		Power capacity	Share of non-fossil		2030	40%	NDC (2016)
India	Power		Power capacity	Renewables (GW)		2030	450	NDC (2019)
India	Power		Power capacity	Solar (GW)		2030	300	NDC (2019)
India	Power		Power capacity	Wind (GW)		2030	140	NDC (2019)

Thailand	Power	Power capacity	Share of renewables		2050	50%	LTS (2021)
Thailand	Transport	Electric vehicles	Share in cars sales		2035	69%	LTS (2021)
Vietnam	Power	Power capacity	Share of renewables		2030	50%	Just Energy Transition Partnership (2022)
Vietnam	Power	Power capacity	No coal new plants after 2030		2030		National Climate Change Strategy (2022)
Vietnam	Power	Power capacity	Reduction of coal fleet after 2035		2035		National Climate Change Strategy (2022)
CIS							
Russia	Energy	Hydrogen	Hydrogen production for export		2024	0.2	Energy Strategy to 2035 (2020)
Russia	Energy	Hydrogen	Hydrogen production for export		2035	2.0	Energy Strategy to 2035 (2020)
Middle East							
Saudi Arabia	Energy	Hydrogen	Hydrogen production (green and blue)		2030	4	NDC (2021)
Saudi Arabia	Energy	Hydrogen	Hydrogen production (green)		2025	0.237	Neom Helios project
Saudi Arabia	Power	Power production	Share of renewables		2030	50%	NDC (2021)
Turkey	Power	Power production	Transmission losses in 2030		2030	15%	NDC (2022)
Turkey	Power	Power capacity	Solar (GW)		2030	10	NDC (2022)
Turkey	Power	Power capacity	Wind (GW)		2030	16	NDC (2022)
Africa							
South Africa	Power	Power capacity	Added renewables in 2025 from 2012 (GW)	2012	2025	12	NDC (2016)
South Africa	Transport	Hybrid vehicles	Share in cars fleet	2016	2030	20%	NDC (2016)
South Africa	Transport	Electric vehicles	Number in cars fleet ('000)	2016	2050	15	NDC (2016)
Bunkers							
Aviation	Aviation	Fuel efficiency	Improvement of at least 2% per year from 2005	2005	2030	-40% (not reached)	ICAO (2019)
Aviation	Aviation	Fuel efficiency	Improvement of at least 2% per year from 2005	2005	2040	-51% (not reached)	ICAO (2019)
Aviation	Aviation	Fuel efficiency	Improvement of at least 2% per year from 2005	2005	2050	-60% (not reached)	ICAO (2019)
Aviation	Aviation	Fuel consumption	Share of biofuels and e-fuels		2025	2%	IATA (2021)
Aviation	Aviation	Fuel consumption	Share of biofuels and e-fuels		2030	5.2%	IATA (2021)

Aviation	Aviation	Fuel consumption	Share of biofuels and e-fuels		2035	17% (not reached)	IATA (2021)
Aviation	Aviation	Fuel consumption	Share of biofuels and e-fuels		2040	39% (not reached)	IATA (2021)
Aviation	Aviation	Fuel consumption	Share of biofuels and e-fuels		2045	54% (not reached)	IATA (2021)
Aviation	Aviation	Fuel consumption	Share of biofuels and e-fuels		2050	65% (not reached)	IATA (2021)
Aviation	Aviation	Fleet	Electric and H2 aircrafts market entry		2035		IATA (2021)
Aviation	Aviation	Activity (passenger and freight)	Share of H2 and electric		2050	13%	IATA (2021)
Maritime	Maritime	Carbon intensity reduction	% reduction of tCO2 per tkm	2008	2030	-40%	IMO (2018)
Maritime	Maritime	Carbon intensity reduction	% reduction of tCO2 per tkm	2008	2050	-70%	IMO (2018)

Table 4: NDC-LTS Scenario – GHG-related policies

Region	Sector	GHG	Subsector	Target	Base year	Target year	Objective	Source
Europe								
EU	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2050		2050	0	LTS (2020)
EU	Transport	All GHG	Emissions reduction	% reduction in 2050 vs 1990	1990	2050	-90%	European Green Deal (2019)
United Kingdom	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 1990	1990	2030	-68%	NDC (2020)
United Kingdom	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2050		2050	0	LTS (2021)
Switzerland	All excl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 1990	1990	2030	-50%	NDC (2020)
Switzerland	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2050		2050	0	LTS (2021)
Norway	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 1990	1990	2030	-55%	NDC (2020)
Norway	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2050 vs 1990	1990	2050	-95%	LTS (2019)
North America								
Canada	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2005	2005	2030	-43%	NDC (2021)
Canada	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2050		2050	0	NDC (2021)
Mexico	All incl LULUCF excl absorption	All GHG	Emissions reduction vs BAU	% reduction in 2030 vs BAU		BAU 2030	-36%	NDC (2020)
Mexico	All incl LULUCF excl absorption	All GHG	Emissions peak year	Peak before		2026	100%	NDC (2020)
Mexico	All incl LULUCF excl absorption	All GHG	Emissions intensity per GDP	% reduction in 2030 vs 2013	2013	2030	-40%	NDC (2020)
Mexico	All incl LULUCF excl absorption	All GHG	Emissions reduction	% reduction in 2050 vs 2000	2000	2050	-50%	NDC (2015)
United States	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2025 vs 2005	2005	2025	-28%	NDC (2021)
United States	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2005	2005	2030	-52%	NDC (2021)
United States	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2050		2050	0	LTS (2021)
Central & South America								
Argentina	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2007	2007	2030	-19%	NDC (2020)
Argentina	All excl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	-2%	NDC (2020)
Argentina	All incl LULUCF	CO_2	Net-zero emissions	Emissions 2050	1990	2050	0	NDC (2021)
Brazil	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2025 vs 2005	2005	2025	-37%	NDC (2020)

Brazil	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2005	2005	2030	-50%	NDC (2021)
Brazil	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2050		2050	0	Brazilian Administration (2021)
Chile	All excl LULUCF	All GHG	Emissions budget	Emissions budget (MtCO2eq)		2030	95	NDC (2020)
Chile	All excl LULUCF	All GHG	Emissions budget	Budget over 2020-2030 (MtCO2eq)	2020	2030	1,100	NDC (2020)
Chile	All excl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2016	2016	2030	-45%	NDC (2020)
Chile	All excl LULUCF	All GHG	Emissions peak year	Peak before		2025	100%	NDC (2020)
Chile	All incl LULUCF	All GHG	Black carbon emissions	% reduction in 2030 vs 2016	2016	2030	-25%	NDC (2020)
Chile	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2050		2050	0	NDC (2020)
Chile	AFOLU	All GHG	Emissions reduction	% reduction in 2030 vs average 2001-2013	av. 2001-2013	2030	-25%	NDC (2020)
Rest of Central America	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	9%	NDC (2017-2021)
Rest of South America	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	8%	NDC (2017-2021)
Pacific								
Australia	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2015	2005	2030	-43%	NDC (2022)
Australia	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2050	1990	2050	0	LTS (2021)
New-Zealand	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2005	2005	2030	-50%	NDC (2021)
New-Zealand	All incl LULUCF	All GHG, exc CH4	Net-zero emissions	Emissions 2050		2050	0	LTS (2021)
New-Zealand	All incl LULUCF	CH4	Emissions reduction	% reduction in 2050 vs 2017	2017	2050	-47%	NDC (2021)
Japan	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2013	2013	2030	-46%	NDC (2021)
Japan	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2050		2050	0	NDC (2021)
Japan	Energy	CO2	Emissions reduction	% reduction in 2030 vs 2013	2013	2030	-45.2%	NDC (2021)
Japan	Non-energy	CO2	Emissions reduction	% reduction in 2030 vs 2013	2013	2030	-14.9%	NDC (2021)
Japan	All incl LULUCF	CH4	Emissions reduction	% reduction in 2030 vs 2013	2013	2030	-11%	NDC (2021)
Japan	All incl LULUCF	N2O	Emissions reduction	% reduction in 2030 vs 2013	2013	2030	-16.8%	NDC (2021)
Japan	All incl LULUCF	F-gases	Emissions reduction	% reduction in 2030 vs 2013	2013	2030	-27%	NDC (2021)
South Korea	All incl LULUCF	All GHG exc NF3	Emissions reduction	% reduction in 2030 vs 2018	2018	2030	-40%	NDC (2021)
South Korea	All incl LULUCF	All GHG exc NF3	Net-zero emissions	Emissions 2050		2050	0	LTS (2020)

Indonesia	All incl LULUCF	All GHG	Emissions budget	Emissions budget (MtCO2eq)		2030	1,683	NDC (2021)
Indonesia	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs BAU	BAU	2030	-41%	NDC (2021)
Indonesia	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2060		2060	0	LTS (2021)
Indonesia	Power	All GHG	Emissions peak year	Peak before, with budget (MtCO2eq)		2030	290	Just Energy Transition Partnership (2022)
Indonesia	AFOLU	All GHG	AFOLU	Emissions budget (MtCO2eq)		2030	180	NDC (2021)
Rest of Pacific	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	130%	NDC (2020)
Asia								
China	All excl non-CO2 sectors	CO2	Emissions per unit of GDP reduction	% reduction in 2030 vs 2005	2005	2030	-65%	NDC (2020)
China	All excl non-CO2 sectors	CO2	Emissions peak	Peak before		2030	100%	NDC (2020)
China	All incl LULUCF	CO2	Net-zero emissions	Emissions 2060		2060	0	LTS (2021)
India	All incl LULUCF	All GHG	Emissions per unit of GDP reduction	% reduction in 2030 vs 2005	2005	2030	-45%	NDC (2022)
India	All incl LULUCF	All GHG	Carbon neutrality	Emissions 2070		2070	0	NDC (2022)
India	Absorption	All GHG, exc CH4	Emissions budget	Over 2020-2030 (GtCO2eq)	2020	2030	2.5-3	NDC (2016)
Vietnam	All excl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs BAU	BAU	2030	-27%	NDC (2020)
Vietnam	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs BAU		2030	-43.5%	NDC (2022)
Vietnam	All incl LULUCF	All GHG	Emissions peak year	Peak before		2035		National Climate Change Strategy to 2050 (2022)
Vietnam	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2050		2050	0	National Climate Change Strategy to 2050 (2022)
Vietnam	Energy	All GHG	Emissions reduction	% reduction in 2030 vs BAU		2030	-24.4%	NDC (2022)
Vietnam	Power	All GHG	Emissions peak year	Peak before, with budget (MtCO2eq)		2030	170 (budget not reached)	NDC (2022)
Thailand	All excl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs BAU		2030	-20%	NDC (2020)
Thailand	All incl LULUCF	All GHG	Emissions peak year	Peak before, with budget (MtCO2eq)		2030	370	LTS (2021)
Thailand	All incl LULUCF	All GHG	Emissions budget	Emissions budget (MtCO2eq)		2050	200	LTS (2021)
Thailand	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2065		2065	0	LTS (2021)
Malaysia	All incl LULUCF	All GHG	Emissions intensity reduction	% reduction vs GDP	2005	2030	-45%	NDC (2021)

Rest of South Asia	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	97%	NDC (2016-2021)
Rest of South-East Asia	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	-11%	NDC (2015-2021)
CIS								
Russia	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 1990	1990	2030	-30%	NDC (2020)
Russia	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2050 vs 1990	1990	2050	-80%	NDC (2021)
Russia	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2060		2060	0	NDC (2021)
Ukraine	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 1990	1990	2030	-65%	NDC (2021)
Ukraine	All incl LULUCF	All GHG	Net-zero emissions	Emissions 2060		2060	0	NDC (2021)
Rest of Central Europe	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	31%	NDC (2016-2021)
Rest of CIS	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	12%	NDC (2016-2021)
Middle East								
Saudi Arabia	All excl LULUCF	All GHG	Emissions reduction	Reduction vs BAU (MtCO2eq)	2019	2030	-278	NDC (2021)
Saudi Arabia	All incl LULUCF	All GHG, exc CH4	Net-zero emissions	Emissions 2060	1990	2060	0	NDC (2021)
Saudi Arabia	All excl LULUCF	CO2	CCS	CO2 captured (MtCO2eq)		2030	44 (not reached)	NDC (2021)
Saudi Arabia	All incl LULUCF	CH4	Emissions reduction	% reduction in 2030 vs 2020	2020	2030	-30%	NDC (2021)
Turkey	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs BAU	BAU	2030	-21%	NDC (2021)
Turkey	All incl LULUCF	All GHG, exc CH4	Net-zero emissions	Emissions 2053	1990	2053	0	NDC (2021)
Egypt	Power	All GHG	Power	Emissions budget (MtCO2eq)		2030	144.8	NDC (2022)
Egypt	Transport	All GHG	Transport	Emissions budget (MtCO2eq)		2030	115.4	NDC (2022)
Egypt	Oil & Gas	All GHG	Oil & Gas	Emissions budget (MtCO2eq)		2030	0.89	NDC (2022)
Mediterranean Middle East	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	0%	NDC (2016-2021)
Rest of Persian Gulf	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	44%	NDC (2015-2021)
Africa								
South Africa	All incl LULUCF	All GHG	Emissions budget	Emissions budget (MtCO2eq)		2030	350	NDC (2021)

South Africa	All incl LULUCF	All GHG (exc. SF6 and NF3)	Net-zero emissions	Emissions 2050		2050	0	NDC (2021)
South Africa	Power	CO2	Net-zero emissions	Emissions 2050		2050	0	NDC (2021)
South Africa	Coal to liquids	CO2	CCS from coal-to-liquid plant	CO2 captured (MtCO2eq)		2030	23 (not reached)	NDC (2021)
Algeria and Libya	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	-19%	NDC (2016)
Morocco and Tunisia	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	-3%	NDC (2021)
Rest of Sub-Saharan Africa	All incl LULUCF	All GHG	Emissions reduction	% reduction in 2030 vs 2010	2010	2030	4%	NDC (2021)
Bunkers								
Aviation	Aviation	CO2	Emissions reduction	Emissions 2050		2050	0 (not reached)	ICAO (2021)
Maritime	Maritime	All GHG	Emissions reduction	% reduction in 2050 vs 2008	2008	2050	-50%	IMO (2018)

Annex 2: Description of POLES-JRC

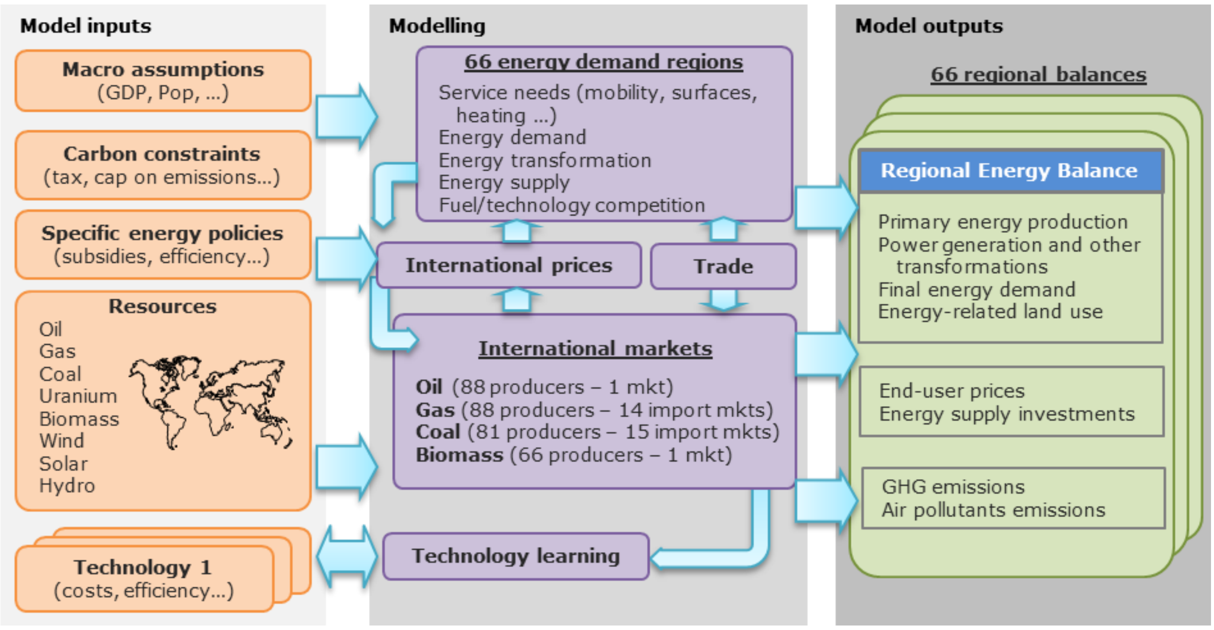
For a more comprehensive description of the model, see (Després, Keramidas, Schmitz, Kitous, & Schade, 2018).

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 62).

The model provides full energy and emission balances for 66 countries or regions worldwide (including an explicit representation of OECD and G20 countries), 14 fuel supply branches and 15 final demand sectors.

This exercise used the POLES-JRC 2019 version as a starting point. Differences with other exercises done with the POLES-JRC model, or with exercises by other entities using the POLES model.

Figure 62. 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: chemicals (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).

The electricity price by sector depends on the evolution of the power mix, of the load curve and of 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 specialised model GLOBIOM-G4M (Global Biosphere Management Model). Biomass can be traded, either in solid form or as liquid biofuel.

Wind, solar and other renewables

They are associated with potentials and supply curves per country.

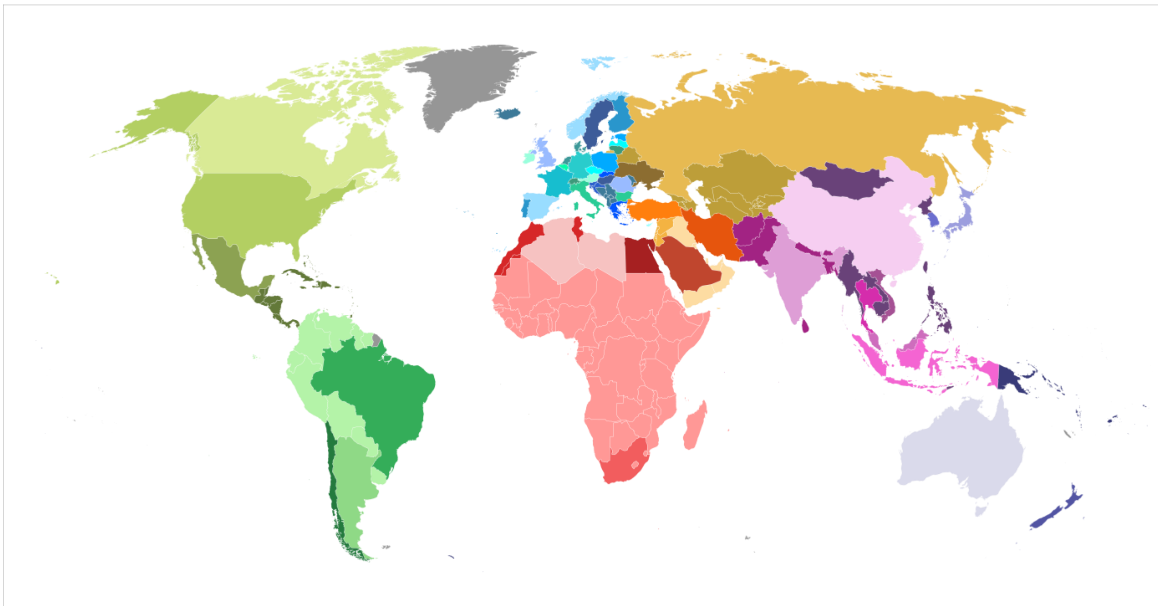
GHG emissions

CO_2 emissions from fossil fuel combustion are derived directly from the projected energy balance. Other GHGs from energy and industry are simulated using activity drivers identified in the model (e.g. sectoral value added, mobility per type of vehicles, fuel production, fuel consumption) and abatement cost curves. GHG from agriculture and LULUCF are derived from GLOBIOM-G4M lookup tables.

Countries and regions

The model decomposes the world energy system into 66 regional entities: 54 individual countries and 12 residual regions see Figure 63, to which international bunkers (air and maritime) are added.

Figure 63. POLES-JRC model regional detail map (for energy balances)



Source: POLES-JRC model

Table 5. 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 Kingdom	Slovenia
United States	Spain
Vietnam	Sweden

Note: Hong-Kong and Macau are included in China.
Source: POLES-JRC model.

Table 6. Country mapping for the 12 regions in POLES-JRC (for energy balances)

Rest Central America	Rest Balkans	Rest Sub-Saharan Africa (continued)	Rest South Asia
Bahamas	Albania	Burkina Faso	Afghanistan
Barbados	Bosnia-Herzegovina	Burundi	Bangladesh
Belize	Kosovo	Cameroon	Bhutan
Bermuda	Macedonia	Cape Verde	Maldives
Costa Rica	Moldova	Central African Republic	Nepal
Cuba	Montenegro	Chad	Pakistan
Dominica	Serbia	Comoros	Seychelles
Dominican Republic	Rest CIS	Congo	Sri Lanka
El Salvador	Armenia	Congo DR	Rest South East Asia
Grenada	Azerbaijan	Cote d'Ivoire	Brunei
Guatemala	Belarus	Djibouti	Cambodia
Haiti	Georgia	Equatorial Guinea	Lao PDR
Honduras	Kazakhstan	Eritrea	Mongolia
Jamaica	Kyrgyz Rep.	Ethiopia	Myanmar
Nicaragua	Tajikistan	Gabon	North Korea
NL Antilles and Aruba	Turkmenistan	Gambia	Philippines

Panama	Uzbekistan	Ghana	Singapore
Sao Tome and Principe	**Mediterranean Middle East**	Guinea	Taiwan
St Lucia	Israel	Guinea-Bissau	**Rest Pacific**
St Vincent & Grenadines	Jordan	Kenya	Fiji Islands
Trinidad and Tobago	Lebanon	Lesotho	Kiribati
Rest South America	Syria	Liberia	Papua New Guinea
Bolivia	**Rest of Persian Gulf**	Madagascar	Samoa (Western)
Colombia	Bahrain	Malawi	Solomon Islands
Ecuador	Iraq	Mali	Tonga
Guyana	Kuwait	Mauritania	Vanuatu
Paraguay	Oman	Mauritius	
Peru	Qatar	Mozambique	
Suriname	United Arab Emirates	Namibia	
Uruguay	Yemen	Niger	
Venezuela	**Morocco & Tunisia**	Nigeria	
	Morocco	Rwanda	
	Tunisia	Senegal	
	Algeria & Libya	Sierra Leone	
	Algeria	Somalia	
	Libya	Sudan	
	Rest Sub-Saharan Africa	Swaziland	
	Angola	Tanzania	
	Benin	Togo	
	Botswana	Uganda	
		Zambia	

Source: POLES-JRC model.

Table 7. POLES-JRC model historical data and projections

Series		Historical data	GECO Projections
Population		(European Commission, 2021), (Eurostat, 2021)	
GDP, growth		(World Bank, 2019); (IMF, 2021) (IMF, 2020)	(OECD, 2014) and (OECD, 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. LULUCF)	EDGAR	POLES-JRC model, GLOBIOM-G4M model
	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: EC JRC, WEC, IEA, TECHPOL database	

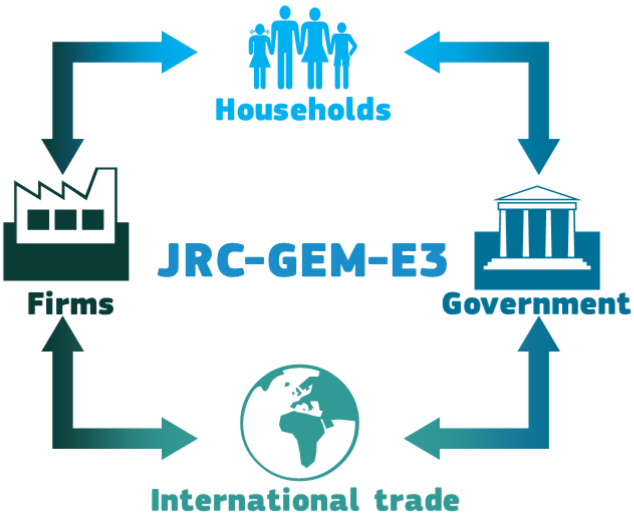
Source: Own elaboration

Annex 3: Description of JRC-GEM-E3

Brief description of main features

The JRC-GEM-E3 model is a global, multi-region, multi-sector, dynamic-recursive computable general equilibrium (CGE) model designed to analyse energy, climate and environmental policies (Capros, et al., 2013).[26] The agents in the model are households, firms and governments (Figure 64). Households that are endowed with factor and spend their income on consumption and savings. Firms produce goods and services using production factors and intermediate inputs. Different regions in the model are connected by international trade. Governments collect taxes, pay subsidies and undertake government consumption.

Figure 64. Schematic overview of the JRC-GEM-E3 model



Source: Own elaboration

The model version used in GECO 2022 is aggregated into 31 sectors, see Table 8, including crude oil, refined oil, gas, coal and electricity generation, the latter further disaggregated into 8 generation technologies. The generation technologies are modelled using a Leontief production function, production in other sectors are described by nested constant elasticity of substitution (CES) production functions. We represent 22 regions and the 27 EU member states, see Table 9. Bilateral international trade flows between these regions are modelled following the Armington formulation and linkages between sectors are included based on the GTAP10a data, described in (Aguiar, Chepeliev, Corong, MacDougall, & Van der Mensbrugghe, 2019).

Production factors labour and capital are assumed to be mobile between sectors, but not between regions. Baseline labour supply and unemployment rates are calibrated to the 2021 Ageing Report (European Commission, 2021) for the EU, and to projections by the International Labour Organisation (ILO, 2017) for non-EU regions. The analyses done for this report build on the assumption of flexible wages, abstracting from short-term rigidities. Investments are determined by the rental price of capital and the cost of the investment good. Holding the real interest rate fixed allows a variation of the balance of payments.

A consumption matrix (Cai & Vandyck, 2020) translates final consumption of production sectors into consumption by purpose. Purchases of durables (vehicles and appliances) are determined by the price of the durable goods and the price of the cost of operation, while purchases linked to the operation of these durables (operation of vehicles and household energy, respectively) are determined by the stock of durables and the cost of operation (Capros, et al., 2013). Household's purchases of the different consumption categories are governed by a Stone-Geary utility function.

[26] See also https://ec.europa.eu/jrc/en/gem-e3.

Table 8. Sectors in the JRC-GEM-E3 model

Sector name		Sector name		Sector name	
Crops	01	Non-metallic Minerals	11	Non-market Services	21
Coal	02	Electric Goods	12	Coal-fired Electricity	22
Crude Oil	03	Transport Equipment	13	Oil-fired Electricity	23
Oil	04	Other Equipment Goods	14	Gas-fired Electricity	24
Gas	05	Consumer Goods Industries	15	Nuclear Electricity	25
Electricity Supply	06	Construction	16	Biomass Electricity	26
Ferrous Metals	07	Transport (Air)	17	Hydro Electricity	27
Non-ferrous Metals	08	Transport (Land)	18	Wind Electricity	28
Chemical Products	09	Transport (Water)	19	Solar Electricity	29
Paper Products	10	Market Services	20	Livestock	30
				Forestry	31

Source: Own elaboration

All GHGs other than CO2 from land use (change) and forestry are covered in the model. Besides CO2 emitted from fossil fuel combustion and industrial processes, all non-CO2 Kyoto GHGs are modelled explicitly in JRC-GEM-E3: methane (CH4), nitrous oxide (N2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulphur hexafluoride (SF6). Abatement of non-CO2 emissions, industrial process emissions and through CCS is implemented by preserving various bottom up technologies in JRC-GEM-E3 (Weitzel, Saveyn, & Vandyck, 2019).

A baseline (reference) is constructed by generating input-output tables based on the initial base year provided by GTAP and projections for economic activities, energy use and emissions. In this way, the economic starting point for the analysis is closely resembling that of energy models POLES-JRC, as described in more detail in the next section. In addition, we also use several inputs from the energy models in the construction of the scenarios (see following section).

Table 9. Regional aggregation of the JRC-GEM-E3 model

Regions in the JRC-GEM-E3 model	Abbreviation
European Union	EU27
United Kingdom	GBR
United States	USA
Japan	JPN
Canada	CAN
Australia	AUS
Russian Federation	RUS
Brazil	BRA
China	CHN
India	IND
Korea	KOR
Saudi Arabia	SAU
Turkey	TUR
South Africa	SAF
Mexico	MEX
Argentina	ARG
Indonesia	IDN
EFTA	EFA
Middle East	MEA
Africa	AFR
Other Americas	OAM
Other Asia	OAS
Rest of Eurasia	REA

Source: Own elaboration

Reference construction

The macroeconomic balances for a reference scenario are constructed on the basis of a variety of data sources, in particular achieving an integration of macroeconomic forecasts with energy balances from the POLES-JRC model, see (Rey Los Santos, et al., 2018) and (Wojtowicz, et al., 2019). In simple terms, our integration approach uses the Platform to Integrate, Reconcile and Align Model-based Input-output Data (PIRAMID) to construct input-output tables for future years in 5-year-steps, using a balancing procedure that ensures consistency of the various data sources within a National Accounting framework. We extend the procedure, commonly known as RAS procedure, to include data from various sources in a multi-regional context (hence, multi-regional generalised RAS, or MRGRAS) (Temursho U., et al., 2021).

The main data sources for the version used in GECO 2022 include:

- The input-output tables and the data on bilateral trade flows are derived from the Global Trade Analysis Project (GTAP) 10 database (Aguiar, Chepeliev, Corong, MacDougall, & Van der Mensbrugghe, 2019). We aggregate the GTAP data to 31 commodities and the regions listed in Table 9.
- GDP growth rates are assumed to be the same as in the POLES-JRC model. The GDP assumptions 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. Short term unemployment projections were taken from IMF as the ILO projections do not include the effects of Covid-19, implying the implicit assumption that Covid-19 will not have an effect on long-term unemployment. For the EU27, data from the 2021 Ageing report (European Commission, 2021) was used.
- Energy and emission data using energy balances from POLES-JRC. 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 scenario between the POLES-JRC and JRC-GEM-E3 models.

Scenario implementation

In the policy scenarios, we are implementing a constraint on which is achieved by implementing a carbon tax. In harmonizing the emissions between models, carbon prices (e.g. in the 1.5°C Scenario) may differ between regions that would have the same carbon prices in POLES-JRC. In reaction to the emission prices, the model is adjusting endogenously the inputs to the production process, switching between different fuels of varying emission intensity, decreasing the input of energy at the expense of additional capital and labour inputs, reducing the use of emission intensive products and applying end of pipe abatement (CCS and non-CO_2 emissions).

In addition to carbon taxes, decarbonisation options for some sectors are implemented by adjusting model parameters in JRC-GEM-E3 based on changes in POLES-JRC. This "soft-link" can help to better align both models and better capture mitigation responses in complex sectors that are represented in more detail in energy models (Weitzel, et al., 2023). Specifically, information is used to adjusting input shares in production functions of JRC-GEM-E3 via a one-way soft-link (Delzeit, et al., 2020), without feeding information (e.g. on activity levels back to POLES-JRC). In order to not only capture the changes in the energy mix in particular sectors, information on costs are also added. There are three main sectors where we make use of this approach: electricity generation, commercial transport sectors, and household energy use (transport and other use, including heating).

For electricity generation, we replace the JRC-GEM-E3 production function that aggregates electricity from the different generation technologies into a single supply sector through a Leontief function and adjust the share parameters based on electricity generation as projected by POLES-JRC.

In commercial transport sectors (aviation, land transport, water transport), fuel use of different energy carriers is imposed exogenously by collapsing the energy nest of the CES production function into a Leontief aggregation and adjusting the share parameters to reflect changes in the fuel mix and efficiency improvements. We account for a more expensive vehicle fleet by adjusting the non-fuel part of the production function of the transport sectors.

For energy use by private households, a similar approach is used for energy used for private transportation and for other energy use, including heating. For private transportation, the shares of different fuels are adjusted in the consumption matrix based on energy modelling results, reflecting a shift towards cleaner transportation. Any additional cost to change the existing fleet by introducing a higher share of more efficient or electric vehicles is introduced by adjusting the efficiency of consumption of the non-durable vehicles consumption category in the consumption matrix. For household heating and electricity use, the share and the efficiency of fuel use is translated into changes of parameters in the consumption matrix to replicate energy use. Additional costs are modelled as increases in the required (or subsistence) consumption in the Stone Geary consumption function and through an efficiency parameter in the purchase in the "housing" consumption categories, resulting in additional expenditure on the housing consumption category.

Calculation of embodied energy and emissions

In GECO 2022, the JRC-GEM-E3 model is used to calculate energy and emissions embodied in international trade. The methods to perform these calculations are well established in the input-output literature, but are typically applied to historical data, using input-output tables at country or global level as inputs. Here, the input-output tables are calculated in PIRAMID framework (for the reference scenario) and the JRC-GEM-E3 model (for the policy scenarios).

The input-output tables are extracted from the JRC-GEM-E3 model and transformed into a multi-regional input-output (MRIO) table. As trade in JRC-GEM-E3 is not specific by purpose (intermediate and final demand), the imported goods are allocated such that they represent an equal fraction both in intermediate and final consumption of a given sector. International trade margins (transport services for international transport) in bilateral trade in the JRC-GEM-E3 model cannot be tracked to exports of international transport services of a specific country. This is because of the structure in the GTAP database that uses the concept of an international pool of transport services. Exports of transport services into this pool are therefore allocated to individual trade flows in the MRIO table using the share of all regions contributions to the international pool.

Energy embodied in a product can be calculated multiplying a vector of direct energy intensity to the Leontief inverse (total requirement matrix, economic coefficients) derived from the MRIO table constructed from JRC-GEM-E3:

E = e' $(I-A)^{-1}$

where E is the energy embodied in a product (or a vector of products) taking into account all energy that was required in the upstream production; (I-A)-1 is the Leontief inverse; and e is the vector of direct energy intensity, which we account at the point where the energy is used in the production process. This implies that for electricity, the use of fossil fuels is accounted for in the electricity generation process (sectors 22 to 24 in Table 8). For zero carbon electricity, we account for the use output of sectors 25-29 into sector 06 which “collects” generation outputs from the different electricity generation sectors.

Energy embodied in final demand can then be calculated by multiplying the vector E with a vector of final demand. Energy embodied in international trade is be calculated by multiplying the vector E with a matrix of bilateral trade. This delivers embodied trade by sector and bilateral trade pair. Likewise, we can report the different energy carriers embodied in trade (coal, oil[27], gas, non-fossil electricity); we are also able to capture non-energy use of energy carriers (e.g. for producing plastics where fossil fuels are not burned, but serve as a feedstock).

In a similar fashion, energy embodied in final consumption or international trade can be computed by representing the direct emission intensity in e. For net trade, the difference can also be calculated by taking the difference between production and consumption based emission accounting.

Emissions can be assigned either to the country or region where they are emitted during production (production-based accounting, PBA) or to the country or region where the final product is consumed (consumption-based accounting, CBA). While production-based accounting is used for UNFCCC reporting, consumption-based accounting can indicate how many emissions are caused by the consumption in a given country or region. Consumption-based accounting considers emissions along the entire value chain, including emissions from the production of intermediate or final goods abroad. The difference between (domestic) production-based emissions and consumption-based emissions is often referred to as the balance of emissions embodied in trade (Keramidas, et al., 2018).

A third metric also explored in the literature is the TCBA - Technology-adjusted Consumption Based Accounting (Kander et al., 2015), which takes differences in technology export sectors of different countries into account to adjust the CBA metric. In the TCBA, export-related emissions are subtracted based on the average carbon intensity for the relevant sector on the world market, rather than the domestic average, under the assumption that a similar good would have been produced at the average emissions intensity on the world market for that sector.

[27] For oil, we consider the energy use of oil products (instead of crude oil), such that trade of refined oil products include only the energy needed in the refining process, but not the energy content of the oil product itself.

Annex 4: POLES-JRC hydrogen trade module

For GECO 2022, a new trade model was developed and integrated into the POLES-JRC model. The trade model allows for hydrogen trade and in a similar way also for trade of liquid e-fuels. It will be explained taking the hydrogen trade as example.

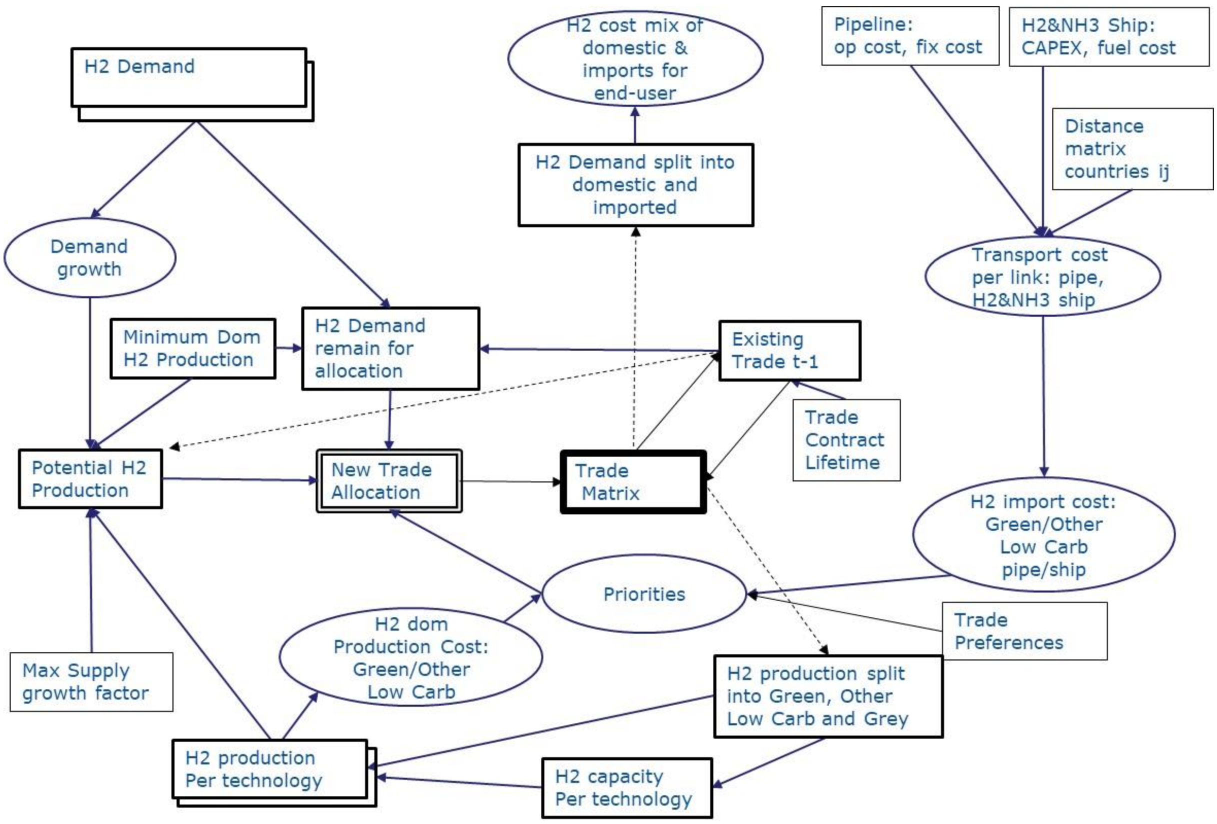
The hydrogen trade model considers multiple supply pathways. Hydrogen can be supplied domestically or can be imported via pipeline or shipping.

POLES-JRC represents pipelines by cost factors only and doesn't consider the existing pipeline network. For pipeline transport POLES-JRC takes fixed and operational costs of onshore and offshore pipelines, and energy inputs into account. Assumptions for cost and other technical parameters were mainly taken from (Khan, et al., 2021) and further sources (Collis and Schomäcker, 2022); (Bartels, 2008); (USDOE, 2006); (Brito and Sheshinkski, 1997).

The shipping pathway can be via H_2 or ammonia (NH_3) shipping, where H_2 liquefaction/reconversion and NH_3 conversion/reconversion costs, handling costs and transport costs are taken account. Cost assumptions, energy requirements and efficiencies on H_2 liquefaction/reconversion and NH_3 conversion/reconversion costs were mainly taken from (IRENA, 2022) and further sources (Johnston et al, 2022); (Lucentini, 2021); (Cechetto et al, 2021); (Lim et al, 2020).

Transportation costs consider investment costs, other costs and fuel cost depending on the engine type and fuel use of the ship and on the energy commodity transported. The investment costs are mainly based on (Taljegard et al, 2014) and further sources (McKinlay et al, 2021); (Hansson et al, 2020). Transport of e-fuels, ammonia and hydrogen is made mostly by ships with ICE using HFO in the next years. Over time ships transporting ammonia and hydrogen switch to engine types, which enable to burn the same of type of fuel as the transported fuel. Transport costs per link are derived by multiplying the transportation costs per transport fuel and distance with a distance matrix between countries.

Figure 65. Schematic of the POLES-JRC hydrogen trade pathways



Source: POLES-JRC model.

The hydrogen trade model allows for two tradeable commodities: green hydrogen and other low carbon hydrogen. Green hydrogen follows the definition of RePowerEU (2022) and allows only hydrogen produced by renewable electrolysis. Other low carbon hydrogen includes blue hydrogen (steam methane reforming with CCS; gasification (of coal and solid biomass, with CCS), turquoise hydrogen (of natural gas, of biomass) and pink hydrogen (low-temperature with dedicated nuclear; high-temperature with dedicated nuclear. Grey hydrogen can be only produced and consumed domestically.

The centre of the trade module consists of a matrix containing all trade links between the individual regions modelled in POLES-JRC, which represents the bilateral trade flows. A key element is that the model considers the long-term character of trade relations by applying a certain lifetime to trade contracts for H_2 pipeline and shipping. Hydrogen trade contracts for pipelines have - due to the high investment cost - a larger lifetime than contracts for shipping of H_2.

The calculation of trade starts with the determination of the hydrogen demand from various sectors like industry, building and transport. As POLES-JRC considers already existing trade the remaining hydrogen demand is determined, which is not supplied by already existing trade contracts.

On the supply side import costs are calculated for domestic H_2 production and H_2 imports via both pipeline and shipping (via liquefied H_2 or ammonia). Imports from a country can be either preferred or blocked as a model input. The hydrogen supply is limited by an annual maximum growth factor, which considers the maximum potentials of hydrogen production of supplying countries.

The allocation function considers the production costs of the remaining H_2 demand and the H_2 import costs and calculates with a cost minimisation function the cost-minimal solution. As a result of the allocation function the model derives annual new trade volumes, which are added to the existing trade volumes of the past year. The resulting trade matrix determines how much H_2 demand is fulfilled domestically and how much green and low-carbon hydrogen is imported, and from which countries those imports come from. The mix of domestically produced and imported hydrogen allows determining the hydrogen price within a country.

The e-fuel trade model is based on the same structure. E-fuel trade is limited to liquid e-fuels, which are produced by green hydrogen and CO_2 originating from direct air carbon capture technologies (DAC). Hence, only one trade category is considered. Transportation of e-fuels can use pipelines and shipping similar to oil products.

Annex 5: Socio-economic assumptions and fossil fuel prices

The population assumptions follow Europop (Eurostat, 2021) for EU and JRC-IIASA projections (Lutz, Goujon, Kc, Stonawski, & Stilianakis, 2018) for the rest of the world.

The GDP projections for the EU are based on the 2022 summer forecast (European Commission, 2022). The GDP projections follow numbers of the 2021 Ageing Report for the EU (European Commission, 2021); for the rest of the world, the sources are IMF World Economic Outlook (IMF, 2022) and the OECD CIRCLE project (OECD, 2018). Historical GDP levels are taken from the World Bank (World Bank, 2022).

Table 10: GDP assumptions

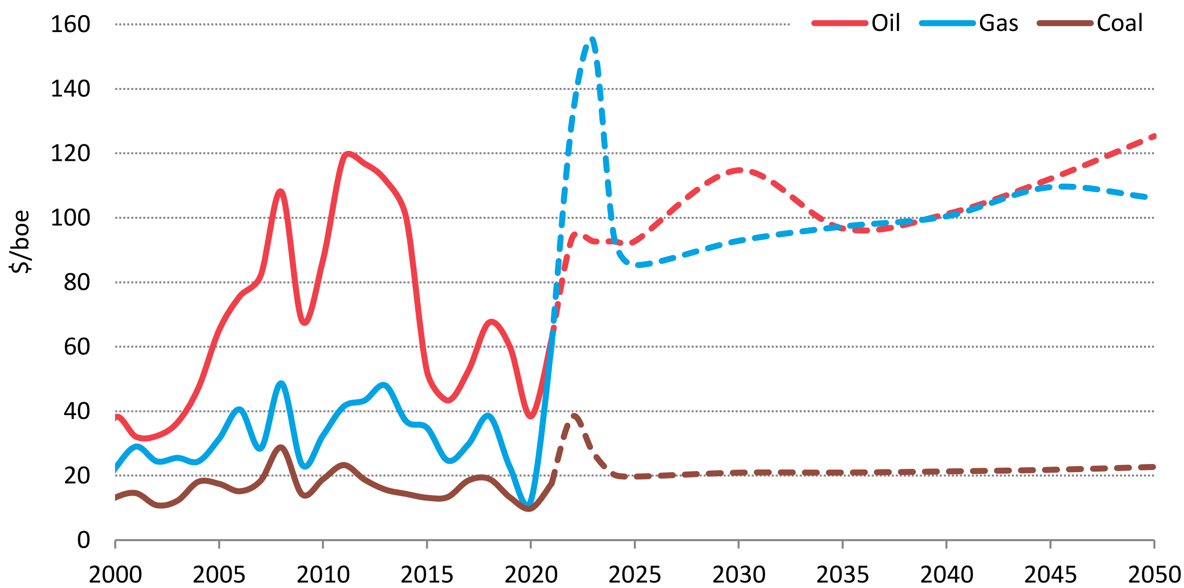
Group	Historical (to 2020)	2021-2027	2028-2030	2031-2050	2051-2060	2061-2070	2071-2100
EU27	WB Apr-2022	Jul-2022 DG ECFIN and 2021 Ageing Report			intrapolation	GDP/cap as SSP x Europop	
Large non-EU	WB Apr-2022	IMF Jun-2022	intrapolation	GDP OECD Jul-2018 (2) / Pop IIASA-JRC		intrapolation	GDP/cap as SSP x Pop IIASA-JRC
Rest of World	WB Apr-2022	IMF Jun-2022	intrapolation	GDP/cap as SSP x Pop IIASA-JRC			

Large non-EU: OECD (Australia, Canada, Chile, Iceland, Japan, Republic of Korea, Mexico, New Zealand, Norway, Switzerland, Turkey, United Kingdom, United States); non-OECD (Argentina, Brazil, China, India, Indonesia, Russia, Saudi Arabia, South Africa).

Covid-19 has had a significant impact on mobility changes and transportation. GECO 2020 (Keramidas, et al., 2021) describes the short-term assumptions related to the pandemic considered in the scenario modelling. GECO 2022 uses the same data sources as GECO 2020, updated to 2022, and delays the report hypotheses of two years. More details are available in Annexes 1 and 2 of GECO 2020.

The international fossil fuel prices in the Reference scenario are shown in Figure 66. They follow internal short-term assumptions until 2025, and beyond were endogenously calculated by the POLES-JRC model.

Figure 66. International fossil fuel prices in the Reference Scenario



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

Source: POLES-JRC model.

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