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The role of hydrogen in energy decarbonisation scenarios

Views on 2030 and 2050

Tarvydas, D

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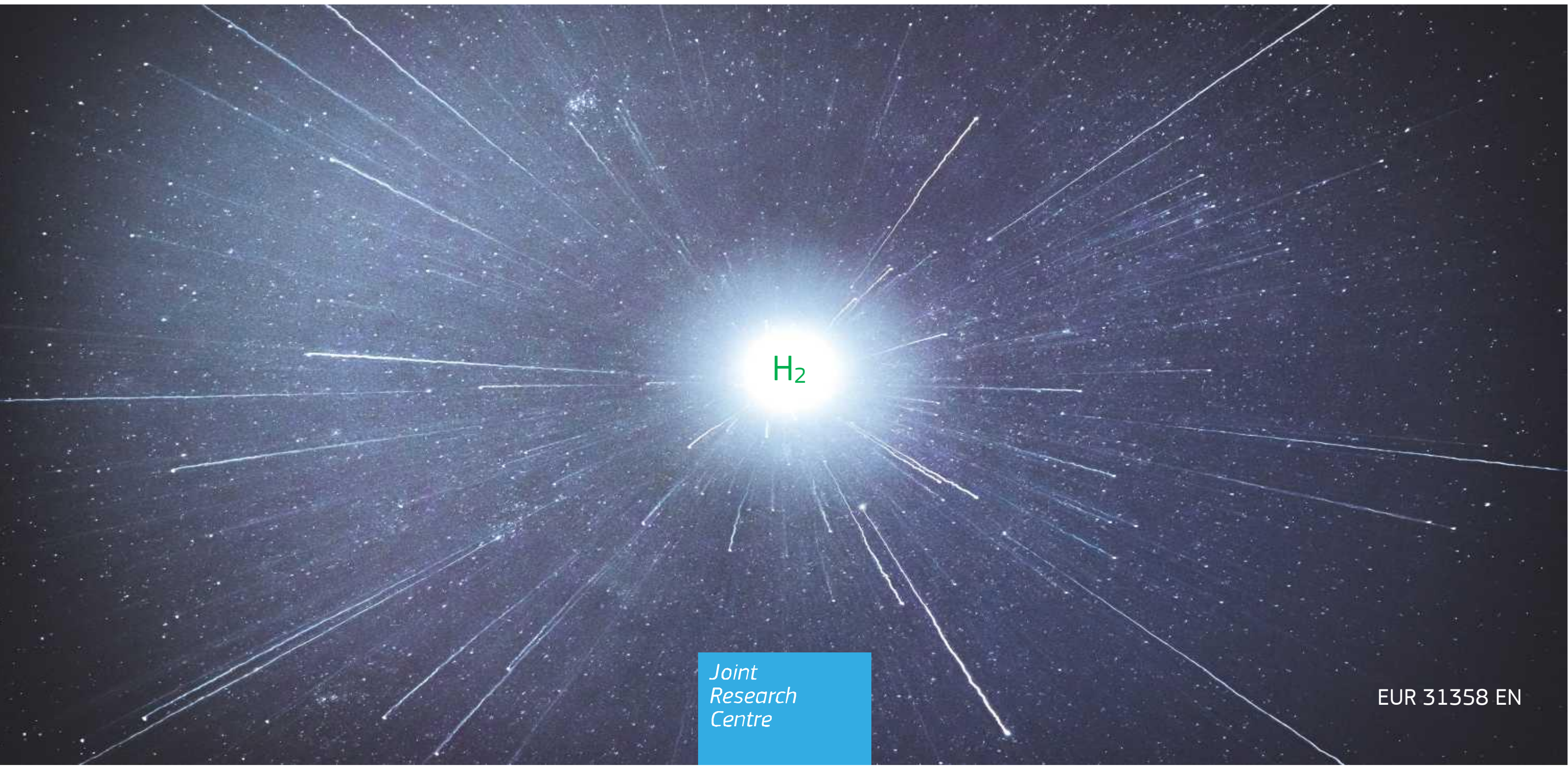

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Contents

Abstract

Driven by the urgent need to decarbonise the economy, international organisations, governments, researchers and other actors are looking for the best ways to reach carbon neutrality. Hydrogen has only started to re-emerge in the last few years as a pivotal technology for the energy transition. While scenario studies do not always agree on how, or in which sectors, hydrogen will play the biggest role, it is evident that its adoption will transform the EU and global energy systems. To accommodate this transition, global hydrogen consumption should increase by to 15 times by 2050 (compared to 2020). In the EU, hydrogen demand could reach to 68 Mt by 2050 (9 times 2020 levels). Assuming that all global hydrogen is green, this means that by 2050, from 8 900 GW to 26 000 GW of electrolyser capacity will be required (compared to the current global capacity of less than 1 GW). A similar global amount, largely of wind and solar generation, needs to be added to the power system just to facilitate this hydrogen production. By 2050, hydrogen production capacity (through electrolysers) could reach to 1 300 GW in the EU, again with a corresponding increase of solar and/or wind capacity. Globally, this means that intermittent power generation needs to grow to 10-30 times its 2020 size by 2050 just to meet hydrogen demand. Expanding dispatchable low-carbon power generation capacities (like nuclear) could considerably reduce the need for electrolysers and intermittent power generation.

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Authors

Tarvydas, D.

1 Introduction

Six years have passed since the entry into force of the Paris Agreement, and in that time, 151 countries have submitted their Nationally Determined Contributions (UNFCCC, 2022). However, the IPCC report of August 2021 noted that efforts thus far have not slowed down climate change (IPCC, 2021). As of March 2022, 33 countries and the European Union have set net-zero emissions targets either through law or policy commitments, with more than 100 countries still considering them (Climateactiontracker, 2022). To analyse possible pathways to climate neutrality, hundreds of net-zero or Paris-compatible studies and scenarios were created, ranging from single city outlooks, to pathways looking at the decarbonisation of the economy at the global scale; from looking at the carbon neutrality of selected sectors to covering all economical activities and changes in behaviour and/or land use. Most of these studies foresee a pivotal role for hydrogen in achieving net-zero targets.

Hydrogen is essential to decarbonise industrial feedstock or as an energy source in industrial high temperature processes. Hydrogen is also vital for the decarbonisation of the transport sector, especially aviation, long distance haulage and the maritime sector. In a world dominated by electricity generated by intermittent renewables, hydrogen is indispensable: it can act as energy storage, supplementing batteries and hydro storage power plants (HSPP) – allowing energy to be stored for longer periods of time, without the negative environmental impacts of big hydro dams or the prohibitive size of lithium batteries. Hydrogen facilitates the integration of variable renewable energy sources (like solar and wind) into the power grid, both as grid-connected or standalone solutions. In some scenarios, in the medium term, hydrogen can also be seen as a transition fuel in the buildings sector, helping to decarbonise heating where heat pumps are not economical, either because of low efficiency building shells or insufficient infrastructure.

In order to understand the importance of hydrogen in future energy systems, some countries have published National Hydrogen Strategies, which contain ambitious hydrogen production targets for the 2030 horizon and beyond. These targets are a significant improvement with respect to today's virtually non-existent green hydrogen production, but are still far from the necessary deployment needed for the 2050 horizon. According to the New Energy Outlook (BloombergBEF, 2021), globally, hydrogen demand by 2050 could increase 16-fold, triggering the exponential growth of the electrolysers market (BloombergNEF, 2022).

In the last two years, several studies have analysed options for the production, transportation, storage and distribution of hydrogen, as well as its possible role in decarbonising the economy. In 2022, IRENA reported on global hydrogen trade options (IRENA, 2022a), available hydrogen transportation technologies (IRENA, 2022b), costs and potential green hydrogen demand based on different production pathways (IRENA, 2022c) and the geopolitical aspects of switching from fossil hydrocarbons to green hydrogen (IRENA, 2022d). Agora Industry with Agora Energiewende looked into the future role of hydrogen in the EU (Agora Industry and Agora Energiewende, 2021). DNV looked into its role in the transition to carbon neutrality in 2050 (DNV, 2022). ENTEC[1] looked into options for the import and storage of green hydrogen in the EU (ENTEC, 2022). EHB explored options to create European hydrogen transmission infrastructure both for import from third countries and transportation to industrial centres (EHB, 2022). EC JRC made of techno-economic assessment of hydrogen transport feasibility within Europe (Ortiz Cebolla, 2022). Harvard Kennedy School published a report looking into the future impact of renewable hydrogen on energy markets and the possible political implications (Alejandro Nuñez-Jimenez, 2022). In 2021, the IEA published a report looking into the current and future status of Hydrogen (IEA, 2021a) globally, as well as the role of hydrogen in the medium term in North West Europe (IEA, 2021b). IRENA looked into green hydrogen supply options and support schemes (IRENA, 2021a). The JRC looked into the implications of blending hydrogen into the European natural gas grid (Kanellopoulos K, 2022). EWI published a short summary on the hydrogen policy framework of supply and demand in key European markets (EWI, 2021). In 2021 the Danish Energy Agency published an updated report and dataset for renewable fuels which included green hydrogen technologies (Energistyrelsen, 2021). In 2020, DNV looked into the role of hydrogen as seasonal storage (DNV, 2020). IRENA explored the cost reduction potential of green hydrogen (IRENA, 2020a) and produced a green hydrogen guide for policymakers (IRENA, 2020b). In 2019, IEA published a report on the future role of hydrogen from production to final demand for non-energy usages (IEA, 2019).

Therefore, there is a plethora of recent, in-depth analysis covering all aspects of the hydrogen supply chain, ranging from production to transition to storage, often at a highly technical level beyond the scope of most ~~energy scenarios and of this repo~~rt. This report will look into the commonalities and differences of the decarbonisation pathways presented in selected energy scenarios, calculating the resulting infrastructure

[1] Consortium of Guidehouse, McKinsey & Company, Inc., TNO, Trinomics and Utrecht University under DG ENER under contract N° ENER/C2/2019-456/ SI2.840317.

expansion efforts needed, but does not go into technological detail. The pros and cons of electrolyser technologies and transportation/storage options is out of the scope of this report.

This study aims to shed light on the role of hydrogen in the future global and EU energy systems. It assesses the scale of the challenge ahead, given that to satisfy hydrogen demand, there need to be huge increases in the installed capacity not only of electrolysers, but also of solar and wind generation.

Quick guide

The report analyses current hydrogen consumption (Chapter 2), and the perspective of the scenario studies on how and where hydrogen will be used in the medium and long timeframes (Chapter 3). Hydrogen production capacities are discussed in Chapter 4, drawing from scenario studies and the author’s own estimates. The conclusions can be found in Chapter 5.

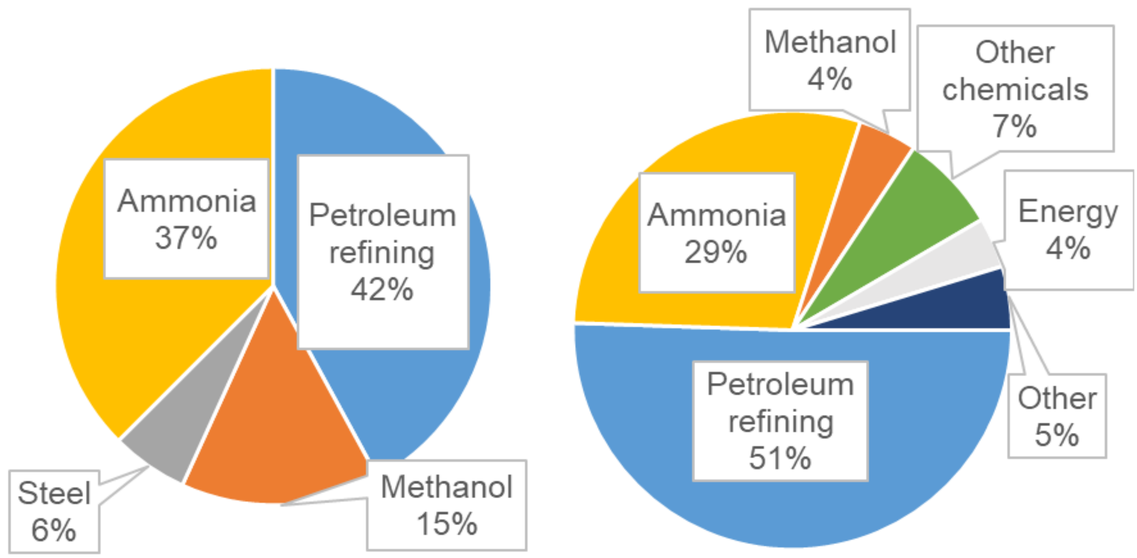
2 Current status

Hydrogen is currently widely used in industry for non-energy purposes. Most of it is produced and consumed onsite, and only a small fraction is traded on the open market (usually only short distance between neighbouring industrial installations/countries). In **global trade**, pure hydrogen is next to non-existent, amounting to only EUR 130 million in 2020 (it was the 3 834th most traded product in the world; down almost 20% compared to 2019) (OEC, 2022). In 2020, 44% of globally traded hydrogen was exported from Canada and 18% from the Netherlands. The main hydrogen importer was the USA (44%), followed by France (8%). Ammonia (the most used hydrogen derivative) was traded more extensively: in 2020 it was the 413th most traded product with a turnover of EUR 6.3 billion (down from USD 10 billion in 2014). The major exporters were Saudi Arabia (32%), Russia (16%) and Trinidad and Tobago (13%), while the major importers were India (22%) and the USA (12%) (OEC, 2022).

Given that hydrogen tends to be produced for onsite [2]use and not internationally traded, statistics for production and consumption are not widely available. The main source for historical global hydrogen production and consumption used in this report is IEA (IEA, 2019), supplemented by updated data from (DNV, 2022) (IRENA, 2022d). At EU level, Eurostat will not start including hydrogen data in its balances until 2024 (for the year 2020) (Eurosat, 2022), therefore datasets from the Fuel Cells and Hydrogen Observatory (FCHO, 2022) will be used.

Currently (2020), **global demand** of hydrogen amounts to around 87 million tonnes (DNV, 2022) (IRENA, 2022d) and is used mainly for ammonia production (37%) mainly in the fertilisers industry and in petroleum refining (42%). Other uses include methanol production (chemical industry) and steel production[3] (direct reduction of iron) (**Figure 1**). **In the EU** (FCHO, 2022), almost 8 Mt was used in 2020: more than half of it (51%) for petroleum refining (**Figure 1**) and 29% for ammonia production. It is worth noting that 4% (300 kt or 10 TWh[4]) was used for energy and another 0.01% (1 kt or 36 GWh) for transport.).

Figure 1 Global hydrogen consumption (left) and in the EU (right) in 2020



Source: JRC, 2022, based on (DNV, 2022) (left) and (FCHO, 2022) data (right)

Currently, **global** hydrogen **production** relies almost entirely on fossil fuels i.e.: natural gas, oil derivatives and coal.. The majority dedicated hydrogen production is produced from natural gas (around three quarters,

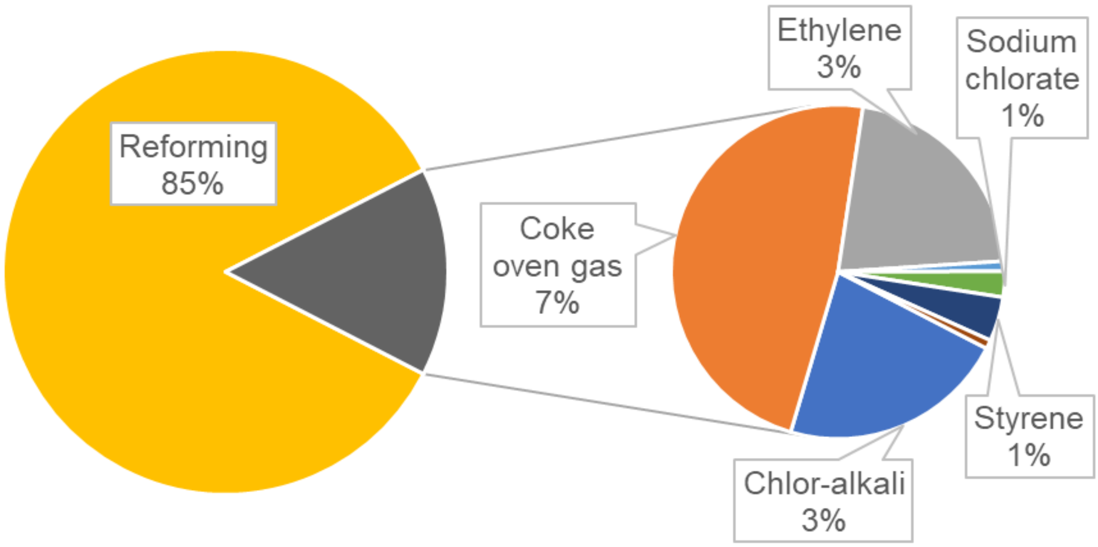
[2] The share of merchant hydrogen (traded) is low. Not all hydrogen produced and not all hydrogen is captive.

[3] Current DRI steel production prosecco uses coal or natural gas. Hydrogen can replace both fossil fuels in the future, but currently is used only in the demonstration installations.

[4] In this report conversion from Mt H_2 to energy (TWh) is used based on lower heating value (LHV).

accounting for about 6% of global natural gas demand), and the remaining quarter from coal (IEA, 2019)[5]. A negligible amount is produced from electricity using electrolysers (30 kt/year) and oil. Another 8 Mt was produced from fossil fuels using CCS (IEA, 2022). In 2020, global hydrogen production resulted in around 800 $MtCO_2$ of emissions per year (IRENA, 2022d). **In the EU** there was 11 Mt of production capacity, 85% of which was reforming (mainly based on natural gas) and another 7% as a by-product from coke oven gases (**Figure 3**). It is worth noting that carbon-free and low-carbon hydrogen production capacities are currently almost non-existent: the installed capacity of electrolysers in the EU is capable of producing only 34 tonnes of hydrogen per day (0.13% of total capacity), and reforming with carbon capture (CCS) can produce only 40 tonnes of hydrogen per day (0.15% of total installed capacity).

Figure 2 Share of hydrogen production capacities in the EU in 2020



Source: JRC, 2022, based on (FCHO, 2022) data

The biggest hydrogen consumer in the **world** is currently China (**Figure 3**), at 24 million tonnes, accounting for around 28% of global hydrogen consumption, followed by the USA (11 Mt and 13%). The EU accounted for only 6% (5.5 Mt)[6] of global hydrogen consumption in 2020. Within the EU, the biggest hydrogen consumer is Germany (1.7 Mt), followed by the Netherlands (1.3 Mt) and Poland (0.8 Mt) (**Figure 3**). Of the EU Member States, only Cyprus, Estonia and Malta have no hydrogen consumption at all.

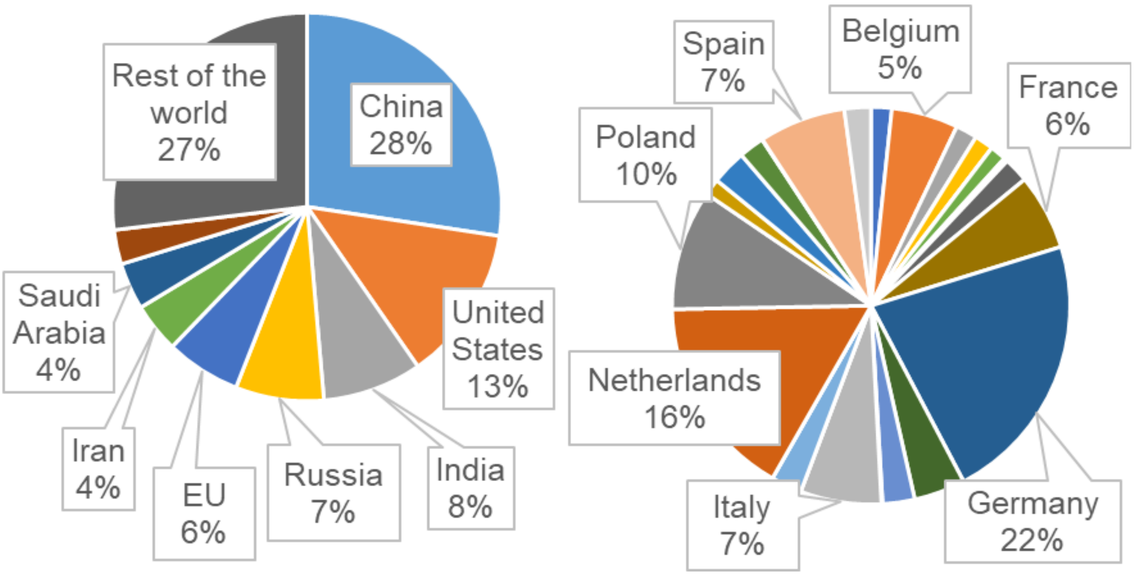
The biggest hydrogen consumers in **the EU** are also the biggest hydrogen producers, so the largest consumer, Germany, boasts 21% of the EU's hydrogen production capacities.

Driven by ever increasing demand for refined oil products and fertilisers, **global** hydrogen **production** has been steadily growing for several decades. In the period from 1975 to 2020, demand for pure hydrogen increased more than 4.5 times (IEA, 2019) (IRENA, 2022d) and reached around 87 Mt in 2020. While the growth in hydrogen demand continues, the rate is slowing down: from a compound annual growth rate (CAGR) in 1975-2000 of 4.1%, it has dropped to 2.6% in 2000-2020. Despite slower growth rates, demand for pure hydrogen in 2000-2020 increased by 35 Mt, almost double the total demand in 1975 (around 19 Mt). The consumption of hydrogen gas mixes also grew, quadrupling from 1975 to reach around 37 Mt in 2020 (IRENA, 2022d). Unlike the case of pure hydrogen, mixed gas saw an increase in growth rates from 2.8% in 1975-2000 to 3.4% in 2000-2020.

[5] If total hydrogen production is considered, share of natural gas is lower, nevertheless natural gas today is the main source for hydrogen production.

[6] Global hydrogen demand and EU demand in this context represent only pure hydrogen demand (5.5 MtH_2). Total EU hydrogen demand in 2020 was 7.8 MtH_2

Figure 3 Share of global[7] hydrogen demand (left) and in the EU (right) in 2020



Source: JRC, 2022, based on (IRENA, 2022d) (left) and (FCHO, 2022) data (right)

Until recently, the growth of hydrogen production and consumption attracted little attention, discussed mainly in the context of the decarbonisation of transport and recently - industrial feedstock. However, awareness is growing fast of hydrogen's decarbonisation potential across the economy, from the transport sector to power generation. Hydrogen could play an important sector integration role, enabling the integration of higher shares of renewables (European Commission, 2020a) By early 2022, 10 members of the G20 had developed hydrogen strategies (BloombergNEF, 2022), and another eight were preparing them (**Table 1**). Japan and the Republic of Korea were well ahead of the rest. Globally, there were 26 countries with fully developed hydrogen strategies, and another 22 in various stages of preparation (BloombergNEF, 2022). In July 2020, (European Commission, 2020a) adopted a hydrogen strategy for a climate-neutral Europe, followed by hydrogen strategies and roadmaps adopted by Member States. By January 2022, more than half of the Member States had adopted hydrogen-related strategies. The remaining Member States were in various stages of hydrogen strategy preparation. The role of hydrogen in decarbonising energy systems is also discussed in the National Energy and Climate Plans (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). In the EU, there were 19 member states with adopted hydrogen strategies or in late stages of discussions (Annex 1)

In 2020, global installed electrolyser capacity was around 300 MW (IEA, 2022), but by 2026 this could be 16.7 GW and by 2030, the figure might reach 120 GW (BloombergNEF, 2022), half of which will be installed in China.

Hydrogen is still in its infancy in the transport sector: by the end of 2021, there were fewer than 8 000 hydrogen-powered buses and commercial vehicles in the world (BloombergNEF, 2022). The same applies to passenger fuel cell vehicles, of which there were only around 40 000 by the end of 2021 (fewer than 2 500 in Europe). Three countries account for 95% of those: South Korea, the US and Japan. Globally, there were only around 740 hydrogen fuelling stations, led by Japan and China. In Germany there were around 100 hydrogen refuelling stations by the end of 2021 (BloombergNEF, 2022).

Despite the currently negligible capacities of hydrogen production and very limited usage, the hydrogen economy is gaining momentum. There are 31 projects in the pipeline before 2025 to produce hydrogen from fossil fuels with CCS (mainly blue hydrogen), mainly in APAC and EMEA[8] regions (BloombergNEF, 2022). This

[7] Original data was aggregated to the EU + United Kingdom level. Based on (FCHO, 2022) the UK share was removed from the EU + UK to the Rest of the world.

[8] APAC- Asia-Pacific; EMEA - Europe, the Middle East and Africa.

number will double by the end of this decade. There are 38 hydrogen-related industrial projects until 2025, mainly exploiting its current uses for ammonia, oil refining, steel and methanol.

Analysis of hydrogen shipping projects by BloombergBNEF shows that the major share of shipments in the future could be via ammonia, accounting for 25 of the 36 projects currently in the pipeline. Almost 11 GW of hydrogen-ready power generation units will be added before 2025 (mostly in the US), and another 6 GW by the end of decade (BloombergNEF, 2022).

Table 1 Hydrogen strategy availability in G20 countries

Country	H_2 strategy available	H_2 strategy in preparation	No activity
Argentina		X	
Australia	X		
Brazil		X	
Canada	X		
China		X	
France	X		
Germany	X		
India		X	
Indonesia			X
Italy	X		
Japan	X		
Republic of Korea	X		
Mexico			X
Russia	X		
Saudi Arabia		X[9]	
South Africa		X	
Turkey		X	
United Kingdom	X		
United States		X	
European Union	X		
Total	**10**	**8**	**2**

Source: (BloombergNEF, 2022)

In the coming eight years, the hydrogen landscape of the EU is expected to change drastically. According to the REPowerEU plan adopted in May 2022 (European Commission, 2022), the consumption of renewable hydrogen should reach 20[10] Mt, (666 TWh) by 2030. Half of it should be produced locally (in the EU) and the rest imported[11]. On top of current industrial uses, other sectors are also projected to adopt hydrogen (Figure 4). The transport sector could consume 4.1 Mt (2.4 Mt pure and 1.8 Mt in the form of synthetic fuels). Its use for energy will increase from 0.7 Mt to 3.7 Mt (mainly for industrial heat).

To produce 10 Mt of hydrogen in the EU, at least 65 GW of electrolysers will be installed[12] (Commission, 2022).

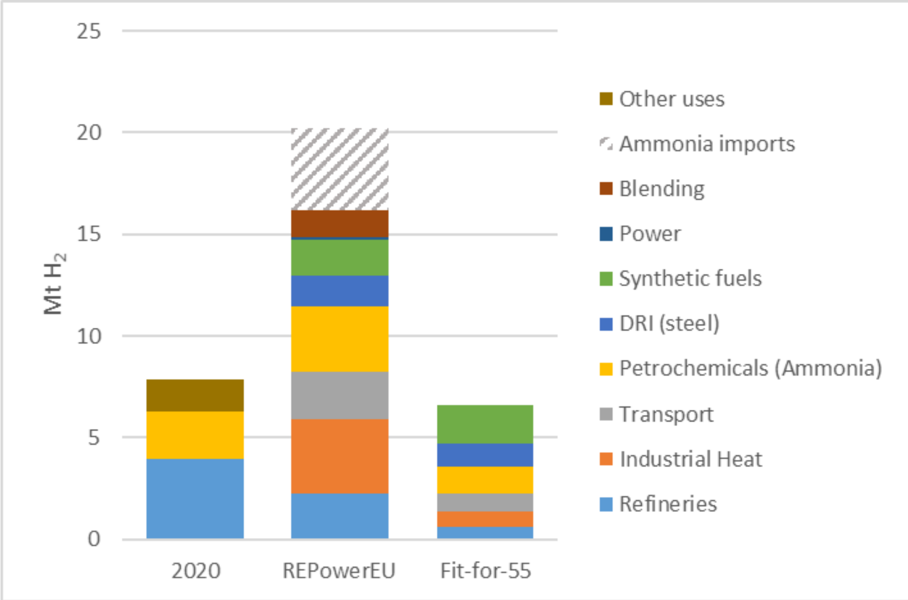
[9] Initial discussions started

[10] Including Ammonia and other derivatives (E-fuels, etc.).

[11] 6 Mt H_2 imported as pure hydrogen, another 4 Mt H_2 as ammonia (Commission, 2022).

[12] Considering the possibility of lower than anticipated running hours, to 80 GW of electrolyser capacity should be installed (Commission, 2022).

Figure 4 Historical hydrogen consumption in 2020 (left) and green hydrogen consumption in REPowerEU and Fit-for-55 in 2030 (right)



Source JRC, 2022, based on (FCHO, 2022) (for historical data) and (Commission, 2022) (for REPowerEU and Fit-for55[13])

[13] Fit-for-55 data comes from (Commission, 2022) and represents MIX H2 scenario, not available from original Fit-for-55 dataset. In this report, if not indicated otherwise, MIX scenario is used.

3 The role of hydrogen in 2030 and 2050

3.1 Scenario selection

In the preparation of this report, 49 scenario studies were taken into consideration, **published from January 2019 to February 2022**. Selection was based on coverage (in terms of geographical disaggregation and the set of technologies reported), relevance (including publishing institution, assumptions and level of ambition) and the availability of data sets. Based on these considerations, 12 studies were selected. The majority of these have scenarios in line with fast European or global decarbonisation, reaching close to zero emissions by 2050 (or by 2100 in the Shell Sky scenario). For each study, only one scenario was used. In the case of several scenarios per study, the selection was based on the level of ambition, and how close assumptions and/or results were to the European Green Deal (European Commission, 2019b). More information about the studies and selection criteria are available in the CETO "Clean Energy Outlooks" report based on a similar set of scenarios (Tarvydas, D., 2022). For this report these scenario studies were used:

Global and Europe/EU combined

The "Global Energy and Climate Outlook", (GECO) published in 2021 by the Joint Research Centre of the European Commission (Keramidas, et al., 2021)[14], focused on global pathways to climate neutrality. In this report we use data from the *1.5°C-Differentiated* scenario, reaching the Paris goal with different CO_2 prices for different world regions. It will be referred to henceforth as ***JRC GECO***. Data from this study (global and regional, including EU) is available in the form of Excel tables and an online data visualisation tool (European Commission, 2022).

'Energy Outlook 2020 edition' was published in 2020 by BP[15] (BP, 2020). For this report the *Net-zero* scenario is used, relying on policy measures such as carbon prices and sectoral transition, along with behavioural changes. This scenario will be referred to as ***BP***.

The book, 'Achieving the Paris Climate Agreement Goals', was published in 2019 by the University of Technology (UTS), University of Melbourne and German Aerospace Centre (Teske, 2019), with an accompanying dataset (UTS, 2019). In this report, the *1.5* scenario (based on the three no approach: no nuclear, no fossil, no CCS) is used, and referred to as ***IFS***.

'New Energy Outlook' published by the BloombergNEF in 2021, (BloombergNEF, 2021X), is based on three scenarios with distinct pathways to net-zero emissions. The *Green* scenario, based on the fast deployment of green hydrogen, is used in this report and referred to as ***BNEF***.

Global only

The World Energy Transition Outlook (WETO), published in 2021 by The International Renewable Energy Agency (IRENA) (IRENA, 2021)[16], is driven by renewables and technologies which are currently readily available, and aligns to the 1.5°C pathway (*1.5°C* Scenario). The data used in this report comes from the tables provided in its annexes and from digitisation of the graphs. The report includes global results and limited regional insights, but these are not sufficient to build a full picture for Europe. This scenario is referred to as ***IRENA***.

The World Energy Outlook (WEO) was published in 2021[17] by The International Energy Agency (IEA) (IEA, 2021e). From this report, we use the *Net-zero* scenario, aligned with the long-term Paris Agreement goal. IEA also published results and conclusions from this scenario as a separate report, 'Net Zero by 2050' (IEA, 2021a). Data and insights from both of these reports are used interchangeably and referred to as ***IEA***.

'Energy transition outlook' (ETO), published in 2021[18] by the DNV, does not include a scenario that reaches carbon neutrality by 2050 or align with the Paris Agreement (DNV, 2021a). However, DNV published a further report (DNV, 2021b) detailing the additional effort needed to reach climate neutrality by 2050. Due to data availability in the form of an Excel file, the main insights are drawn from *ETO*, and where possible, complemented by the *Net-zero* scenario. The ETO is referred to as ***DNV***.

'The Energy Transformation Scenarios' report was published in 2021 by Shell (Shell, 2021), as an update of the influential study, 'Sky: Meeting the goals of the Paris Agreement', published in 2018 (Shell, 2018), taking into account recent developments in socioeconomics and technology. In this report, data and insights from the *Sky 1.5* scenario is used, where CO_2 emissions go

[14] An updated version of JRC GECO report, focusing on hydrogen, will be available by the end of 2022

[15] At the time of publication of this report, a newer version of this report, BP Energy Outlook 2022 is available (BP, 2022).

[16] At the time of publication of this report, a newer version of IRENA 1.5°C scenario is available (IRENA, 2022).

[17] The 2022 version of IEA World Energy Outlook is expected in October. From 2021, the IEA WEO does not publish full regional balances. Partial data for the EU is available only for less ambitious scenarios (SDS, APS), but not for Net-zero).

[18] DNV used to publish the ETO on an annual basis (in September), but at the time of writing this chapter (28/09/2022) there are no indications of whether an updated report will be published in 2022.

below zero after 2050 and the Paris target is reached by the end of the century. Shell reports have high data availability (Excel files), but the data aggregation differs from other scenario studies, making comparison difficult at times. In this report, the *Sky 1.5* scenario is used and is referred to as ***SHELL***.

Europe only

In July 2021, within the framework of the European Green Deal (European Commission, 2019b), the European Commission proposed the Fit-for-55 package (European Commission, 2021c) to reduce the European Union's greenhouse gas emissions by 55% by 2030. It builds upon the decarbonisation pathways defined in the 2050 long-term strategic vision (European Commission, 2019a) and the 2030 Climate Target Plan (Commission, European, 2020b). There were three core policy scenarios behind Fit-for-55 (European Commission, 2021a). This report uses *MIX H2 variant*[19], which relies on the extension of carbon pricing and a high intensification of energy and transport policies and takes into account the EU hydrogen strategy. The modelling results for the core scenarios are available (European Commission, 2021d) up to 2030 (for the EU and at the country level). For 2050, the EU results are available in the online energy scenario tool (European Commission, 2021a). In May 2022, the European Commission presented the REPowerEU Plan (European Commission, 2022d) in response to the global energy market disruption caused by Russia's invasion of Ukraine, with a significant expansion of the use of green hydrogen among its measures. Insights from REPowerEU will be used where they are available. In this report, the *EC Fit for 55 MIX* H2 scenario variant is used and referred to as ***EC Fit-for-55***.

In 2020, McKinsey & Company published 'Net-Zero Europe: decarbonisation pathways and socioeconomic implications' (McKinsey & Company, 2020), based on the *Net-Zero energy* scenario for EU27, where all sectors reach net zero (or close to net zero) by 2050, except agriculture (offset by LULUCF). While data availability is limited to graphs only, it provides interesting insights on how, led by the power sector, the EU could reach climate neutrality by mid-century. In this report, the *Cost Optimal* scenario is used and referred to as ***McKinsey***. Insights from the Hydrogen breakthrough scenario are also used where relevant (and referred to as McKinsey BT).

'Transition pathways to a carbon neutral EU28' (a series of reports and online tool) was published in 2020 by a consortium partially funded by the EU Horizon 2020 programme[20] (EUCALC, 2020). We use the *Tech* scenario, which assigns technology as the main driver for decarbonisation, without substantial changes in human behaviour. The scenario is referred to as ***EUCalc***.

The 'Paris Agreement Compatible Scenarios for Energy Infrastructure' (PAC) report was published in 2020 by a consortium consisting of Climate Action Network (CAN) Europe, the European Environmental Bureau (EEB), the Renewables Grid Initiative (RGI) and REN21 (PAC project, 2020). It aligns with the Paris Agreement's objective to limit global warming to 1.5°C, incorporating the policy demands of civil society, and is referred to as ***CAN***.

The *JRC EU TIMES* model and accompanying data set were created by the Joint Research Centre of the European Commission as part of various policy support activities (Nijs, Castello, Tarvydas, Tsiropoulos, & Zucker, 2018). In 2021, *JRC EU TIMES* was released into the public domain (EC JRC, 2021). The *Net Zero* scenario, reaching carbon neutrality in the EU by 2050, is used in this report and referred to as ***JRC TIMES***.

3.2 Hydrogen's role in global energy use

3.2.1 Final demand

Final energy demand at **global** level was over 100 000 TWh in 2019 (IEA, 2022), about 40% higher than in 1990, a compound annual growth rate (CAGR) of 1.6%. In the last decade (2010-2019), growth was slightly slower at only 1.3% CAGR. Based on the global energy scenarios analysed, growth will continue during the next decade at around 0.7% CAGR, peaking at around 112 000 TWh in 2030 (**Figure 5**). In 2050, the total final demand (average across scenarios) will drop close to today's levels (100 000 TWh). In scenarios that reach climate neutrality by 2050, the reduction of final demand is even higher (around 93 000 TWh on average). It is worth noting that scenario studies disagree substantially on future total final demand. In 2050, the highest values (Shell) are almost double the lowest (IFS). In IFS, renewables and electrification play the biggest role, while Shell still sees a prominent role for fossil fuels in 2050.

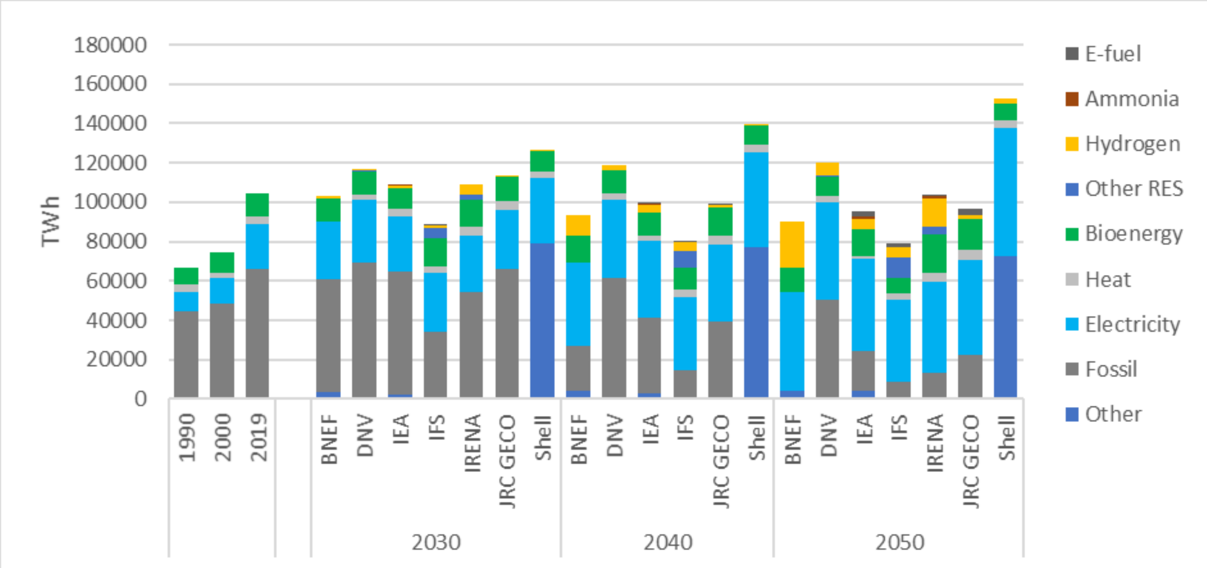
Compared to 2019, in terms of the fuel mix of final demand, there are more significant changes. The increase in electrification observed in historical data (from 14% in 1990, to 17% in 2000, and 22% in 2019) continues in all scenarios analysed, reaching 28% on average in 2030 (ranging from 26% in JRC GECO and IEA to 33% in

[19] In REPowerEU, the Commission also references Fit for 55 modelling results from the MIX H2 variant. The MIX H2 variant scenario results for this report were provided by DG Energy.

[20] EU Calculator: trade-offs and pathways towards sustainable and low-carbon European Societies - EUCalc

IFS). In 2040, electrification reaches 40% on average (from 34% in DNV to 46% in BNEF and IFS). In 2050, electricity provides almost 50% of total final demand, ranging from 41% in DNV to 56% in BNEF. Historically, the share of fossil fuels in final demand has been stable at around 65%. Based on the energy scenarios analysed, that share will drop to 53% on average by 2030 (ranging from 60% in DNV to 39% in IFS). By 2050, the share of fossil fuels will drop below 20% on average, and will be dominated by oil and oil products in the transport sector, followed by natural gas in industry and buildings.

Figure 5 Global final demand by fuel[21]



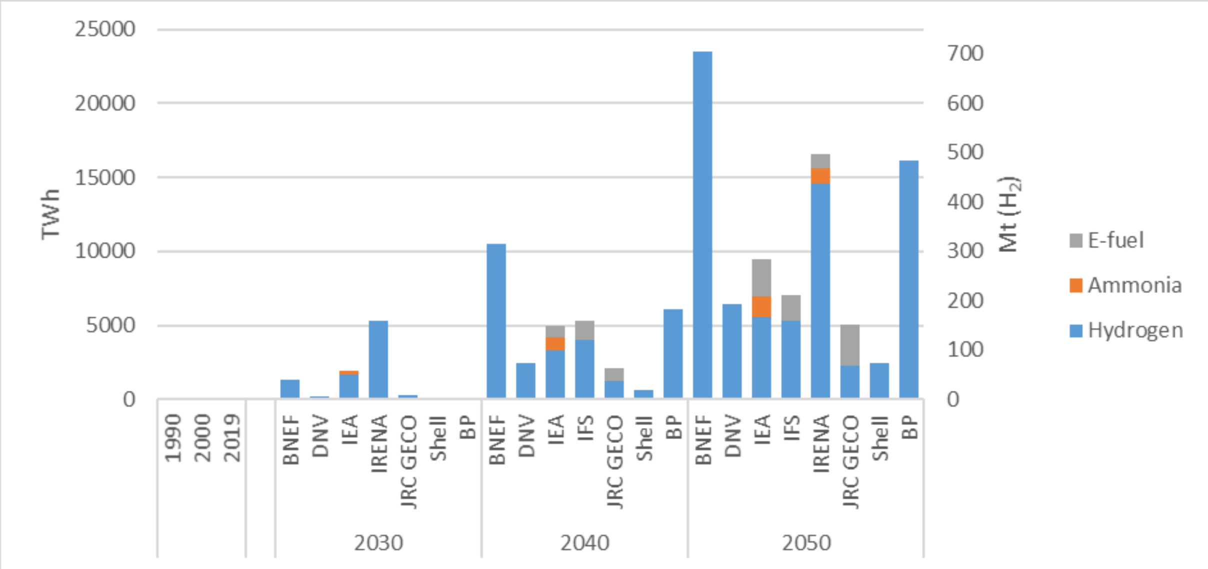
Source: JRC, 2022, based on scenario studies. Historical data (IEA, 2022)

Historically, hydrogen has been used mainly in industrial processes as a feedstock and not as energy carrier. Current hydrogen usage in final demand is negligible (below 0.1% of all hydrogen used) and mainly used in the transport sector (mostly in South Korea, the USA and Japan). A very limited amount of hydrogen is also used in the buildings sector in Japan.

Hydrogen usage in end-use sectors remains negligible until 2030, only reaching an average of 1% of global final demand (ranging from 0.1% in Shell to 2% in IEA). Up to 50 Mt will be used in end-use sectors globally in 2030 (**Figure 6**) (around one third of the current global non-energy use of hydrogen). By 2040, hydrogen could provide on average almost 5% of total final demand, ranging from 0.5% in Shell to 11% in BNEF. In the period 2040-2050, global hydrogen demand in end-use sectors more than doubles (on average), and together with decreasing demand will provide over 10% of total final demand, ranging from less than 2% in Shell to 26% in BNEF. BNEF is the only study reviewed in this report to fully transition to a hydrogen economy.

[21] Some studies provide final demand data including non-energy (IRENA and JRC GECO). IRENA final demand includes non-energy hydrogen.

Figure 6 Global hydrogen and derived fuels demand in end-use sectors[22]



Source: JRC, 2022, based on scenario studies. Historical data (IEA, 2022)

To supply the hydrogen, a vast amount of electrolysers needs to be installed. IRENA foresees around 5 000 GW of electrolyser capacity in 2050 (compared to less than 0.5 GW today). DNV puts the figure at 3 000 GW (and 5 800 GW in their Net-zero scenario). Despite the rapid deployment of electrolysers, hydrogen is still partly produced from fossil fuels in most scenarios. IRENA still sees around 30% of blue hydrogen (produced from natural gas with CCUS) in 2050. IEA projects similar numbers (less than 40% of hydrogen produced from fossil fuels with CCS in 2050). BP splits production equally between green and blue hydrogen. In BNEF's Green scenario, production is dominated by green hydrogen, mainly coupled with dedicated wind and solar installations. Other studies also see the importance of coupling renewable electricity production with the production of green hydrogen.

Based on IRENA estimates, investment in hydrogen and related infrastructure could amount to around EUR 116 billion per year[23].

3.2.2 Transport

Since 1990, energy consumption in the transport sector (road, aviation and marine) has grown by slightly above 2% annually, reaching around 33 600 TWh in 2019. As one of most fossil fuel-dependent end-use sectors (at over 95% in 2019), it has a long way to go in order to meet the zero-carbon goal.

There is wide disagreement on the global transport sector's future evolution (**Figure 7**). By 2030, the highest projected energy demand (DNV at 35 600 TWh) is already almost twice the size of the lowest (IFS at 16 600 TWh), but on average, demand reduction is around 15%. The downward trend continues in 2040 with an average reduction of 35% over 2019, and in 2050 the reduction is almost 40%, with the highest estimate (DNV) now three times the lowest (IFS). The differences are driven by assumptions on decarbonisation targets, societal/behavioural changes and rates of efficiency improvements (mainly electrification).

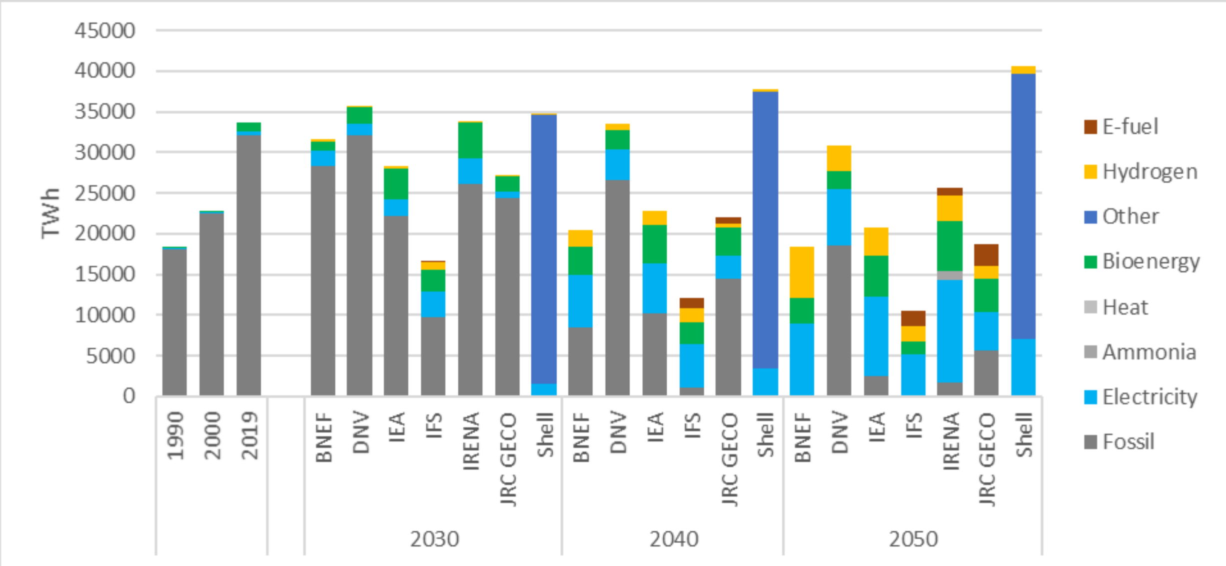
Change is also happening fast in the transport sector's fuel mix. By 2030, the share of fossil fuels already drops to an average of 80% (ranging from 60% in IFS to 90% in JRC GECO and DNV). By 2040, it drops below 50% (ranging from just 9% in IFS to 80% in DNV). By 2050, the share is to 18% on average. Several studies (BNEF and IFS) see the transport sector as fully decarbonised, while DNV still projects that 60% of the mix will still be fossil fuels, and JRC GECO puts the figure at 30%. While the share of fossil fuels and the total energy demand reduce, there is substantial growth in electrification: from just 1% in 2019 to an average of 8% in 2030 (ranging

[22] Ammonia and e-fuel are displayed at face value (not converted to hydrogen). IRENA final demand includes non-energy hydrogen, and BP includes hydrogen production (all other studies include hydrogen and derivatives consumption by end-use sector).

[23] Original text referring to USD 116 Billion per year, but taking into account currently observed USD/EUR parity this and subsequent monetary values are converted into EUR.

from 4% in DNV to 18% in IFS); 25% in 2040 (ranging from 11% in DNV to 45% in IFS), and 40% on average in 2050 (ranging from 23% in DNV and 25% in JRC GECO to 50% in IFS, followed closely by IRENA (49%), BNEF 48% and IEA (47%)). Bioenergy is adopted more slowly, reaching an average of 10% by 2030 (compared to 3% today), 16% in 2040 and 18% in 2050 (ranging from 7% in DNV to 24% in IRENA and IEA).

Figure 7 Global demand in transport sector by fuel

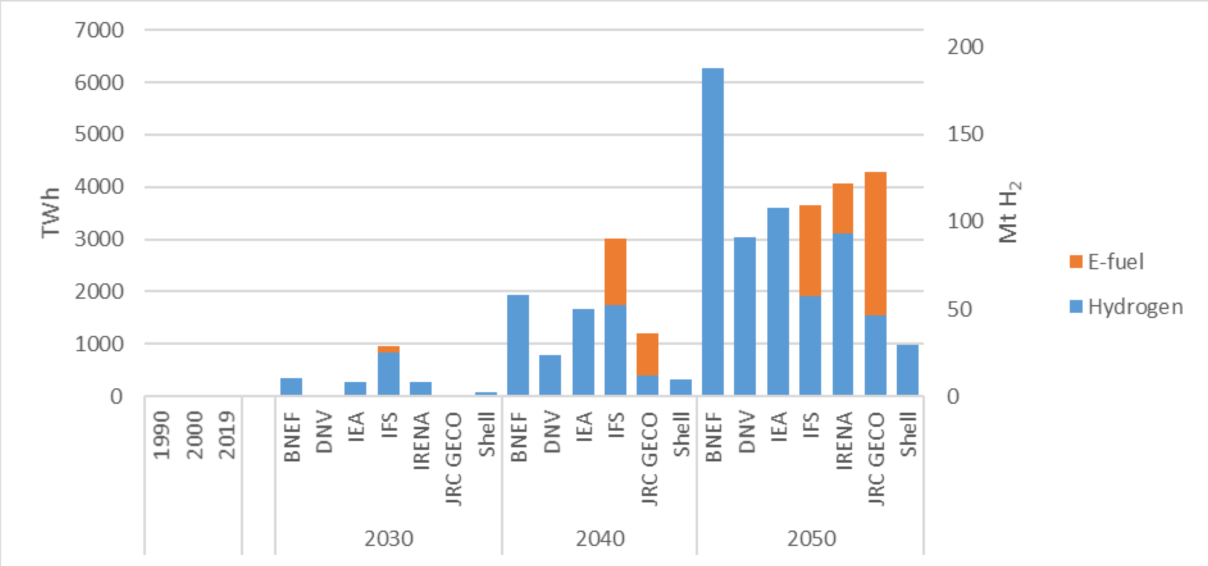


Source: JRC, 2022, based on scenario studies. Historical data (IEA, 2022)

A very limited amount of hydrogen is currently used in transport sector. Globally, at the end of 2021 there were less than 40 000 hydrogen fuel cell vehicles on the road (90% of which were in South Korea, the US and Japan), around 6 000 buses and less than 1 000 commercial vehicles (BloombergNEF, 2022), making hydrogen demand in the transport sector negligible. According to global energy scenario studies, hydrogen uptake in the transport sector will be slow, reaching less than 10 Mt on average in 2030 (**Figure 8**). Only IFS foresees a noteworthy consumption of hydrogen and e-fuels (around 30 Mt, which is 6% of the energy used in transport). By 2040, hydrogen demand reaches an average of 51 Mt (ranging from 24 Mt in DNV to 91 Mt in IFS, where it amounts to 25% of the total energy used in the transport sector). By 2050, global hydrogen and derived fuel demand in the transport sector will reach 125 Mt on average, ranging from 91 Mt in DNV to 188 Mt in BNEF. Not all studies provide data on the split between pure hydrogen and derived fuels, but it is evident that some hydrogen in hard-to-abate sectors will be used, either as e-fuels in aviation and road transport, or in some cases as ammonia in marine transport.

All scenario studies agree that the main road transport decarbonisation pathway is electrification (with the exception of long-haul transport, where hydrogen could have a role). Less agreement exists on the decarbonisation of other transport subsectors. For air transport, the majority of the studies still see partial usage of fossil hydrocarbons complemented either by biofuel or hydrogen-based synthetic fuel, or a mix of both. All studies also see a role for hydrogen in the decarbonisation of marine transport, but opinions diverge on whether that is pure hydrogen or its derivatives (mainly ammonia).

Figure 8 Global hydrogen demand in transport sector



Source: JRC, 2022, based on scenario studies. Historical data (IEA, 2022)

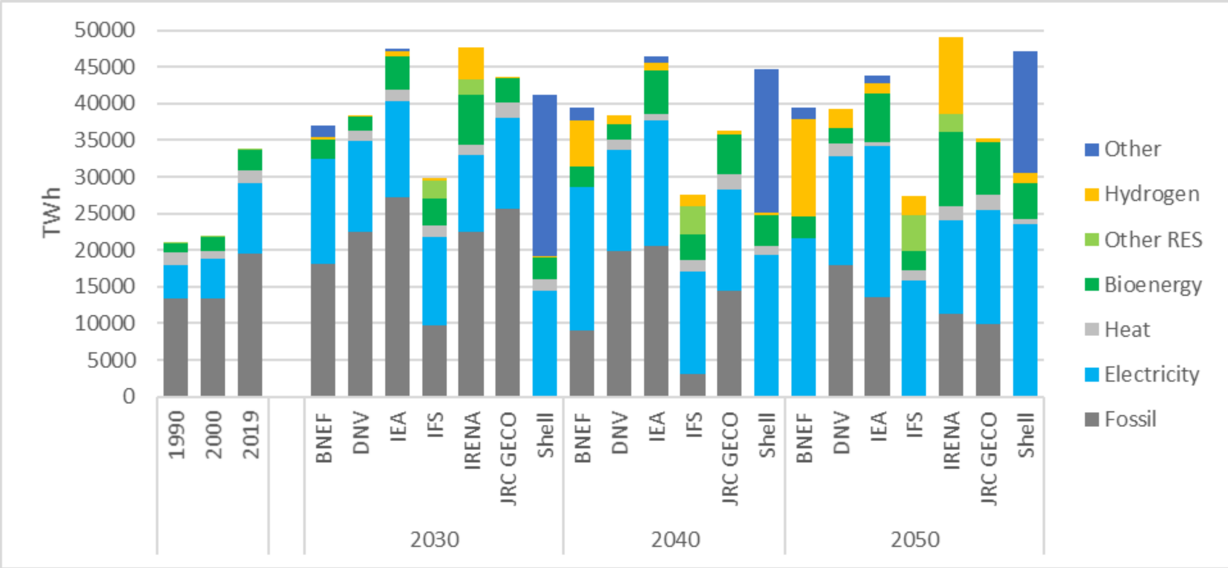
3.2.3 Industry

Since 1990, global energy demand in industry has grown by around 1.7% annually. However this growth has not been steady, with hardly any in 1990-2000, and a jump to 3.5% in 2000-2010. In the last few years (2015-2019), demand has reduced to 0.7% per year, reaching 34 000 TWh in 2019. In the coming decade (until 2030), the majority of scenarios see a growth of energy demand in industry of 32%, on average, compared to 2019. In 2030, all studies but IFS (at 30 000 TWh) see an increase in industrial energy demand, reaching almost 48 000 TWh in the case of IEA (**Figure 9**). In 2040, industrial energy demand is generally slightly lower, ranging from 28 000 TWh in IFS to 47 000 TWh in WEO. The situation remains similar in 2050 with an average demand of almost 40 000 TWh, ranging from 27 000 TWh in IFS to 44 000 TWh in WEO.

Decarbonisation takes considerably more time in industry than in transport. In 2019, fossil fuels accounted for 64% of global industrial energy demand. In 2030, it reduces to an average of 51%, ranging from 33% in IFS to 59% in JRC GECO. By 2040, fossil fuels account for an average of 38%, ranging from 11% in IFS to 52% in DNV. By 2050, BNEF and IFS do not project the use of any fossil fuels in industry, bringing the average rate to 21%. DNV still sees a 46% share of fossil fuels, and IEA 31%.

Most studies see electrification as the major driver for industrial decarbonisation. The electricity share in industry remains steady between 2019 and 2030, increasing from 31% in 2019 to 32% on average in 2030, (ranging from 22% in IRENA to 40% in IFS). In absolute terms, all scenarios see an increase in electricity consumption. By 2040, the share of electrification in industry rises to 42%, (from 36% in DNV to 51% in IFS and 50% in BNEF). By 2050, the share of electricity will be around 45% on average, of global industrial demand, ranging from 26% in IRENA to 55% in BNEF. In most scenarios, bioenergy plays a much smaller role in industrial decarbonisation, growing from 9% in 2019 to 13% in 2050, (ranging from only 5% in DNV to 21% in IRENA and JRC GECO).

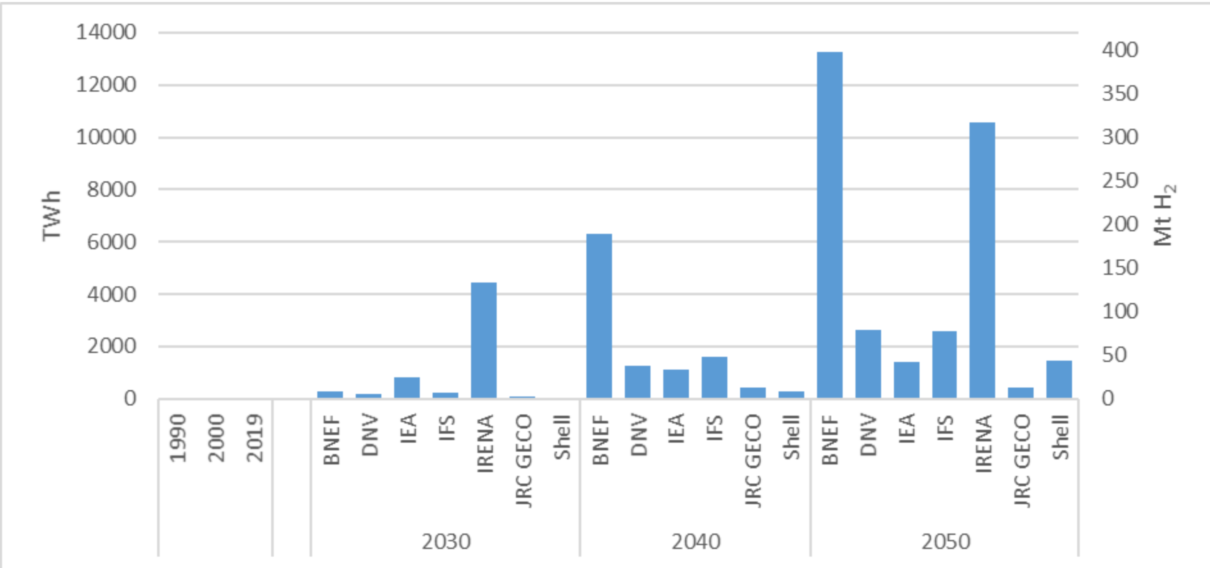
Figure 9 Global demand in industry by fuel



Source: JRC, 2022, based on scenario studies. Historical data (IEA, 2022)

The use of hydrogen to satisfy industrial energy demand starts slowly. In 2030, all studies project that it will account for less than 2%[24] (**Figure 10**) of industrial energy demand (ranging from 2 Mt in JRC GECO to 25 Mt in IEA). By 2040, the share of hydrogen will rise to 6% on average, ranging from 14 Mt in JRC GECO, to 190 Mt in BNEF (16% of industrial energy demand). By 2050, hydrogen usage for energy will increase to 11% on average, ranging from just 13 Mt in JRC GECO to almost 400 Mt in BNEF (34% of total industrial energy demand).

Figure 10 Global hydrogen demand in industry



Source: JRC, 2022, based on scenario studies. Historical data (IEA, 2022)

[24] IRENA is not taken into account, because it included both energy and non-energy use of hydrogen.

3.2.4 Buildings

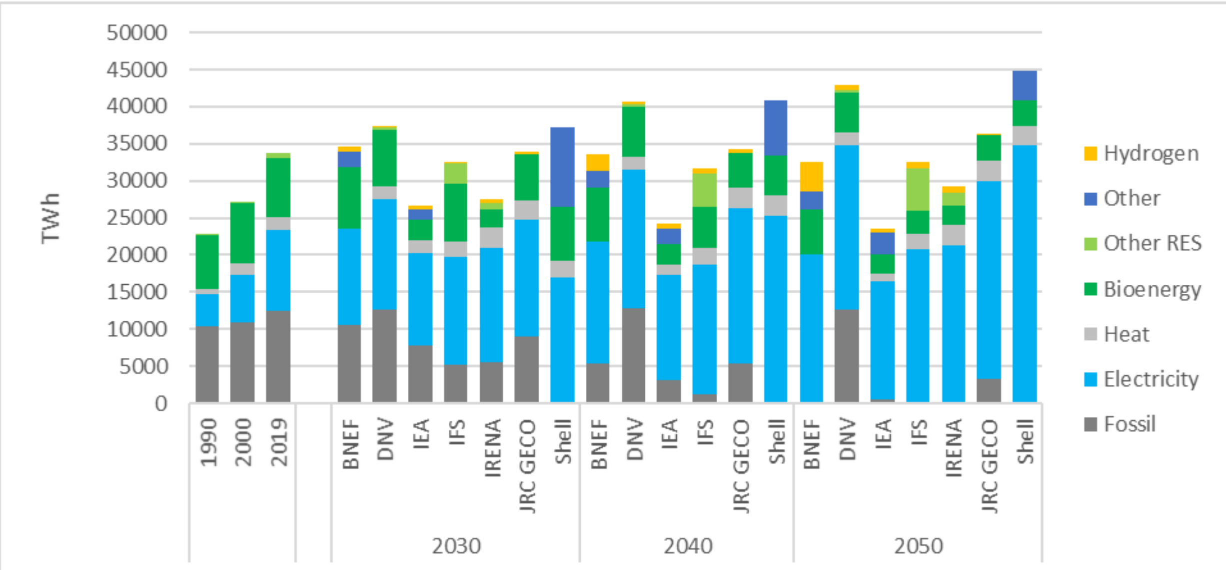
With constant population growth and increasing demand for comfort, it is no surprise that energy demand in the global buildings sector is steadily growing. From 1990, the growth rate of global energy demand in buildings was 1.4% per year (CAGR), ranging from 0.5% in period 2010-2015 to 1.76% in 1990-2000. Despite historical evidence, all scenarios but one see the sector's energy demand as either stable or contracting in 2030 (IFS, BNEF and JRC GECO see values similar to today. IEA sees a 20% decrease while the outlier, DNV, sees an 11% increase, resulting in an overall average reduction of 9%). In 2040, the average demand remains similar to that of 2030, but studies vary from 24 200 TWh (a 28% reduction compared to 2019) to 40 700 TWh (a 21% increase compared to 2019). In 2050, the average remains similar but the range widens further: from 23 400 TWh in IEA (a 30% reduction compared to 2019) to 43 000 TWh in DNV (a 27% increase compared to 2019).

Meanwhile, the share of fossil fuels in the buildings sector is steadily decreasing. In 1990, it accounted for 45% of energy in the global buildings sector. By 2000, it dropped to 40% and in 2019 to 37%. Despite the decreasing share, in absolute terms, 20% more fossil fuel was used in the buildings sector in 2019 than in 1990. In the near term (to 2030), almost all scenarios see a reduction of fossil fuels in the sector globally both in absolute and relative terms. In 2030, the share will be only 26%, ranging from 16% in IFS (5 200 TWh: a 60% reduction compared to 2019) to 34% in DNV (12 700 TWh: a 2% increase compared to 2019). This reduces further in 2040, accounting for 16% of the total energy demand in buildings, ranging from only 4% in IFS (1 300 TWh or a 90% reduction compared to 2019) to 32% in DNV (12 900 TWh, or a 3% increase compared to 2019). By 2050, a number of studies (BNEF, IFS, and IRENA) see the full decarbonisation of the buildings sector globally, bringing the average fossil fuel share to 6% on average. DNV sees the fossil fuel share relatively unchanged in comparison with 2030 and 2040, at around 12 700 TWh.

In the buildings sector, the main driver for decarbonisation will be electrification (replacing fossil fuels in heating, cooling and cooking), reaching an average across the scenarios of 45% in 2030 (from 32% in 2019), ranging from 56% in IRENA (15 400 TWh or an increase of over 40% compared to 2019) to 37% in BNEF (13 000 TWh or an 18% increase compared to 2019). By 2040, electrification of the global buildings sector will reach 54% on average, ranging from 46% in DNV to 62% in JRC GECO. In 2050, electrification of the buildings sector will reach 65% on average, ranging from 51% in DNV to 73% in IRENA and JRC GECO. In JRC GECO, electricity consumption will reach 27 000 TWh: 215% higher than in 2019. Some of this will be used by heat pumps to provide heating/cooling.

The majority of the studies see a decrease in the use of bioenergy in the sector, mainly driven by the move from traditional biomass to modern energy services in the developing world, and to more comfortable heating solutions in the developed world (for example replacing individual pellet boilers with heat pumps). By 2050, only 12% of final demand in the global buildings sector will be met by bioenergy (down 24% from 2019).

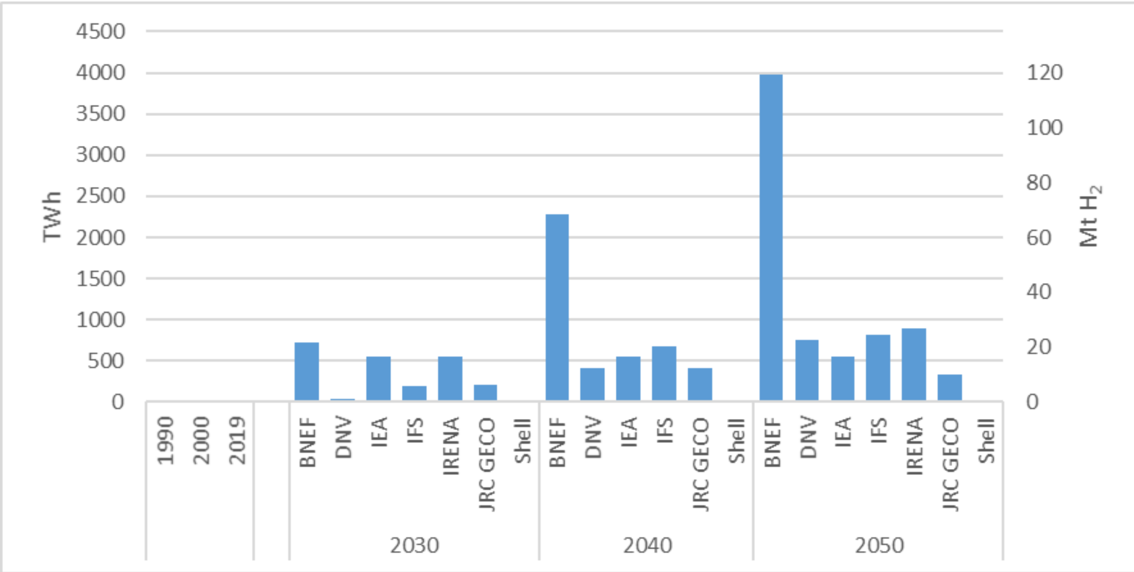
Figure 11 Global energy demand in the buildings sector by fuel



Source: JRC, 2022, based on scenario studies. Historical data (IEA, 2022)

Global hydrogen demand in the buildings sector could reach around 11.5 Mt in 2030, ranging from 1.2 Mt in DNV to 22 Mt in BNEF, where it accounts for only 2% of the sector's total energy supply. By 2040, hydrogen consumption could reach 26 Mt on average, ranging from just 13 Mt in JRC GECO and DNV (providing 1% of global demand in buildings) to 68 Mt in BNEF (7% of demand). By 2050, hydrogen demand could reach 34 Mt on average, ranging from less than 10 Mt in JRC GECO, to 120 Mt in BNEF (12% of demand). A number of studies do not see much growth of hydrogen consumption in the buildings sector between 2040 and 2050 (IEA, IFS), and others even see contraction (JRC GECO), while BNEF and DNV see it almost double in this period.

Figure 12 Global hydrogen demand in the buildings sector



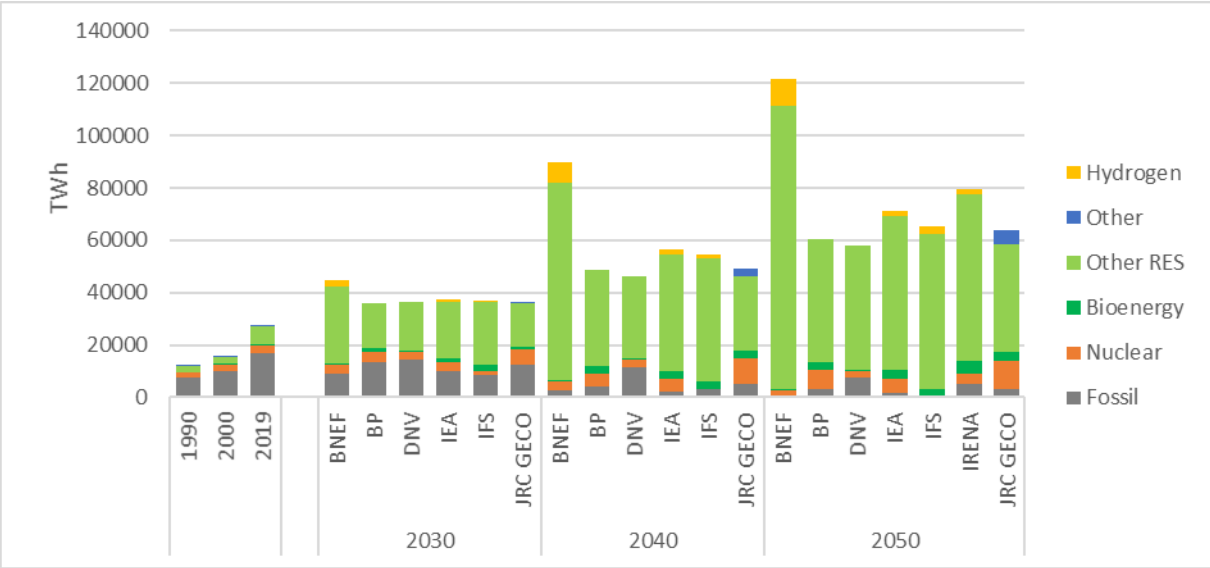
Source: JRC, 2022, based on scenario studies. Historical data (IEA, 2022)

3.2.5 Power generation

In 2015-2019, **global** power generation grew at a rate of around 2.6% per year, and since then it has been growing steadily at 2.9% per year. All but one of the global scenarios analysed in this report see a continuation of this growth rate until 2030, at 2.7% on average. In BNEF, driven by the emerging hydrogen economy, the figure is put at 4.7%, reaching 44 700 TWh, while the other scenarios put power generation at an average of around 37 000 TWh (**Figure 13**). In the period 2030-2040, BNEF sees an even higher rate of growth in global power generation, at almost 7.2% (reaching almost 90 000 TWh in 2040), while the others are more conservative with 3.7% on average, reaching only 52 000 TWh of total power generation. By 2050, BNEF still leads at 3.7% (121 500 TWh), with the other scenarios come in at an average 2.5% (66 000 TWh), ranging from 58 000 TWh in DNV to 71 000 TWh in IEA. The main driver for growth in BNEF is the considerably faster deployment of hydrogen technologies in all sectors, coupled with a reliance on green hydrogen alone (while the other studies still see blue hydrogen covering almost half of demand in 2050).

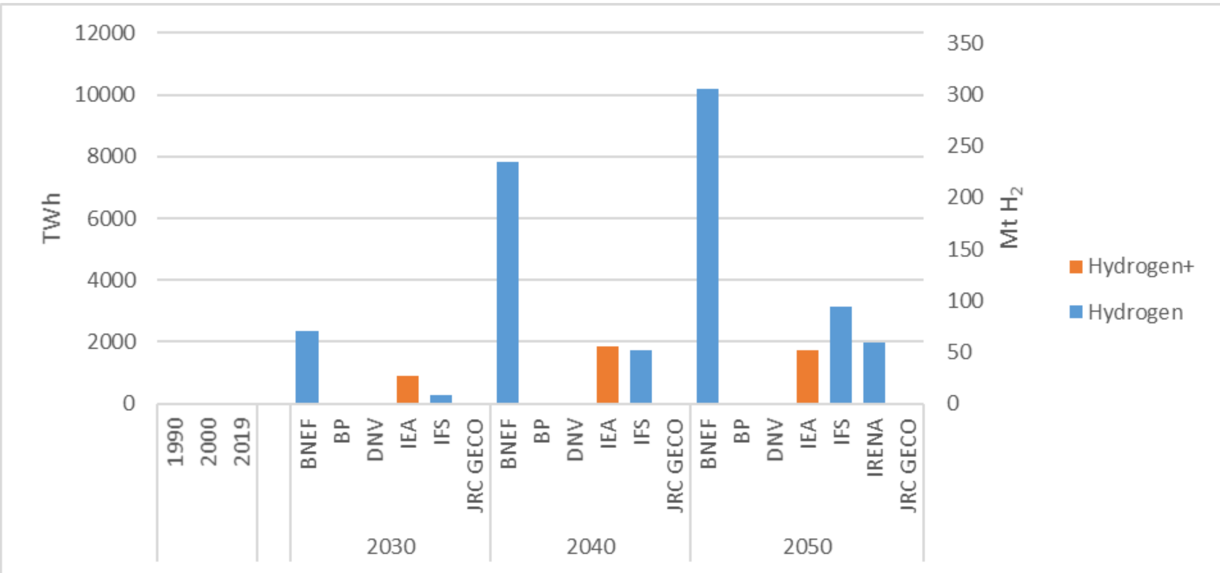
Despite growing numbers of renewables, since 1990 there has been no real progress in the decarbonisation of global power supply. The share of fossil fuels was 63% in both 1990 and 2019. Due to increasing levels of power generation, the amount of fossil fuels used more than doubled in this period. The global share will, however, drop considerably over the next decade, from 63% in 2019 to 30% on average in 2030 (ranging from 20% in BNEF to 40% in DNV) driven mainly by an increasing share of renewables (from 26% in 2019 to almost 60% in 2030). During this period, the share of bioenergy will rise from 2% to 4%, and other renewables (mainly wind and solar) will reach 55% on average. By 2040, the fossil fuel share in power generation drops further, to 9% on average, led by BNEF (3%) and IEA (4%). DNV still sees a share of around 25% in total power production. In this period the share of renewable energy continues to grow, reaching 91% in IFS. At the other extreme, JRC GECO sees 64% of renewables contributing to power production. In 2050, several studies see fossil fuels eliminated from electricity generation (BNEF, IFS), pushing the average share to 5%. In all the studies analysed, renewables provide over 80% of global electricity (except in JRC GECO, where nuclear energy plays an important role in the decarbonisation of the power sector), reaching 95% in IFS, and 89% in BNEF.

Figure 13 Global power generation by fuel



Source: JRC, 2022, based on scenario studies. Historical data (IEA, 2022)

Figure 14 Hydrogen usage in global power generation[25]



Source: JRC, 2022, based on scenario studies. Historical data (IEA, 2022)

The current levels of hydrogen consumption for power production are negligible, and this situation will not change much by 2030. Only one study, NEF, projects more than 1 TWh of electricity being generated from hydrogen: it puts the figure at 2 300 TWh, a share of 5% (**Figure 14**). This would entail the consumption of around 120 Mt (with an assumed efficiency of 60%). By 2040, three studies see a role for hydrogen in power generation: BNEF, with almost 8 000 TWh of electricity (almost 9% of total generation), consuming close to 400 Mt; and IEA and IFS with around 80 Mt of hydrogen used (generating around 1900 TWh), providing around 3% of power generation. By 2050, the rate of growth slows down: BNEF sees around 10 TWh of electricity generated using hydrogen (about 8.4% of total generation, 510 Mt). In IFS, the hydrogen generation share

[25] Numbers in the graph represent electricity generation from the hydrogen. Depending on generation efficiency, hydrogen consumption could double.

reaches almost 5% (156 Mt). IEA and IRENA are close to each other with 86 Mt and 98 Mt respectively, providing close to 2.5% of power.

3.3 Hydrogen's role in the EU's energy use

3.3.1 Final demand

Final demand in the **EU** did not change much in the period between 1990 and 2020 (contrary to trends observed at global level), remaining steady at around 10 500 TWh (IEA, 2022), with a slight downward trend in last two decades (of around -0.2% per annum). The studies used in this report do not agree on the future trend of total final demand in the EU, with figures diverging by as much as 35% just for the next decade. Only one study – DNV – sees a slight increase of around 10%, while others (BP, JRC Times) project no change, and another group (CAN, EUCalc, IFS, EC Fit-for-55) forecasts a reduction in final demand of around 25% on average in the next 10 years.

By 2040, all EU studies see a contraction in final demand, but they diverge even more than for 2030, ranging from a reduction of just 5% (compared to 2020) in DNV to almost 45% in CAN. The same trend continues for 2050: DNV see a minimal reduction in final demand of around 10% compared to 2020, while others (EUCalc, CAN) put the figure at over 50%. In Fit-for-55, the total final demand in 2050 is projected to be around 40% lower than in 2020.

These variations in final demand are driven by the assumptions embedded in the underlying models: studies that rely on increased electrification and efficiency see only a moderate reduction in final demand, partly offset by improved quality of life. Studies that see the highest rates of reduction couple increased efficiency with behavioural changes in areas such as diet, mobility and social aspects.

At the same time, the fuel mix is also changing noticeably. While the fossil fuel share in final demand dropped from 72% in 1990 to 60% in 2020, it could drop further to 50% on average by 2030. BP projects a share of fossil fuels similar to current levels, and at the other extreme, IFS sees it drop to 37% by 2030. By 2040, the fossil fuel share will drop to 26% on average. CAN foresees no direct fossil fuel use at all by 2040 in end-use sectors, and at the other extreme, DNV[26] still projects a share of 48%. By 2050, the average share of fossil fuels in the mix drops to 14%. By 2050, the fossil fuel share in final demand will drop down to 2% according to EC Fit-for-55.

In almost all the scenarios analysed, electrification rates increase: from 18% in 1990 to 23% in 2020, reaching 30% (on average) in 2030 and almost 50% (on average) in 2050. All energy scenarios except EUCalc see an increase in both electrification rates and electricity consumption in absolute terms, while EUCalc, driven by the rapid reduction of demand in electricity, drops to 19% in 2030, with a corresponding doubling of bioenergy consumption. By 2050, electrification ranges between 36% in EUCalc, to 61% in CAN, reaching 56% in EC Fit-for-55

Studies do not agree on bioenergy's future role. On average, it will contribute around 14% of final demand in 2030 (compared with 10% today), but all but two studies (EUCalc at 26% and JRC Times at 13%) see a reduction in bioenergy both in relative and absolute terms. By 2050, bioenergy consumption contracts in most studies in absolute terms, but still supplies an average of around 13%, ranging from 4% in CAN to 23% in EUCalc. In EC Fit-for-55, bioenergy contributes 11% in 2050.

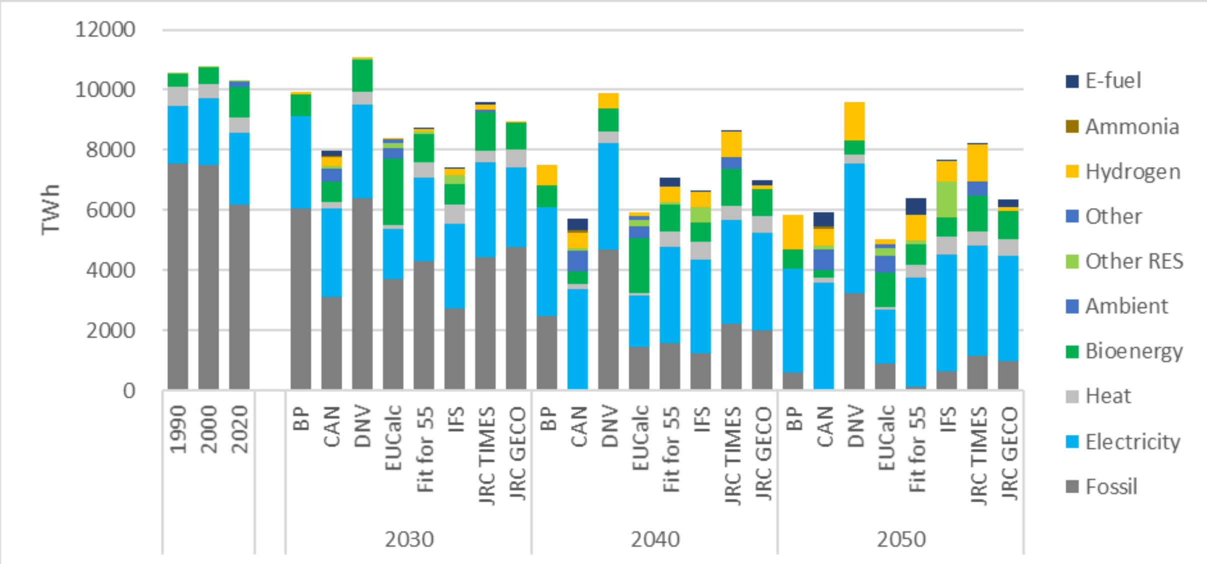
It is also worth noting that ambient heat could contribute around 10% to final demand in 2050 (up from 1% in 2020), but no definitive conclusion can be reached as not all studies provide data on ambient demand, despite several mentioning its importance, especially in the buildings sector.

As with global trends, hydrogen and its derivatives are next to non-existent in current EU final energy demand. With the exception of some pilot projects in transport and industry, hydrogen is used exclusively in EU industry for non-energy purposes. Based on the energy studies analysed, hydrogen usage in end-use sectors will remain negligible in the next decade; in the majority of scenarios, hydrogen and its derivatives are responsible for 1% or less of the energy used. Only three studies put the figure above 1% in 2030: JRC TIMES at 2.6% (6 Mt), IFS at 2.6% (7 Mt) and CAN at 6.3% (15 Mt). In comparison REPowerEU plan foresee only 9 Mt of end use green

[26] DNV is one of the two studies in this report that do not reach net-zero by 2050.

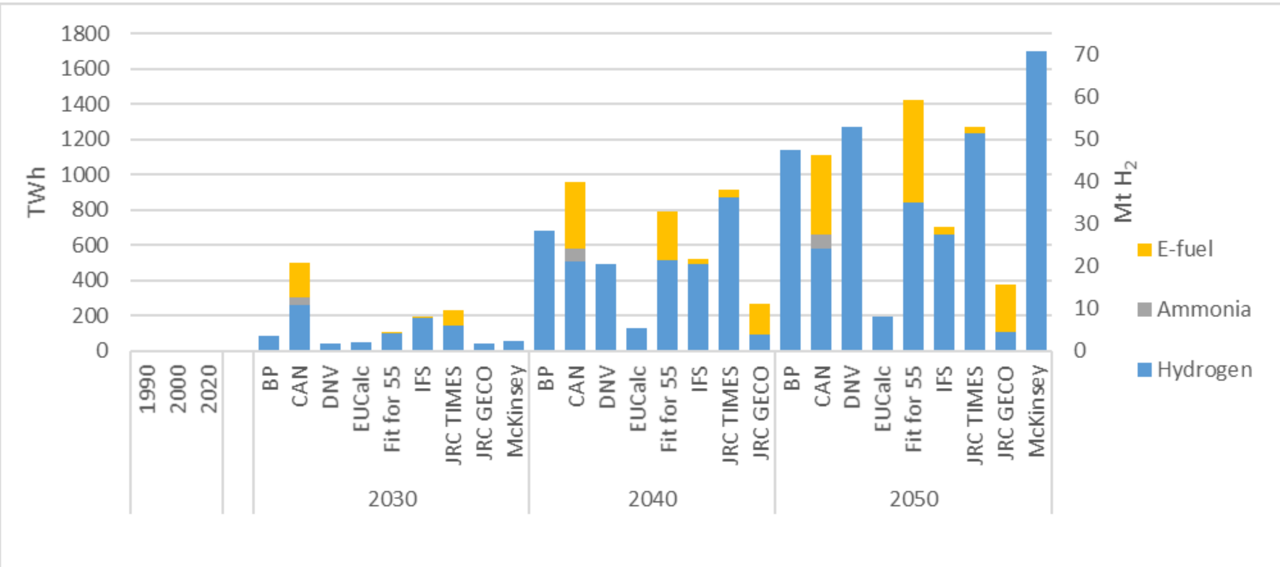
hydrogen in 2030[27]. By 2040, hydrogen demand reaches 18 Mt on average, ranging from 4 Mt in EUCalc to 29 Mt in CAN, where it meets 17% of final energy demand. By 2050, hydrogen demand in the EU will reach 32 Mt on average, meeting more than 10% of final demand according to most of the scenario studies. In EC Fit-for-55, hydrogen and e-fuels provide more than 20% of final energy in the EU.

Figure 15 Final demand by fuel[28] in the EU



Source: JRC, 2022, based on scenario studies. Historical data (Eurostat, 2022)

Figure 16 Hydrogen and derived fuels demand in EU end-use sectors



Source: JRC, 2022, based on scenario studies. Historical data (Eurostat, 2022)

Following the Russian invasion of Ukraine and the urgent need to reduce energy dependence on fossil hydrocarbons from Russia, the European Commission published the REPowerEU Plan (European Commission, 2022c) on 18 May 2022, detailing hydrogen and bio methane targets (European Commission, 2022e) in order to reduce natural gas consumption. Building on the Fit for 55 ambitions, REPowerEU accelerated the short-term projections for hydrogen utilisation in Member States, from slightly above

[27] Fit-for-55 MIX-H2 scenario had only 3.5 Mt of hydrogen in final demand sectors.
[28] Fit55 and JRC GECO include non-energy

6 Mt to 16 MT in 2030 (Figure 4), not including an additional 4 Mt of imported ammonia and related hydrogen derivatives. REPowerEU foresees a rapid increase in green hydrogen penetration in both non-energy (replacing brown/grey hydrogen) and final energy sectors: 4.1 Mt in transport (direct and as derivatives), 3.6 Mt in the industrial sector, and 1.3 Mt in buildings.

3.3.2 Transport

In the EU, the transport sector has been stable at around 3 300 TWh per year since 2005 (in comparison with global trends which showed steady growth). The 2020 drop to 2900 TWh was most likely caused by the COVID-19 pandemic and will bounce back in the coming years. Although statistical data do not show growth in energy demand in the transport sector, the majority of the studies expect a slight increase in energy consumption: BP and DNV see demand rising above 3 500 TWh in 2030. However, CAN and IFS see a substantial reduction in energy demand: below 2 500 TWh in CAN (driven mainly by electrification) and below 1 300 TWh in IFS[29]. By 2040, all studies see a contraction in demand in the transport sector. The same trend continues in 2050, on average reaching 1 900 TWh, ranging from only 780 TWh in IFS to 2 600 TWh in BP. EC Fit-for-55 expects energy demand in the transport sector to drop down to 1 300 TWh in 2050.

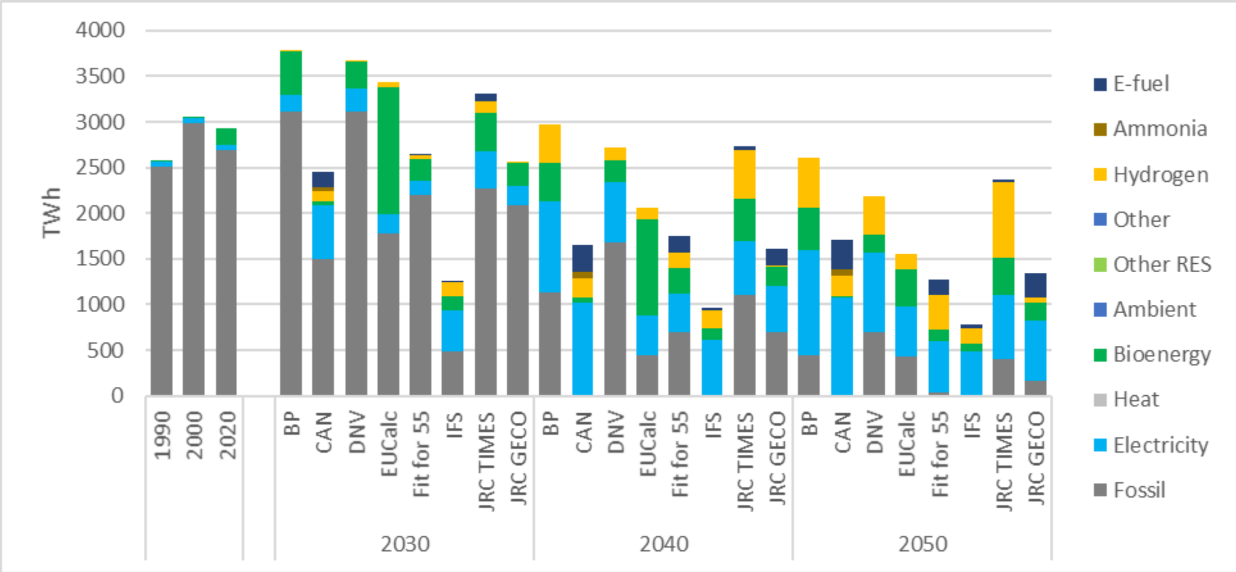
The European fuel mix is projected to change much faster than it does globally. In 2020, fossil fuels amounted to 92% of total demand in the EU transport sector, but by 2030, that share reduces to 70% on average, ranging from 85% in DNV to 39% in IFS. This fossil fuel reduction trend continues in 2040, dropping below 30% on average, and some studies (CAN and IFS) almost entirely eliminate its use. By 2050, the share of fossil fuels drops to 15% on average (most studies put it below 20%), ranging from zero in CAN and IFS, to 32% in DNV, and 28% in EUCalc. EC Fit-for-55 sees only 3% of demand in the transport sector met by fossil fuels in 2050.

Studies disagree on decarbonisation pathways for the European transport sector, especially in the short and medium term. Fuels of biological origin currently make up to 6% of demand in the EU transport sector **Figure 17**). By 2030, biofuels could increase to around 13% on average, but there is huge disagreement among studies, ranging from as low as 2% (43 TWh) in CAN, to 41% in EUCalc (1 400 TWh). By 2040, the share of bioenergy in Europe could rise to 17%, but disagreement remains. CAN puts the role of bioenergy at only 3% (54 TWh) while in EUCalc, the share of bioenergy grows to 52% (despite a decrease in absolute terms to 1060 TWh). No other studies see bioenergy surpassing 17% in 2040. By 2050, bioenergy usage in the transport sector contracts: on average it contributes only 15% to final energy demand in transport, ranging from almost zero in CAN, to 26% in EUCalc. In absolute terms, less than 300 TWh (on average) of bioenergy will be used in the EU by the middle of the century. EC Fit-for-55 does not expect a prominent role for bioenergy in the future: only 9% of final demand in transport sector will be met by bioenergy in 2050.

All energy scenario studies agree on the increasing role of electrification in the transport sector, but, as in the case of bioenergy, there are wide discrepancies. While in 2020, electricity constituted only 2% of total energy demand in the EU transport sector, it reaches 13% on average by 2030, ranging from 6% in BP, to 37% in IFS. By 2040, the electrification rate in the transport sector could reach 35%, ranging from 21% in EUCalc, to 62% in CAN, or 64% in IFS. By 2050, 46% of energy demand in the transport sector will be met by electricity, ranging from 30% in JRC TIMES, to 63% in CAN or IFS. In EC Fit-for-55, electrification will reach 44%. In 2050, electricity demand in the transport sector will range from 500 TWh in IFS, to 1 140 TWh in BP.

[29] IFS provides data only for OECD Europe. Numbers in the graph and text are scaled down based on historical the EU share in OECD Europe.

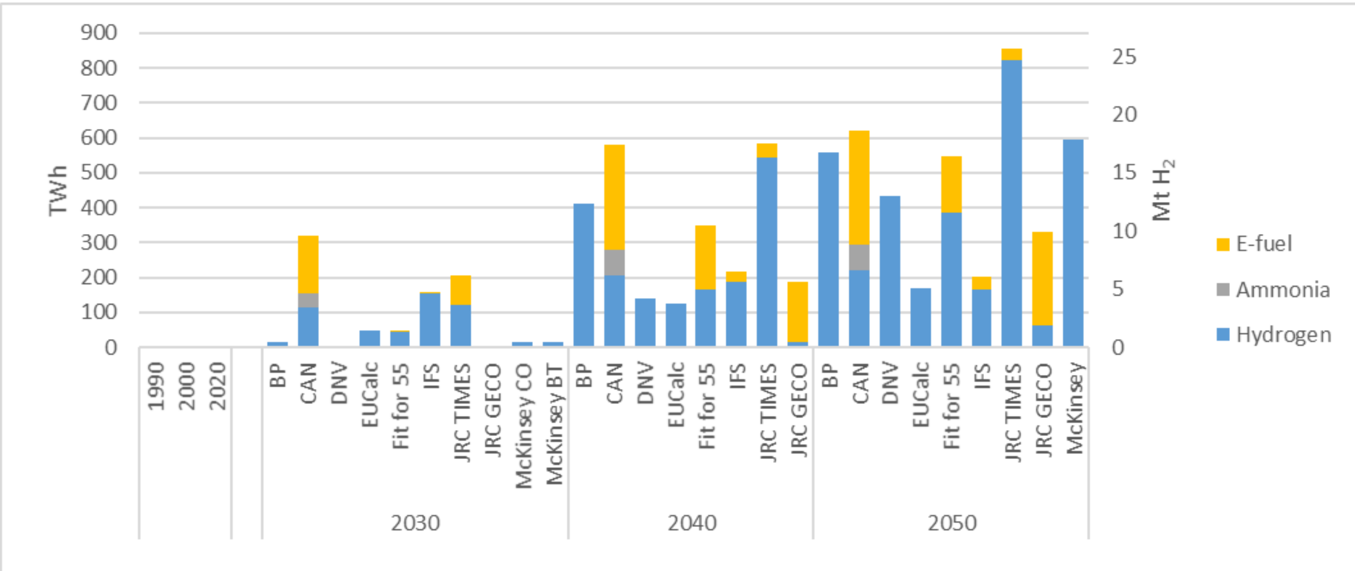
Figure 17 The EU demand in transport sector by fuel



Source: JRC, 2022, based on scenario studies. Historical data (Eurostat, 2022)

Like the global trends, the uptake of hydrogen and its derivatives will be slow in the EU. In 2030, an average of only 4% of total demand in transport will be met by hydrogen. Most studies see less than 2 Mt used in the transport sector by 2030, but there are three exceptions: CAN at 10 Mt, JRC Times at 6 Mt, and IFS at 5 Mt. In the latter, due to a drastic reduction in energy demand in the transport sector, hydrogen could provide to around 12% of total demand. By 2040, the share of hydrogen and derived fuels could reach 17%, ranging from 4 Mt in EUCalc, to 18 Mt in CAN and JRC Times. In 2050, the share of hydrogen in transport sector will rise to 27% on average, ranging from 5 Mt in EUCalc, to 26 Mt in JRC. In EC Fit-for-55, hydrogen and e-fuel consumption reaches 16.5 Mt H_2. Transport and industry will be the two main EU sectors in which hydrogen will be used.

Figure 18 Hydrogen demand in the EU transport sector



Source: JRC, 2022, based on scenario studies. Historical data (Eurostat, 2022)

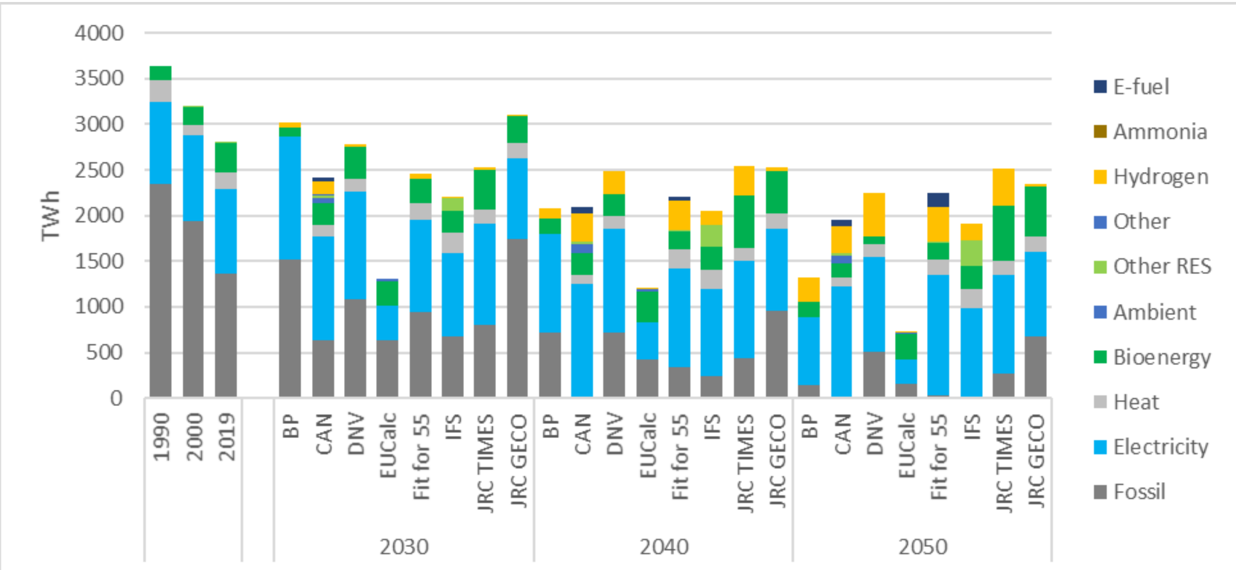
3.3.3 Industry

Total industrial energy demand in the **EU** has decreased steadily, by almost 1% per year, since 1990, with a small increase of around 0.5% per year in 2015-2019. Unlike the global scenario results, European scenarios disagree widely on pathways for energy consumption in industry. In 2030 (**Figure 19**), the majority of studies see a reduction in industrial energy consumption (ranging from 9% in JRC TIMES to 43% in EUCalc). BP sees an increase of 8%. The JRC GECO results combine energy and non-energy demand, but it can be concluded that JRC GECO sees a decrease in industrial energy demand. After 2030 there is a general downward trend of about 23% on average by 2040 (ranging from 9% in JRC Times to 57% in EUCalc). In 2050, industrial energy demand is down by 32% on average, ranging from 10% in JRC TIMES to 77% in EUCalc. In 2050, EC Fit-for-55 projects that industrial energy demand will be 19% lower than in 2019.

In 2019, fossil fuels accounted for slightly less than 50% of final industrial energy demand (down from 61% in 2000). By 2030, the share of fossil fuels will drop on average to 40%. Some studies do not see a fossil fuel reduction in industrial energy (BP), while others see a reduction in absolute terms but little change in the overall share (in EUCalc, fossil fuel usage in industry drops by more than 50%, but due to rapidly decreasing industrial demand, the share remains more or less unchanged). By 2040, the fossil fuel share will drop to 23% on average. In some studies, fossil hydrocarbons still provide around 35% of industrial energy (BP) in 2040, but others (CAN) expect it to be fully decarbonised already. By 2050, the fossil fuel share has dropped to 12% on average (and in most cases is coupled with CCS). Studies that do not consider CSS as an option, eliminate fossil fuels from the industrial energy balance completely by 2050 (CAN, IFS). In Fit-for-55, fossil fuels meet only around 1% of final energy demand in industry.

In order to decarbonise industry, all studies see a rapid increase in electrification. By 2030, electrification rates in EU industry will reach 40% on average (compared to 33% in 2019). By 2040, electrification will reach an average of 46%, and almost 50% in 2050. In EC Fit-for-55, electricity constitutes almost 60% of final demand in industry. The uptake of bioenergy will be considerably slower, reaching only 17% in 2050 (compared to 11% in 2019) and in absolute terms, all but two studies (JRC TIMES and JRC GECO) expect bioenergy consumption in the EU's industrial energy demand to be lower than in 2019.

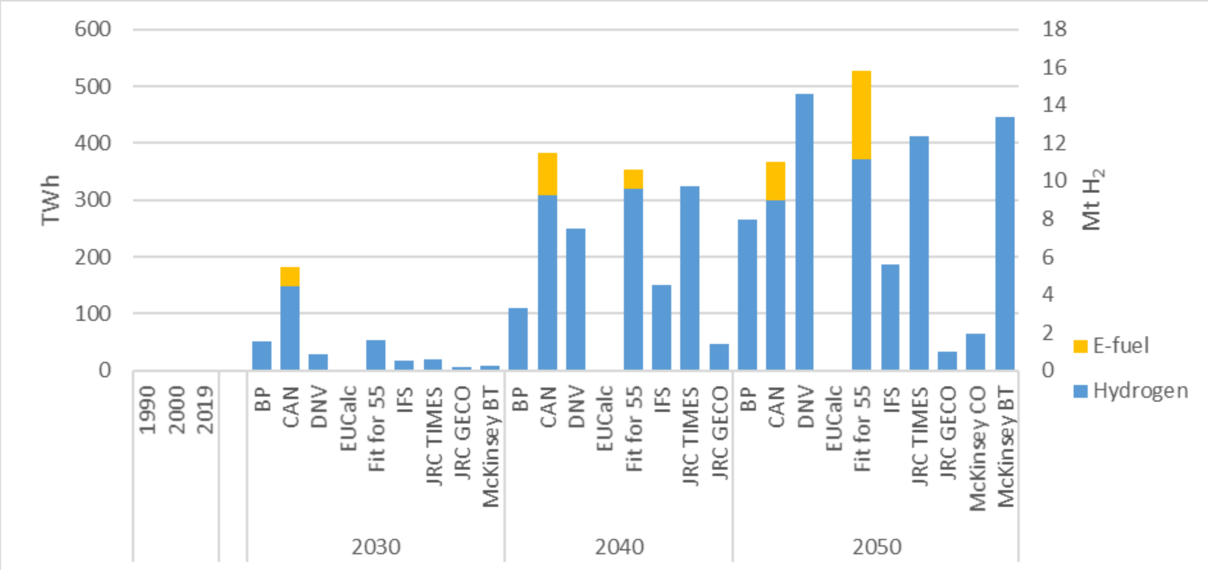
Figure 19 EU industrial energy demand by fuel



Source: JRC, 2022, based on scenario studies. Historical data (Eurostat, 2022)

Hydrogen demand in industry will be slow to take off in **the EU** (Figure 20). Only CAN considers it worth mentioning for 2030, reaching around 5.5 Mt and suppling more than 7.5% of total industrial energy in the EU. Other studies see a hydrogen consumption of below 2 Mt: BP and McKinsey BT see it at slightly over 1.5 Mt. All other studies put the figure below 1 Mt for 2030. By 2040, studies see around 6 Mt of hydrogen used in industry (as energy), ranging from just 0.03 Mt in EUCalc to 11.5 Mt in CAN and EC Fit-for-55. In 2050, around 8.3 Mt will be used in the EU industry, ranging from 0.06 Mt in EUCalc to 13.4 Mt in McKinsey BT and 15.8 Mt in EC Fit-for-55. By 2050, hydrogen and its derivatives, in some studies, could supply over 20% of industrial energy demand (BP, DNV, EC Fit-for-55, and McKinsey). Transport and industry will be the two main EU sectors where hydrogen will be used.

Figure 20 Hydrogen demand in the EU industry sector



Source: JRC, 2022, based on scenario studies. Historical data (Eurostat, 2022)

It can be concluded that hydrogen will compete with bioenergy and fossils with CCS in decarbonising hard-to-abate industrial subsectors.

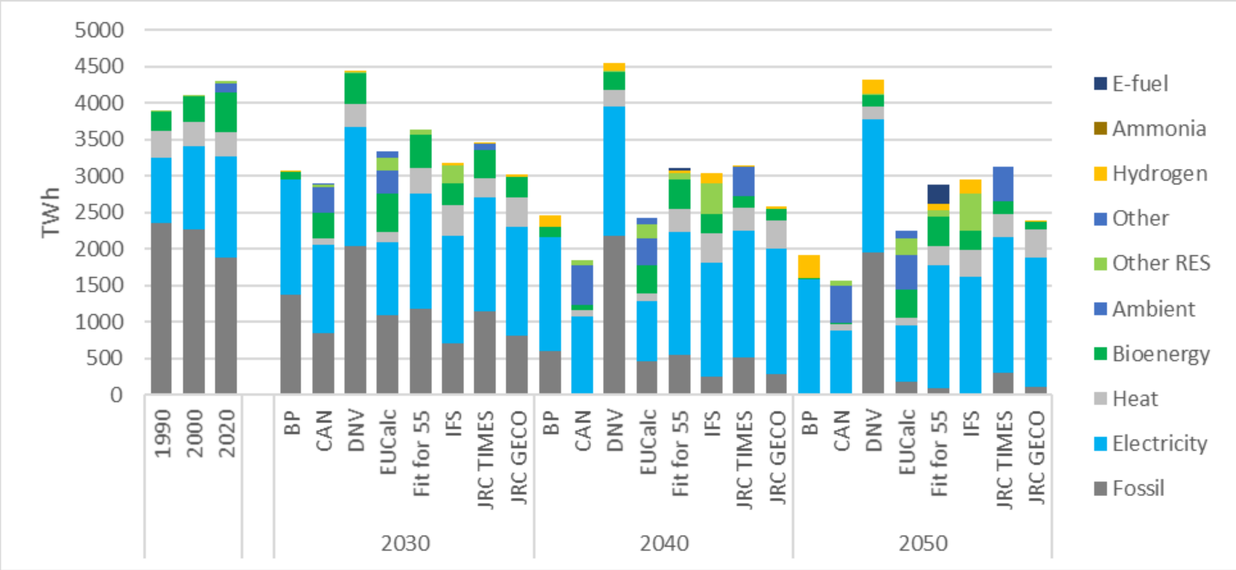
3.3.4 Buildings

Historically, there has been limited growth in energy demand in **the EU** buildings sector. In the period from 1990 to 2020, the CAGR was only 0.33%. In the period 1990-2010 it was 1.13%. Between 2010-2015 it was 2%, and after that it remained relatively constant. By 2030, all but one see a substantial reduction of energy demand in EU buildings (averaging a drop of 21% from 2020). Across the scenarios, the projections range from a reduction of 30% in JRC GECO to a growth of 3% in the outlier, DNV (Figure 21). By 2040, energy demand declines further by an average of 33% compared to 2020, ranging from -64% in CAN, to 6% in DNV. In 2050, on average, the reduction (compared to 2020) will be around 38%, ranging from -64% in CAN to 0% in DNV. In EC Fit-for-55, energy demand in the buildings sector will drop by 33% compared to 2020.

In 2020, 44% of energy in EU buildings sector came directly from fossil fuels. This share will decrease to 33% by 2030, ranging from 22% in IFS, to 46% in DNV. Due to the decrease in total energy demand in the EU buildings sector, fossil fuel demand will drop by 40% on average, but in some cases (CAN, IFS, and JRC GECO), the reduction will exceed 50%. By 2040, the share will drop to 18% on average, ranging from full decarbonisation in CAN to 48% in DNV. On average, fossil fuel usage will drop to a third in 2040 compared to 2020. By 2050, fossil fuel will provide only 9% of the EU buildings sector's energy. Four studies see full decarbonisation at this stage (BP, CANand IFS). At the other extreme, DNV (which does not have the goal of decarbonisation by 2050) still projects a 45% fossil fuel share for 2050.

As the share of fossil fuels reduces, the drive to decarbonise will increase electricity demand in the buildings sector. In 2020, electricity amounted to 32% of total energy supply in the sector. By 2030, its share will increase to 43%, ranging from 30% in EUCalc to 45% in JRC TIMES. Several studies put electricity demand in 2030 lower than it was in 2020: by 30% in EUCalc and by 13% in CAN. By 2040, the electrification rate will jump to 53%, ranging from 34% in EUCalc to 66% in JRC GECO. By 2050, electrification will reach 58% on average, ranging from 34% in EUCalc to 75% in JRC GECO. In absolute terms, projected electricity usage differs widely across the studies, from just 775 TWh in EUCalc (a 44% reduction compared to 2020) to 1 847 TWh in JRC TIMES (a 33% increase compared to today). EC Fit-for-55 puts the rate of electrification rate at 59% in 2050. The share of bioenergy will reduce from 13% in 2020 to an average of 10% in 2030, ranging from only 3% in BP to 15% in EUCalc. In 2040, average bioenergy use in the buildings sector will drop to 8%, staying at a similar level in 2050, ranging from just 1% in BP and CAN to 17% in EUCalc. By 2050, bioenergy usage will have dropped by 66% on average since 2020, providing only around 180 TWh.

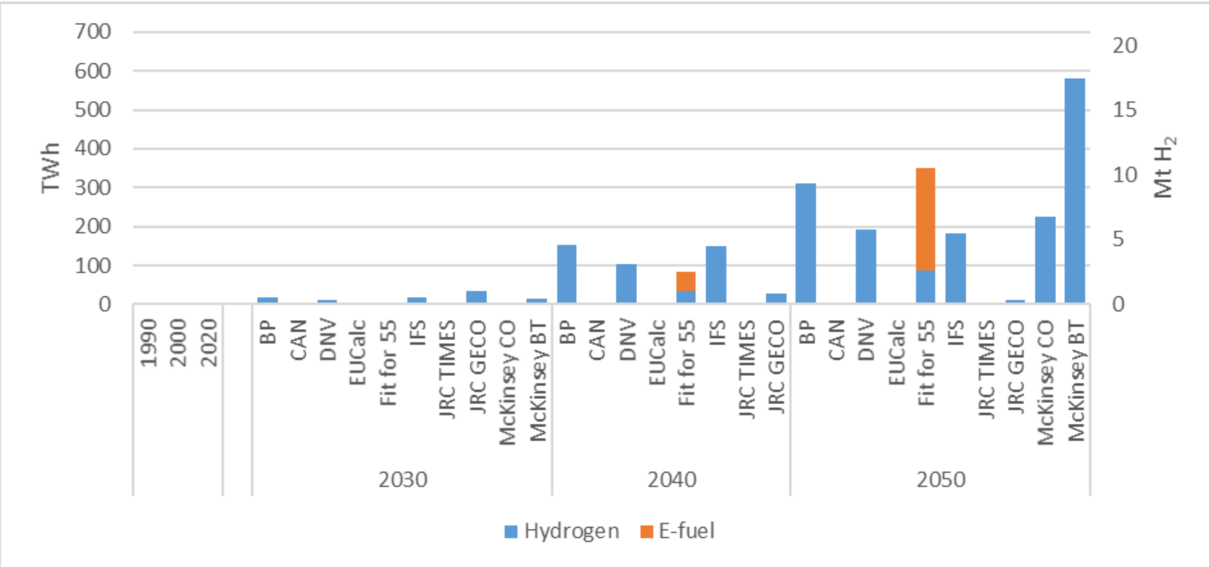
Figure 21 EU energy demand in the buildings sector by fuel



Source: JRC, 2022, based on scenario studies. Historical data (Eurostat, 2022)

According to European scenario studies, in 2030, the buildings sector will not yet be making significant use of hydrogen. Only five of the nine scenarios see hydrogen used in buildings at this stage, and even in these cases, it provides 1% or less of total energy consumption in buildings, ranging from 0.25 Mt in JRC TIMES to 1 Mt in JRC GECO. By 2040, this starts to change. More studies see a role for hydrogen in the buildings sector, providing 6% of final demand in BP, but in absolute terms it remains below 5 Mt in scenarios with the highest hydrogen penetration: BP and IFS. By 2050, the hydrogen share could increase to 16% (in BP), reaching 17.5 Mt in McKinsey BT[30]. According to EC Fit-for 55, 10.5 Mt of hydrogen and its derivatives will be used in the buildings sector by 2050, providing more than 10% of total demand.

Figure 22 EU hydrogen demand in the buildings sector



Source: JRC, 2022, based on scenario studies. Historical data (Eurostat, 2022)

[30] The full energy balance is not available to calculate hydrogen share in buildings.

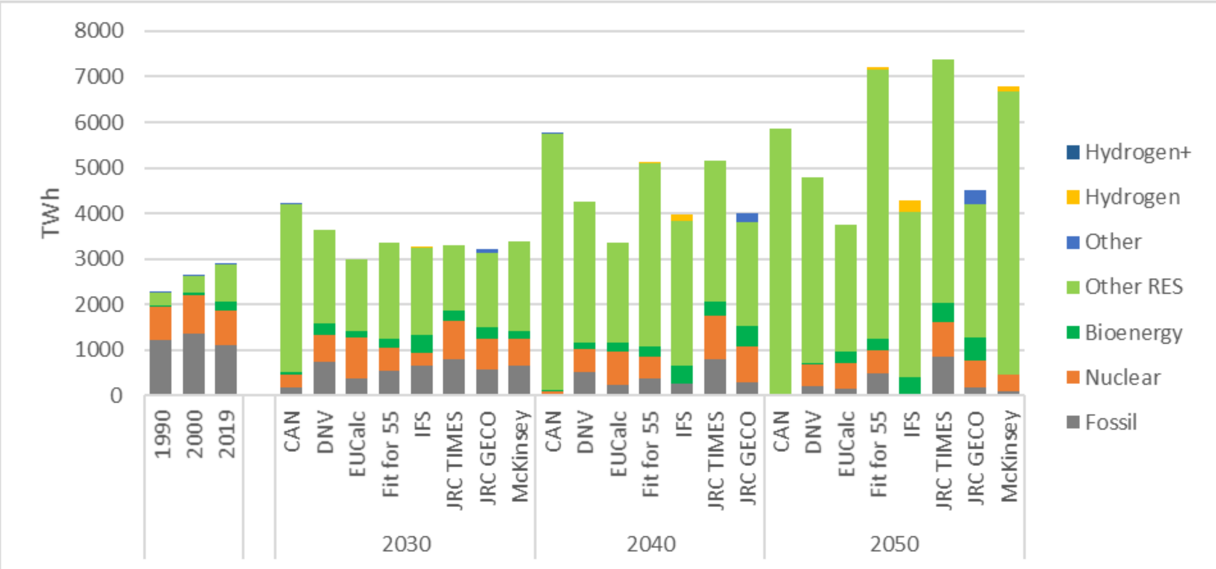
3.3.5 Power generation

Electricity demand is growing more slowly in **the EU** than globally. From 1990 until 2019, the EU's compound annual growth rate (CAGR) of electricity consumption was only 0.85%. From 2010 till 2019 there was even a small reduction of around 0.3% per year. Currently fossil fuels play a less important role in the EU power mix. In 1990, fossil fuels provided 54% of the EU's electricity, in 2010, the share dropped to 48%, and in 2019 it reached 39%. Fossil fuel-based electricity generation peaked around 2010 (reaching 1 424 TWh) and in 2019 dropped to 1 111 TWh (slightly below the 1990 level of 1 220 TWh). During the period 1990-2019, the share of other renewables increased from 13% (290 TWh) to 29% (824 TWh). While in 1990 that was mainly driven by hydro, in the last decade it was fuelled by the increasing importance of wind/solar. By 2019, renewable generation (35%) was catching up with fossil fuels (39%) and had surpassed nuclear (27%).

By 2030, the share of fossil fuels in EU power generation will drop to 17% (on average), ranging from only 4% in CAN to 24% in JRC TIMES. Fossil fuels are being replaced by increasing deployment of solar and wind, driving the share of other renewables to 58% on average, ranging from 44% in JRC TIMES to 88% in CAN. Only two scenario studies, EUCalc and JRC TIMES, see an increase in nuclear generation.

By 2040, the share of fossil fuels drops to 8% on average, ranging from CAN with no fossil fuels left in the mix at all, to 15% in JRC Times. EU power generation is dominated by renewables, providing 76% of electricity on average, led by CAN with 99% of renewables in the mix. In 2050, the trend continues: only 4% of fossil fuels are left in the mix. Only 7% of power is generated from fossil fuels in EC Fit-For-55. On average, renewable sources provide around 85% of power. Two studies (CAN and IFS) do not see a role for nuclear in the EU power mix in 2050. In other studies, nuclear energy still plays an important role: 15% in EUCalc and 13% in JRC GECO.

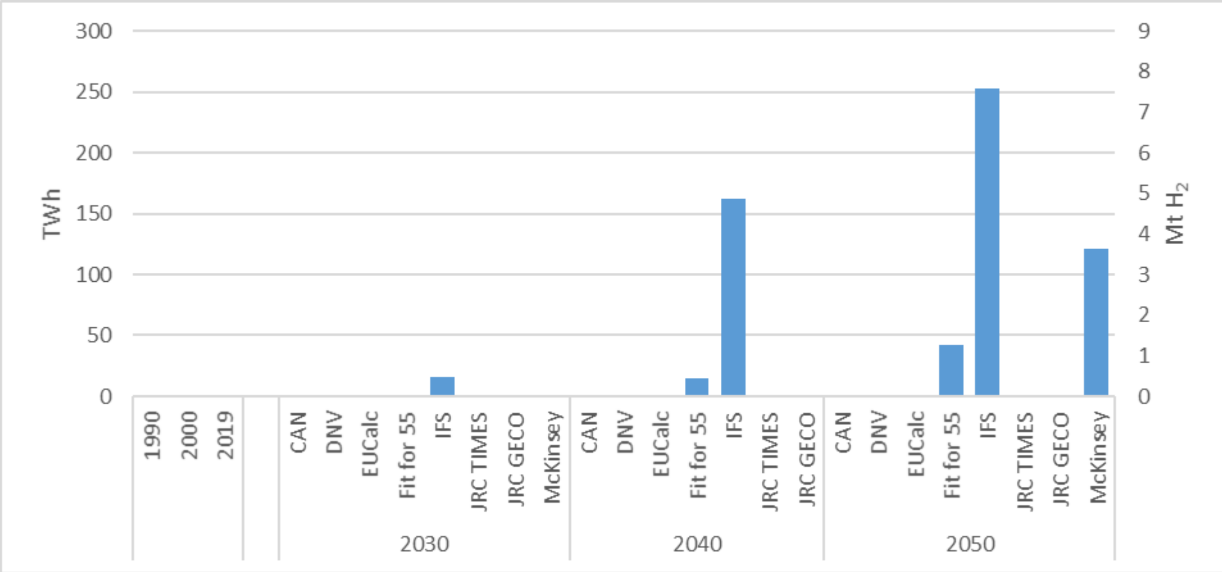
Figure 23 EU power generation by fuel



Source: JRC, 2022, based on scenario studies. Historical data (Eurostat, 2022)

Scenario studies do not see hydrogen playing an important role in **the EU** power generation. In 2030, there is only one study (IFS) that sees 16 TWh of electricity generated (0.8 Mt used) in 2030. In 2040, two studies see a role for hydrogen in power generation: EC Fit-for-55 and IFS. In IFS, power generation from hydrogen increases tenfold (compared to 2030) and reaches 162 TWh. In 2050, the majority of the studies still do not see any role for hydrogen in power generation, with the exception of IFS, with 253 TWh (using around 13 Mt and supplying 5% of demand), EC Fit-for-55 (42 TWh, providing less than 1% of electricity) and McKinsey, with 130 TWh (7 Mt used, supplying around 4% of electricity demand).

Figure 24 Hydrogen usage in EU power generation



Source: JRC, 2022, based on scenario studies. Historical data (Eurostat, 2022)

4 Infrastructure needs for hydrogen production

4.1 Hydrogen demand

Currently almost all hydrogen is used in industry for non-energy related purposes. In the future, the role of hydrogen as an energy carrier in final demand sectors and power generation will increase. By 2040, both globally and in the EU, demand for hydrogen and its derivatives in end use sectors surpass current non–energy demand. Nevertheless, in order to understand hydrogen demand, especially in the near future, non-energy uses should also be considered. Currently (2020), around 87 Mt is used globally, and almost 8 Mt in the EU. In the future, non-energy usage of hydrogen will change: following the decarbonisation of the transport sector, hydrogen demand in refineries will decrease, but on the other hand, novel uses (for example in DRI steel production) will increase it. Despite its important role in decarbonisation, hydrogen usage for non-energy purposes does not tend to be reported in energy scenario studies. In the studies that provide data for non-energy demand in industry, information is limited to fossil fuels and (sometimes) bioenergy demand (for example IFS, DNV). Other studies which do report hydrogen usage in industry, combine the energy and non-energy uses together (for example IRENA, JRC GECO[31]). Some studies only report market-traded low-carbon hydrogen and its derivatives (JRC TIMES). Historically, the majority of hydrogen has been produced onsite, therefore only the (fossil) fuel needed to produce it was available in the balances. In order to estimate full hydrogen demand, historical demand for non-energy hydrogen is included, both for historical years as well as added to scenario results at the same, historical, level. Studies that discuss hydrogen use for non-energy purposes foresee an increase of 50-100% in 2050, compared to current use (FCH, 2019; McKinsey & Company, 2020)[32]. However, this will not be taken into account in this report when estimating future hydrogen demand, due to a lack of quantitative information in most of the scenario studies under analysis. In some cases, new (green) hydrogen is already included in industrial demand, and in 2050, the possible share of non-energy hydrogen consumption will not make a significant difference (at less than 15% of average global hydrogen demand overall in 2050). In this report, non-energy hydrogen demand (feedstock) will be estimated to be 87.2 Mt, and 7.9 Mt for Europe.

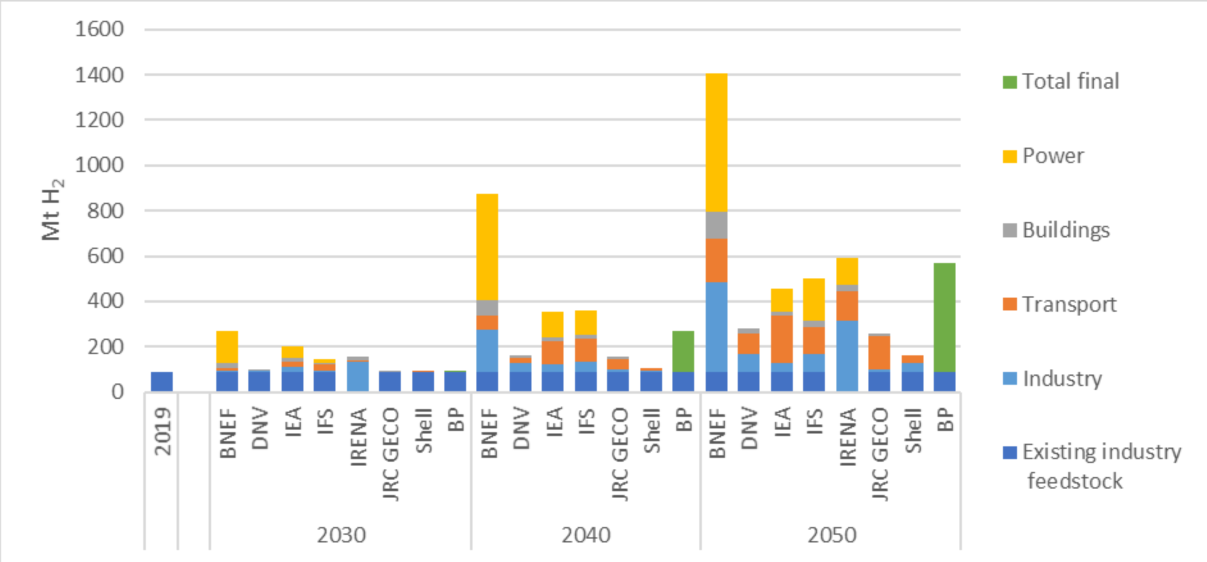
4.1.1 Global hydrogen demand

By 2030, projected hydrogen demand already varies significantly between studies (**Figure 25**), ranging from just above 90 Mt in Shell, BP, DNV and JRC GECO, to above 200 H_2 Mt, led by BNEF (**269 Mt**). With average demand at only **150 Mt,** the growth is very moderate at only 5% annually (CAGR). The range between the highest and lowest projected demand is greater, reaching 178 Mt, mainly driven by BNEF (with 11% CAGR). By 2040, hydrogen demand will grow faster on average at 8% per year, resulting in an average increase of more than double (compared to average values from 2020), reaching 330 Mt. The average figure is driven mainly by BNEF, which shows growth of 12% per year and reaching 873 Mt. This is an outlier: the next highest demand shown in the studies is in the range of 350-360 Mt. Shell does not project a noticeable growth in hydrogen utilisation in end-use sectors, contrary to BP, where annual growth in period 2030-2040 reaches 11%, and hydrogen demand is 270 Mt. By 2050, the growth rate slows to an average 5% per year, reaching 520 Mt. Despite slower growth (only 5% per year), BNEF remains a clear leader, with the next highest hydrogen demand coming from BP, at only 571 Mt (8% CAGR), followed by IFS, at 500 Mt. Many studies see high hydrogen deployment rates in the first two decades (2020-2030 and 2030-2040), reaching above 10% CAGR, and in the period 2040-2050, and these rates slow in all cases to 3-5% per year. Based on the scenario studies analysed, it can be concluded that **in 2050,** global hydrogen demand could be around **530** Mt in a balanced approach: the majority of studies see hydrogen demand at around 450-590 Mt in 2050. But in a full transition to net-zero, based on green hydrogen produced from intermittent renewable sources, hydrogen demand could exceed **1400** Mt.

[31] In JRC GECO only fossil fuels needed to produce hydrogen on site is included, therefore grey hydrogen demand is invisible.

[32] According to the McKinsey hydrogen breakthrough scenario, hydrogen use as feedstock in the EU will increase from 305 TWh in 2017 to 435 TWh in 2050. According to the FCH ambitious scenario, hydrogen demand as feedstock in industry will increase from 325 TWh in 2015 to 647 TWh in 2050

Figure 25 Global hydrogen demand



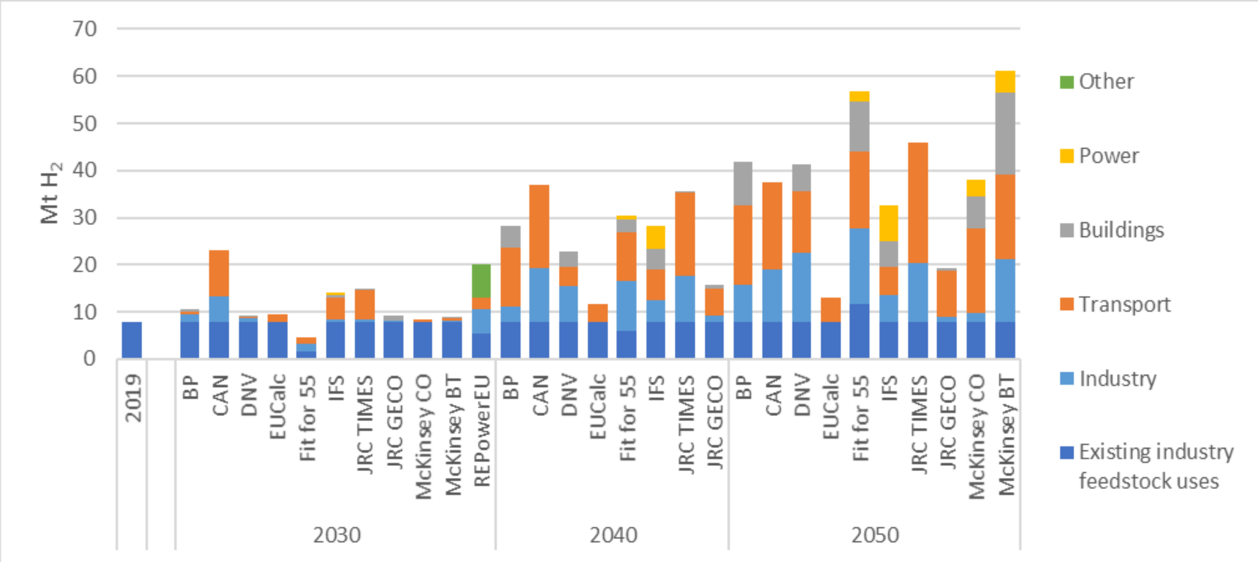
Source: JRC, 2022, based on scenario studies. Historical data (IEA, 2022)

4.1.2 Hydrogen demand in the EU

By 2030, the situation in the EU hydrogen market is similar to the global picture: the majority of studies analysed do not see a noteworthy increase in hydrogen demand, except REPowerEU plan with 20 Mt (more, if some industrial feedstock remains fossil-based[33]) and CAN with **23 Mt**, but on average, all studies reviewed see only **12 Mt** demand (**Figure 26**), with an average annual growth rate of just 4%. The projected hydrogen demand in REPowerEU represents at least 9% CAGR. By 2040, the situation in the EU changes noticeably. The average hydrogen demand grows by 8% and reaches an average of 26 Mt across the scenarios. Only two of the seven studies project less than 20 Mt demand in 2040, reaching 37 Mt in CAN. By 2050, in line with global trends, the growth in hydrogen demand slows to 5% annually, reaching 40 Mt on average between studies. There is a more than fivefold difference between the lowest and highest projected demand, ranging from 19 Mt in JRC GECO to 67 Mt in EC Fit-for-55. Based on the scenario studies analysed, it can be concluded that **in 2050**, EU hydrogen demand could be around **40** Mt in a balanced approach: the majority of studies put it at around 38-46 Mt in 2050. But in a faster transition to net-zero, the upper bound could be **68** Mt.

[33] REPowerEU refers only to green hydrogen. It is not clear if in 2030 grey hydrogen is used, and if it is, to what extent.

Figure 26 Hydrogen demand in the EU



Source: JRC, 2022, based on scenario studies. Historical data (Eurostat, 2022)

4.2 Production

4.2.1 Production of hydrogen in scenario studies

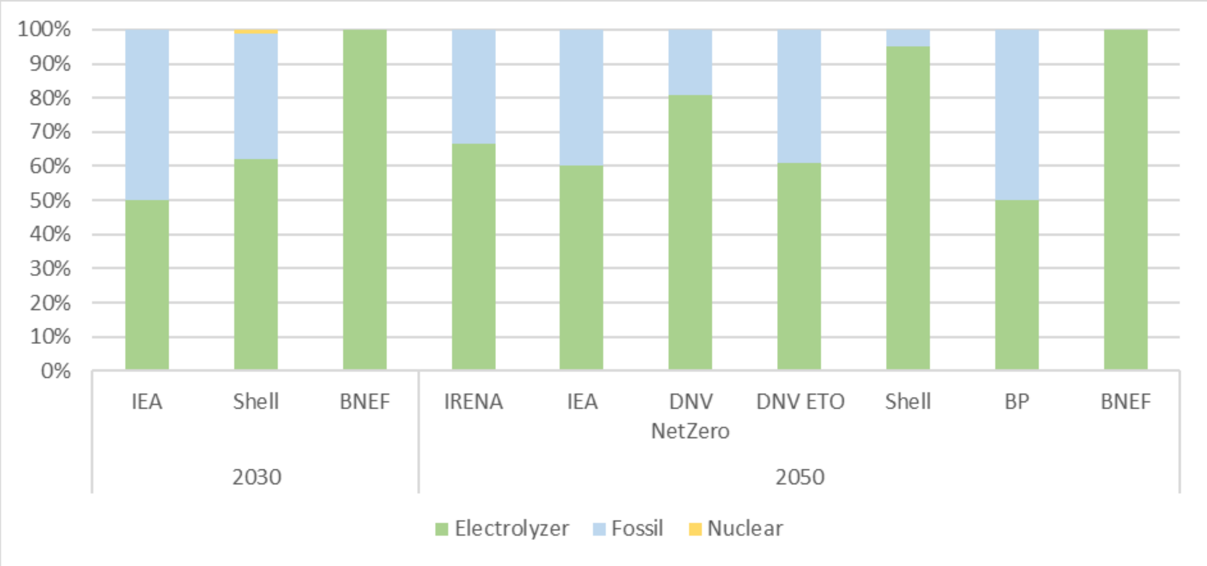
Not all scenario studies are vocal about the ways in which hydrogen is produced, but from the available information it can be concluded that the majority of global hydrogen production in the future will be electricity-based (**Figure 27**). Not all scenarios indicate a source of power for the electrolysers, but in 2050, in all scenarios analysed, at least 90% of electricity is low carbon (renewables, in some cases supplemented by nuclear). There is only one exception: DNV ETO, with an 87% low-carbon electricity share in the mix.

By 2050, **IRENA** sees global electrolyser capacity grow more than 10 000-fold, from the 0.3 GW of electrolyser capacity today to 5 000 GW by 2050. In this period, on average, 160 GW of electrolysers will be installed globally per annum. Electrolysers will supply two-thirds of global hydrogen demand, producing 409 Mt. This entails a high capacity utilisation factor of 39%[34]. The remaining third, or 205 Mt, will be produced from natural gas (blue[35]). According to IRENA, 30% of electricity produced will be used for producing hydrogen and its derivatives.

[34] Hereafter the assumption is made, that electrolyser capacity is expressed in input power and efficiency of 80%. In this case, the resulting 39% capacity factor is higher than what is available from solar PV and some wind power plants.

[35] Blue hydrogen is produced from natural gas coupled with carbon capture and storage (CCS).

Figure 27 Global hydrogen production by technology



Source: JRC, 2022, based on scenario studies

By 2030, **IEA** puts hydrogen consumption at 210 Mt (from 87 Mt in 2020). The share of low-carbon hydrogen will rise from just 17% in 2020 to 70% (150 Mt of low-carbon hydrogen in 2030). Half of low carbon hydrogen is green (produced from renewable electricity), and the remainder is produced from coal and natural gas with CCUS. By 2030, 850 GW electrolysers will be installed globally. This means a high capacity factor of 42%, suggesting usage of grid electricity or coupling offshore wind with dispatchable power generation. By 2050, the production of 99% of hydrogen is low-carbon. Compared to 2030, low-carbon hydrogen production will more than triple to 520 Mt, with 60% of it produced using electrolysers. With the same capacity factor, this would require over 3 000 GW of electrolyser installed globally.

According to **DNV** (ETO), in 2030, only 8% of the world's hydrogen supply will come from electrolysers (globally, 102 GW dedicated off-grid, and 77 GW of grid-electricity electrolysers will be installed). In 2030, Europe will be leading in electrolysis investment, reaching 41 GW grid-based and 4 GW off-grid (solar) capacity. By 2050, 61% of the world's hydrogen supply comes from electrolysers: 16% with solar PV, 16% with onshore wind, 11% with offshore wind and 18% with grid electricity. Total installed electrolysis capacity will reach 3 TW (1.8 TW of dedicated off-grid capacity) and provide 171 Mt/y (of 281 Mt/y) by 2050. Fossil fuel-based (blue) hydrogen will provide 39% of hydrogen supply for energy purposes by 2050. In order to reach net-zero goals by 2050, hydrogen production should almost double to 525 Mt. This entails a ramping up of electrolyser capacity, with 3.8 TW of dedicated off-grid and 2 TW of grid-connected electrolysers needed in 2050. In the Net-zero scenario, electrolysers provide 81% of hydrogen (35% with grid electricity and 46% with dedicated off-grid installations). In this case, 17% of electricity is used exclusively for hydrogen production.

Shell sees a slower deployment of hydrogen-based decarbonisation solutions. Globally, hydrogen will only start replacing fossil fuels after 2040, but the decarbonisation of hydrogen production will start earlier: in 2030, 62% of hydrogen is green, 1% comes from nuclear, and the remaining 37% comes from fossil fuels. In 2050, the share of green hydrogen increases to 95% and the remaining 5% is split between fossil fuels (3%) and nuclear (2%).

In 2050, **BP** still sees a significant role for fossil fuels in hydrogen production, with only 50% of the hydrogen produced globally coming from renewable energy sources. The remaining 50% comes from fossil fuels with CCS – predominantly natural gas. Wind and solar are used for green hydrogen production, using 33% of the global wind and solar supply. According to BP, eliminating the remaining fossil fuels in hydrogen production would require the deployment of wind and solar power plants in 2050 to more than double to 1 400 GW per year compared to the figure of less than 600 GW in Net Zero.

BNEF has three net-zero scenarios. In this work, we are using the Green scenario[36], where all hydrogen for energy purposes is produced using green electricity from solar and wind. In 2030, 28 000 TWh of renewable electricity is already being used to produce hydrogen (around 17% of total power production), producing 165 Mt. The majority of this hydrogen (125 Mt) is consumed in the power sector and 11 Mt in households. By 2040, electricity consumption for hydrogen increases to 131 000 TWh, reaching 213 000 TWh in 2050, consuming around 50% of total electricity generation. In 2030, around 20% of hydrogen is made from solar electricity, and the remaining 80% from wind. This ratio remains more or less unchanged until 2050, when 43% of all solar and 63% of all wind is used for hydrogen production. In 2050, power production remains a major hydrogen consumer, responsible for 42% of total hydrogen demand (553 Mt out of 1 314 Mt). 341 Mt is used in industry, 102 Mt in buildings and 161 Mt in transport. In 2050, 13.1 TW of electrolysers are installed.

In **IFS,** almost 23% of electricity generated is used for hydrogen production in 2050, producing around 350 Mt globally, and around 40 Mt in OECD Europe.

According to **McKinsey**, 25% of EU power generation in 2050 goes to green hydrogen (1 125 TWh to make 27 Mt).

Clean hydrogen plays a pivotal role features in all recent **European Commission** publications. Electrolysers are the main source of hydrogen in EC LTS (European Commission, 2019a), EC CTP (European Commission, 2020) and Fit-for-55 (European Commission, 2022c). In the Fit for 55 mix scenario, 0.47 Mt of clean hydrogen[37] is used for energy purposes in 2030. By 2050, hydrogen usage in final demand rises to 60 Mt (industry and transport each use 25 Mt, and hydrogen is used in buildings). Triggered by the global energy market disruption caused by Russia's invasion of Ukraine, REPowerEU ramped up the EU's ambitions for green hydrogen consumption. By 2030, the EU will use 20 Mt of green hydrogen, with 10 Mt produced domestically. 7.3 Mt will be used in end-use sectors, and 9 Mt will replace grey hydrogen in industry for non-energy uses.

4.2.2 Estimation of hydrogen production capacities needed

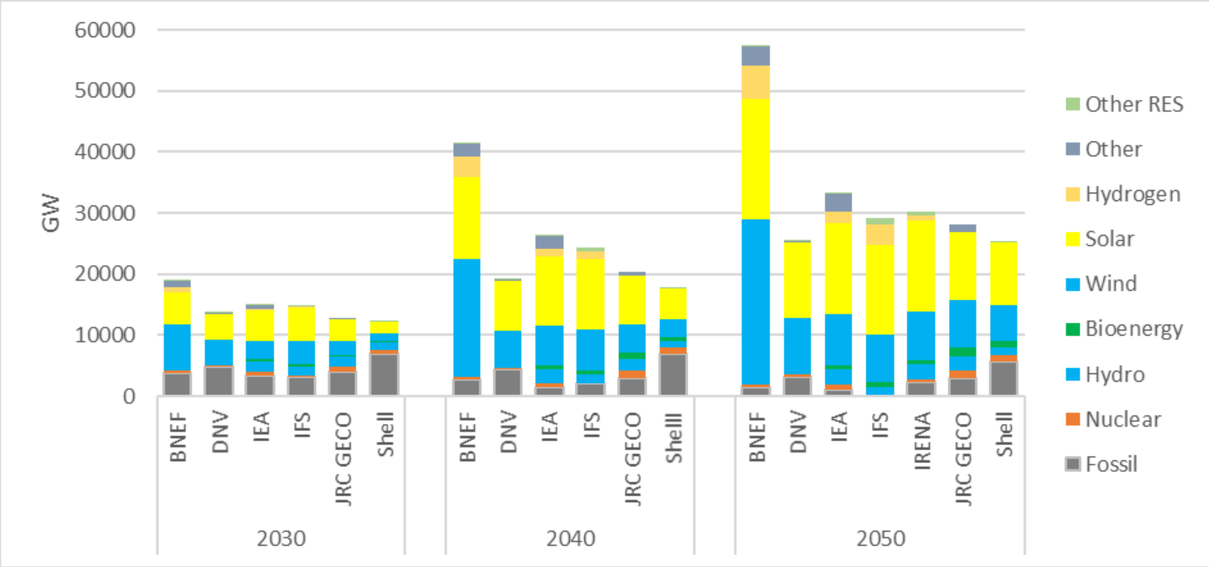
Every energy scenario study has its own estimates on technologies supplying hydrogen to the economy, depending on factors such as the available technology pool, generation mix, cost assumptions and social aspects. In some scenario studies, up to half of the hydrogen is produced from fossil fuels (with CCS) even in 2050. Since the Russian invasion of Ukraine, in the EU and, to some extent globally, there is an emerging understanding that fossil fuels, in general, and natural gas, in particular, are not a sustainable option, even as a transition technology, in decarbonisation pathways. According to energy scenarios (**Figure 28**), by 2050, global solar and wind power generation capacities will vary between 65% and 80% of total installed capacity.

In Europe, this number varies between 70% and 85% (**Figure 29**). Moreover, only three studies see an increase in globally installed nuclear capacity, and none of them project an increase in the EU. Other low-carbon options also have a limited growth potential. This means that by mid-century, most clean (low-carbon) hydrogen will be produced using electricity coming from solar and wind power plants. Any increase in clean hydrogen demand will result in increased deployment rates for these power plants.

[36] There is also the Red scenario, where hydrogen is produced also from nuclear electricity.

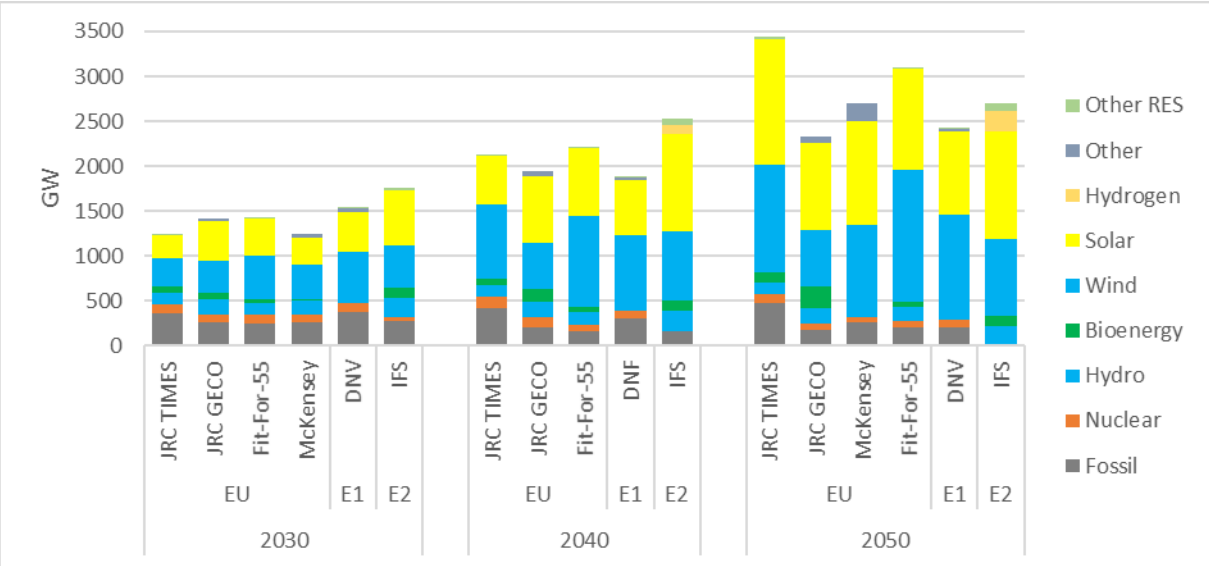
[37] REPowerEU has different data for the Fit-for-55 scenario (unknown), listing 1.6 Mt H_2 of green hydrogen in 2030: 756 t H_2 for industrial heat and 882 t H_2 for transport sector..

Figure 28 Global power generation capacities



Source: JRC, 2022, based on scenario studies

Figure 29 Power generation capacities in the EU[38]



Source: JRC based on scenario studies

To illustrate the global and EU challenges facing the transition to a hydrogen economy **if only green hydrogen is used**, the hydrogen demand reported by these studies is below converted into electrolyser demand (with an assumption of 80% efficiency[39] and electricity provided by dedicated solar PV and wind installations with the assumed capacity factors provided in **Figure 30**). The average hydrogen demand observed in global and EU scenario studies will be used as a proxy for the "Likely" scenario, and the highest value will set the upper bound.

[38] In this graph E1 refers to Europe as defined by DNV (the EU plus , E2 – OECD Europe.

[39] Currently average electrolyser efficiency is around 65%, while the best available technology could reach 76% (IRENA, 2020). There are also announcements from researchers claiming up to 95% electrolyser efficiency (Hysata, 2022). In this report 80% electrolyser efficiency was used to take into account future improvements in the period to 2050. Higher value reduces projected need of power generation capacities by 10%-20%, but do not significantly affect conclusion.

In order to identify the range of ratios between solar and wind installations in the 2030 and 2050, data were used from the scenarios analysed.

Figure 30 Assumed capacity factors for Wind and Solar[40]

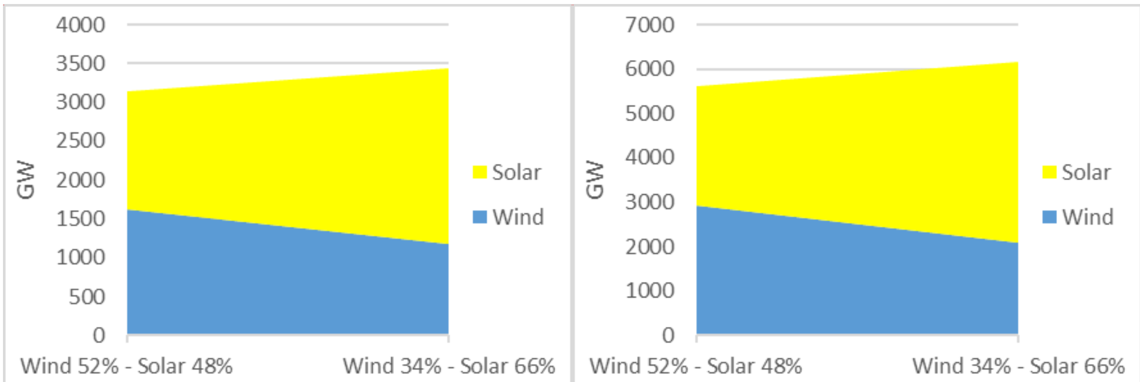
		Capacity factors	
		Global	The EU
Wind	2030	28%	30%
	2050	32%	35%
Solar	2030	17%	12%
	2050	20%	14%

Source: JRC, 2022

Global

Assuming all hydrogen demand is met by electrolysers, 6244 TWh of electricity will be required in the average demand scenario in 2030, and double that in the maximum scenario. To produce this hydrogen using **dedicated solar and/or wind installations**[41], between 3100 GW and 3400 GW of electrolysers will be needed in the average demand scenario (see Figure 31). In the case of maximum hydrogen demand, capacity requirements range from 5600 GW to 6200 GW. The same amount of intermittent renewable capacity should be installed. The required capacity could be reduced by installing short-term energy storage (batteries) or using grid electricity. In order to meet electricity demand for green hydrogen production in the period between 2020 and 2030, the installed wind capacity would therefore need to grow by at least 170% in the average hydrogen demand scenario. In the maximum demand scenario, wind/solar capacity would have to grow by up to 600%.

Figure 31 Global wind and solar capacity requirements under average (left) and max (right) hydrogen demand in 2030



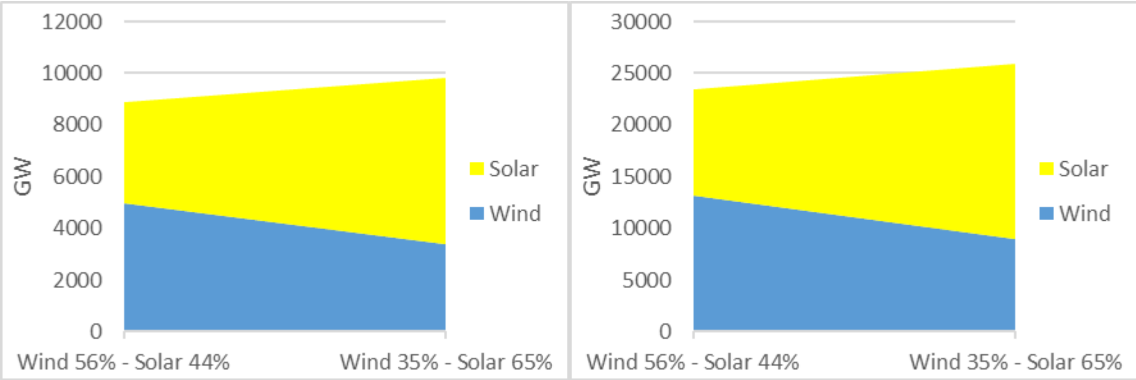
Source: JRC, 2022

Between 2030 and 2050, electricity demand for hydrogen production grows to 21 000 TWh in the average hydrogen demand scenario, and to 56 000 TWh in the maximum hydrogen demand scenario. Here, the electrolyser and intermittent renewables generation capacities will have to grow. In the average hydrogen demand scenario, the electrolyser capacity should be between 8 900 GW and 9 900 GW (see **Figure 33**). In the case of a full transition to a hydrogen economy (maximum hydrogen demand scenario), the aggregated electrolyser and associated intermittent renewable power generation capacity should grow between 23 000GW and 26 000 GW.

[40] Based on IRENA renewable energy statistics (IRENA, 2021), in 2019, the wind capacity factor (combined) was around 25%, up by more than 5% in a decade. In 2019, the capacity factor for solar PV was around 12% in the EU and 13.5% globally. From 2009, it increased by around 2.5% in the EU and 3.2% globally. In the scenario studies analysed, the future capacity factor of wind will rise globally by around 28% in 2030 and 32% in 2050. The EU numbers are slightly higher. The global solar capacity factor can reach 17% in 2030, increasing to 19% in 2050. In the EU, solar capacity factors will be around 12%-14%.

[41] In the short term Purchasing Power Agreements (PPA) or Certificate of Origin (CoO) could increase electrolyze capacity factors, but in the long term, close to 2050, the power system will rely mostly on intermittent renewable energy sources, therefore it is unlikely that there will be excess flexibility to facilitate higher capacity factors for electrolysers.

Figure 32 Global wind and solar capacity requirements under average (left) and max (right) hydrogen demand in 2050

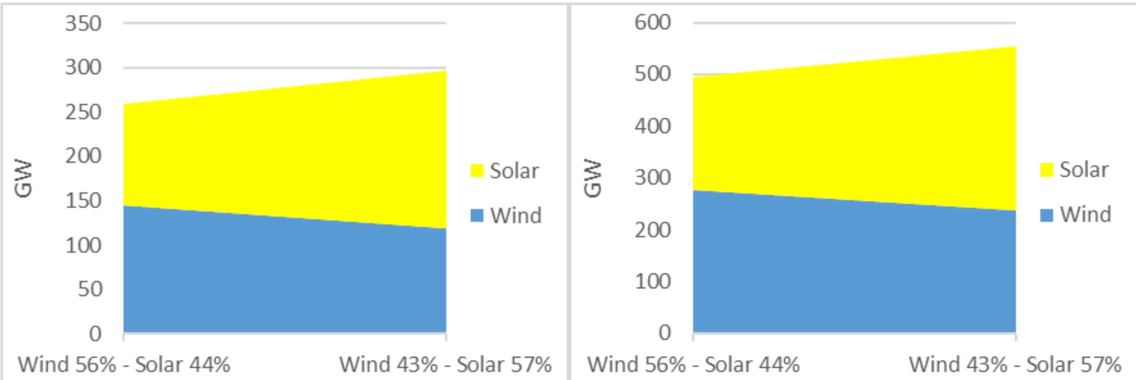


Source: JRC, 2022

The EU

In 2030, under the same assumptions (100% green hydrogen), EU electricity demand in the average hydrogen demand scenario accounts for 500 TWh, and almost double that in the maximum hydrogen demand scenario (957 TWh). To produce this hydrogen using dedicated solar and wind installed capacity, 260-300 GW of electrolyser capacity would be needed in the average scenario (see Figure 33) and 500-550 GW in the maximum scenario. The same amount of intermittent renewable capacity should be added to provide electricity. The required capacity could be reduced by installing short-term energy storage (batteries). In order to meet electricity demand for green hydrogen production in the EU, installed wind capacity will need to grow by 50% between 2020 and 2030 in the average hydrogen demand scenario. In the maximum scenario, both solar and wind install capacity would have to almost triple.

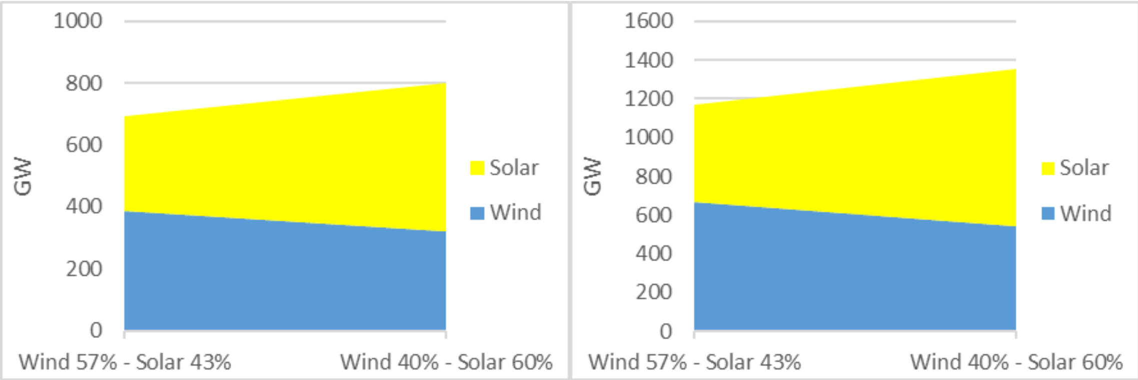
Figure 33 EU wind and solar capacity requirements under average (left) and max (right) hydrogen demand in 2030



Source: JRC, 2022

Between 2030 and 2050, electricity demand for hydrogen production grows to 1600 TWh in the average hydrogen demand scenario, to 2 700 TWh in the maximum hydrogen demand scenario. This means electrolyser and intermittent renewables generation capacities would have to grow. In the average scenario, electrolyser capacity should be between 700 GW and 800 GW (see **Figure 34**), reaching 1 200-1 400 GW in the maximum hydrogen demand scenario in the EU.

Figure 34 EU wind and solar capacity requirements under average (left) and max (right) hydrogen demand in 2050



Source: JRC, 2022

5 Conclusions

Pressed by the urgency of slowing down and eventually stopping climate change, research institutions, companies, NGOs, governments and intergovernmental organisations are exploring all possible pathways for reducing carbon emissions. Among these options, low-carbon hydrogen is swiftly gaining importance in all areas of economic activity. Just five years ago, very few energy scenarios projected any role for hydrogen in decarbonisation pathways. In the 2016 IEA WEO report, hydrogen was mentioned only 11 times and was not separately included in data annexes. The 2021 IEA WEO report includes two subchapters dedicated to the role of hydrogen in different sectors and the data file included not only pure hydrogen, but also its derivatives reported separately. It is expected that in upcoming reports and analysis, there will be increasing attention to the role of hydrogen.

Today, hydrogen is used almost exclusively in the industrial sector. In 2020, 87 million tonnes of hydrogen was used globally. Less than 10% of it (around 8 Mt) was consumed in the EU. Almost all of this hydrogen was produced from fossil fuels. Currently, the majority of hydrogen is used in petroleum refining (42% globally) and to produce ammonia (37% globally). Its production and consumption are widely distributed around the world (in parallel with the chemical and petrochemical industries). The biggest hydrogen producer (and consumer) is China, followed by the United States and India. Today, production and consumption of hydrogen are part of the industrial process chain: hydrogen is produced and consumed onsite, and only a small fraction is traded internationally. So while hydrogen transportation and storage technologies exist, the world still lacks the infrastructure and experience of transporting hydrogen at scale.

Low-carbon hydrogen is essential for decarbonising industrial feedstock and replacing fossil fuel-based hydrogen in current processes, like ammonia production in the chemical industry. New uses of hydrogen, like DRI steel, could further reduce the industrial carbon footprint. The energy scenarios analysed in this report usually include the decarbonisation of industrial feedstock, but rarely provide any detailed, quantifiable data. Despite the current importance of hydrogen as a feedstock, in the future, most of the expected hydrogen consumption will take place in the final energy demand sectors.

All scenarios analysed (both global and EU) see electricity as the main contributor to the energy sector's transition towards carbon neutrality. By 2050, all end-use sectors will benefit from higher direct use of electricity. The scenarios are also unanimous that there will still be a role for the molecules in 2050, but do not agree on which will play a major role in the hard-to-abate sector. Hydrogen (and its derivatives) could be used, or bioenergy, or in some cases, fossil fuels.

The global role of hydrogen in energy decarbonisation scenarios

Globally, all the scenarios analysed expect hydrogen deployment to be slow in the coming years. In 2030, hydrogen and its derivatives could provide only 2% of **final energy demand**. In absolute terms that means 40-50 Mt at the high end, and below 5 Mt at the low end. Industrial feedstock will still be a main user of hydrogen. In 2040, all studies agree on the increasing importance of hydrogen, but due to differing assumptions, hydrogen demand varies from 18 Mt (0.5% of final demand) in Shell to 320 Mt (11% of final demand) in BNEF. By 2050, hydrogen could provide more than 25% of final energy (706 Mt, an increase of more than eight-fold compared to current feedstock use), if a full transition to a hydrogen economy is assumed (BNEF). The remaining scenarios see up to 10% of final demand covered by hydrogen and its derivatives by 2050 (ranging from 73 Mt to 280 Mt). It is evident that end use sectors will become the main market for hydrogen in 2050.

All **global** studies see a role for hydrogen consumption as energy in **industry** already in 2030, but in the majority of cases, it is still at or below 1% (ranging from 2 Mt to 26 Mt) of industrial demand. By 2040, hydrogen demand grows significantly and by 2050 could reach 400 Mt in BNEF (covering 34% of demand). Other studies put hydrogen consumption for energy purposes at between 1% in JRC GECO (13 Mt) and 9% in IFS (78 Mt), replacing fossil fuels in processes requiring high-temperature heat.

In 2030 the usage of **Global** hydrogen and its derivatives in the **transport** sector ranges from 0.3 Mt (JRC GECO) to 12 Mt (IEA), with the exception of IFS, which sees a fast hydrogen adoption reaching 29 Mt (6% of energy demand in transport). By 2050, there is still considerable disagreement between the studies on hydrogen's role in the transport sector, ranging from just 10 Mt in Shell (1%) to 91 Mt in IFS (25%). On top of electrification, biofuels and fossil fuels play an important role.

Some **global** scenarios identify a role for hydrogen in the **buildings** sector already in 2030: most of the scenarios show that up to 2% of final demand will be supplied by hydrogen, ranging from just 1 Mt (DNV) to 22 Mt (BNEF). By 2040, hydrogen consumption is only seen to grow in BNEF (which shows 68 Mt being used –

7% of energy demand in buildings – to replace fossil fuels where heat pumps are not suitable, and to reduce electricity demand during high-demand seasons). All other scenarios stay at or below 2%. In 2050 similar trends can be observed: hydrogen demand grows to 120 Mt (12% of demand) in BNEF. All other scenarios, while showing some slight growth, do not exceed 27 Mt or 3% of final demand in the buildings sector.

The role of hydrogen in EU energy decarbonisation scenarios

Compared to global trends, some of **the EU** scenario studies see a faster adoption of hydrogen. According to CAN, hydrogen and its derivatives could already cover over 6% of final energy demand and reach 15 Mt by 2030 (almost doubling current hydrogen demand as a feedstock in industry). Other scenarios expect growth to be slower, ranging from almost non-existent in DNV, JRC-GECO and McKinsey to 3% (6 Mt) in IFS. In the Fit-for-55 Mix H2 variant, hydrogen demand in end use sectors amounts to 3 Mt and provides slightly above 1% of demand. In REPowerEU, hydrogen adoption happens faster: 14 Mt is used in final demand. By 2040, the importance of hydrogen in final energy demand grows much faster in the EU than globally, reaching 17% of final demand in CAN (27 Mt). Other scenarios also see substantial growth, ranging from 2% in EUCalc (4 Mt) to 11% in JRC Times (27 Mt). 24 Mt is used in the Fit-for-55 MIX H2 variant, 300% higher than the demand for hydrogen as feedstock in 2019 and surpassing 2030 demand in REPowerEU by over 70%. By 2050, the majority of scenarios see more than 30 Mt used in final energy demand, reaching 43 Mt in EC Fit-for-55 (21% of end use energy), surpassed only by the McKinsey BT scenario (51 Mt).

In the **EU,** in line with global trends, hydrogen adoption in **industry** is still slow in 2030. Only CAN sees rapid growth, reaching 5.5 Mt (7.6% of final industrial energy demand) already in 2030. Most other studies see little or no hydrogen used for energy, with figures staying below 1%. In the Fit-for-55 MIX H2 variant, hydrogen demand is at 1.6 Mt. By 2040, all the scenarios analysed, except for one, see a role for hydrogen in energy supply, ranging from 2% in JRC GECO (1.4 Mt) to 18% in CAN (11 Mt). By 2050, hydrogen adoption in industry slows down, reaching 16 Mt in EC Fit for 55 MIX H2 variant and providing 23% of final demand. Other scenarios see a lower consumption, ranging from only 1 Mt to 13 Mt.

The energy studies disagree on the role of hydrogen in the **EU transport** sector in 2030. While the majority see hydrogen and e-fuel consumption at or below 1% of total demand in the sector, others anticipate a fast transition, with CAN at 13% (10 Mt), and IFS at 12% (5 Mt) covered by hydrogen-based fuels. In EC Fit-for-55, 1.4 Mt is used in the transport sector, providing 2% of final demand in the transport sector in 2030. By 2040, more studies see hydrogen increasing in importance. CAN is still the leader with 17 Mt (35%), but its role also becomes significant in JRC TIMES (18 Mt; 21%) and BP (12 Mt; 14%). In EC Fit-for-55, 10.5 Mt is used in transport. In IFS, despite a high hydrogen penetration rate of 23%, this accounts for only 6.5 Mt due to low energy consumption in the transport sector. By 2050, hydrogen and its derivatives provide from 11% (EUCalc) up to 43% (EC Fit-for-55 MIX H2 variant) of final energy in transport. It is worth noting that the highest hydrogen demand in the transport sector is to be found in JRC TIMES (26 Mt compared to 17 Mt in Fit-for-55), but due to different demand projections in JRC TIMES, hydrogen and its derivatives provide only 36% of final demand in transport in 2050.

Contrary to the global trends, hydrogen demand is negligible in **the EU buildings** sector in 2030. Only JRC GECO sees 1 Mt (1% of final demand), but from 2040, hydrogen starts to pick up. IFS and BP see around 5 Mt used in the EU buildings sector (mainly direct combustion), covering 6% of demand. In the EC Fit-for-55 MIX H2 variant it is 2.5 Mt. In 2050, hydrogen demand could reach 17 Mt (McKinsey BT). BP and EC Fit-for-55 see hydrogen demand at around 10 Mt, covering 10% of demand in the buildings sector.

Way forward to meet the hydrogen demand

Global energy studies do not agree on the rate of hydrogen uptake, but from available data, it can be concluded that global hydrogen demand in 2030 could be around 150 Mt, and with a fast transition to a hydrogen economy it could reach 270 Mt. Assuming that all hydrogen in the future will be green, produced from dedicated intermittent renewable energy sources (wind and solar), substantial investment will be needed in both electrolysers and the expansion of renewable electricity generation capacities. In this case, to produce 150 Mt per year, the installed capacity of electrolysers required would be around 3 100 GW to 3 400 GW. In fact, the achievement of the maximum hydrogen demand scenario in 2030 will require an installed electrolyser capacity of between around 5 600 GW and 6 200 GW.

By 2050, **global** hydrogen demand could reach on average 530 Mt, and 1 400 Mt in a fast transition scenario (BNEF). To meet this demand, between 8 900 GW and 9 800 GW of electrolysers and renewable electricity production capacities need to be installed in the average case. In the fast transition case with high hydrogen demand, the installed capacity of electrolysers could reach between 23 000 GW and 26 000 GW. A corresponding amount of wind and solar installations would need to be added in order to provide the renewable electricity for the conversion, entailing 25-35 times more global wind/solar installations than today.

In **the EU**, hydrogen demand in 2030 could reach around 12 Mt on average and 23 Mt in the fast transition to hydrogen scenario. To meet this demand, between 260 GW and 300 GW of electrolysers have to be installed in the EU by 2030. Under a fast transition and high hydrogen consumption scenario, the capacity of electrolysers should reach between 500 GW and 550 GW. If some hydrogen and its derivatives are imported or hydrogen is produced using electricity from the grid (not necessarily from green origin), the requirements for new installed electrolysers will be considerably lower.

By 2050, hydrogen demand in **the EU** could triple on average (reaching 40 Mt), while in a fast transition scenario it could be as high as 68 Mt. To meet this hydrogen demand, between 700 GW and 800 GW of electrolysers will be needed in the EU under an average penetration scenario. A fast transition to a hydrogen economy would need between 1 200 GW and 1 4000 GW of electrolysers (depending on the renewable electricity technology mix). The same amount of wind and/or solar installations would be needed (this equates to a three- to-nine-fold increase of wind/solar installations in the EU, just to produce the electricity needed for hydrogen).

All the estimations provided above result from the author's own assumptions, based on efficiencies and capacity factors, assuming that only dedicated wind and solar installations will be used to produce clean hydrogen. The possible role of batteries or other low-carbon sources of electricity (like nuclear) was not taken into account. Using batteries for short-term electricity storage or the ability to consume power from nuclear power plants or the grid could result in considerably higher capacity factors for the electrolysers, substantially reducing the required electrolyser capacities (possibly reducing the required electrolyser capacities by a factor of two or even three). This would also considerably lower the wind and solar capacity needs. Improving the capacity factors of intermittent generation (with better location or advancement of technologies) could further reduce the wind/solar installed capacity needs.

References

Agora Industry and Agora Energiewende. (2021). *12 Insights on Hydrogen.* Berlin: AGORA.

Alejandro Nuñez-Jimenez, N. D. (2022). *The Future of Renewable Hydrogen in the European Union.* Cambridge: Harvard Kennedy School.

BloombergBEF. (2021). *New Energy Outlook 2021.* BNEF.

BloombergNEF. (2021X). *New Energy Outlook 2021.* Bloomberg Finance.

BloombergNEF. (2022). *1H 2022 Hydrogen Market Outlook.* BloombergNEF.

BP. (2020). *BP Energy Outlook 2020 Edittion.* BP p.l.c.

BP. (2022). *Energy Outlook 2022.* London: BP.

Climateactiontracker. (2022, 09 15). *Net zero targets*. Retrieved from climateactiontracker: https://climateactiontracker.org/methodology/net-zero-targets/

Commission, E. (2022). *IMPLEMENTING THE REPOWER EU ACTION PLAN: INVESTMENT NEEDS,.* European Commission.

Commission, European. (2020b, 09 17). *Climate Action*. Retrieved from Commission, European: https://ec.europa.eu/clima/eu-action/european-green-deal/2030-climate-target-plan_en

DNV. (2020). *THE PROMISE OF SEASONAL STORAGE.* Arnhem: DNV GL Netherlands B.V.

DNV. (2021a). *Energy Transition Outlook 2021.* Høvik: DNV.

DNV. (2021b). *Pathway To Net Zero Emissions.* Høvik: DNV.

DNV. (2022). *Hydrogen forecast to 2050.* Høvik: DNV AS.

DNV. (2022). *Hydrogen forecast to 2050. Energy Transition Outlook 2022.* Høvik: DNV.

EC JRC. (2021). *The JRC European TIMES Energy System Model*. Retrieved from Joint Research Centre Data Catalogue: https://data.jrc.ec.europa.eu/collection/id-00287

EHB. (2022). *European Hydrogen Backbone.* Brussels: ehb.

Energistyrelsen. (2021). *Technology Data - Renewable Fuels. .* Copenhagen: Energistyrelsen.

ENTEC. (2022). *he role of renewable H_2 import & storage to scale up the EU deployment of renewable H_2.* Luxembourg: Publications Office of the European Union.

EUCALC. (2020). *The European Calculator*. Retrieved from The European Calculator: http://tool.european-calculator.eu/

European Commission. (2019a). *2050 long-term strategy*. Retrieved from European Commission: https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en

European Commission. (2019b). *A European Green Deal*. Retrieved from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

European Commission. (2020). *2030 Climate Target Plan*. Retrieved from European Commission: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12265-2030-Climate-Target-Plan_en

European Commission. (2020a, 07 8). A hydrogen strategy for a climate-neutral Europe. Brussels, EU. Retrieved from https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

European Commission. (2021a). *Energy scenarios - Explore the future of European energy*. Retrieved from JRC Digital Media Hub: https://visitors-centre.jrc.ec.europa.eu/en/media/tools/energy-scenarios-explore-future-european-energy

European Commission. (2021c). *European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions*. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541

European Commission. (2021d). *Policy scenarios for delivering the European Green Deal*. Retrieved from European Commission: https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en

European Commission. (2022, 09 13). *Global Energy and Climate Outlook 2021: Advancing towards climate neutrality*. Retrieved from EU Science Hub: https://joint-research-centre.ec.europa.eu/geco-2021_en

European Commission. (2022). *REPowerEU Plan.* Brussels: European Commission. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0230&from=EN

European Commission. (2022c). *REPowerEU Plan {COM(2022) 230 final}.* Brussels: European Commission.

European Commission. (2022d). *REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition*. Retrieved from European Commission: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

European Commission. (2022e). *SWD(2022) 230 final IMPLEMENTING THE REPOWER EU ACTION PLAN: INVESTMENT NEEDS, HYDROGEN ACCELERATOR AND ACHIEVING THE BIO-METHANE TARGETS.* Brussels: European Commission.

European Commission. (2022f, 07 21). *Hydrogen*. Retrieved from European Commission: https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en

Eurosat. (2022, 07 21). *New energy statistics 2022 to support the Green Deal*. Retrieved from Home - Eurostat: https://ec.europa.eu/eurostat/web/main/home

Eurostat. (2022, 08 02). *Energy balances*. Retrieved from https://ec.europa.eu/eurostat/web/energy/data/energy-balances

EWI. (2021). *Contrasting European hydrogen pathways: An analysis of differing approaches in key markets.* Oxford: Oxford Institute for Energy Studies.

FCH. (2019). *Hydrogen roadmap Europe.* FCH.

FCHO. (2022, 06 17). *Hydrogen Demand* . Retrieved from Fuel Cells & Hydrogen Observatory: https://www.fchobservatory.eu/observatory/technology-and-market/hydrogen-demand

FCHO. (2022, 06 17). *Hydrogen Supply Capacity* . Retrieved from Fuel Cells & Hydrogen Observatory: https://www.fchobservatory.eu/observatory/technology-and-market/hydrogen-supply-capacity

Fuel Cells and Hydrogen 2 Joint Undertaking. (2020). *Opportunities for Hydrogen Energy Technologies Considering The National Energy & Climate Plans.* FCH 2 JU.

Gas Infrastructure Europe. (2022, 09 14). *The LNG Database*. Retrieved from Gas Infrastructure Europe: https://www.gie.eu/transparency/databases/lng-database/

Hysata. (2022, 12 01). *Hysata's electrolyser breaks efficiency records*. Retrieved from Hysta: http://hysata.com/news/hysatas-electrolyser-breaks-efficiency-records-enabling-world-beating-green-hydrogen-cost/

IEA. (2019). *The Future of Hydrogen.* Paris: IEA Publications.

IEA. (2019). *The Future of Hydrogen. Seizing today's opportunities.* Paris: IEA.

IEA. (2021a). *Global Hydrogen Rewview.* Paris: IEA.

IEA. (2021a). *Net Zero by 2050 A Riadnao for the Global Energy Sector.* Paris: IEA Publishing.

IEA. (2021b). *Hydrogen in North-Western Europe. A vision towards 2030 .* Paris: IEA.

IEA. (2021e). *World Energy Outlook.* Paris: IEA Publications.

IEA. (2022, 07 22). *Hydrogen*. Retrieved from International Energy Agency: https://www.iea.org/reports/hydrogen

IEA. (2022). *IEA World Energy Statistics and Balances.* IEA. doi:10.1787

IEA. (2022, 09 13). *Techno-economic inputs* . Retrieved from IEA: https://www.iea.org/reports/world-energy-model/techno-economic-inputs

IPCC. (2021, 08 09). *Newsroom*. Retrieved from IPCC: https://www.ipcc.ch/2021/08/09/ar6-wg1-20210809-pr/

IRENA. (2020). *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal.* Abu Dhabi.: International Renewable Energy Agency. Retrieved from https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

IRENA. (2020a). *Green Hydrogen Cost Reduction. Scaling up Electrolysers to meet the 1.5C climate goal.* Abu Dhabi: IRENA.

IRENA. (2020b). *Green Hydrogen. A Guide to Policy Making.* Abu Dhabi: IRENA.

IRENA. (2021). *Renewable Energy Statistics 2021.* Abu Dhabi: IRENA.

IRENA. (2021). *World Energy Transitions Outlook.* Abu Dhabi: IRENA .

IRENA. (2021a). *Grteen Hydrogen Supply. A guide to Policy making.* Abu Dhabi: IRENA.

IRENA. (2022). *World Energy Transitions Outlook 2022.* Abu Dhabi: IRENA.

IRENA. (2022a). *GLOBAL HYDROGEN TRADE TO MEET THE 1.5°C CLIMATE GOAL. Part I. TRADE OUTLOOK FOR 2050 AND WAY FORWARD.* Abu Dhabi: IRENA.

IRENA. (2022b). *GLOBAL HYDROGEN TRADE TO MEET THE 1.5°C CLIMATE GOAL. Part II. TECHNOLOGY REVIEW OF HYDROGEN CARRIERS.* Abu Dhabi: IRENA.

IRENA. (2022c). *GLOBAL HYDROGEN TRADE TO MEET THE 1.5°C CLIMATE GOAL. Part III. GREEN HYDROGEN COST AND POTENTIAL.* Abu Dhabi: IRENA.

IRENA. (2022d). *Geopolitics of the Energy Transformation. The Hydrogen Factor.* Abu Dhabi: IRENA.

IRENA. (2022d). *Global hydrogen trade to meet the 1.5C climate goal. Part I.* Abu Dhabi: IRENA.

Kanellopoulos K, B. S. (2022). *Blending hydrogen from electrolysis into the European gas grid.* Luxembourg:: Publications Office of the European Union.

Keramidas, K., Fosse, F., Díaz Vázquez, A., Dowling, P., Garaffa, R., Després, J., . . . Soria Ramirez, A. V.-M. (2021). *Global Energy and Climate Outlook.* Luxembourg: Publications Office of the European Unio. doi:10.2760/41061

McKinsey & Company. (2020). *Net-Zero Europe.* McKinsey & Company.

McKinsey & Company. (2020). *Net-Zero Europe Decarbonization pathways and socioeconomic implications.* McKinsey & Company.

Nijs, W., Castello, P. R., Tarvydas, D., Tsiropoulos, I., & Zucker, A. (2018). *Deployment Scenarios for Low Carbon Energy Technologies.* Luxembourg: Publications Office of the European Union.

OEC. (2022, 07 21). *Hydrogen*. Retrieved from The Observatory of Economic Complexity: https://oec.world/en/profile/hs/hydrogen-6280410

Ortiz Cebolla, R. D. (2022). *Assessment of Hydrogen Delivery Options.* Luxembourg:: Publications Office of the European Union.

PAC project. (2020). Retrieved from Paris Agreement Compatible Scenarios for Energy Infrastructure: https://www.pac-scenarios.eu/pac-scenario.html

Shell. (2018). *Sky. Meeting the goals of the Paris Agreement.* Shell International B.V.

Shell. (2021). *The Energy Transformation Scenarios.* Shell International B.V.

Tarvydas, D. (2022). *Clean Energy Outlooks: Analysis and Critical Review – 2022 Clean Energy Technology Observatory Status Report.* JRC. Luxembourg,: Publications Office of the European Union. doi:10.2760/309952

Teske, S. (2019). *Achieving the Paris Climate Agreement Goals.* Cham: Springer.

UNFCCC. (2022, 06 15). *Nationally Determined Contributions (NDCs*. Retrieved from UNFCCC: https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs

UTS. (2019). *One Earth Climate Model*. Retrieved from One Earth Climate Model: https://oneearth.uts.edu.au/

List of abbreviations and definitions

GHG	Greenhouse gases
CAGR	Compound annual growth rate
PPA	Purchase power agreement
CoO	Certificate of origin
EU	European Union

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Annexes

Annex 1. Hydrogen strategies/roadmaps in the EU

Country	Date	Comment
EU	July 2020	
The Netherlands	April 2020	
Germany	June 2020	
Portugal	August 2020	
France	September 2020	
Spain	October 2020	Roadmap
Italy	November 2020	Guidelines
Hungary	May 2021	
Slovakia	June 2021	Under preparation
Luxembourg	September 2021	
Poland	November 2021	
Sweden	November 2021	Proposal/Discussion
Denmark	December 2021	Under discussion
Croatia	March 2022	
Czech Republic	June 2022	
Greece	June 2022	Only in press
Lithuania	June 2022	Under preparation
Austria	June 2022	
Ireland	July 2022	Under consultation
Belgium	October 2022	
Bulgaria	Not found	
Cyprus	Not found	
Estonia	Other	Analysis
Finland	Other	Roadmap
Latvia	Not found	
Malta	Not found	
Romania	Other	Under discussions
Slovenia	Not found	

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