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Contact information
Name: Tarvydas D.
Email: Dalius.TARVYDAS@ec.europa.eu
Tel.: +31 22456-513

EU Science Hub
https://joint-research-centre.ec.europa.eu

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Abstract

The report assesses energy scenario studies published by major intergovernmental organisations, industry, academia and NGOs between the beginning of 2019 and the end of 2021. It provides an aggregated view of possible future development trends on selected low carbon energy technology groups: bioenergy, solar energy, geothermal energy, ambient heat, hydrogen, hydropower, ocean energy and wind energy. It highlights the possible role of these technologies in the energy mix globally and in the EU, as well as the EU share in deployment of these technologies.

A comparison of energy scenarios created by different actors can facilitate a better understanding of the role that these technologies could play in future energy systems, how they might interact with each other, what is needed to integrate them into existing systems and how they could be affected by social and behavioural changes. The report distils views on the main technologies driving the decarbonisation effort, as seen by energy scenario studies in a medium term (2030) and long term (2050) time frame, averaging the effort needed and discussing the possible assumptions behind the outliers.

Foreword

This report is an output of the Clean Energy Technology Observatory (CETO). CETO's objective is to provide an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal; and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market.

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Authors

Tarvydas, Dalius

Executive Summary

Despite the Paris agreement, global greenhouse gas emissions continue to rise. The COVID-19 pandemic was able to cause a slight reduction in 2020, but this did not last. In 2021, CO_2 emissions rose again, and 2022 is expected to chalk up a new world record. With the European Green Deal and the recent REPowerEU plan, the European Union is accelerating efforts to decarbonise its economy and reduce greenhouse gas emissions by at least 55% by 2030, achieving carbon neutrality by 2050.

Russia's invasion of Ukraine triggered vast global energy market disruption. Many scenario studies, relaying on natural gas as transition fuel, lost they relevance. This report is based on the scenario studies published before Russian invasion (except REPowerEU) and do not take into account geopolitical upheaval and instability of energy prices. Nevertheless, insides provided are still useful in understanding challenges energy of energy sector transition to carbon neutrality.

There are many energy scenario studies which focus on net-zero or Paris-compatible futures. This report looks into thirteen studies and focuses on eight groups of technologies that could facilitate the transition to a carbon-neutral economy. From each study, one scenario was selected, looking into deep decarbonisation pathways.

Across these studies, there is one common understanding: the future belongs to electricity. Despite differences in levels of ambition, methodological approaches and transformation speeds, all studies see electrons driving both the global and the European economies. There may be disagreements on how electricity will be generated and used, but consensus is clear: to reduce emissions, a considerable increase in electrification in all end-use sectors is needed. It can be done either directly or via enabling intermediate technologies, like green hydrogen and synthetic fuels. By 2030, electricity and electricity-based fuels could satisfy above 40% of total final demand in the EU. According to some energy scenario studies, by 2050, electricity and electricity-based fuels could satisfy up to 90% of total final demand in the EU. Globally, electrification reaches lower levels, at around 30% of total final demand in 2030 and approaching 70% on average by 2050.

While the jury is out on the future energy mix, two main technologies are set to dominate the power sector: wind (both onshore and offshore) and solar (mostly PV). In the majority of scenarios, these two technologies provide around 70-80% of all electricity generated in 2050. In some extreme cases, the share of wind and solar can reach as high as 90%. Scenario studies do not agree on whether solar or wind will be more important.

Solar energy and **wind** are currently the fastest evolving electricity production technologies and, according to scenario studies, they will dominate the market by 2050. In the next 10 years, global installed solar capacity will grow sevenfold on average, reaching around 5 000 GW of total installed solar power. In the same period, global wind installed capacity will grow to 3 000 GW on average (with some outliers seeing almost 6 000 GW), with generation increasing almost sixfold compared to 2019. After 2030, growth continues: by 2050 installed solar capacity will reach 10 000-15 000 GW globally, providing 22-40% of total electricity generation. By 2050, global wind installations could reach 7 000-8 000 GW and, on average, generate over 30% of the world's electricity. In most of the studies reviewed, around 80% of global power is produced using wind and solar installations by the middle of the century. In the EU, solar power growth is slower – with 'only' a threefold increase over ten years, averaging around 370 GW of installed power capacity in 2030. Afterwards, the trend continues, reaching around 1 000 GW on average and providing 13-22% of the EU's electricity in 2050. In the EU install capacity of wind will be similar to solar in 2030 (averaging around 365 GW), but lower in 2050 (averaging around 670 TGW)

In the future, most **hydrogen** will be produced by intermittent renewable electricity. By 2030, hydrogen demand for energy is negligible, both globally and in the EU. Studies do not agree on which sectors will drive its transformation, but between 2030 and 2050, hydrogen consumption increases, led by transport and industry.

The majority of **bioenergy**, both globally and in the EU, is used in final demand sectors. In the medium term (2030), it shows a slight increase on current levels. Despite small changes in bioenergy consumption levels, there are shifts in sectoral demand. Studies see a decreasing demand for solid biomass in the buildings sector, while more bioenergy will be used in the industry and transport sectors. In 2050, global trends diverge: some scenarios see growth after 2030, while others see a decrease. In the EU, bioenergy utilisation will be lower in 2050 compared to 2030, with the buildings sector leading the reduction.

Geothermal power installations are still low in number and statistically comparable to emerging technologies. In 2020, there was only 14 GW of geothermal power capacity installed globally, which could reach around 200 GW in 2050. In the EU, studies anticipate no significant additions to geothermal capacity, resulting in a negligible share even in 2050.

Hydropower is currently the main renewable energy source used for power production, accounting for 50% renewable power capacities and 63% generation. By 2030, none of the global or EU energy scenarios see any major development in hydropower. By 2050, hydropower could reach around 2 000 GW of total installed capacity globally providing less than 10% of total electricity supply in most studies.

Ocean energy is an emerging technology with only 0.5 GW currently installed globally, half of which is in the EU. It can be concluded that even with high growth potential, ocean energy will not play a significant role by 2050.

Heat pumps (ambient heat) are not usually directly included in energy scenario studies results. Nevertheless, energy scenario studies stress the importance of ambient heat in the future end use energy mix. Heat pumps could cover heating demand in the buildings sector and low and medium temperature heat in industry. In 2030, the number of heat pumps could vary between 200 million and 600 million globally, reaching up to 1 800 million by 2050. In the EU, heat pumps could provide 530 TWh of final energy in 2050.

1 Introduction

During the six years after the signature of The Paris Agreement, 194 countries submitted Nationally Determined Contributions (UNFCCC, 2022b). However, the world is even further away from the climate targets now than in 2015. The COVID-19 crisis resulted in a slight reduction of global CO_2 emissions in 2020, but not for long – in 2021 there was a return to pre-pandemic levels, to continue to new heights on its CO_2 emissions journey. In August 2021, the official The Intergovernmental Panel on Climate Change (IPCC) announcement of the first instalment of its Sixth Assessment Report (AR6) was entitled, "Climate change widespread, rapid, and intensifying" (IPCC, 2021). The IPCC essentially concluded that climate is warming up at a faster pace than previously anticipated and therefore, immediate action should be taken. On the other hand, there are positive signs of change – the EU can be seen as a showcase for efforts to reduce CO_2 emissions: despite its growing economic output, greenhouse gas emissions in the European Union have steadily decreased since 2015. Nevertheless, in order to minimise climate change, decarbonisation efforts should be strengthened globally.

There is a common understanding that climate change should be stopped, and that the timeframe for doing so is closing. There is a broad set of ways in which the economy can be decarbonised. Everybody agrees that part of the solution should (at least partially) be technology based: in order to reduce the CO_2 footprint of the economy, we should replace fossil fuels with renewable energy resources. This still leaves the question of which renewable technologies should be used and to what extent. Another open question is how much energy we will actually need in the future. Consumption which does not stop growing may hit hard planetary limits (Club Of Rome, 2022). Increasing energy efficiency is part of the solution, but behavioural and social changes may also be necessary.

Technology innovation and deployment, as well as the availability of resources, economic growth, changes in society and even dietary preferences, not to mention unpredictable events like the pandemics, extreme weather events or geopolitical upheavals, will affect how humans produce, transform and consume energy and the degree to which the energy system is environmentally sustainable. The global energy market disruption caused by Russia's invasion of Ukraine triggered paradigm change in energy scenario studies (e.g. REPowerEU plan (European Commission, 2022d) amended Fit for 55 (European Commission, 2019b)). There is obviously uncertainty on the degree to which these factors will affect the energy systems transformation. The longer the time horizon, the wider the uncertainty range is. That is why there is a multitude of energy scenarios looking into the medium term (2030) and long term (2050 and beyond), which incorporate broader societal and macroeconomic trends impacting the energy system. Using different assumptions, scopes and tools, scenario studies provide a wide range of views of how the energy system could evolve in the future.

An in-depth review of a range of energy scenarios created by a variety of actors is needed to better understand the role that selected technologies could play in future energy systems, how they interact with each other, what is needed to integrate them into existing systems and how they will be affected by social changes. Scenarios created by different actors – such as national and international organisations, private corporations, non-governmental organisations (NGOs), research institutes and academia – allow us to see the broader picture, representing a wide range of stakeholder views outside any single professional bubble.

The comparative assessment of energy scenarios is useful, because on the one hand it may identify the basic set of technologies dominating the majority of energy scenario projections. On the other hand, the most 'extreme' scenarios would allow understanding the boundary conditions under which the energy system could evolve. While inherently uncertain, such information could form the basis for developing "no regret" solutions, based on commonalities observed in scenario results. Differences among scenario results may indicate higher uncertainty (risk) areas where more research may be needed and decisions should be made more carefully.

This report is based on ***thirteen energy scenario studies*** published by different stakeholders, focusing on Net-Zero or Paris-comparable pathways. We look into eight groups of technology that could drive the transition to a carbon-neutral economy (bioenergy, solar energy, geothermal energy, ambient heat, hydropower, ocean, wind and hydrogen). The latter group, hydrogen, include technologies for the production, storage and transport of hydrogen which could have multiple applications. Hydrogen could be used for power generation or in end uses (transport, buildings, industry), while acting as demand-side management or storage technology that would enable the integration of intermittent renewable energy sources like solar and wind. It can also be used as an intermediate step in decarbonising hard-to-abate sectors in the form of synthetic fuels. From each study, one scenario was selected, looking into deep decarbonisation pathways for the global and/or European energy systems.

This report focuses on insights derived from a quantitative comparison of selected energy scenario results, distilling possible deployment ranges of these eight technology groups in the mid- and long-term future. Their roles are assessed in power generation and final demand both globally and in the EU. Looking into future global markets, the possible role of the EU is discussed.

2 Energy scenarios

2.1 Background

Scenario studies examine a range of possible futures, driven by underlying assumptions. Energy scenarios are outlooks that describe how energy supply and demand may develop in the future, based on a coherent set of assumptions. Wide utilisation of energy scenarios was triggered by the energy crisis of the 1970s (Shell, 2008), and today they are used by a wide range actors, including oil companies (Shell, 2021) (BP, 2020), governments and intergovernmental organisations (European Commission, 2020), and are an indispensable tool for decision-makers in particular and public discourse in general (CAN, 2022). Energy scenarios are also an indispensable tool for the better understanding pathways to mitigate climate change. They can help us to understand complex relations between factors such as changes in energy demand, lifestyles and dietary preference. Scenarios are instrumental in the struggle to fight climate change (UNFCCC, 2022a).

In the past, energy scenarios were technology-driven and based on simulation or optimisation models, but with ever increasing data availability and computational power, the models behind energy scenarios have evolved. In some cases, energy scenarios are the results of integrated modelling frameworks linking together different specialised models covering not only energy production and consumption technologies, but also land use, behavioural changes, socioeconomic aspects, etc. This approach allows for a better understanding of links and the feedback loops of different components. A prominent example of the linking of different models is the integrated assessment models used by the IPCC.

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement (UNFCCC, 2015) triggered the development of a multitude of energy scenarios driven by climate goals. These range from global studies considering the possibility of reaching carbon neutrality by a set date (in the latest studies usually 2050 or earlier) or staying within a carbon budget (The Global Carbon Project, 2022) (with or without offset), to national or regional studies into ways to become zero-carbon (European Commission, 2019b).

This report is predominantly based on normative[1] energy scenario studies based on optimisation or simulation models or modelling suites[2]. The majority of energy scenario studies used in this report have a normative goal of reaching net-zero emissions by 2050. Despite their common goal of decarbonisation, these scenario studies see very different pathways to achieving it: driven by different assumptions on technology development, the economy and behavioural changes, resulting in different levels of demand and ways to achieve it. Comparing different studies helps us to understand the complex interactions between future technologies and drivers, prioritising one set of solutions over another.

2.2 Selection criteria

In the preparation of this report, 47 scenario studies were taken into consideration, published from January 2019 to February 2022. Our 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, 13 studies were selected. The majority of these have scenarios in line with fast global decarbonisation, reaching close to zero emissions by 2050. For each study, only one scenario was used. In the case of several scenarios per study, selection was based on the level of ambition, and how close assumptions and/or results were to the EU Green Deal (European Commission, 2019b).

In **Figure 1** and **Figure 2**, a summary of scenario coverage is presented. In these tables, "Yes" indicates that information is available either in the study itself or in the accompanying materials, and "No", that information is not readily available. "Detailed" indicates that the scenario provides a disaggregation of selected variables, for example in the case of wind, information is available for both onshore and offshore. In some cases, studies provide even higher levels of disaggregation, for example offshore wind, fixed or floating. In the case

[1] Normative scenarios (explorative or target-seeking scenarios in other sources) strive to achieve a normatively defined future, with a clear vision on the state of a set of elements or variables at a given point of time in the future. Normative scenarios are usually target driven (for example achieving net-zero GHG emissions or abandoning all fossil fuel by a certain point in time). Normative scenarios may also have other constraints (for example a limited set of possible future technologies: no new nuclear power plants).

[2] While historically, energy sector studies were usually based on a single model looking only at the energy sector, model scenario studies are often based on several (often softly) interlinked models, dealing with different areas. For example, *JRC GECO* (Keramidas, et al., 2021) uses the POLES-JRC (JRC, 2018) model of the world energy system for the energy sector and greenhouse gas (GHG) emission forecasting, and JRC-GEM-E3 (JRC, 2022) is used to evaluate the economic impacts of each scenario developed. UTS/ISF (Teske, 2019) used an even more complex modelling suite of six models dealing with the energy system, transport, renewable technology assessment, the power system and several models to assess emission pathways (UTS/ISF, 2017).

of hydrogen, "Split" means that information on final demand is available for pure hydrogen and synthetic fuels. "Partial" indicates that information is available, but not sufficient to fully cover the selected technology. For example, hydrogen and synthetic fuels are combined. In the case of the EU, it indicates data availability in the geographical coverage closest to the EU27. If the report covers both the EU27 and Europe, EU27 values were used. In other cases (EU28, OECD Europe, and Europe), original data, when possible, were scaled down to EU27 level in order to make them comparable.

It is worth noting that "Not Avail." does not indicate that the selected technology or parameter was not used/available in the analysis covered by the selected scenario study. In most cases it only indicates that the selected variable was not provided in the data tables or graphs for this scenario or was reported in an aggregated way, not suitable for the technology disaggregation level used in this report.

Figure 1. Coverage of selected scenarios

Scenario	EU	World	GDP	Population	Investments	Primary	Capacity	Generation	Final	Emissions
JRC GECO	EU27	Yes	Yes	Yes	Not Avail.	Yes	Yes	Yes	Yes	Yes
IRENA	Not Avail.	Yes	Not Avail.	Not Avail.	*Partial*	Not Avail.	Yes	Yes	Yes	Yes
IEA WEO	EU27/Partial	Yes	Yes	Yes	Partial	Yes	Yes	Yes	Yes	Yes
EC Fit55	Yes	Not Available	Yes	yes	Partial	Yes	Yes	Yes	Yes	Yes
DNV	Europe	Not Available	Yes	Yes	Partial	Yes	Yes	Yes	Yes	Yes
Shell	No	Yes	Yes	Yes	Not Avail.	Yes	Yes	Fuel Input	Partialy	Yes
McKinsey	EU27	Not Available	Not Avail.	Not Avail.	Not Avail.	Not Avail.	Yes	Yes	Partial	Yes
EUCalc	EU28	Not Available	Not Avail.	Not Avail.	Not Avail.	Yes	Not Avail.	Yes	Yes	Yes
CAN	EU28	Not Available	Not Avail.	Not Avail.	Not Avail.	Yes	Yes	Yes	Yes	Tes
BP	EU28/Partial	Partial	Yes	Yes	Not Avail.	Partial	Not Avail.	Yes	Partial	Yes
JRC TIMES	EU27	Not Available	Not Avail.	Not Avail.	Not Avail.	Yes	Yes	Yes	Yes	Yes
IFS	OECD Europe	Yes	Yes	Yes	Not Avail.	Yes	Yes	Yes	Yes	Yes
BNEF	Not Avail.	Yes	Not Avail.	Not Avail.	Yes	Yes	Tes	Yes	Yes	Yes

Source: JRC analysis

Figure 2. Technologies represented in selected scenarios

Scenario	Year	Bioenergy	Solar	Geothermal	Heat Pumps	Hydrogen	Hydro	Ocean	Wind
JRC GECO	2021	Yes	Yes	Yes	Not Avail.	Yes	Yes	Yes	Yes
IRENA	2021	Yes	Yes	Yes	Not Avail.	Yes	Yes	Yes	Yes
IEA WEO	2021	Detailed	Detailed	Yes	Not Avail.	Yes	Yes	Yes	Detailed
EC Fit55	2021	Detailed	Detailed	Yes	Not Avail.	yes	Yes	Not Avail.	Yes
DNV	2021	Yes	Yes	Yes	Not Avail.	Yes	Yes	Not Avail.	Detailed
Shell	2021	Yes	yes	Yes	Not Avail.	Yes	Yes	Detailed	Detailed
McKinsey	2020	Yes	Detailed	Yes	Not Avail.	Yes	Yes	Not Avail.	Yes
EUCalc	2020	Yes	Yes	Not Avail.	Not Avail.	Yes	Yes	Yes	Detailed
CAN	2020	Detailed	Detailed	Yes	Yes	Yes	Yes	Yes	Detailed
BP	2020	Detailed	Detailed	Yes	Yes	Yes	Yes	Not Avail.	Detailed
JRC TIMES	2019	Detailed	Yes	Yes	Not Avail.	Yes	Yes	Detailed	Yes
IFS	2019	Detailed	Detailed	Yes	Yes	Yes	Yes	Detailed	Yes
BNEF	2021	Detailed	Detailed	Yes	Not Avail.	Yes	Yes	Not Avail.	Detailed

Source: JRC analysis

The Joint Research Centre (JRC) annual report, "Global Energy and Climate Outlook", (GECO) published in 2021 (Keramidas, et al., 2021), focused on global pathways to climate neutrality. It covers four distinct scenarios, two of which (CurPol and NDC-LTS) do not achieve climate neutrality (in this case a 1.5°C target). The remaining two 1.5°C-Uniform and *1.5°C-Differentiated* are in line with the Paris Agreement long-term goal of a temperature rise over pre-industrial times of well below 2°C at the end of the century with 50% probability of not exceeding 1.5°C of warming. The main normative difference between these scenarios is the carbon price: in 1.5°C-Uniform, the carbon price is uniform for all regions (distributing the burden of climate action equally among the regions), while in 1.5°C-Differentiated, the carbon price varies by region (distributing the mitigation efforts based on per capita income rather than just energy usage). In this report we used data from the 1.5°C-Differentiated scenario, referred to henceforth as ***JRC GECO***. JRC GECO has very high data availability, in the form of excel tables and an online data visualisation tool (European Commission, 2022).

The International Renewable Energy Agency (IRENA) annual report, *World Energy Transition Outlook (WETO)* (IRENA, 2021), focuses on the 1.5°C pathway. Its two main scenarios are the Planned Energy Scenario (a reference scenario based on national energy plans and targets as they now stand) and the 1.5°C Scenario, based on currently readily available technologies, scaled up at the necessary pace and rate to meet the 1.5°C climate ambition. This study uses the 1.5°C Scenario, which will henceforth be referred to as ***IRENA***. The availability of data for WETO is moderate: the majority of the data used in this report comes from the data tables provided in its annexes.

The International Energy Agency (IEA) annual report, World Energy Outlook (IEA, 2021e), covers four distinct scenarios: Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS), Sustainable Development Scenario (SDS) and *Net Zero Emissions by 2050 scenario (NZE)*. Only one of these scenarios is aligned with the long-term Paris Agreement goal of reducing emissions to keep the temperature rise below 2.0°C, essentially ensuring global carbon neutrality by 2050. IEA WEO NZE is also published as a separate report on the global net zero target. Both the IEA WEO NZE scenario and the IEA report, "Net Zero by 2050" (IEA, 2021a), are based on the same dataset, with only one difference: the Data Annex of IEA WEO is more precise (to one more decimal place, which makes a huge difference in energy flows expressed in PJ). All the data used in the graphs comes from the IEA WEO report, but insights are drawn from both. Of the scenario studies reviewed in this report, IEA WEO is amongst those with the highest data availability: in addition to the scenario results provided in the excel tables, the underlying assumptions, such as technology and fuel costs, are also publicly available (IEA, 2022). In this report we use the IEA WEO NZE scenario, referring to it as ***IEA***.

In July 2021, within the framework of the European Green Deal (European Commission, 2019b) the European Commission (EC) proposed the package for Delivering the Green Deal, 'Fit for 55' (European Commission, 2021c), designed 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 strategy vision (European Commission, 2019a) and the 2030 Climate Target Plan (Commission, European, 2020c). There were three core policy scenarios behind the Fit for 55 (European Commission, 2021a) package: REG – relying on high intensification of energy and transport policies in the absence of carbon pricing for road transport and buildings sectors; *MIX* – relying on both the extension of carbon pricing to road transport and buildings and the high intensification of energy and transport policies; and MIX-CP – representing a more carbon price-driven policy mix, with revised energy efficiency and renewables directives, lower intensification of current policies, and the extension of the carbon price signal to new sectors. Despite significant improvements in data availability, official EC scenarios do not provide the full datasets needed for this report, as this modelling exercise focused on policies for the achievement of the 2030 target (and not 2050). While medium term (2030) modelling results are available (European Commission, 2021d), the dataset for a longer time horizon (2050) is not directly available. The Online Energy Scenario Tool (European Commission, 2021a) only provides highly aggregated numbers for final demand. In this report we will be using results from the MIX scenario. In May 2020 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. When available, insights from REPowerEU (not scenario specific) will be used.

The DNV annual 'Energy transition outlook' (ETO) report is one of two energy scenario studies included in this analysis that do not reach zero carbon emissions by 2050 and are not in line with the Paris Agreement (DNV, 2021a). DNV also published another report (DNV, 2021b) detailing the additional effort needed to reach climate neutrality by 2050, but due limited data availability (i.e. in the form of an excel file), The ETO report was selected for analysis and its main scenario was used in this report which will henceforth be referred to as ***DNV***.

Shell, in line with other oil majors, regularly publishes scenario-based studies looking into possible evolution of energy systems in the future. In 2021, Shell published 'The Energy Transformation Scenarios' report (Shell, 2021), updating three scenarios originally introduced in the influential 'Sky: Meeting the goals of the Paris Agreement' report, published in 2018 (Shell, 2018), taking into account recent developments in socioeconomics and technology. In the Waves scenario, economic performance is prioritised (the main measure of success is GDP growth), with a trade-off on environmental sustainability (e.g., carbon emission reductions and lower air pollution). Despite this, renewables become cost-competitive by 2030, but the Paris target is missed. The Islands scenario focuses on self-sufficiency, with increasing gaps between nations in terms of economic growth and climate mitigation, leaving the Paris Agreement out of reach. The third scenario, *Sky 1.5*, sees cooperation between countries and social groups inside them, with the environment as a key priority, pushing CO_2 emissions below zero after 2050 and reaching the Paris target by the end of the century. Shell reports have high data availability (Excel files), but the data aggregation differs from other scenario studies, making comparisons difficult at times. In this report the Sky 1.5 scenario is used and will henceforth be referred to as ***SHELL***.

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 the graphs only, it provides interesting insights on how, led by the power sector, the EU could reach climate neutrality by mid-century.

In 2020a consortium[3], partially funded by the EU Horizon 2020 programme, published a series of reports and an online tool, '*Transition pathways to a carbon neutral EU28*', which makes it possible for the general public to produce their own scenarios. The project developed 16 predefined scenarios (EUCALC, 2020), some of which reach climate neutrality before 2045. *The Tech scenario,* which is assessed in this report assumes that the decarbonisation of the economy would be driven by technology, and that there would be minimal changes in the behaviour of citizens (in line with the *LTS baseline*). The data availability is high (all data is available in the form of csv or excel files). In this report, the scenario will be called ***EUCalc***.

In 2020, a consortium of Climate Action Network (CAN) Europe, the European Environmental Bureau (EEB), Renewables Grid Initiative (RGI) and REN21 published '*Paris Agreement Compatible Scenarios for Energy Infrastructure*' (PAC) (PAC project, 2020) aligned with the Paris Agreement's objective to limit global warming to 1.5°C and which embodies the policy demands of civil society. Driven by NGOs (members of CAN and EEB), the scenarios represent a broader view of how climate neutrality could be achieved. The report has high data availability (Excel file) and in this report will be called ***CAN***.

In 2020, BP published its 'Energy Outlook 2020 edition' (BP, 2020), covering three main scenarios: Business-as-usual – assuming that government policies, technologies and social preferences will continue their current trend and decarbonisation will not be achieved by 2050; *Rapid* – relying on policy measures to increase carbon prices and sector-specific measures resulting in a 70% CO_2 reduction by 2050; *Net-Zero* – based on the Rapid scenario measures, complemented with behavioural changes, resulting in a 95% reduction in CO_2 emissions by 2050. The data availability is high (Excel files). The Net-Zero scenario, henceforth referred to as ***BP*** is used in this report.

The JRC EU TIMES model and accompanying data set were created at the Joint Research Centre of the European Commission in support of various activities, including a series of Low Carbon Energy Observatory (LCEO)[4] reports (Nijs, P., D., I., & A., 2018). In 2021, JRC EU TIMES (with slightly modified data sets) was released into the public domain (EC JRC, 2021). From this dataset, the *Net Zero scenario*, reaching carbon neutrality in EU27 by 2050, is used. It has high data availability and technology disaggregation. This will be called ***JRC TIMES***.

In 2019, teams from the University of Technology (UTS) / Institute for Sustainable Futures (ISF), University of Melbourne and German Aerospace Centre published the book, '*Achieving the Paris Climate Agreement Goals'*, (Teske, 2019), and accompanied by the public dataset (UTS, 2019). Based on the most restrictive assumption among all scenario studies analysed, the study envisioned a net zero global energy system by 2050, without the use of any fossil fuels, nuclear power or CCS. The study has high data availability (excel files) and is referred to here as ***IFS***.

The BloombergNEF annual report, New Energy Outlook (BloombergNEF, 2021), is based on three scenarios with distinct pathways to net zero emissions. All three scenarios rely strongly on electrification and renewable energy. The *Green Scenari*o is based on fast deployment of green hydrogen, used to provide both storage and balancing for all energy needs. The Gray Scenario relies on fossil fuels (with CCS) and blue hydrogen (hydrogen produced from natural gas and supported by carbon capture and storage) for hard-to-decarbonise sectors while in the *Red Scenario*, renewables are complemented with an increasing share of nuclear for both power generation and the production of red hydrogen (generated through electrolysis powered by nuclear energy). The report has high data availability (excel tables). The Green Scenario referred to as ***BNEF***, is assessed in the context of this report.

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

[4] The LCEO analyses the state of play in EU research and innovation trends and the policy measures for eleven low-carbon technologies.

2.3 Methodological approach

All data behind this report are compiled based only on information from publicly available sources on energy scenarios[5]. For each indicator, data was converted into a single unit. Conversion factors are available in Annex 1. The following indicators were considered:

- Net installed capacity of power generation technologies (GW);
- Primary energy (Mtoe);
- Final energy (per sector if applicable, Mtoe);
- Gross electricity generation, expressed in terawatt hours (TWh);
- CO_2 emissions or GHG emissions (GtCO2 or GtCO2eq);
- Population (million people);
- Gross Domestic Product Euros (€2015).

Primary energy values are harmonised between studies (when possible), aligned to the Eurostat definition of Gross Inland Consumption (for Europe). Harmonisation is detailed in the first instance used. The figures on final energy use exclude non-energy uses.

The assessed studies use different definitions of Europe (Europe, EU27, EU28, and OECD Europe). In order to make the results comparable, they were harmonised to EU27, based on 2019 shares of EU27 in the selected region.

For the representation of historic data and geographical normalisations (2019/2020), data from Eurostat, IEA and IRENA were used. Energy scenario data is presented only for the milestone years of 2030 and 2050 (when available).

The base year (2019/2020) is established based on available statistical information for the world and the EU. More specifically:

- Gross installed capacity of renewable energy technologies, and energy from renewable sources (generation) are based on IRENA (IRENA, 2022c)
- Energy from fossil fuels and nuclear sources (primary energy, final energy, generation), primary and final energy from renewable sources are based on IEA (IEA, 2021c);
- CO_2 emissions from fuel combustion are based on IEA (IEA, 2021c);
- GDP and Population growth rates are established based on the historical years of each scenario study (when available).

The assessed studies follow different sectoral definitions and boundaries when reporting results for final energy. Some provide very detailed data down to subsectors, while others aggregate several sectors. In this report, all final energy was aggregated to 4 main sectors (when available): Industry, Transport, Buildings and Other[6]. Due to the differences in boundaries in sectoral definitions, aggregated sectors may vary slightly in scope (for example industry to include agriculture sector).

We name scenarios based on the publishing organisation. Only where several studies from the same organisation are used do we also use the study name. For example, there are three European Commission studies used: EC FIT55, JRC GECO and *JRC TIMES*.

[5] All scenario studies and data sets are publicly available and downloadable free of charge, except BNEF NEO, which was specifically mentioned in the terms of reference for this report.

[6] Depending on the study, *Other* sectors could include Agriculture and Fisheries. In some cases, the energy industry is also reported under the *Other* sector. This is indicated in the affected graphs.

3 Energy system developments in low carbon futures

3.1 Primary energy

At the global level

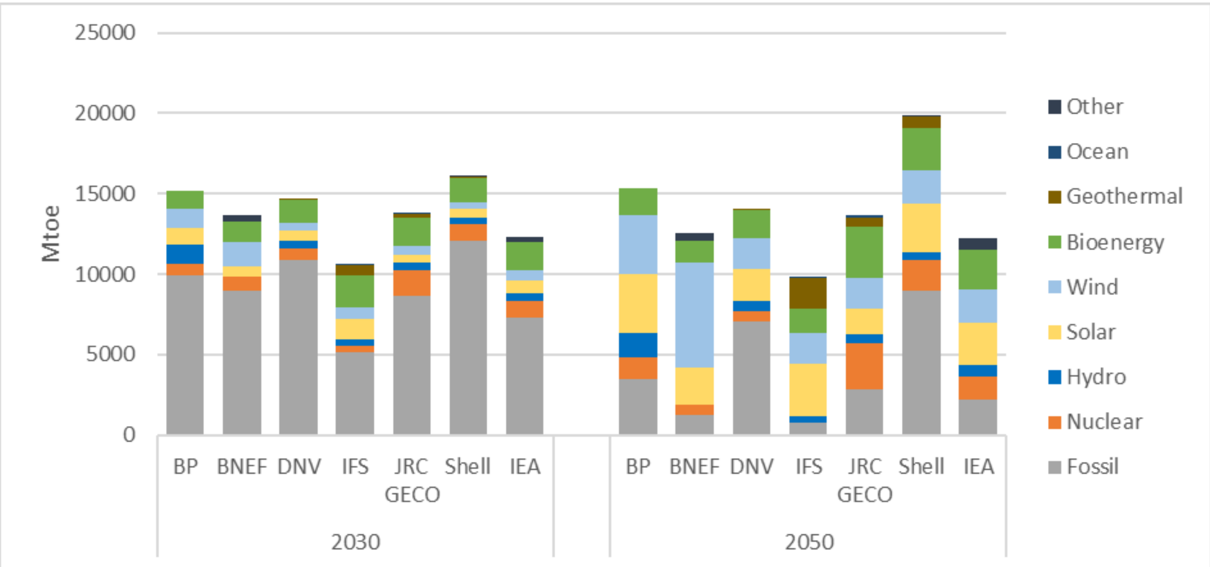
In 2019, almost 14 500 Mtoe (OECD, 2022) of primary energy was consumed globally, the highest amount in recorded history. While slowing its growth from a 2.5% compound annual growth rate (CAGR) in 2000-2010 down to 1.4% in the period 2010-2019, nevertheless, in two decades, only one slight drop in global primary energy was observed in 2009 (due to the global economic downturn). Increasing primary energy demand does not necessarily translate into higher CO_2 emissions, but, even in the best case it means bigger decarbonisation efforts.

In the medium term (2020-2030), the majority of energy scenarios reviewed see a reduction in primary energy demand (or increase in primary energy efficiency), leading to primary energy demand between 10 000 Mtoe and 15 000 Mtoe. Two scenarios, *BP* and *DNV*, project a similar energy consumption to today's level. There are clear outliers (**Figure 3**): at the high end, the oil major, Shell, anticipates an increase of over 10%, with net-zero achieved only after 2050. *Shell* also has the highest fossil fuel demand in both 2030 and 2050. At the lower end, *IFS* sees a decrease of 25%, with very strong decarbonisation normative assumptions driving energy efficiency fast, early in the process, in order to avoid the need of CCS.

While between 2020-2030, the majority of global energy scenario studies reviewed see a significant increase in primary energy efficiency, in the long term not all of them see a continuation of the trend. *Shell* depicts a continuation of the upward trend (by 23%), reaching almost 20 000 Mtoe in 2050 (**Figure 3**). At the other extreme, *BP* and *IEA* project primary energy demand remaining stable (with changes of less than 1.5%). All other studies see a reduction in primary energy demand, but at a considerably lower rate compared to the period 2020-2030, reaching only 4-8%.

On top of increasing energy efficiency, a transformation in the composition of primary energy is evident, shifting from fossil fuels to renewable and nuclear. While in 2019, 80% of primary energy supply was fossil fuel-based, in 2030 this shifts to 65% on average (in *IFS* it drops below 50%). By 2050, the situation changes, dropping down to 25% (below 10% in *BNEF* and *IFS*). While fossil fuels remain an important part of the primary energy supply mix even in 2050, wind and solar become the dominant energy sources in most of the global scenarios analysed.

Figure 3. Global primary energy consumption



Source: JRC analysis based on scenario studies

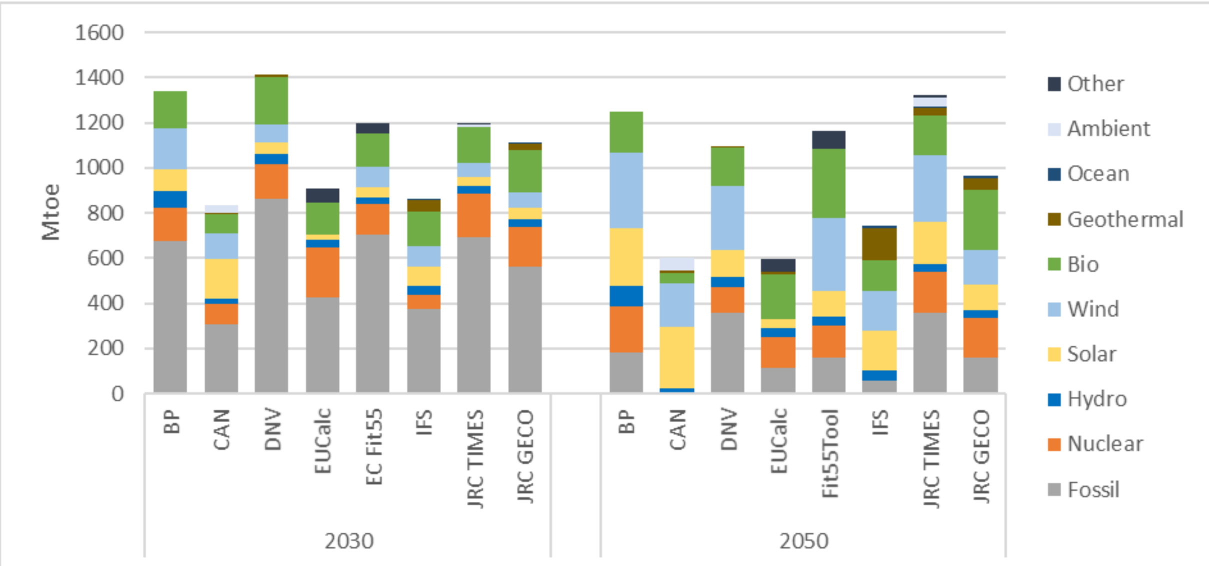
At EU level

Primary energy demand in the EU peaked in 2006 at 1 600 Mtoe, afterwards slowly decreasing to 1 402 Mtoe in 2019 (OECD, 2022). In the period 2013-2019 there were no noteworthy changes – primary energy demand fluctuated around 1 400 Mtoe.

Contrary to the conclusions of global scenario studies, there is more divergence in the EU on future primary energy. By 2030 there is already a 40% difference between the highest and lowest projections. At the high end, *BP* and *DNV* see primary energy demand at similar levels to current consumption. Studies originating from the European Commission (EC Fit55, *JRC GECO* and *JRC TIMES*) see a reduction of around 15% in the next ten years, while the most ambitious studies (CAN, *EUCalc* and *IFS*) see a reduction of around 35%. By 2050 the situation diverges even more, and two main groups of scenarios can be identified. The first is made up of scenarios which project a (relatively) high primary energy demand for the EU (between 1 000 Mtoe and 1 300 Mtoe), including significant demand for hydrogen and e-fuels. The second group of scenarios is characterised by lower primary energy demand in the EU ranging between 600 Mtoe and 800 Mtoe, underlying higher levels of direct electrification along with behavioural changes.

In 2019, 70% of the EU primary energy supply was provided by fossil fuels. Based on energy scenario results, this share will already drop significantly in 2030 – to below 50% on average (32% in the case of CAN). By 2050, the role of fossil fuels in primary energy supply will go down to 16% on average, with *IFS* and *CAN* seeing it drop below 10%. In 2050, based on the results of the majority of the scenario studies, wind and bioenergy are projected to be the two major fuels in the EU, while solar and nuclear also play an important part.

Figure 4. Primary energy consumption in the EU



Source: JRC analysis based on scenario studies

3.2 Energy use in sectors

At the global level

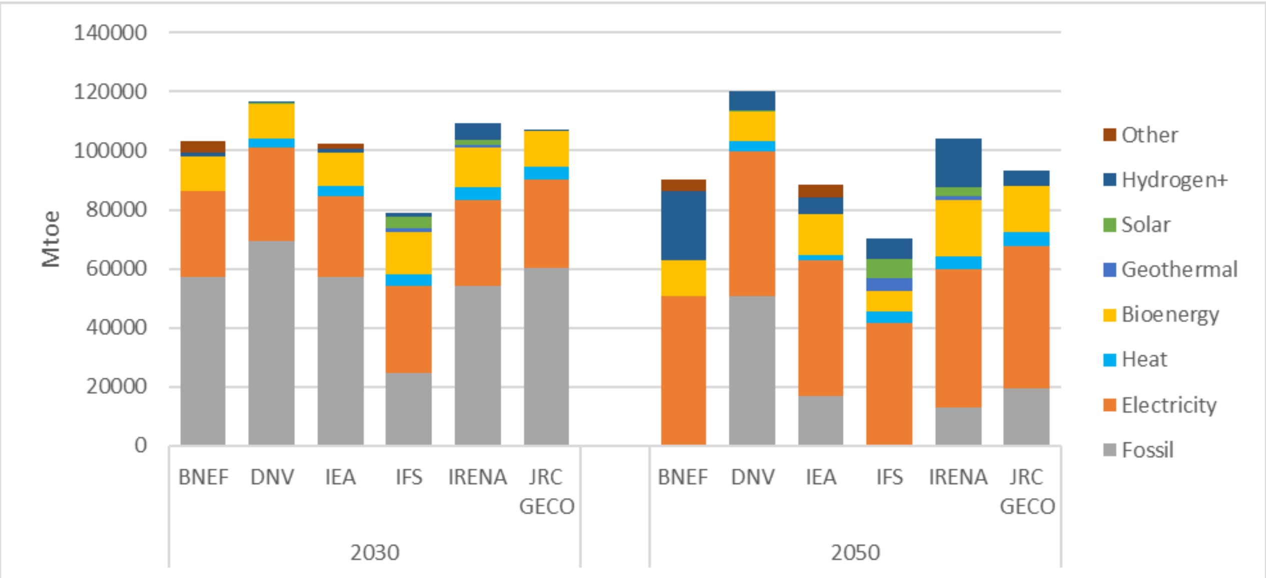
According to scenarios analysed the total amount of energy used in end use sectors would not change drastically both in the medium term (up to 2030) and the long term (from 2030 to 2050). Despite population and economic growth (discussed in chapter 3.4), total final demand is projected to decline by around 1% annually in the period till 2030, and reach an average of 10 000 Mtoe annually (**Figure 5**). Between 2030 and 2050 the decline continues, at a slower pace (around 0.5% per year on average). There is only one outlier – *IFS* sees a drastic reduction in energy demand, dropping by around 40% by 2050. However, although the changes in total energy demand are small, they are drastic at the level of fuels and sectors. While in 2019, fossil fuels contributed 66% of the total energy demand in end use sectors, complemented by 20% electricity and 10% bioenergy, in 2030, the majority of scenarios see a decline in fossil fuels to around 55% and an increase of electrification to around 30%. In the case of *IFS*, the changes are even more striking: fossil fuels decrease to 31% and electricity increases to 38%. By 2050, the changes are even bigger: in the majority of scenarios, fossil fuels play only a marginal role (if any), while electricity becomes dominant in end use sectors, ranging between 50% and 60%. Bioenergy provides 10-20%, and in most scenarios, hydrogen and synthetic fuels start playing a role, staying below 10%, except in *BNEF*, where they reach 26%.

At sectoral level, decarbonisation happens at different paces. It is achieved faster, via electrification, in the buildings sector. By 2030, around 45% of total final demand in the buildings sector is provided by electricity (up from 34% in 2019) and fossil fuel usage is reduced to below 30% (from 34%). By 2050, only two of the six global studies see fossil fuels still used in buildings. Electricity will cover more than 60% of total final demand in buildings, supplemented by bioenergy. Some of the studies also see a role for direct solar heating.

In contrast with the buildings sector, changes in transport will take much longer. By 2030, more than 80% of energy is still be provided by fossil fuels, supplemented by bioenergy and electricity. It is worth noting that some scenario studies see a drastic decrease in future energy demand in transport; according to *IFS*, final demand in the transport sector drops by more than 40%, resulting in drop to a third of fossil fuel demand (compared to current consumption), although it still contributes around 65%. By 2050, fossils no longer play a major role in the transport sector: up to a half of energy for transport could come from electricity. Bioenergy and hydrogen-based fuels also play an important role according to all the scenario studies analysed.

In industry, the pace of change is faster than transport, but slower than the buildings sector. In 2030, the majority of scenario studies still project that more than half of its energy will come from fossil fuels. Even in 2050, only two of the six studies depict a fully decarbonised industry: around 20% of total energy is provided by fossil fuels[7]. Electricity becomes the main industrial source of energy, followed by bioenergy and fossil fuels. Scenario studies do not agree on the role of hydrogen and synthetic fuels in industry: according to *BNEF* they contribute around one third, but other studies, such as *JRC GECO*, see a less prominent role for hydrogen.

Figure 5. Global final energy demand by fuel 2030 and 2050[8]



Source: JRC analysis based on scenario studies

At EU level

Over the medium term (until 2030), projections on total final energy demand from the energy scenarios assessed show the EU following a similar trajectory to global trends (**Figure 6**), with only 1% annual reduction in energy consumed in end use sectors. Despite average values being similar, there is wider disagreement among studies those with strong normative decarbonisation (*CAN* and *IFS*) see a significant reduction of demand already in 2030. Differences in future energy demand become even more evident in 2050, where some of the studies reviewed see a reduction in energy demand reaching around 40% compared

[7] In most cases emissions are offset by CCS/CCUS or BECCS in industry or other sectors.

[8] *IRENA* also includes non-energy

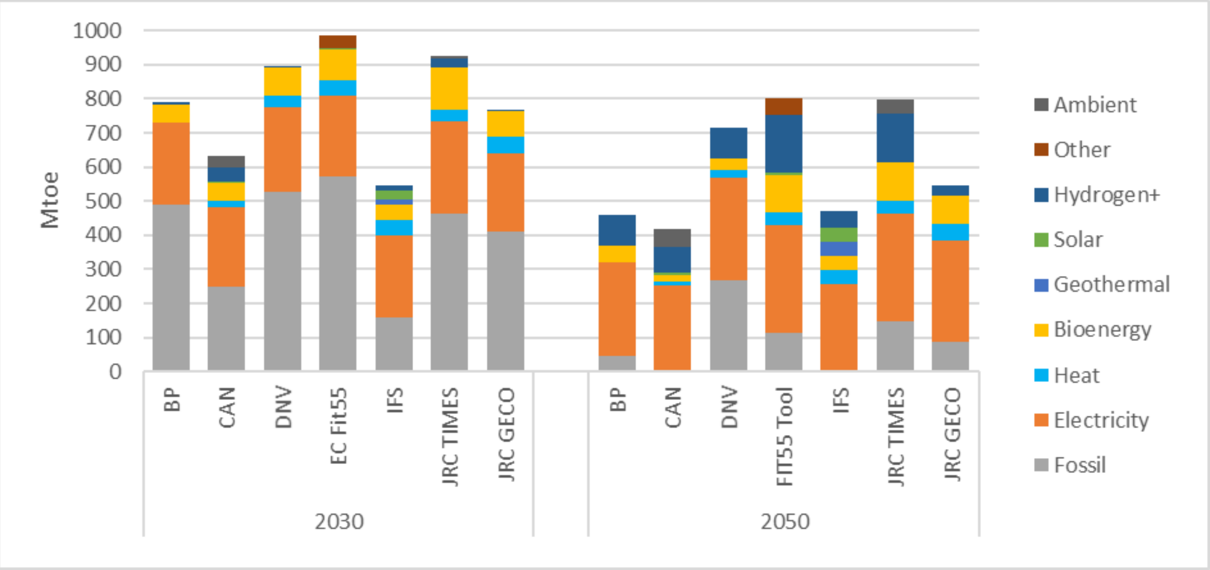
to 2019, driven by decarbonisation across all dimensions: changes are seen not only in technology, but also in behaviour and social dimensions.

Decarbonisation in the EU is happening slightly faster. If today (2020) around 65% of final demand is met by fossil fuels, by 2030 this share drops to around 50% on average (in *IFS* it drops below 30%). Electrification is increasing from around 20% today to above 30% on average (43% in *IFS*). By 2050, electricity becomes the dominant fuel, providing on average around 50% of total final demand (61% in *CAN*), while fossil fuels provide less than 15%, and are completely eliminated from the final demand of specific sectors. It is worth noting that all studies reviewed see an increase in hydrogen-based fuel consumption after 2030, providing around 15% of final demand on average, while the role of bioenergy decreases to 10% on average.

At sectoral level, decarbonisation takes place at different paces. The buildings sector decarbonises the fastest, thanks to electrification. By 2030, around 45% of total final demand in the buildings sector is provided by electricity (up from just above 30% in 2020) and fossil fuel usage is down to 33% (from above 45%). By 2050, only half of the scenarios analysed see a continued use of fossil fuels in the buildings sector (below 10% of final energy). Electricity is used to meet around 65% of total final demand in buildings (85% in *CAN*), supplemented by district heat (10% on average). By 2050, bioenergy in the EU buildings sector drops to around 6%.

Unlike the buildings sector, decarbonisation of the transport takes place at much slower pace. By 2030, more than 70% of energy would still be provided by fossil fuels (compared to over 90% today), supplemented with bioenergy and electricity. It is worth noting that some scenario studies see a drastic decrease in future energy demand in transport. According to *IFS*, final demand in the transport sector will drop by more than 50%, resulting in a drop to a quarter of fossil fuel demand (compared to current consumption), though it still contributes around 40%. By 2050, fossil fuels no longer play a major role in the transport sector, accounting for 12% or less, according to the majority of studies. Electricity, together with hydrogen-based fuels, becomes the main energy carrier. On average, electricity provides around 43% of final demand in transport (in *CAN* and *IFS*, over 60%). Hydrogen-based fuels provide around 32%, and according to *JRC TIMES*, almost 50%.

Figure 6. Final energy demand by fuel in the EU in 2030 and 2050[9]



Source: JRC analysis based on scenario studies

In line with the global picture, industry in the EU transitions faster than transport, but slower than buildings. In 2030, on average, scenario studies project that over 41% of energy is met by fossil fuels (compared to almost 65% today). Even in 2050, only two of the seven studies with a European scope predict a fully decarbonised industry: around 15% of total energy is provided by fossil fuels. All studies see an increase in electrification: on average 40% of the total final demand in industry is met by electricity (compared to less than 25% today). By 2050, on average, the electricity share rises to almost 50%. Scenario studies do not agree on the role of hydrogen and synthetic fuels in industry: the majority anticipates a share of around 20%,

[9] BP does not cover all end use energy

while others also see a high rate of bioenergy utilisation: in *JRC GECO* and *JRC TIMES*, bioenergy provides around 23% of final demand in industry. Only *IFS* gives commercial heat a significant role (at around 10%), and others place it at around 5%.

3.3 Greenhouse gas emissions

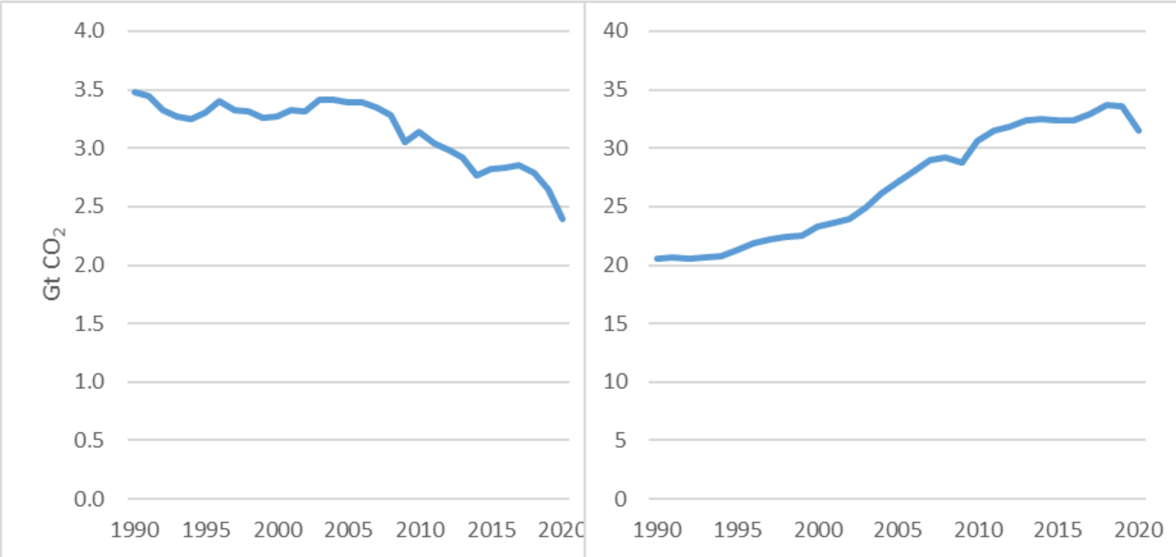
In 2020, **global** CO_2 emissions from fuel combustion shrank about 6% compared to the previous year, but in period between 1990 and 2019 there was an increase in global CO_2 emissions by almost 64% (IEA, 2021), **Figure 7**. Moreover, the latest data (IEA, 2022a) show that the 2020 emissions reduction was temporary, likely conditioned by the global COVID-19 pandemic, and in 2021, CO_2 emissions returned to similar levels as those observed in 2018 and 2019.

Despite increasing global CO_2 emissions, **the EU** has shown a clear emissions reduction trend since 2007 (**Figure 7**), resulting in 24% less CO_2 emitted in 2019 than in 1990[10], and a reducing the EU share of global CO_2 emissions, from 17% in 1990 to 8% in 2019. Driven by COIVD-19 pandemic, in 2020 the EU CO_2 emissions dropped by 7%. Based on the historical trend observed since 1990, it is likely that the EU share in global CO_2 emissions will continue to decrease in the future. In 2019, CO_2 emissions from fuel combustion in the EU was more than 30% lower than those of 1990 (IEA, 2021).

In the medium term (by 2030), the majority of energy scenarios analysed in this report see an average reduction in **global** CO_2 emissions from fuel combustion of more than 30% compared to today (**Figure 8**), but this will still be over 13% more than 1990 levels. *Shell* is the one clear outlier, showing emissions close to 2019 levels, and another – *IFS* – sees a global CO_2 reduction of over 61% compared to 2019 and 37% lower than 1990. IRENA, while reporting similar emissions levels to *IFS*, does not include the emissions from energy sector, and therefore should have total CO_2 emissions close to *IEA* results.

By 2050, the majority of the studies analysed in this report project **global** CO_2 emissions from fuel combustion at or close to zero. The only two that don't are *DNV* and *Shell*, which don't reach climate neutrality by mid-century. Other studies still have net positive CO_2 emissions from fuel combustion. These emissions are offset by other means, for example LULUCF in the case of JRC. GECO

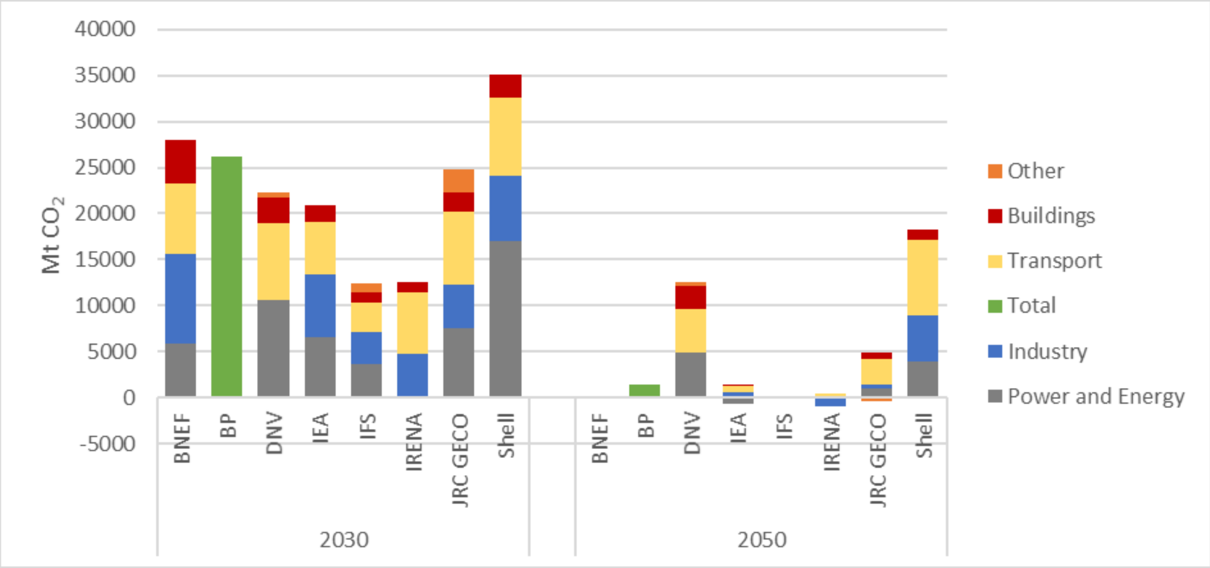
Figure 7. EU (left) and Global (right) CO_2 emissions from fuel combustion from 1990



Source: (IEA, 2021)

[10] In the period between 1990 and 2007 EU CO_2 emissions remained almost stable (-0.2% CAGR). The EU noticeable decrease in CO_2 emission started in 2007, decreasing annually (CAGR) by 2%, despite slight growth in period 2014-2018 (0.21% CAGR).

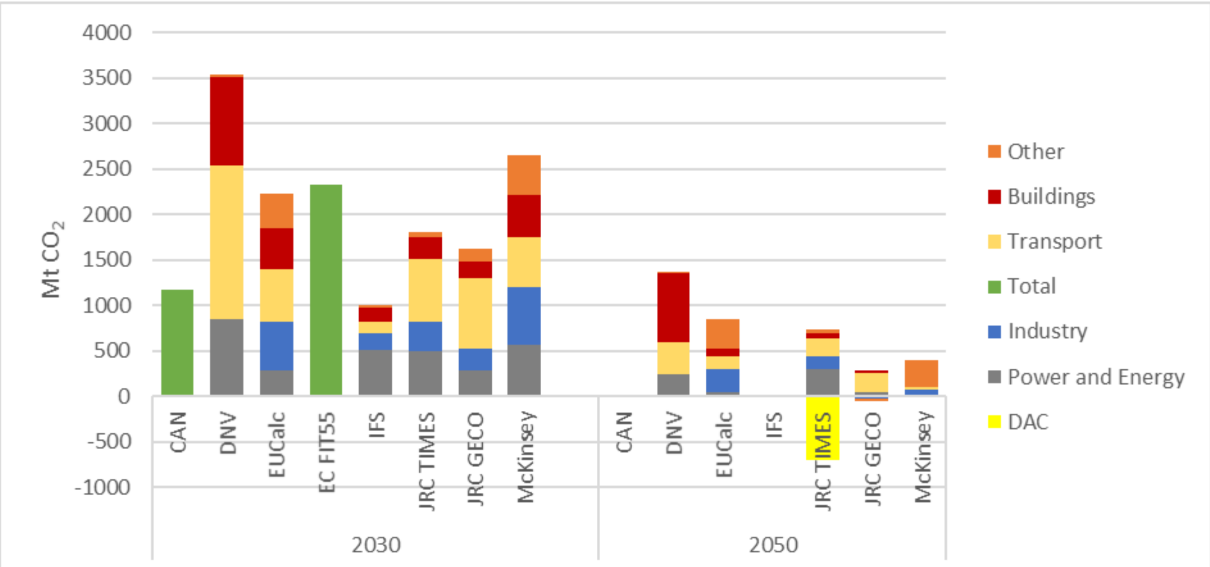
Figure 8. Global CO_2 emissions from fuel combustion in 2030 and 2050



Source: JRC analysis based on scenario studies

There is significant variations amongst scenarios on projected direct CO_2 emissions in **Europe** (**Figure 9**). In 2030 there is a threefold difference between the highest and lowest emitting scenarios. By 2030, some of the studies do not see a significant reduction in CO_2 emissions, while others see it cut in half. At the low end, *CAN* and *IFS* rely heavily on behavioural changes (reducing final energy demand) alongside a speedy transition to carbon-free fuels. *CAN* does this mainly via green electricity, while *IFS* posits the use of a wider range of technologies in end use sectors. By 2050, all scenarios except DNV reach carbon neutrality. The remaining CO_2 emissions from direct fuel combustion are offset by changes in land use (LULUCF) and direct air capture (DAC).

Figure 9. CO_2 emissions from fuel combustion in the EU in 2030 and 2050



Source: JRC analysis based on scenario studies

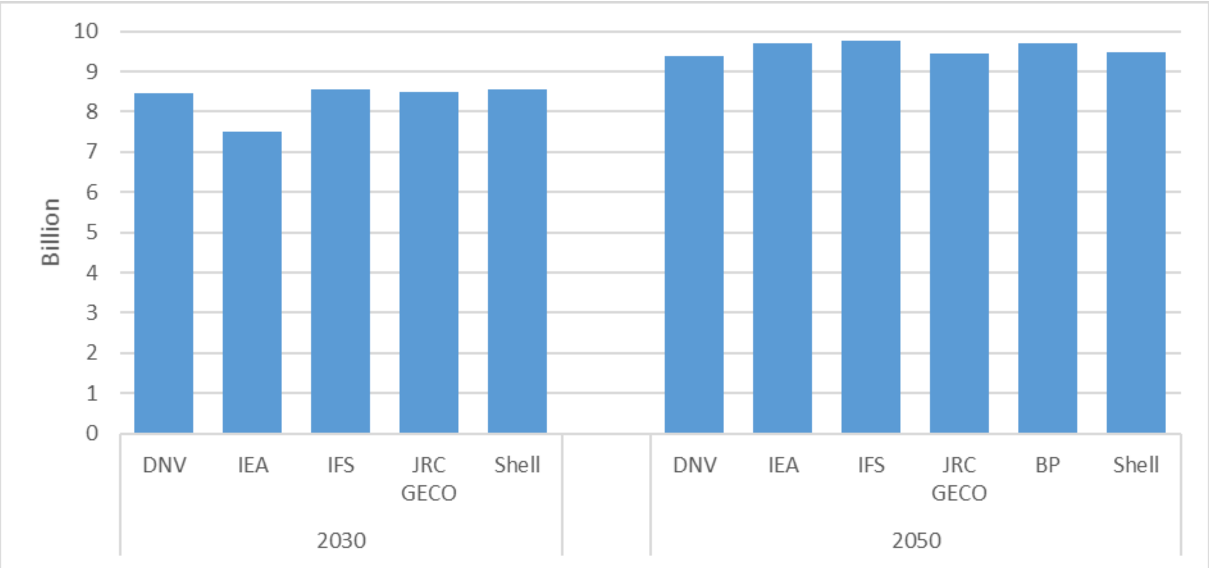
3.4 Macro-economics

At the global level

The main socio-economic indicators reported by energy scenario publications are population size and GDP (or GDP growth). In the energy scenario studies reviewed, the global population grows from around 7.7 billion in 2020 to 8.3 billion in 2030 (on average between scenarios with a standard deviation of only 0.45) and to 9.6 billion in 2050 (on average, with an even lower standard deviation of only 0.16, **Figure 10**). Essentially, in the long run, all scenarios posit a similar population size, so the differences in energy use (discussed in sections 3.1 and 3.2) are mainly due to differing assumptions on technology and socio-economic development, and lifestyle changes driven by political constraints. While global trends show a modest population growth (less than 1% CAGR between 2020 and 2050), the European population will remain stable. According to EC (European Commission, 2020), the EU population will decrease from 447 million in 2020 to 445 million in 2050. Other studies, with a wider definition of Europe, also see no major changes: the CAGR in the period 2020 -2050 is between -0.1% and 0.1%.

Comparing the GDP forecasts of scenario studies is less straightforward. Most of the global studies (but not all) measure GDP in USD, recalculated based on Purchasing Power Parity (PPP), while others do not adjust for PPP. Even when comparing historical or near-future results between different studies, numbers do not always align. For example, *JRC GECO* reports global GDP at 118 trillion USD2015/PPP in 2020, while *IEA* puts it at 129 trillion USD2015 PPP in 2018, *Shell* at 134 trillion USD2015 PPP in 2019, and *DNV* at USD 105 trillion. For Europe, the comparison is even more complicated: some studies provide data in USD, and others in EUR, meaning that efforts to convert data from different energy scenarios into one single, comparable measurement involves adjustments based on three parameters: inflation, changes of PPP in the selected region and currency conversion (in the case of Europe). This makes the exercise prone to high uncertainty and misleading results, and therefore in this report, percentage changes (CAGR) are used instead of absolute values (Tsiropoulos I. T. D., 2019), thus eliminating differences in currency conversion and inflation and reducing the effects of PPP. In the case of Europe, different geographical scopes are used in different scenario studies, ranging from EU27 to OECD Europe[11].

Figure 10. Global population in 2030 and 2050



Source: JRC analysis based on scenario studies

According to global scenarios assessed, in the period 2020-2030, the global economy is projected to grow by 3.6-4.0% annually (**Figure 11**). Differences across the studies between assumed economic growth projections are insignificant (four of the five use the figures 3.6% or 3.7%). In the period 2030-2050, energy

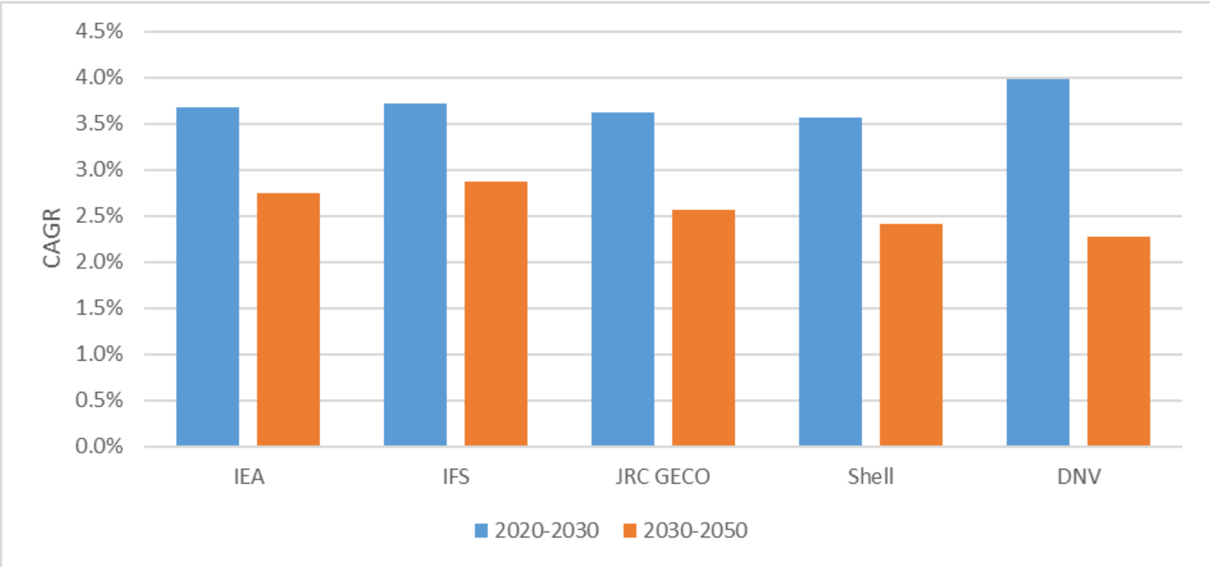
[11] OECD Europe does not include some EU27 countries (for example Bulgaria) but does include Turkey. While these differences in geographical definitions influence GDP growth rates (for example Turkey tends to grow faster compared to EU27), due to the size of the economies, the effect of differing geographical scopes is not significant.

scenario studies converge on projecting slower economic growth compared to 2020-2030, but diverge on the extent of it, with a range of 2.3% and 2.9%. It is worth noting that if both periods are combined, all studies are aligned on very similar global economy growth rates between 2.8% and 3.1% in the period 2020-2050.

At the EU level

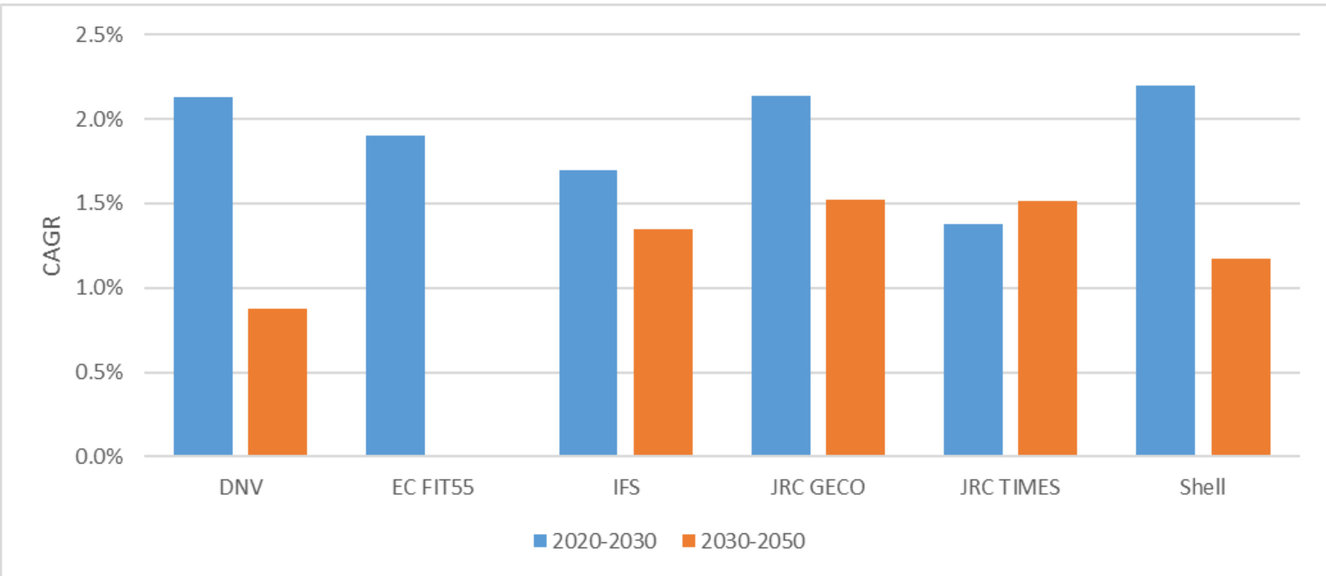
The GDP growth projections for the European Union are lower in all scenario studies, ranging from 1.4% to 2.2% in 2020-2030, and slowing down in 2030-2050 to 0.9-1.5% per year (**Figure 12**). There is also considerably less convergence (also influenced by differences in geographical scope) between scenario studies: GDP growth is almost 50% higher in *Shell* than in *JRC TIMES*. As with the global scenarios, GDP growth forecasts in 2020-2050 are more uniform, ranging only between 1.3% and 1.7%.

Figure 11. Global GDP growth



Source: JRC analysis based on scenario studies

Figure 12. GDP growth in Europe[12]



Source: JRC analysis based on *scenario* studies

[12] Regional definitions differ per scenario study: *EC FIT55* and *JRC TIMES* – EU27, *DNV* and *Shell* – Europe, *IFS* – OECD Europe

3.5 Investment in renewable generation capacities

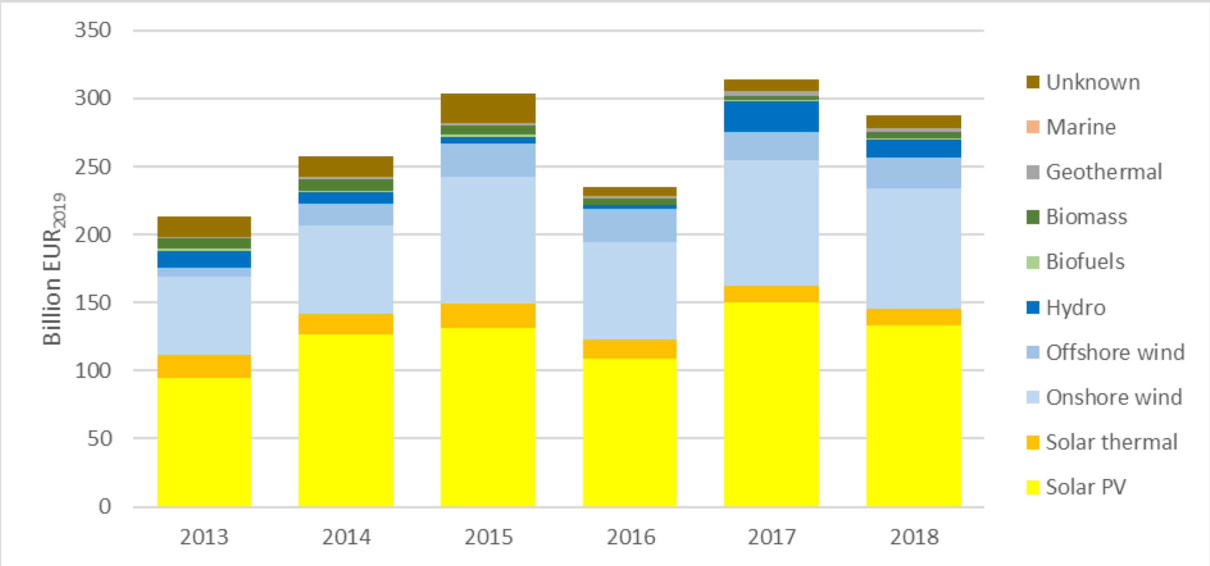
Global investment in renewable energy in the period 2013-2018 ranged between EUR 210 billion and EUR 310 billion (IRENA and CPI, 2020) per year, peaking in 2017. Of that, 72-78% was dedicated to installations of solar PV (43-49%) and onshore wind (26-31%). For example in 2018, 46% of total investment in renewables went to solar and another 31% to onshore wind (**Figure 14**) over the 2013-2018 time frame annual investments in solar PV ranged from EUR 95 billion to EUR 150 billion per year, and in onshore wind from EUR 58 billion to EUR 93 billion per year (**Figure 13**). While investment in these two technologies is, in general, following an upward trend, investment in renewable energy tends to follow global economic cycles (or regional for China). A drastic 25% drop in investment was observed in 2016, for example, and a 10% reduction in 2018.

Other renewable technologies have attracted much less investment. Solar thermal has seen an ever-decreasing amount of investment (with the exception of 2015), from EUR 17 billion in 2013 to EUR 12 billion in 2018. The same pattern can also be observed for biomass, which decreased from EUR 8 billion in 2013 to EUR 3 billion in 2017, with a slight recovery in 2018. There was an enormous drop in investment for biofuels which decreased from EUR 1.7 billion in 2013 to EUR 0.2 billion in 2016. This is significant contraction relative to the peak in investments observed in 2007 of over EUR 20 billion. By contrast, in 2013-2018, there was an upward trend in investment for geothermal (from EUR 0.8 to EUR 4 billion) and offshore wind (from EUR 6 to EUR 25 billion). The investment in ocean power was negligible during this period.

Based on the data available, it can be concluded that investment in renewable energy correlates closely with economic cycles; during the market slowdowns of 2015-2016 and 2018, investment in renewables dipped.

IRENA and CPI 2020 report (IRENA and CPI, 2020) do not provide regional data disaggregation at the EU level, but at the level provided, it is clear that the leaders in renewable energy investment are western Europe (with a downward trend of global investment from 22% to 18%), east Asia and Pacific (investments ranging from lows of 27% in 2013 and 2018 to 36% in 2015) and OECD Americas, with an upward trend (from 16% of global investment in 2013 to 25% in 2018).

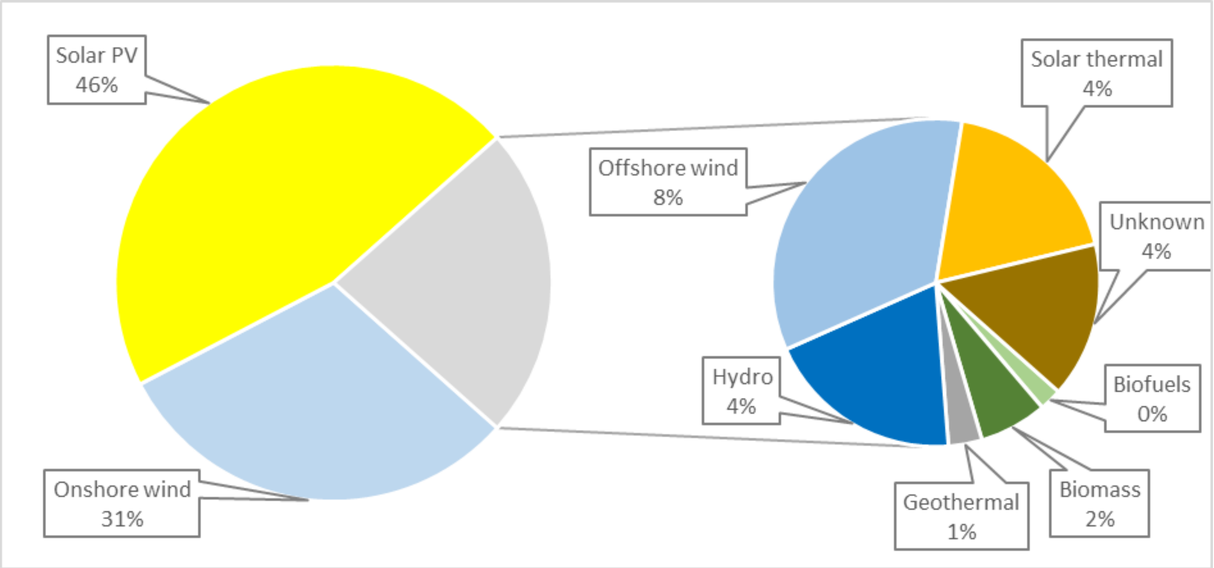
Figure 13. Global investment in renewable energy



Source: (IRENA and CPI, 2020)

It is worth noting that of the EUR 290 billion spent on deploying renewable energy in 2018, only EUR 16 billion came from public funds (IRENA, 2022b), with the highest intensity of public sector investments observed in hydro power (where almost EUR 6 billion was public funding out of a total of EUR 13 billion). Of the EUR 16 billion spent in public funding, EUR 4 billion were invested in the EU. In the last decade (2011-2022), the majority of public support came in the form of loans: 80% from standard loans and 12% concessional loans.

Figure 14. Global distribution of investment in renewable energy in 2018



Source: (IRENA and CPI, 2020)

Other sources (IEA, 2021d), (BNEF, 2022) and (Frankfurt School-UNEP Centre/BNEF, 2020), provide more recent data points and insights into European developments, but do not have a high technology aggregation level, essentially providing data only on two main technologies: solar and wind. (IEA, 2021d) shows the continuation of investment patterns observed in (IRENA and CPI, 2020). The majority of renewable power investment goes to solar PV and onshore wind, together totalling around EUR 250 billion in 2020 and distributed along the same lines as in 2018: about 15-20% more for solar PV than for onshore wind. It is worth noting that, despite an increase in investment in these technologies of only around 25% compared to 2015, new capacity produced more than double the electricity, signalling both an increase in efficiency (capacity factor) and a decrease in investment costs. According to (IEA, 2021d), in order to reach the global net zero goal by 2050, annual investment in renewable power generation will have to increase more than threefold (the majority going to onshore and offshore wind and solar PV). According to (BNEF, 2022), the latest data reveal a moderate preference for wind power investment (from EUR 143 billion in 2019 down to EUR 131 billion in 2021) and the rapid growth of solar PV: from EUR 120 billion in 2019 up to EUR 183 billion in 2021. In Europe[13], investments in both solar and wind grew in this period (from EUR 30 billion to EUR 35 billion for solar, and from EUR 32 billion to EUR 42 billion for wind). It is worth noting that Europe's share in global wind and solar investment is constantly decreasing. In 2005, 83% of global solar investment and 62% of global wind investment took place in Europe, but in 2021, despite an increase in absolute numbers, Europe's share dropped to 19% and 30% respectively.

Based on the scenario studies analysed in this report (results for low-carbon technologies are provided in Chapter 4), investment in renewable energy capacities will have to increase considerably in the coming decades. The studies adopt various views on how the generation mix will develop, but everyone agrees that solar (PV) and wind (both onshore and offshore) will be the two main power generation technologies in 2050. Nevertheless, there are significant differences in terms of foresight. For example, the majority of the studies increase the annual rate of wind power installations from threefold to fivefold, but *BNEF* sees the installation rate increase over tenfold, driven by the rapid development of the hydrogen economy. The same is true for other technologies. For example, most of the studies (that provide data) on geothermal power see around 10 MW of new installations per year, but *IFS* puts the figure three times higher.

[13] The BNEF definition of Europe is wider and on top of EU28 it also includes neighbouring countries.

4 Low carbon energy technology outlooks

4.1 Bioenergy

In the energy scenarios, bioenergy is one of the most difficult technologies to assess. It can be used in both power and heat generation, as well as in the majority of end use sectors, but the main issue is that the definition and scope of bioenergy used in energy scenario studies varies greatly. In some scenarios studies, all bioenergy can be aggregated in just one variable (including solid biomass, biogas, bio methane, all bio liquids, and renewable fraction of waste and, in some cases, total waste). Global scenarios can also differentiate between traditional and commercial biomass. While the underlying models for energy scenarios usually have a lower level of aggregation of bioenergy, reporting is often done by aggregating liquid and gaseous bioenergy, or liquid, solid and waste. Other combinations are also possible.

In this chapter, we split bioenergy into three distinct parts where data allows:

- Biofuels – liquid bioenergy. In the transport sector (if not specified otherwise), all bioenergy is considered to be liquid.
- Biomass – solid bioenergy. Commercial and traditional biomass are merged, and renewable waste is included.
- Biogas – gaseous bioenergy, including biomethane.

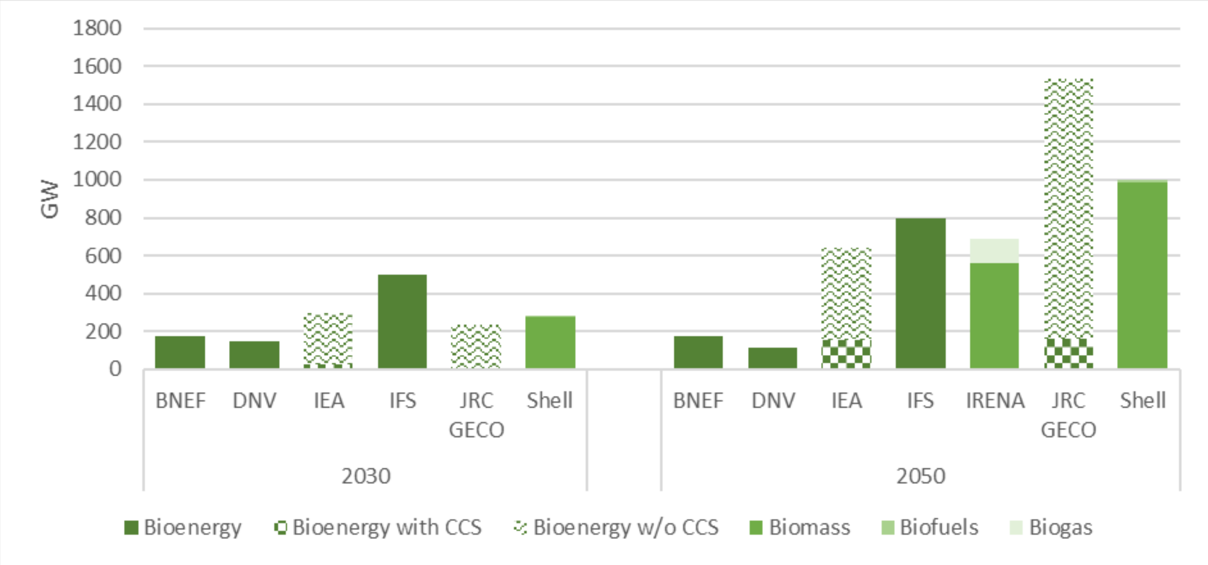
When a clear split is impossible, we aggregate all information under the term bioenergy, assuming that solid (including waste) and/or gaseous bioenergy can be used in power/heating, buildings and industry, and liquid bioenergy in transport.

In 2020, **globally**, over 127 GW of bioenergy-based power generation capacity was installed. The majority of it (104 GW) was solid biofuels-based (mainly biomass). Only 20 GW was biogas. In 2019, bioenergy-based generation accounted for almost 560 TWh of electricity. In the last five years, global bioenergy-based installed capacity has grown by around 7% annually, mainly driven by the growth of solid biomass generation capacities. Biogas has grown at a slower rate of only 5% annually.

In 2020, **in the EU**, there was over 34 GW of bioenergy-based power generation capacity, 21 GW of which used solid bioenergy (biomass, renewable waste, etc.). Around a third of total installed capacity in the EU was biogas-based (12 GW). In 2019, 160 TWh of electricity was generated using bioenergy (55 TWh of which was produced using biogas). In contrast with global trends, the growth in the EU of solid bioenergy-based capacity has been considerably slower in the last five years, at only 3% annually, compared to biogas-based generation with an annual growth rate of almost 9%. **Global** energy scenarios are unclear on the role of bioenergy in future energy systems. In the next decade, all energy scenarios analysed see a global growth of bioenergy-based power generation capacity (**Figure 15**), but disagree on the growth rate and importance in the generation mix. On average, the compound annual growth rate (CAGR) is 7-8%, but some scenarios see growth rates as low as 2-3% (driven mainly by market-based assumptions), and others as high as 15% (reaching almost 500 GW of installed capacity globally), driven by normative targets to fully abandon fossil fuels and nuclear power, without deploying CCS, by 2050. In all scenarios that provide information on bioenergy with carbon capture and storage (BECCS), there are no major developments until 2030: very little bioenergy capacity is installed with CCS. In power generation, solid biomass remains the dominant biofuel (some scenarios report small amounts of biogas). Following installed capacity trends, the majority of scenarios see an increase of bioenergy-based power generation, led by *IFS* (15% CAGR), reaching 2407 TWh in 2030. Other scenarios also see a growth of generation in line with the capacity increase, with only one exception. Despite a slight growth in installed capacity, *BNEF* anticipates a slight decrease in power generation (-2% CAGR). A decrease in load factor is driven by the increased generation from intermittent energy sources (solar and wind) (**Figure 16**).

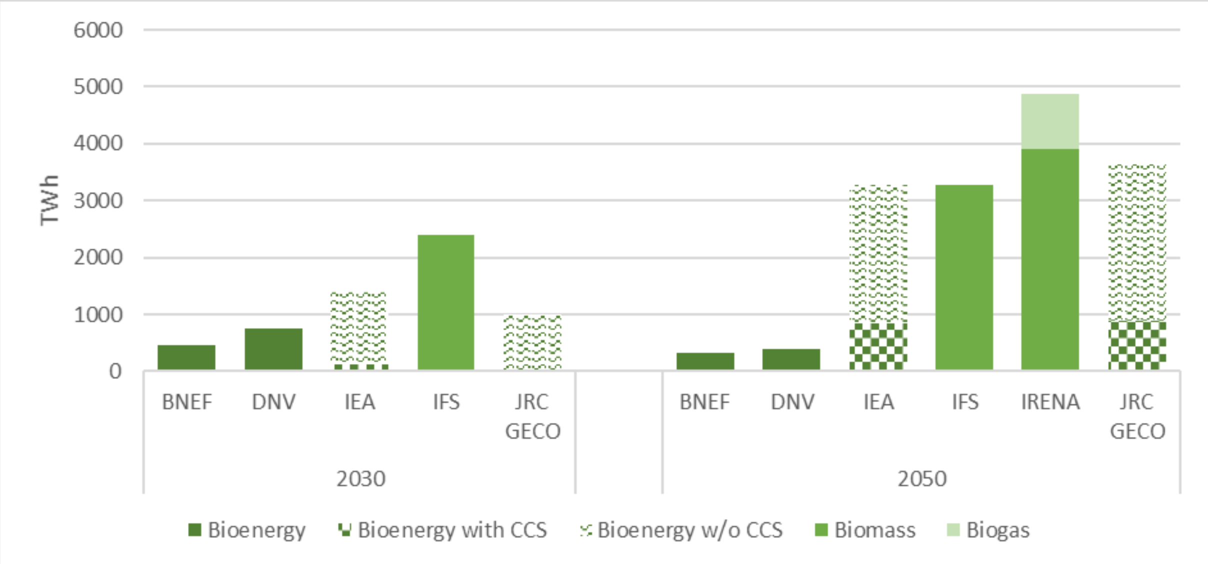
While globally, all scenarios see a growth in installed capacity, this is not the case for the **EU**, where some scenarios are stagnant (*DNV*) or slightly decreasing (*McKinsey*). Some of the scenarios analysed provide generation data without including installed capacity. Three of these latter scenarios see a contraction in bioenergy power generation (*CAN*, *EUCalc* and *McKinsey*).

Figure 15. Global installed bioenergy power capacity



Source: JRC analysis based on scenario studies

Figure 16. Global electricity generation from bioenergy

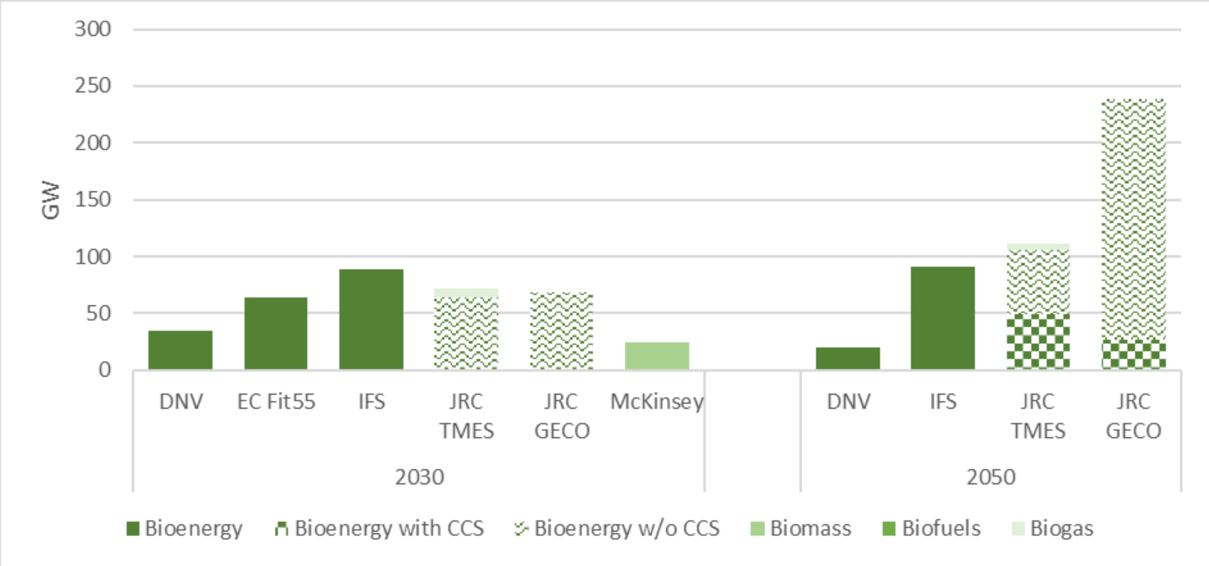


Source: JRC analysis based on scenario studies

Most **EU** scenarios also see a moderate growth in installed bioenergy power capacity (though noticeably lower than in global scenarios), reaching around 5% CAGR, on average, with *IFS* out front, growing 10% annually and reaching 90 GW of installed power capacity by 2030 (**Figure 17**). Taking into account additional scenarios that provide only electricity generation data, there are three scenarios that anticipate a contraction in bioenergy power generation (*CAN*, *EUCalc* and *McKinsey*).

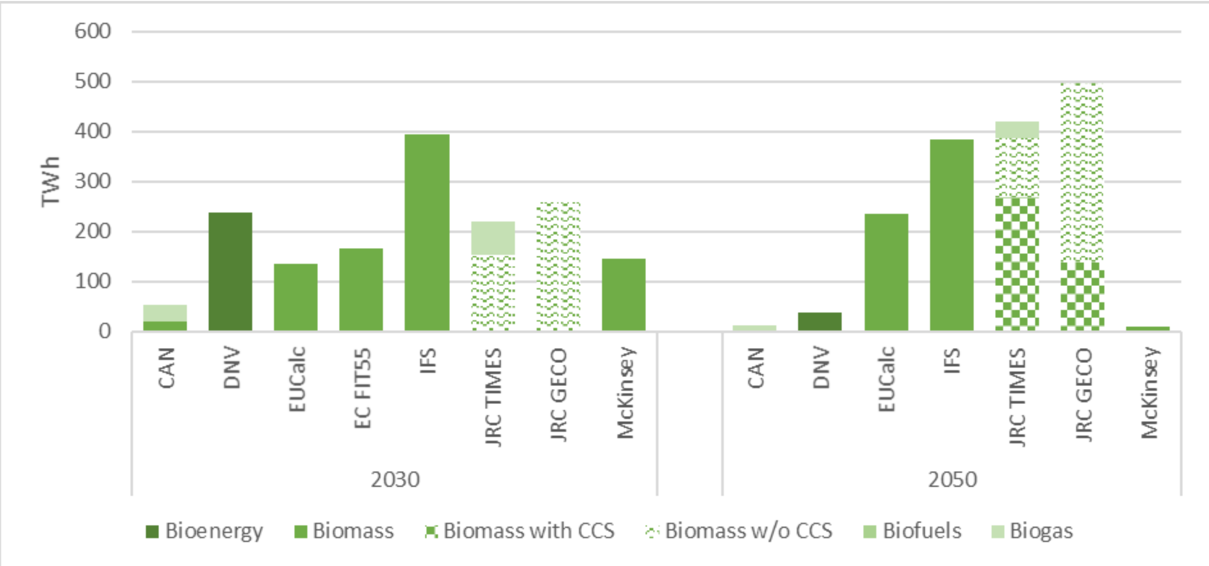
The CAGR of bioenergy-based generation over all scenarios is only 1%. In terms of capacity installation trends, *IFS* remains a clear leader, with 9% CAGR and 135 TWh of electricity generated from biomass (**Figure 18**). In 2030, some scenarios see an increasingly important role for biogas (in *CAN* amounting to more than 60% of the electricity generated from bioenergy), but nevertheless, the majority of scenarios in the EU give preference to solid biomass without CCS. By 2030, an average of about 6% of electricity generated in the EU comes from bioenergy, ranging from 1% in *CAN* (with a downward trend in bioenergy utilisation for power production) to 9% in *IFS* (relying only on renewables in 2050).

Figure 17. Installed bioenergy power capacity in the EU



Source: JRC analysis based on scenario studies

Figure 18. Electricity generation from bioenergy in the EU



Source: JRC analysis based on scenario studies

By 2050, installed capacity in bioenergy shows a lot of variability. Some **global** studies see a stagnation or downward trend (*BNEF* and *DNV*), whereas most depict a moderate growth (6-7% CAGR, slower than 2020-2030). There is only one clear outlier opposing this trend – *JRC GECO* sees almost 10% CAGR and 1530 GW of installed capacity in 2050. Biomass dominates bioenergy-based power generation, and the deployment of CCS play a noticeable role in some studies in 2050: in the case of IEA, almost a quarter of all bio power installations come with CCS (10% in GECO). After the fast deployment of new capacity in 2020-2030, *IFS* projects a slower growth rate, dropping from 15% to 2.4% per year. Global generation follows the installed capacity pathway, with highest growth in the scenarios deploying bioenergy with CCS (*IEA* and *JRC GECO*). *BNEF* and *DNV*, both market-driven scenarios, see a reduction in bioenergy-based power generation, with its share in total electricity production dropping below 1% in 2050. Other more optimistic scenarios estimate a bioenergy share in power generation ranging from 4.6% to 6.2%.

The **global** market for installed bioenergy capacity will be limited and could range from 2 GW up to 37 GW of new installations per year in addition to about 6 GW of refurbishment of existing power plants. In the most ambitious studies, it could reach up to 37 GW of installed capacity per year, but this is still a fraction of the new installations seen in wind and solar. After 2030, the global market size of bioenergy power installations is more uncertain. Some scenario studies see no new capacity additions, while others see limited market growth, reaching up to 65 GW per year of new installations (including 5 GW of BECCS according to *JRC GECO*).

In the **EU** in the period 2020-2030, bioenergy power markets will range from 0 GW to 5.5 GW per year (refurbishment of existing capacities will add an additional 1.5 GW per year). After that, the total EU bioenergy power market could range from 1 GW (where there are no new installations of bioenergy-based power plants and only limited end-of-life refurbishments of existing capacities) to 8.5 GW (where bioenergy is projected to grow in the EU). Some new bioenergy generation capacity in the EU will be bundled with CCS (2.5 GW per year according to *JRC TIMES* and 1.4 GW in *JRC GECO*).

Most of the bioenergy is used in final sectors, both globally and in the EU. Although power generation is an important area for bioenergy, it consumes only a fraction of the bioenergy used for energy. Globally, the buildings sector consumes around four times more bioenergy than power generation, and bioenergy consumption in industry is comparable to power generation. Although transport consumes considerably less bioenergy, during the last decade it has shown a steady increase in demand (mainly driven by decarbonisation policies).

Most of the studies provide insights on the bioenergy used in final demand sectors, but not all of them provide disaggregated information on the type of bioenergy used. In the graphs (**Figure 19**, **Figure 20**) we use the bioenergy definitions and aggregation levels of the original study, but in order to compare results from different scenarios, we assume in the text that the bioenergy used in the transport sector is in the form of biofuels (liquid bioenergy).

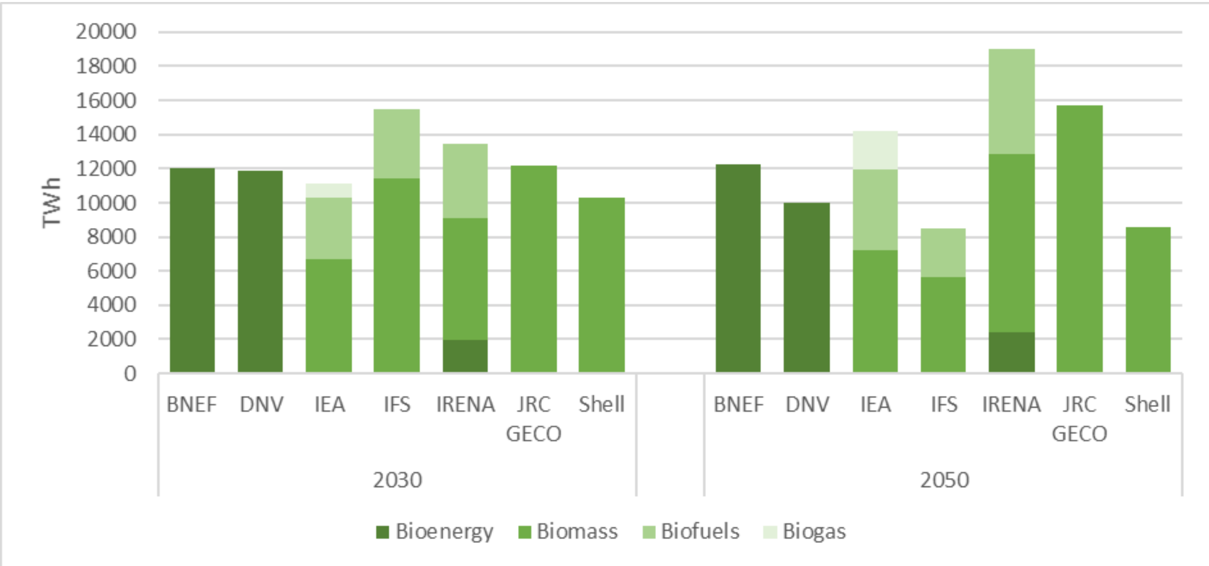
Until 2030, **globally**, bioenergy consumption as a proportion of final demand stays comparable to current levels, with a slight upward trend. Only the *IEA* scenario shows a slight decrease (of around 5%) in bioenergy consumption between 2020 and 2030. All other studies show a slight an increase of up to 7% over 10 years, except *IFS* – where the highest increase of around 21% can be observed (**Figure 19**). In addition to high bioenergy demand in final sectors, *IFS* also foresees the most ambitious use of bioenergy in power generation. Although the differences in total final bioenergy consumption are small, scenario studies disagree on the sectoral consumption and types of bioenergy used. For example, *IEA* sees a 67% drop in bioenergy consumption in the buildings sector, triggered by a complete abandonment of traditional biomass by 2030. This decrease is partly compensated in the buildings sector by a doubling of the use of commercial biomass. Although other studies also depict downward trends, they do not foresee a drastic reduction in biomass use. Solid biomass remains the main bioenergy used in the buildings sector, while some scenarios also show a growth in biogas consumption. All studies agree on an increase in bioenergy demand in industry, but greatly disagree on the growth rate, ranging from 16% to 78%. The highest increase is observed in the *IEA* study, where both biomass and biogas consumption in industry grow. The increase in bioenergy consumption is even higher in the transport sector, ranging from 76% in *BNEF* (where electrification and hydrogen/e-fuels play an important role) to a potential quadrupling in IEA, which relies on biofuels to decarbonise the transport sector. In 2030 the global biofuel consumption could range from 1 200 TWh to 3 500 TWh.

While scenario studies are in general agreement on global trends for bioenergy use in final demand, they completely disagree on bioenergy's role in the **EU** until 2030. At the lower end, *CAN* and *IFS* see a decrease in bioenergy consumption of about 30%, while *DNV* and *JRC GECO* see bioenergy consumption at similar levels to today. *JRC TIMES* expects an increase of 30% and in *EUCalc*, consumption more than doubles. This is not clearly evident in **Figure 20** because *DNV* and *IFS* cover considerably larger regions, which can explain part of the divergences. The majority of studies see an average reduction of biomass consumption in the buildings sector of about 20%, while *IFS* sees an even higher reduction of over 40%. Most see a slight increase in bioenergy consumption in industry: around 15% on average, and over 50% in *EUCalc*. However, studies do not agree on the transport sector. At the lower end, *CAN* sees a reduction of around 80% in biofuel use by 2030, driven by high electrification, the deployment of synthetic fuels and the abandonment of first generation biofuels. IFS sees a 10% reduction. Other studies foresee a growth of around 50% on average, and *EUCalc* by more than 800% (mainly driven by biodiesel consumption).

By 2050, the **global** trends diverge even more. Four scenario studies see a slight growth in bioenergy use in final demand sectors (1-2% per year). In BNF, bioenergy consumption remains constant until 2030, and another three scenarios see a reduction (of 1-3% per year). Most scenarios see a contraction of direct biomass use (IRENA appears to be the only exception) and an increase in the use of biofuels/biogas (for scenarios that do provide disaggregated data). All scenarios agree that by 2050, bioenergy will provide around 6-18% of final demand. In the period 2030-2050, bioenergy (mainly biomass) consumption in the buildings sector decreases by 25% on average (*IFS* foresees a reduction of 40%; IRENA an increase of 15%). In the industrial sector, all scenarios see an increase in bioenergy consumption by an average of around 40%, except *IFS*, with a 30% reduction. In transport, we can observe a similar situation: all scenarios see an increase in the use of biofuels of about 50% on average over the 20-year period, except *IFS*, with a reduction of almost 40%. It is worth noting that in all end use sectors, *IFS* is a clear outlier, seeing a reduction in bioenergy consumption where all other studies anticipate growth. The *IFS* trend is driven by two main drivers: an increase of efficiency in end use (decreasing final demand) and more wide-scale electrification (especially in the transport sector). The *IFS* scenario also sees more direct use of solar and geothermal heat in the industry and buildings sectors, leaving more bioenergy for power generation.

In **Europe**, all studies see a decrease in bioenergy utilisation at the level of final demand (with only one exception – *JRC GECO* sees a small 0.4% annual growth), but with different reduction rates, ranging from 5.6% in *CAN* to just 0.3% in *BP*. Most of the studies see the consumption of bioenergy in buildings contracting by around 50% on average. There are outliers at both ends of the spectrum: at the higher end, *CAN* sees a reduction of around 95%, and at the lower end, *EUCalc* sees a reduction of only 25%. On other hand, the majority of scenarios see an increase in bioenergy utilisation in industry (15% on average). *JRC GECO* has the most ambitious increase in bioenergy consumption, doubling it in twenty years. On the other hand, *DNV* sees a 75% reduction between 2030 and 2050 (after a 33% growth by 2030). In the transport sector, the majority of the studies see a decrease in bioenergy consumption due to the rapid transition to electric mobility and the rollout of hydrogen-based synthetic fuels. *CAN* sees only 9 TWh of biofuels used (a continued downward trend from 2030) while *McKinsey* sees over 1000 TWh of biofuels used in transport by 2050. It is worth noting that many scenarios studies see biofuel consumption in the EU peaking in 2030 and then following a downward trend.

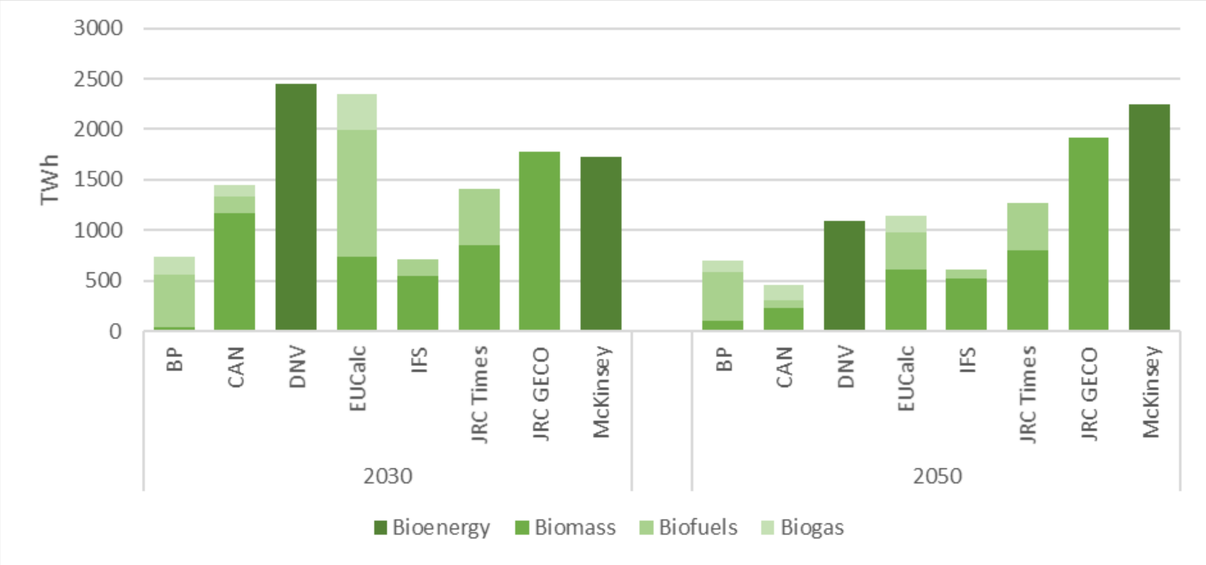
Figure 19. Global final bioenergy demand



Source: JRC analysis based on scenario studies

Following Russia's war against Ukraine and the urgent need to reduce energy dependence on fossil hydrocarbons coming from Russia, the European Commission published the REPowerEU Plan (European Commission, 2022) on 18 May 2022, detailing updated hydrogen and biomethane targets (European Commission, 2022). In order to reduce natural gas consumption in Member States, 35 billion cubic meters (bcm) of biomethane (equal to about 30 Mtoe) could be produced in the EU by 2030.

Figure 20. Final bioenergy demand[14] in the EU



Source: JRC analysis based on scenario studies

4.2 Solar energy

Solar energy is used for producing electricity in the power sector (centralised) or in end use sectors (distributed). For power generation there are two main sets of technologies: photovoltaic (PV), used both in the power generation sector and in end use (mainly in buildings and industry) and concentrated solar power plants (CSP), used only in the power sector. Globally, there was an installed capacity of 578 GW of PV and 6 GW of CSP in 2019. In the EU, there was 116 GW of PV and 2 GW of CSP (IRENA, 2022c).

The solar power generation market is currently dominated by PV: **globally**, 98% of solar power is generated by PV, and in the EU, 96%. In the past, power generation from both PV and CSP demonstrated remarkable growth: in the last eight years, the global compound annual growth rate (CAGR) for PV was 43% and for CSP 28% (in the EU, the CAGR was 22% for PV and 26% for CSP). In 2010, the EU was the global leader, generating 70% of global PV electricity, but it is currently rapidly losing its position. The EU share of global PV generation in 2018 dropped down to 20%.

Trends in installed capacity are similar: the **EU** share dropped from 47% in 2010 down to 21% in 2018 (PV) and from 51% down to 41% (CSP). In 2020, the biggest market for solar PV was China, growing its share from 20% in 2015 up to 36% in 2020. The EU remains in second place, halving its share of 38% in 2015 to 19% in 2020.

It is worth noting that in some scenarios, the results do not include behind-the-meter solar PV installation and power generation and in some others, it is not clear if behind-the-meter solar PV is included or not. When data is available, both central (connected to the transmission network) and distributed PV are added together. In future, behind-the-meter solar PV could make up a substantial share of solar PV installed capacity and generation: for example, in 2030, the Shell 1.5 scenario concludes that 50% of global solar PV capacity is installed in end use sectors (in 2050 this share drops slightly below 40%). Another possible issue comparing results from different scenarios is related to hydrogen generation. Depending on the modelling approach, sometimes solar/wind capacities/generation dedicated to hydrogen production are bundled together with electrolysers and do not appear in the power sector, but rather are reported in the energy transformation sector. If information is available, PV installation/generation for power and hydrogen production are added together. For example, in the case of *BNEF*, in 2030, 25% of utility-scale PV installations[15] are already dedicated exclusively to hydrogen production. By 2050, dedicated PV installation for hydrogen production accounts for 42% of solar PV installations.

By 2030, the majority of scenarios see an average **global** solar capacity growth of up to around 5 000 GW (**Figure 21**), constituting a sevenfold increase in 10 years. Scenarios that split results into PV and CSP

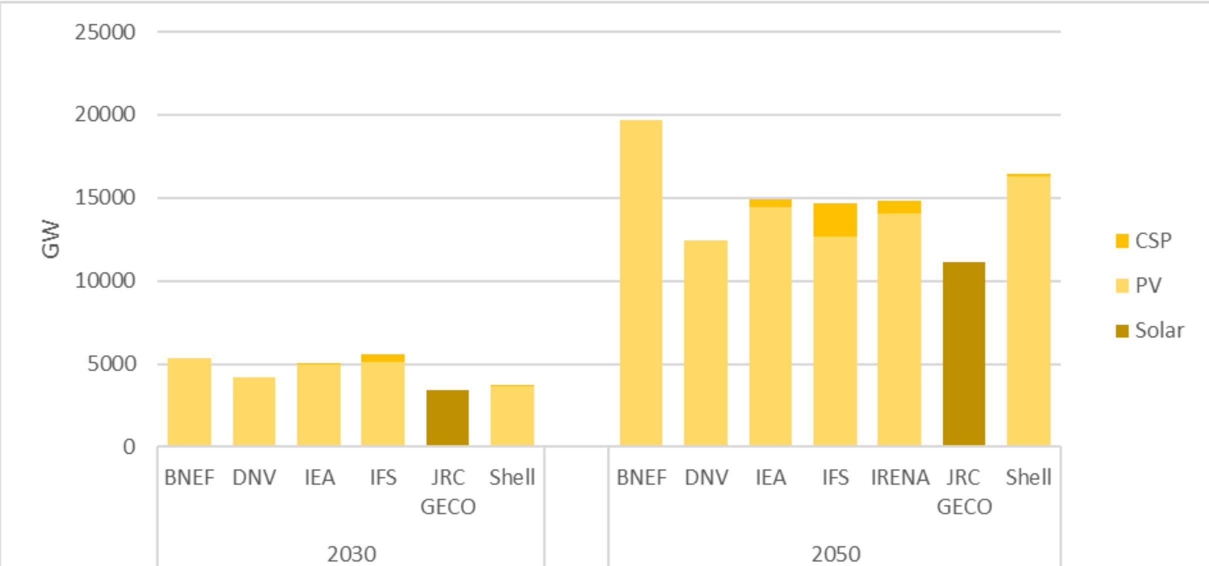
[14] Not adjusted for the differences in geographical scope.
[15] Solar PV power plants connected (usually) to transmission grid (medium voltage) and dispatched centrally.

confirm a continuation of current trends – the majority of new installations only develop PV, with CSP having a negligible share even in 2050. There are two studies (*JRC GECO* and *Shell*) that see slower growth rates for solar energy. Both of them also have smaller power sectors in general, and tend to postpone the transition toward net-zero energy sector to later stages (after 2030). In the case of *Shell*, natural gas power plants still have the highest installed capacity. In GECO, the wind and solar power installed capacity already exceeds natural gas in 2030. The generation pattern in 2030 is defined by the installed capacity. The majority of scenarios analysed project around 6 000-7 000 TWh generated (

Figure 22), almost a tenfold increase compared to 2019. There are some noticeable outliers – *IFS*, on the high side, pushes out all fossil fuels and nuclear by 2050, and therefore has to rely on renewables in the early stages, including the rapid growth of CSP (to offset the intermittence of PV and wind). On the lower side, *BP* and *JRC GECO* see a slower transition in the early stages and an increasing role for CCS in the future.

In the **EU**, all scenarios agree that by 2030, the growth of installed solar power capacity is slower than the global trend. Capacity slightly less than triples on average, compared with a tenfold increase globally in the same period. There is a continuously decreasing trend in the EU share of global installed capacity. On average, by 2030, the total Installed capacity in the EU of solar energy could reach around 350 GW, and it shows a higher variability than global results. On the lower side, *JRC TIMES*, at only 250 GW) depicts a slower transition and relies on CCS in the future, whereas on the higher side, *IFS* shows a very rapid transition (540 GW of solar installed), completely phrasing out fossil fuels and nuclear by 2050. REPowerEU mention even higher solar installed capacity: 592 GW of PV in 2030. In terms of generation, there is a clear outlier (**Figure 23**) – *CAN* (which does not provide capacity data), driven by ambitious assumptions on decarbonisation, more than doubles the solar-based generation of all other studies and shows a tenfold increase compared to 2019 (similar to global trends). All other studies see only a two- to fivefold increase. According to the scenarios that provide data on installed capacity, CSP will not play a noticeable role in Europe.

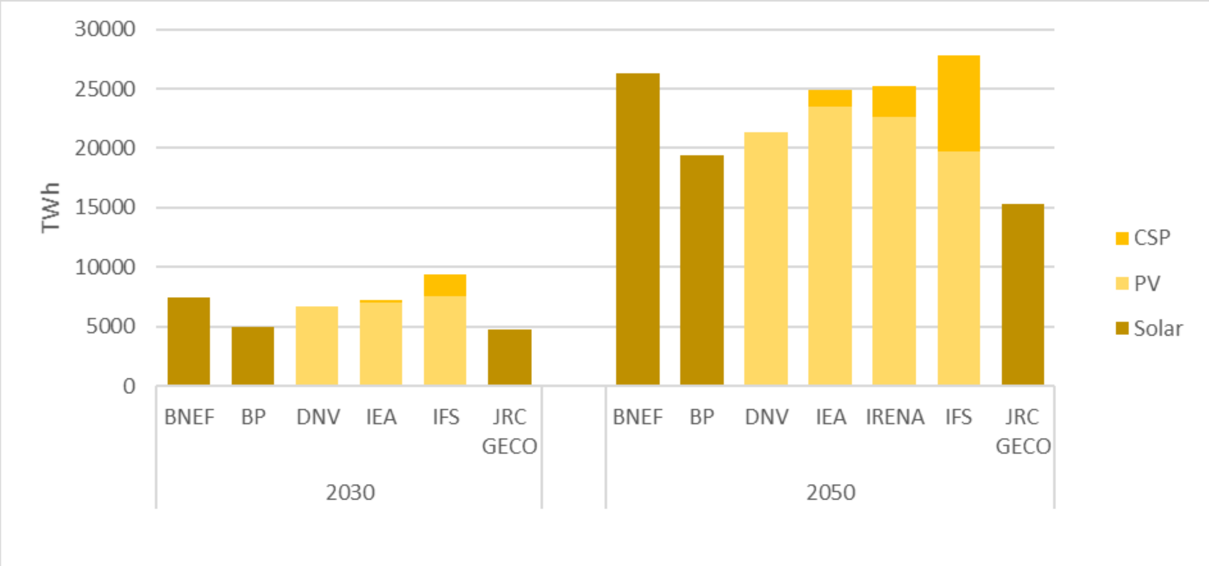
Figure 21. Global installed solar power capacity



Source: JRC analysis based on scenario studies

By 2050, solar, together with wind, will become the dominant source of energy in the power sector, providing 22-40% of electricity in all scenario studies. Most **global** scenarios see 20 000-25 000 TWh of electricity generated by solar (**Figure 22**). This is more than a thirtyfold increase compared with current generation. It is worth noting that globally, up to half of this generation may be distributed. Solar PV will dominate the market, while CSP still plays only a niche role, amounting to less than 10% of global solar generation in all the scenarios that provide data, except for one – *IFS* – where it totals almost 30%. Global installed capacity sees a similar trend: solar can amount from 35% to 65% of global installed capacity. The majority of scenarios see solar installed capacity ranging between 10 000 GW and 15 000 GW, with *BNEF* as a clear outlier reaching almost 20 000 GW – its market-driven scenarios show a quadrupling of installed solar capacity globally. *IFS* sees the most potential for CSP with around 15% of total global solar capacity. All other studies put it at below 5% of total solar capacity.

Figure 22. Global electricity generation from solar



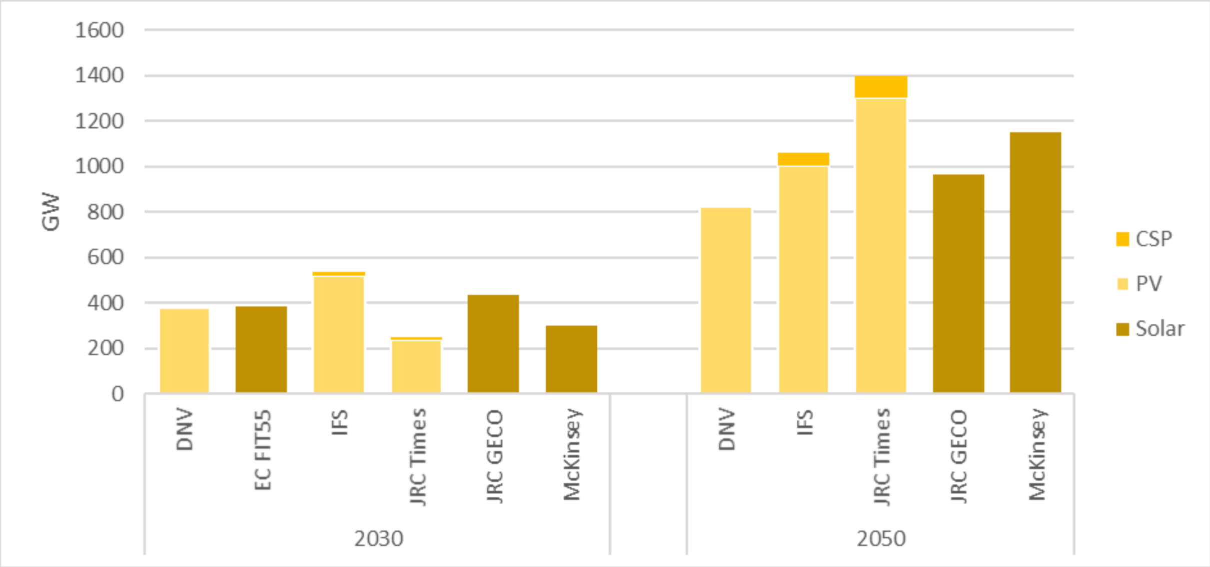
Source: JRC analysis based on scenario studies

In 2050, scenario studies do not agree on the solar role in **Europe** (**Figure 24**). The highest values are four times the lowest. At the lower end, *EUCalc* (which mainly relies on wind for power generation) projects no more than a continuation of current trends for PV. CSP grows faster, but with low numbers to start with, its share of EU solar generation does not increase hugely. At the higher end, *CAN* and *McKinsey* see over 2 000 TWh generated by solar energy. In *CAN* this means a doubling of the figures for 2030, but for *McKinsey* this means they quadruple in 20 years. There is also no consensus on future solar capacity in the EU. The highest capacity (1 400 GW) and highest growth (560% in 20 years) are observed in *JRC TIMES*. Solar contributes 15% of total installed capacity, mainly driven by hydrogen and synthetic fuels demand. Other studies see a share of 13-22% solar in the total generation portfolio. Solar generation varies between 18% and 34% (excluding *CAN*, with a 12% solar share). The CSP share reaches up to 15% (excluding *EUCalc*, with 32% of solar generation). In 2030-2050, the EU share of the global solar power market is still shrinking, dropping below 8% of total installed solar generation capacity.

It is worth noting that almost all studies see an increasing capacity factor (the electricity produced against the total that would have been produced at full capacity per year) for solar power plants in the future. The current global capacity factor is 13% (12% in the EU). Similar numbers can be observed in historical data from energy scenarios, but in the future, the capacity factor could increase to 16-18% in 2030 and 20% in 2050. This increase can be attributed to technological improvement, better locations and bundled storage. In the EU, these numbers are slightly lower: on average, around 15% in 2030 and 14% in 2050, with one outlier (*McKinsey*) showing a capacity factor of above 20% in 2050.

The **global** solar power market could grow in the next decade from the current 120-130 GW new installed capacity per year up to 300-500 GW (more in case of *BNEF*) per year until 2030. From 2030, global market increases could reach 400-700 GW per year. On top of new installations, there will also be around 250-350 GW per year of replacement solar power installations at the end of the economic lifetime, moving the total market growth up to 1 000 GW of installed capacity per year. The **EU** solar market will not show so much growth. In the next decade, the rate of new solar power installation will remain steady: from 20 GW per year today, to 20-40 GW per year until 2030 (median 24 GW/year). In case of REPowerEU it could reach 45GW per year. From 2030, the installation of new solar power plants will slightly increase to above 35 GW per year. Another 20 GW per year could come from replacement solar power installations at end of life.

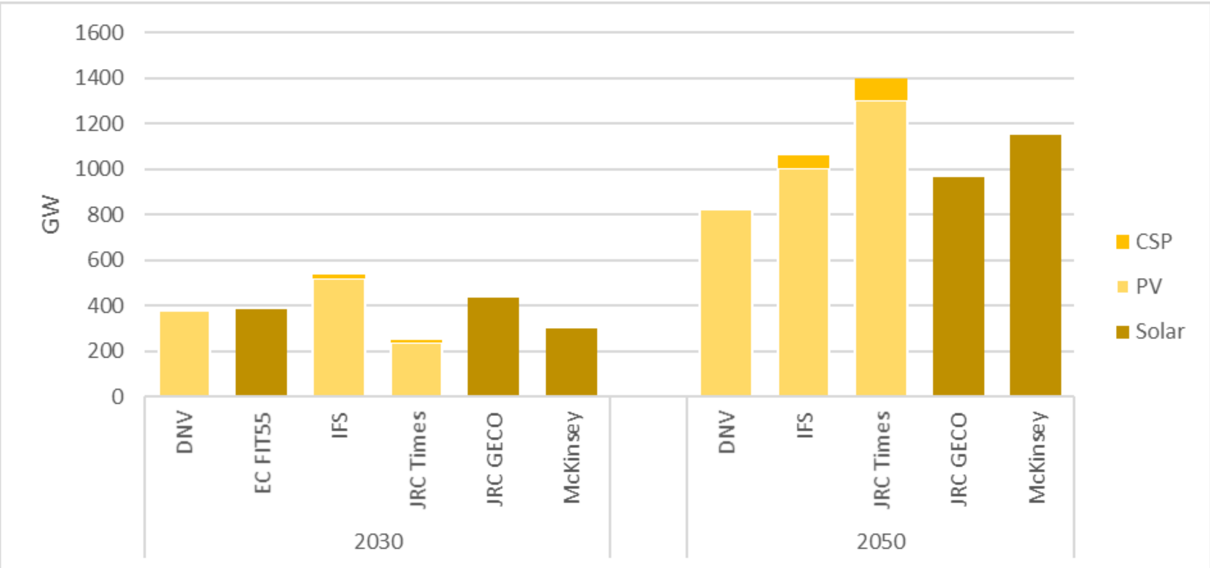
Figure 23. Installed solar power capacity in the EU



Source: JRC analysis based on scenario studies

The majority of scenarios assessed in this report do not provide sufficient information on solar thermal utilisation in end use sectors. Only *DNV*, *IFS* and IRENA make global data available, reporting on solar thermal usage in buildings and industry. Due to noticeable differences, even in historical data, we can conclude that the assumptions behind technological and sectoral boundaries differ significantly. *IFS* and IRENA see a rapid development in solar thermal installations in end use sectors. Industry grows faster than buildings, reaching a thermal consumption of 3 000 TWh (industry) and 3 500 TWh (buildings) in 2050. *IRENA* puts this at 1 700 TWh and 1 350 TWh respectively. *DNV* sees solar thermal slowly diminishing in the future, providing only 125 TWh of thermal energy in 2050.

Figure 24. Electricity generation from solar in the EU



Source: JRC analysis based on scenario studies

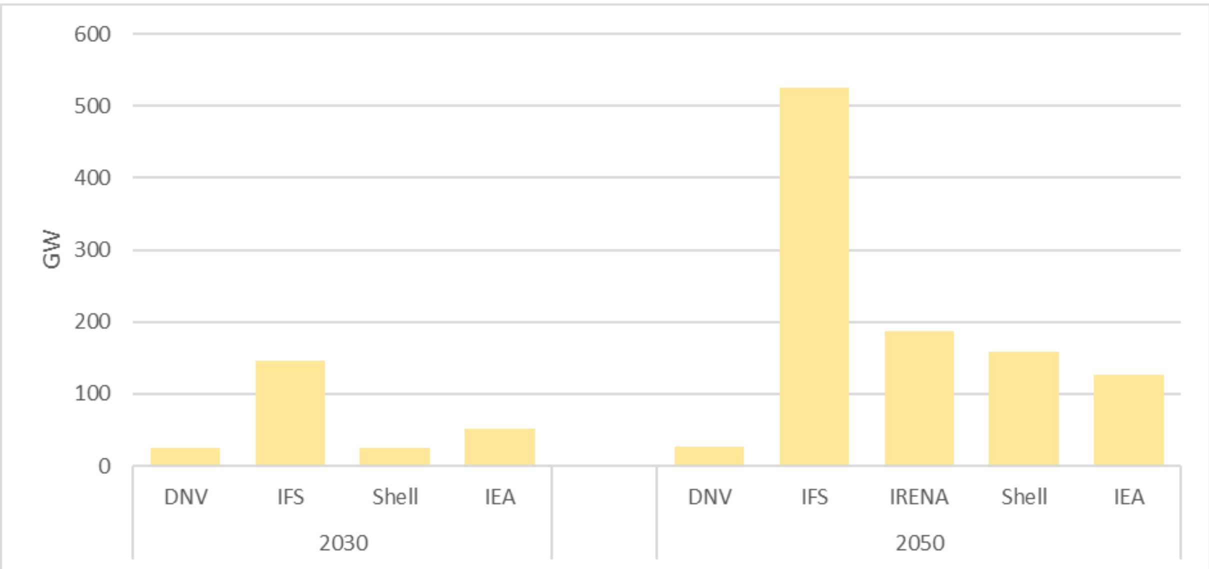
For **Europe** there are more data points available, but due to variations in geographical scope and the lack of historical data to normalise, it is difficult to provide a comparable assessment in absolute numbers. *CAN* and *EUCalc* project a moderate growth for solar thermal. *DNV*, as with the global picture, sees a rapid reduction. Only *IFS* reports a noteworthy growth of solar thermal in both industry and residential sectors, but this could be triggered by the wider geographical scope: *IFS* covers OECD Europe, and therefore also includes Turkey with its substantial solar potential.

4.3 Geothermal

Geothermal energy is used for electricity generation in the power sector and as a direct source of thermal energy in end use sectors (mainly in buildings and industry). Despite being technologically mature (it uses technologies from other well developed areas like oil drilling and steam turbines), the deployment rates of geothermal power installations are still low and comparable to emerging technologies. In 2020, there was only 14 GW of geothermal power installed globally (IRENA, 2022c) – less than 0.2% of total renewable power installations. The growth rate of new geothermal power installations is one of the lowest of all the clean energy technologies in this report, totalling about 4% CAGR over the last 10 years (only hydro has a lower CAGR). The EU situation is even less encouraging: less than 1 GW of geothermal power was installed by 2020 (6% of global installations). With a CAGR of around 2%, the EU share of geothermal in the global context is decreasing. Geothermal power generation is still niche: only 92 TWh was generated globally in 2019 (7 TWh in the EU), accounting for less than 1.3% of total renewable generation globally and less than 0.7% in the EU. Even though geothermal energy has a high capacity factor (comparable to coal and nuclear power plants) of 90% in the EU and 76% globally, it still fails to capture a significant share of the global renewable energy market.

Geographically, the utilisation of geothermal energy for power production is distributed very unevenly. Market leaders represent a major share of any selected region. For example Indonesia and Philippines represent 90% of total installed capacity in Asia. It also makes less accurate the comparison with the EU of scenario results. Countries with the highest installed capacity in Europe are Turkey, with 1 613 MW and Iceland, with 756 MW, while the whole EU27 has only 857 MW of geothermal power capacity installed. Based on 2020 data, geothermal installed capacity in the EU27 was only 28% of OECD Europe. In this report, geographical adjustment, scaling down the EU28 and OECD Europe to EU27, is done based on historical data. In this case, geothermal power results may be distorted due to more favourable conditions in European countries outside the EU27. There is also some discrepancy between statistical data provided by (IRENA, 2022c) and historical data provided by scenarios studies. There is a common understanding between scenario studies, that there was around 15 GW of geothermal power installed globally by 2019, but according to (IRENA, 2022c) it was only 13.9 GW. For the derived numbers in this chapter, 15 GW for 2020 was used.

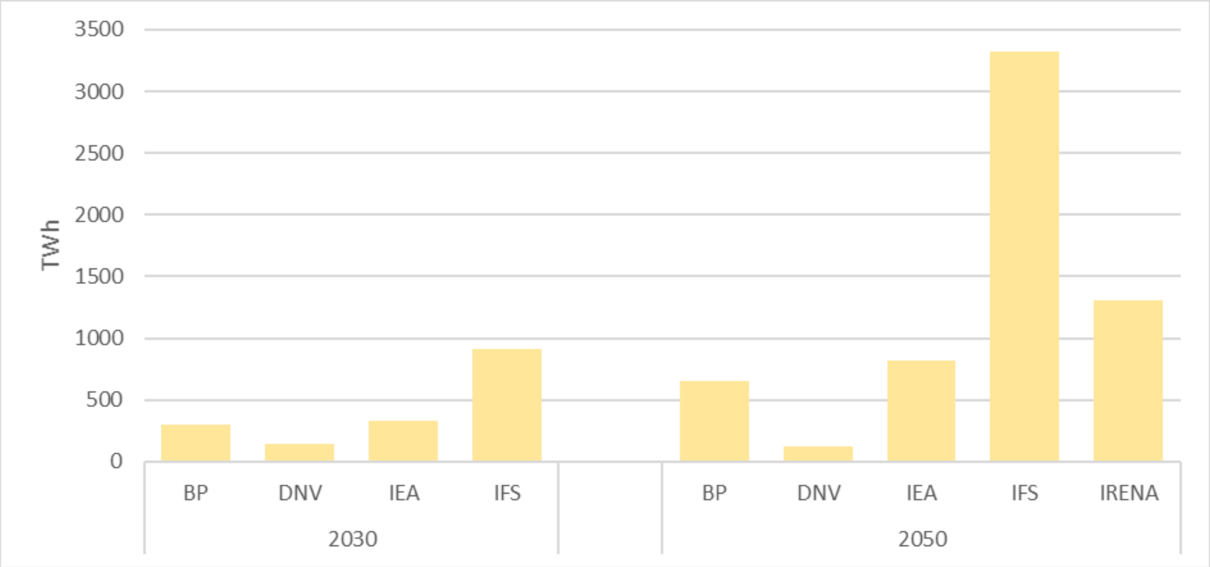
Figure 25. Global installed geothermal power capacity



Source: JRC analysis based on scenario studies

The majority of scenario studies analysed do not provide disaggregated data on the installed capacity of geothermal power plants. From the available data points it can be concluded that, **globally** by 2030, there is a growth of geothermal power capacity (**Figure 25**). Two studies see a moderate growth of about 1 GW of installed capacity per year compared to about 150 MW installed in 2020. *IEA* sees a growth of 3.7 GW per year. *IFS* is a clear outlier, seeing a boom in geothermal installation of about 14 GW per year (2020-2030) compared to 14 GW of total installed capacity of thermal power plants in 2020. This growth is fuelled by model assumptions which abandon all fossil fuels and nuclear by 2050 and see limited uptake of the hydrogen economy. Power generation follows a similar pattern: the majority of studies see a moderate growth (multiplied by 2-4 compared with 2020) with a clear outlier – *IFS*, which sees a tenfold increase in geothermal power production over next decade (**Figure 26**). Even in this case, geothermal energy constitutes only 2.5% of the total power generated in this scenario. In other scenarios, the geothermal electricity share is below 1% of total generation.

Figure 26. Global electricity generation from geothermal

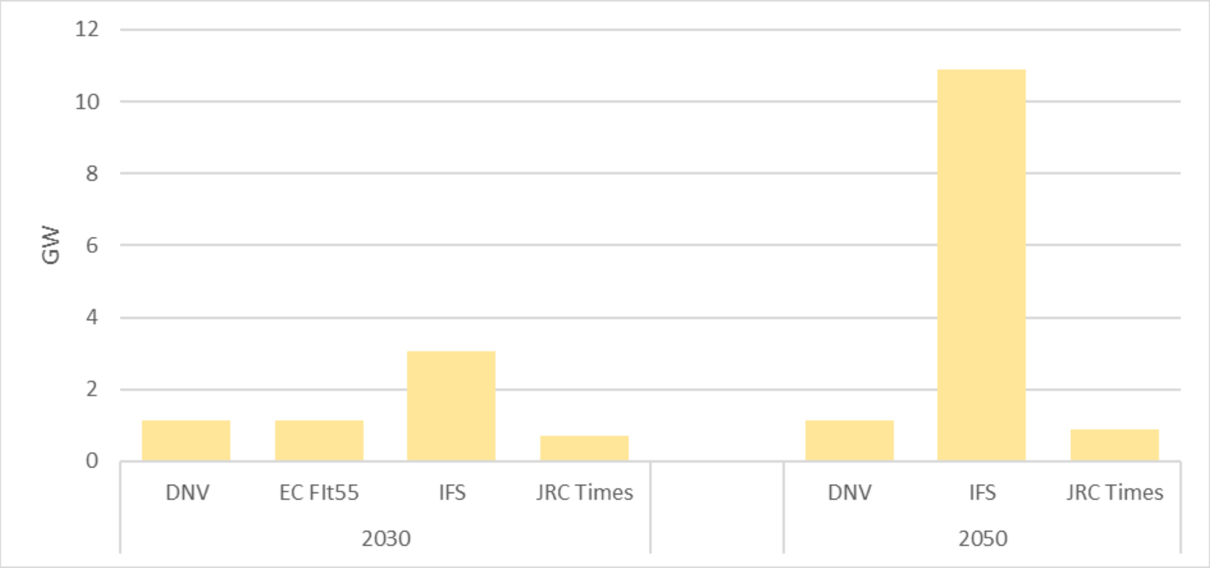


Source: JRC analysis based on scenario studies

In the **EU**, the majority of scenario studies do not see any substantial growth potential in geothermal power. By 2030, all scenarios see installed capacity at a level similar to today, except *IFS*, as was the case with the global. But even in this case, the growth is rather moderate – only tripling compared to a tenfold increase globally. More studies provide geothermal power generation results than those providing installed capacity (**Figure 28**). From the results, it is evident that studies using a classical optimisation modelling approach see a lower geothermal potential (except *IFS*), but studies with a simulation approach see a considerable geothermal uptake in the next decade. In this case we have three scenario studies (all of them optimisation modelling) with generation close to current levels and another three scenario studies (two simulation and one optimisation modelling) that see a three to six-fold growth of geothermal generation between 2020 and 2030. Moreover, in this case, *EUCalc* has the highest growth, but even with six fold increase, geothermal provides less than 0.5% of the total power generated in Europe.

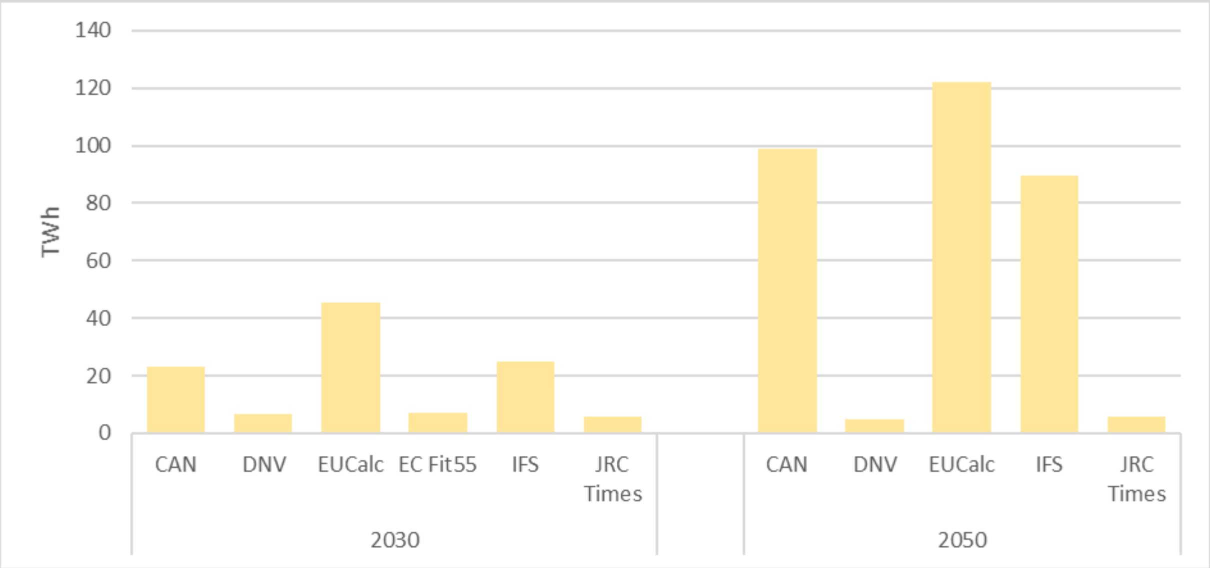
By 2050, the majority of **global** studies see a moderate growth in geothermal power installations, increasing by 4-7 GW of installed capacity every year. There are two outliers – *DNV*, that does not see changes in installed capacity at all, and *IFS*, that sees a continuation of rapid development, installing almost 20 GW per year in 2030-2050, thus reaching 525 GW installed capacity by 2050. By way of comparison, the next highest installed capacity is recorded in *IEA*, at only 126 GW. Power generation follows the growth of installed capacity, ranging from 125 TWh in *DNV* to 3 300 TWh in *IFS*, but even here it amounts to only 5% of total power generation. In most other scenarios, the share of geothermal power generation is between 1% and 2%.

Figure 27. Installed geothermal power capacity in the EU



Source: JRC analysis based on scenario studies

Figure 28. Electricity generation from geothermal in the EU



Source: JRC analysis based on scenario studies

EU studies do not foresee a noticeable growth of geothermal power generation capacity: two out of three see an increase of less than 10 MW per year in the period 2030-2050. Following global trends, *IFS* sees the highest growth at about 400 MW per year (this also could be affected by the scaling down of OECD Europe in this report) and reaches 11 GW in 2050 (compared to about 1 GW in other studies). On the generation side, due to different sets of studies, we see a different picture. Studies that do not see any growth in installed capacity (*DNV* and *JRC TIMES*) also show the lowest generation (5-6 TWh in 2050), one of which (*JRC TIMES*) sees a peak of geothermal generation in 2040 (7 TWh) and then drops back to 2030 levels. Three other studies show a remarkable growth, reaching up to 120 TWh in 2050 (*EUCalc*). Driven by external assumptions on the economic potential, geothermal power provides almost 3% of total power generation in the EU (*EUCalc*). In other studies (*CAN* and *IFS*), this share is only 1.5%. It is worth noting that all scenarios which see a bigger role for geothermal in EU power markets project a lower growth in 2030-2050 than in 2020-2030.

In addition to power generation, geothermal energy could be used to generate heat for end use sectors, but very few energy scenario studies provide sufficient data to properly analyse trends in direct geothermal energy use. Moreover, based on the data available, it is evident that different studies use different scopes for their definition of geothermal energy. For example, at **global** level, there are only three studies in our selection that provide some insights on direct geothermal usage in end use sectors, but based on the historical data in these studies, it is evident that each of them has different boundaries (historical results vary widely). In 2019, *DNV* sees only 3.5 TWh of geothermal energy used in industry, while *IFS* sees 97 TWh in 2018 and *IRENA* sees 305 TWh in the same year. Based on this wide variation of definitions it makes no sense to compare results of different studies, and therefore only trends are analysed. *DNV* does not see any potential for geothermal energy globally. In line with geothermal power, there is no geothermal end use growth either. Geothermal use in buildings drops by more than half between 2019 and 2050 (from 111 down to 41). Geothermal use in industry disappears before 2030. Only other sectors see a small increase (from 28 TW in 2019 to 44 TWh in 2050). In terms of geothermal energy for end uses, *IFS* follows power generation trends, with a constant increase both in industry and buildings: from 4 and 96 TWh in 2015, up to 747 TWh and 832 TWh in 2030, and 2 001 TWh and 2 271 TWh in 2050, respectively. According to *IRENA*, there will be an increase in geothermal use in 2030 and then a decrease towards 2050.

In Europe, most scenarios that provide data (*CAN*, *EUCalc* and *IFS*) agree that buildings will be the main area of geothermal heat application in end use sectors, with very limited deployment in industry, but even the most ambitious scenarios do not see it as a noteworthy source of end use energy, supplying below 1% in most cases.

Only *DNV* sees no role at all for geothermal heat: in 2030 it drops below 1 TWh and then completely disappears in 2050.

4.4 Heat pumps

Until recently, neither heat pumps nor ambient heat (harnessed from ambient air by heat pumps) was not usually included in energy scenario study results. A number of scenario studies consider ambient heat as part of the end-use mix, but it is usually reported only as part of electricity consumption (just the part consumed by heat pumps) and not separated in any way. While in the developed world (and in the EU in particular) the increase in electricity consumption could be used as a proxy for electricity used by heat pumps (Nijs, Tarvydas, & Toleikyte, 2021), that is not the case for the global numbers[16].

Currently, there are no energy statistics on the utilisation of ambient heat, either at global level or at country level (IEA, 2021b). Only Eurostat (from 2019) includes ambient heat for EU Member States (Eurostat, 2019) in the energy balances.

None of the **global** scenario studies analysed in this report provides data on ambient heat demand in energy balances, and only three provide quantitative data at European level. Nevertheless, a number of studies mention heat pumps (or ambient heat) as an important contributor to decarbonising the economy, especially the buildings sector, providing quantitative data on heat pump installations, either by million units or GW installed. By 2030, *IRENA* sees 182 million heat pumps installed (142 million in buildings, equal to 2 800 GW, another 35 million in industry) *BNEF* also sees a similar number (186 million households with heat pumps installed globally by 2030), while the *IEA* is considerably more ambitious, with 600 million heat pumps installed globally by 2030, providing 20% of total heating supply, in 400 million dwellings.

By 2050, the number of heat pumps installed **globally** could range between 400 million (*IRENA*; 290 million in buildings, equal to 5800 GW, and 80 million units in industry) to 1 800 million heat pumps (*IEA*). *IEA* projects that 1 200 million houses will have heat pumps installed (providing around 55% of total heat demand) while *BNEF* foresees installations in 1400 million households. A rapid deployment of heat pumps could account for around 74% of emission abatement in the buildings sector by 2050 (*BNEF*). Heat pumps (single or multi-stage cascading) could also provide up to 30% low to low/medium temperature heat in the industrial sector (*IEA*). Other studies also emphasise the importance of heat pumps: according to *DNV*, heat pumps will provide 42% of space heat in buildings in 2050, while consuming only 15% of the energy used for space heating. In industry, when temperature requirements are moderate, heat pumps will increasingly be commercially competitive as their high coefficient of performance will increase by a factor of 6. According to

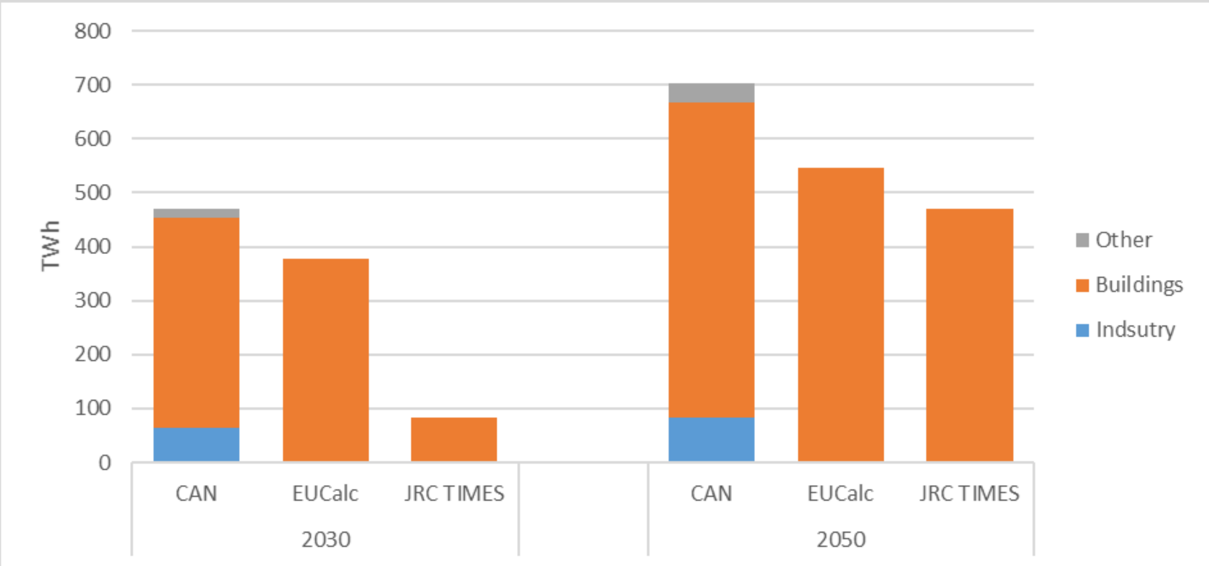
[16] The global increase of electricity consumption is driven by a number of factors, including increased access to electricity and/or use of white/brown appliances in the developing world. In the developed world, including the EU, the increased use of electricity in the household sector is driven mainly by new uses of electricity (heating directly or using heat pumps), but this approach gives only very approximate results because of behaviour changes (some scenarios foresee a drastic reduction in end use energy in the buildings sector), and due to a possible increase in electricity consumption for cooling (not considered as ambient heat by definition).

IFS, global installed capacity of heat pumps will grow tenfold between 2015 and 2030 (from 89 GW to 967 GW) and another 2.5 times between 2030 and 2050 (to 2430 GW).

In **Europe**, scenario studies do not agree on the take-off speed of heat pump installation (**Figure 29**): the highest figure for 2030 (CAN) is almost six times the lowest (*JRC TIMES*), but for 2050, the results are very similar: in the buildings sector, from 470 TWh (*JRC TIMES*) to 580 TWh (*CAN*) of ambient heat could be utilised. On top of that, *CAN* also foresees the use of around 35 TWh of ambient heat in other sectors, mainly industry. According to *McKinsey*, 9% of residential and commercial buildings will use heat pumps for space and water heating by 2030, reaching 40% by 2050 (compared to 2% now). According to *IFS*, the installed capacity of heat pumps in OECD Europe will grow six-fold between 2015 and 2030 (from 29 GW to 183 GW) and another 2.5 times between 2030 and 2050 (to 444 GW).

Global energy scenario studies agree that the heat pump market will grow in next decade and till 2050. With a CAGR ranging from 8% (IRENA) up to almost 20% (BNEF), by 2030 the global market could reach at least EUR 120 billion, doubling by 2050. In line with other developing world, the EU growth rate could be higher than the global average.

Figure 29. Ambient heat consumption in EU[17]



Source: JRC analysis based on scenario studies

4.5 Hydrogen

Hydrogen is the only intermediate (secondary) energy carrier covered in detail in this report (all others are renewable energy sources). While hydrogen is the most abundant element in nature, it usually forms part of another compound (the most relevant to hydrogen production are water, H_20, and methane, CH_4). In order to use hydrogen as an energy source (or as feedstock in industry), it has to be produced from other sources of energy. Today, globally, hydrogen is mainly produced from fossil fuels (around 60 Mt without CCS and 8 Mt with CCS) and as a by-product in refineries (about 18.6 Mt). Only 0.5 Mt was produced using electrolysers (not necessarily based on renewable electricity) (IEA, 2022c). In the last few years, driven by flexible decarbonisation needs, hydrogen has become one of the technologies widely covered by scenario studies. While in 2019 there were only a handful of scenario studies covering hydrogen in the context of decarbonisation pathways (JRC, 2019), in this review, the majority of scenarios selected include hydrogen usage.

In the future, hydrogen used as an energy carrier will most likely be produced from electricity (the majority of the studies see a role only for green hydrogen, especially after 2030). We can also observe a correlation between hydrogen production and the installed capacity of wind and solar power plants. There are just a few studies that see a role for hydrogen in power production. Hydrogen could be considered as a means for both

[17] CAN and EUCalc provide data on EU28, while JRC TIMES covers EU27. Ambient heat consumption could be used as a proxy to understand heat pump deployment in Europe.

long and short term energy storage, but due to significant losses, it is not widely adopted as such in the majority of energy scenario studies.

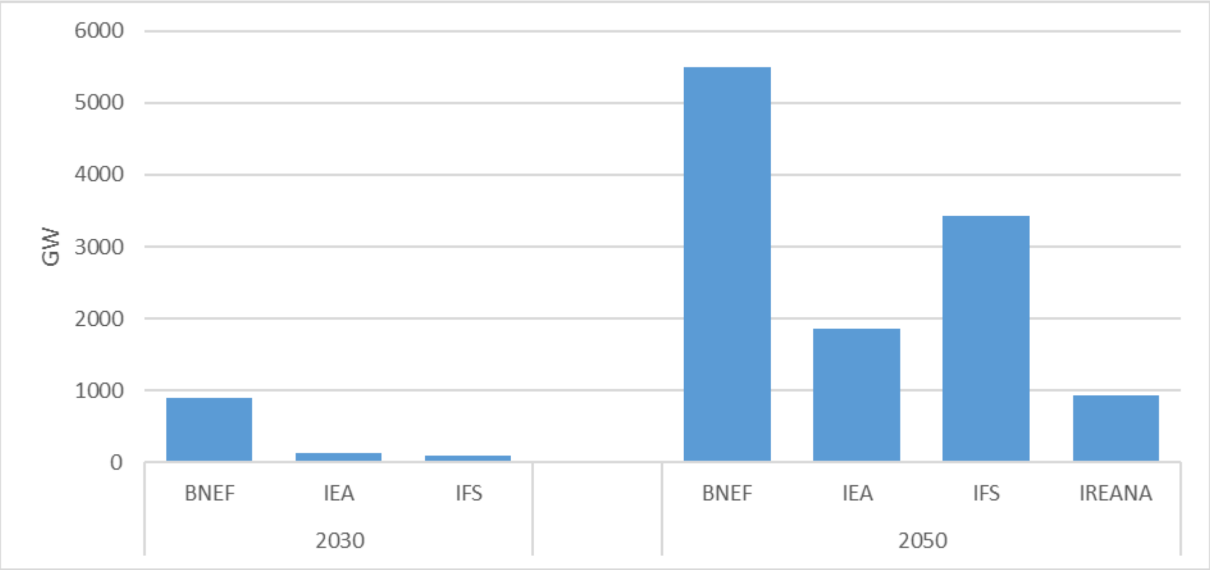
Globally, only three studies[18] see dedicated hydrogen power generation capacity installed before 2030. IEA and IFS only see around 100 GW of hydrogen capacity installed, while *BNEF* sees 900 GW. With a significant increase in intermittent generation, *BNEF* (**Figure 30**) already sees hydrogen as a flexibility/storage provider in 2030. There is more variation in hydrogen power generation than in installed capacity (**Figure 31**). While *IFS* and *IEA* have similar installed capacities, the electricity produced differs significantly. Both *BNEF* and *IFS* have capacity factors of around 30%, indicating regular peaking/flexibility usage of such capacities, while *IEA* shows capacity factors of over 70%. It is unlikely that in this case, hydrogen power plants are used as baseload, but it (probably) indicates that hydrogen is used in mixes with natural gas. According to scenario studies, in 2030 there will be between 16 Mt and 150 Mt of hydrogen used for power generation globally.

In 2030, only one scenario study sees a role for hydrogen in power generation in **Europe**. By 2030, *IFS* sees less than 7 GW of hydrogen installed (in OECD Europe), producing almost 20 TWh of electricity, meeting the peaking/flexibility unit profile.

By 2050 the situation will not change much. **Globally**, there are only four scenario studies with dedicated hydrogen power production capacity (**Figure 30**). *BNEF* still sees the highest potential for hydrogen power generation, but other studies are catching up. While *BNEF* has only 9% CAGR in 2030-2050, *IFS* will reach 19%. Global hydrogen-based power generation will grow less rapidly than installed capacity, with a CAGR ranging from 3% in *IEA* to 13% in *IFS*. That translates to lower capacity factors of around 20%. All studies except *IRENA* (a clear outlier with a capacity factor of 38%) see power hydrogen generation moving even more towards peaking/flexibility. By 2050 in **Europe**, only one study (*IFS*) provides installed capacity of hydrogen generation, with a 19% CAGR (in period 2030-2050), in line with *IFS* global trends. On the generation side, in addition to *IFS*'s hydrogen-based power generation of 300 TWh, *McKinsey* sees a generation of around 120 TWh, providing about 2% of total generation.

The power sector is not the main market for hydrogen (although hydrogen-based power generation capacity evolves fast in the period 2030-2050). Most of the scenarios see that the majority of hydrogen is used in the end use sector. For example, about 90 Mt of hydrogen is currently used in industry (non-energy) globally. In comparison, on average, only 70 Mt is used for power generation in 2030 (ranging from 20 Mt to 140 Mt).

Figure 30. Global installed hydrogen power capacity

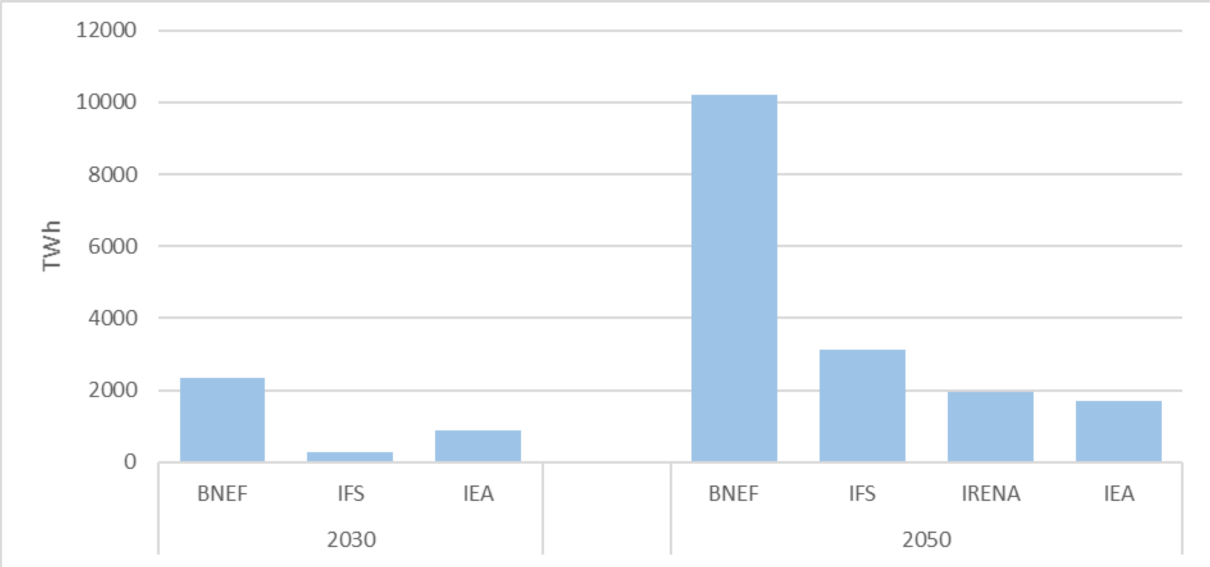


Source: JRC analysis based on scenario studies

[18] Hydrogen can also be used (in various mixes with natural gas) in gas turbines, whether currently operational (with or without upgrade) or new. These capacities may not be reported as hydrogen-based in energy studies.

The majority of scenario studies reviewed in this report foresee (and provide data on) hydrogen use in end use sectors, but the sectoral scope and fuel definition boundaries of these studies differ significantly. Some scenario studies provide hydrogen and synthetic fuel consumption (sometimes called e-fuels) separately, while others bundle them together. In previous reports (Tsiropoulos I. N. W., 2020), synthetic fuels were converted back to hydrogen using reversed production efficiencies, but in order to align with reports that do not separate hydrogen from synthetic fuels, this report uses face values. Most studies do not include non-energy in final energy demand, but *IRENA* includes hydrogen as a feedstock in industry. This is chiefly why, of all the scenarios, *IRENA* sees the highest hydrogen demand in 2030. In *IEA*, not all synthetic fuels are attributed to a final demand sector, therefore this energy is reported as consumed in other sectors (in line with earlier IEA WEO publications). For European scenarios, where possible, hydrogen and e-fuels usage is also split into bunkers and non-energy.

Figure 31. Global hydrogen power generation



Source: JRC analysis based on scenario studies

In 2020, about 90 Mt (around 3 000 TWh) of hydrogen was used in industry (IEA, 2022c): 50 Mt in the chemical industry and 40 Mt in refineries, but none of this was used as an energy source, but rather as a feedstock, and is therefore not always included in scenario study results. In end use sectors in 2020, only around 3 TWh (or 90 kt) of hydrogen was used for energy in the transport sector.

In 2030, the majority of **global** energy scenario studies see hydrogen starting to appear in all end use sectors (**Figure 32**). But studies do not agree on which sector will lead the adoption of hydrogen. Three out of seven studies see buildings as the main early adopter (*BNEF*, *JRC GECO* and *IRENA* (if adjusted for industrial feedstock)). According to *DNV* and *IEA*, industry will be the main consumer of hydrogen, while *IFS* and *Shell* see transport as an early adopter. Despite being adopted in all end use sectors, hydrogen remains a niche energy form in 2030, providing less than 1 000 TWh of energy globally on average (ranging from less than 4 Mt in *Shell* to 65 Mt in *IEA*. Putting end use together with feedstock, *IRENA* sees around 162 Mt of hydrogen used by 2030 (compared to 90 Mt as feedstock today).

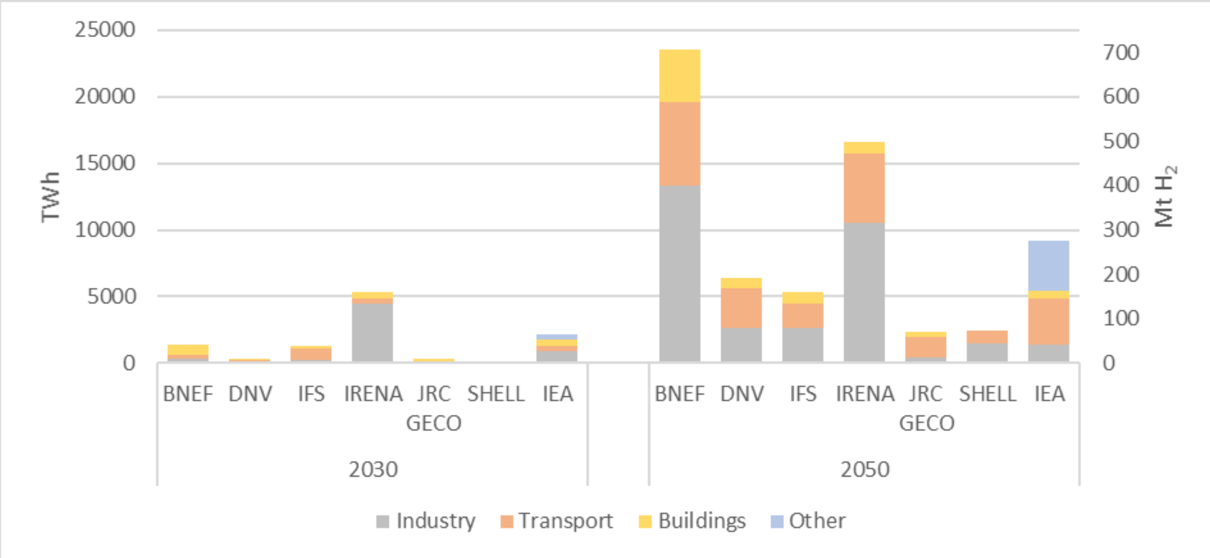
Looking at **Europe**[19], energy scenario studies are more coherent: the majority anticipate that the transport sector will be first to implement the hydrogen option (**Figure 33**): six out of nine studies see the highest consumption occur in transport. Two studies (*DNV* and *BP*) see industry as an early adopter, and only *JRC GECO* sees buildings as the preferred sector to implement hydrogen first. Despite generally agreeing on the main sectors to implement hydrogen technologies, the speed of adoption differs significantly: hydrogen usage varies between 15 TWh and 208 TWh among the studies that put transport first. Total hydrogen usage also differs significantly: five of the nine studies put it at less than 2 Mt of hydrogen per year, while two put it at around 10 Mt (*CAN* and *JRC TIMES*).

[19] Data not adjusted for geographical differences between the studies.

By 2050, **global** hydrogen usage in end use sectors changes significantly: none of the scenario studies sees buildings as the main source of hydrogen demand. Four out of seven studies see industry as the main hydrogen market, while the remaining three give that honour to transport. Another area where studies do not agree is the total amount of hydrogen used in end use sectors, varying from only 70 Mt in *JRC GECO* and *Shell*, to over 700 Mt in *BNEF*, averaging around 260 Mt per year. These differences can be translated into a 15% CAGR in the case of *BNEF*, down to 5-7% in *IEA*, *IRENA* and *IFS*. In *BNEF*, hydrogen will provide about a quarter of final energy demand, while the average across the scenarios is only 10%.

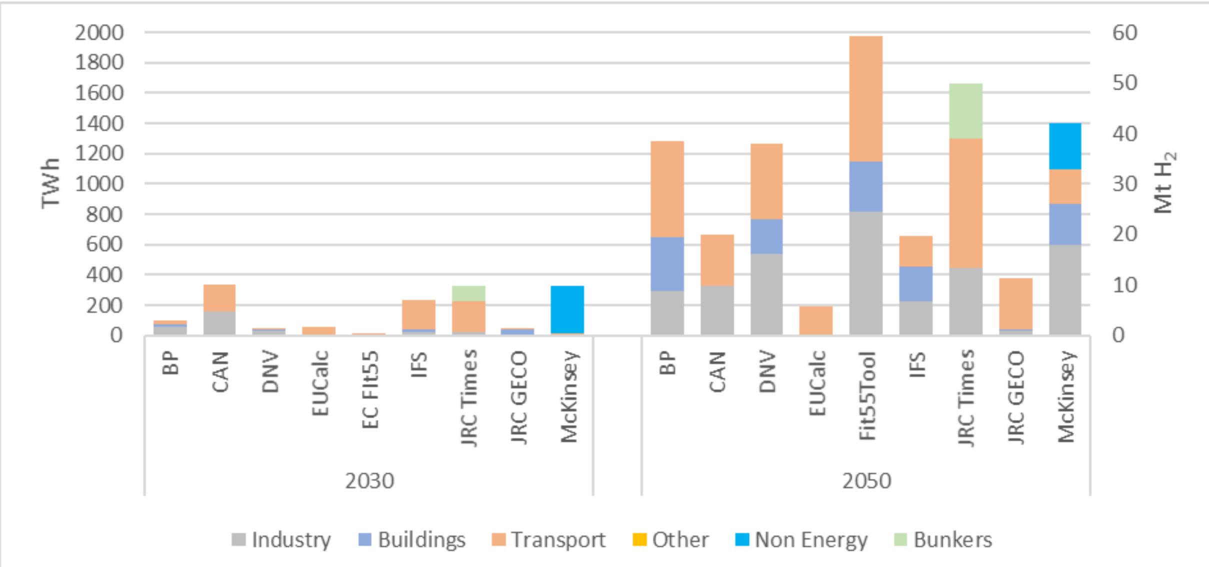
In **Europe**, the transport sector remains the main market for hydrogen. Six out of nine studies see transport as the sector with highest hydrogen demand. The other three put industry first. None of the studies believes that buildings will have any substantial demand for hydrogen. The growth of demand varies among scenarios, from only 3% in *CAN* to more than 25% in *McKinsey* (including non-energy) and *EC FIT55* (including the energy sector). Hydrogen demand in Europe could vary between 6 Mt and 60 Mt in 2050.

Figure 32. Global final hydrogen demand per sector



Source: JRC analysis based on scenario studies

Figure 33. Hydrogen final demand in Europe per sector



Source: JRC analysis based on scenario studies

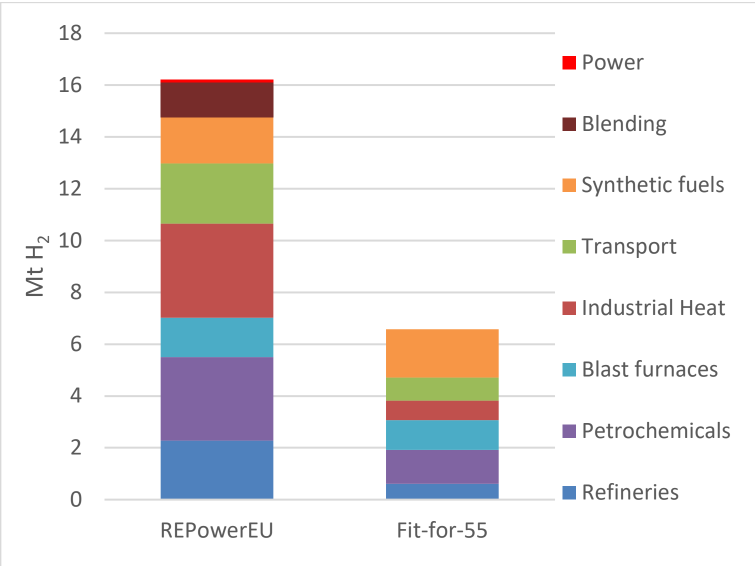
There is significant disagreement among energy scenario studies on the future hydrogen market. In 2030, the **global** market could vary between 6 Mt and 70 Mt in end use sectors, plus non-energy of at least 90 Mt (current levels). Added to that, up to 140 Mt could be used for power generation, averaging out across the scenarios at about 200 Mt per year. The EU market could reach up to 10 Mt (without feedstock).

By 2050, the **global** hydrogen market could vary from 70 Mt (*JRC GECO*) to 700 Mt (*BNEF*). Non-energy use will probably amount to more than 100 Mt. Power generation could add another 100-600 Mt, reaching over 1 400 Mt according to *BNEF*. In the EU, hydrogen demand could reach 60 Mt (EC FIT55, including the energy sector and non-energy).

It is worth noting that in studies that see a high growth rate of hydrogen utilisation, hydrogen is mostly produced from intermittent renewable sources. It is partly driven by the need to balance the power system in a zero emissions world in 2050, but also affected by scenario selection. For example, in the case of *BNEF*, the Green scenario was selected, to correlate better with the European Green Deal and EC Fit55 scenario results.

Following Russia's war against Ukraine and the urgent need to reduce energy dependence on fossil hydrocarbons coming from Russia, the European Commission published the REPowerEU Plan (European Commission, 2022c) on 18 May 2022, detailing hydrogen and biomethane targets (European Commission, 2022e) in order to reduce natural gas consumption. Building on the Fit-for-55 ambitions, REPowerEU accelerated the medium-term projections for hydrogen utilisation in Members States, from slightly above 6 Mt to 16 MT in 2030 (**Figure 34**), not including an additional 4 Mt to replace imports of ammonia and related products. REPowerEU foresees a rapid increase of hydrogen usage in transport (direct and as synthetic fuels), the industrial sector will experience major changes (both in high temperature industrial heat and industrial processes) and in the buildings sector, hydrogen blending will be used.

Figure 34. Hydrogen consumption in REPowerEU and EC Fit for 55 in 2030



Source: European Commission, 2022

4.6 Hydro

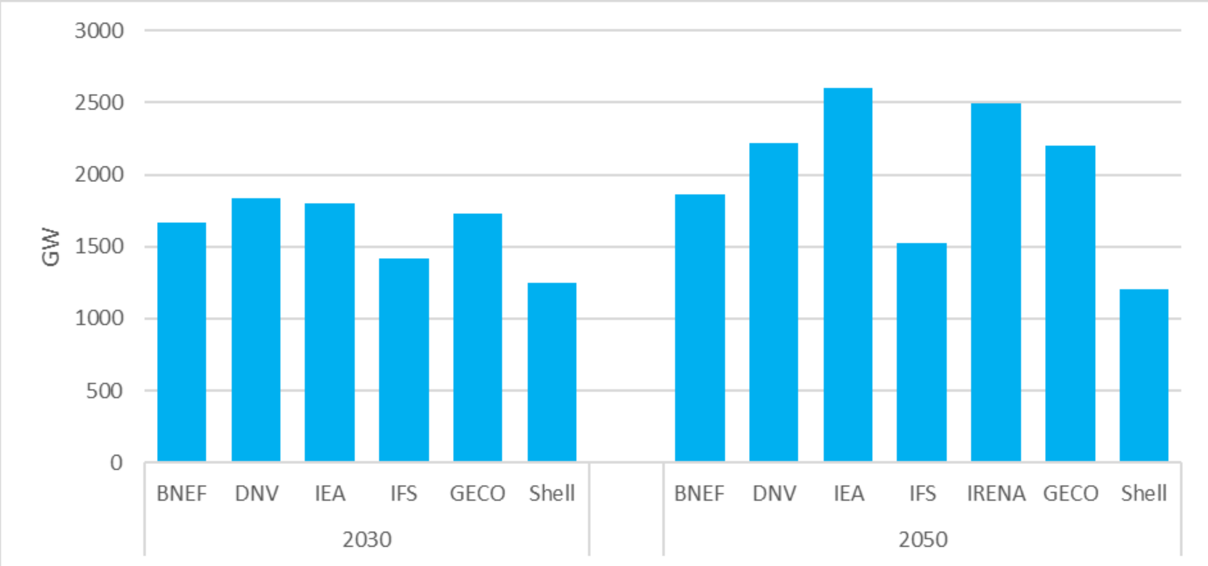
Hydro energy is the first renewable energy source used at scale for electricity production. In 2000, there was already over 750 GW of hydro power plants installed and in 2020, this number reached 1 333 GW, providing around 50% of global renewable capacities and 63% of electricity generation). There are two main types of hydropower plant, both based on well-established technology: hydropower plants which use only natural inflows (usually with a dam for output regulation) and Pumped Storage Hydropower (PSH) that pump water upstream to reuse for power generation. These two types of technology can be used separately or combined into mixed power plants with natural inflows and pumping capabilities.

In 2020, there was 1 212 GW of installed capacity globally of pure hydro and mixed plants, along with a further 121 GW of pure PSH, totalling 1 333 GW of hydropower capacity. In the EU, pure hydro and mixed power plants made up 129 GW of installed capacity, plus another 23 GW of pure PSH, totalling 151 GW

(IRENA, 2022c). As an established technology, hydropower does not enjoy the same rapid growth as other renewable technologies like wind and solar: in the last decade, the global CAGR of hydro technology was around 2% and in the EU, only 1%. In 2020, only 11% of global installed capacity was in the EU.

Although hydropower is a well-established technology, the comparison of scenario results is not straightforward: while the majority of the scenario studies combine all hydro power plants together, some (like *BNEF*) consider only pure hydro and mixed power plants, leaving pure PSH as part of the storage technology mix. In other cases (like *Shell*), it is not clear if pure PSH is included. For this report, the sum of all hydro technologies is used as the main indicator.

Figure 35. Global installed hydropower capacity



Source: JRC analysis based on scenario studies

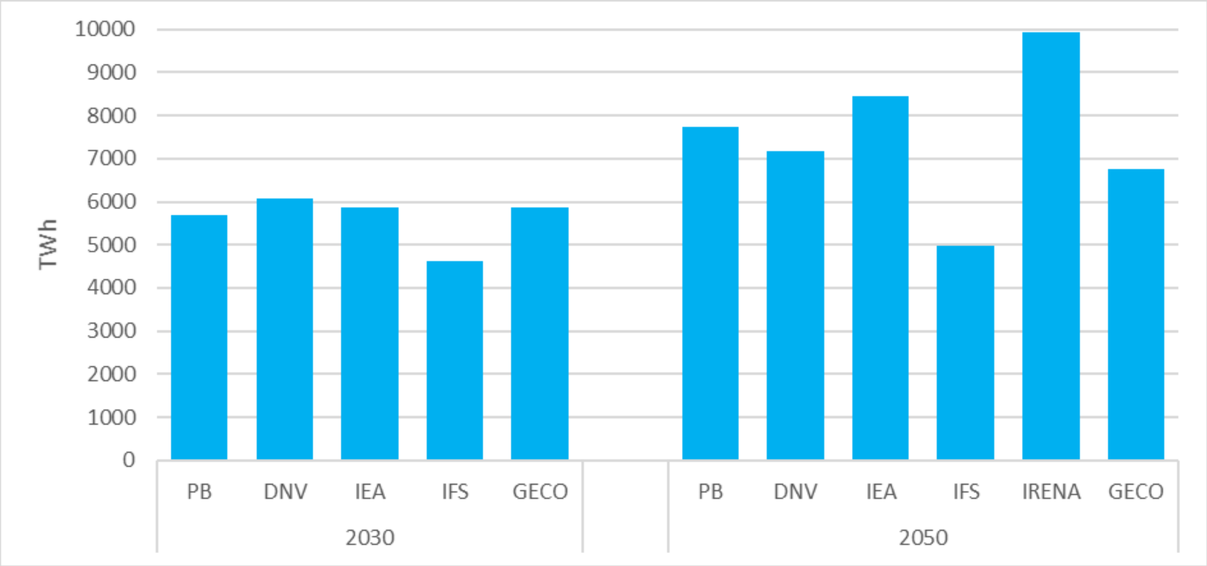
By 2030, none of the scenarios sees any major development in installed capacity of hydropower plants. **Globally**, only between 8 GW and 50 GW of installed capacity is added yearly. That translates to a CAGR of less than 3.5%. The largest growth can be observed in scenarios relying on a full set of technologies (*DNV*, *IEA*). *IFS* shows one of the lowest growths, relying mainly on intermittent renewable energy in 2050 (Figure 21). SHELL only sees a marginal growth of about 5 GW a year, compared to its own baseline, but due to different technology boundary assumptions[20] (**Figure 35**), SHELL data seems lower on the graph. The majority of scenarios analysed see hydro production of around 5 500-6 000 TWh (**Figure 36**), a growth of about 3% CAGR, in line with the growth of installed capacity. The only clear outlier, *IFS*, anticipates a CAGR of less than 2%. In 2030, hydropower generation will provide 13-17% of all electricity generated in the world.

In the **EU**, the situation is very similar. Due to limited potential and environmental regulations, there is very little growth of new hydro installations to be seen in the majority of scenario studies – a rate of below 0.5 GW per year (compared to the studies' own baselines) (**Figure 37**)[21]. This is considerably slower than that of the majority of other renewable technologies. There is more information given in the studies on generation than on capacity, but each paints a very similar picture: hydro potential is almost exhausted and there is no room for meaningful expansion (**Figure 38**). All studies show a moderate annual growth, compared to their own baselines, of 1-3%.

[20] Historical years do not correspond to IRENA statistical data.

[21] In the graph, the boundaries of hydro technology were not aligned. The majority of scenarios use hydro, mix and pure storage definitions, and others (EC FIT55) use only pure and mix. For *JRC TIMES* and *JRC GECO*, the boundaries are unclear (*JRC TIMES* has a lower historical value than pure hydro and mix, and JRC GECO a higher value than mix plus pure hydro).

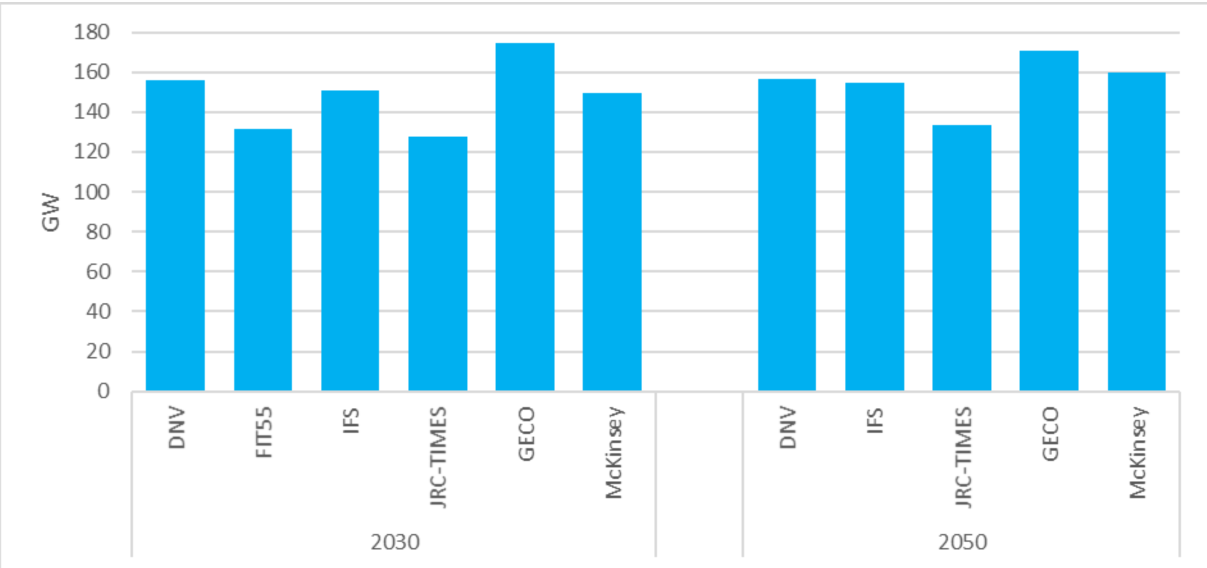
Figure 36. Global electricity generation from hydro



Source: JRC analysis based on scenario studies

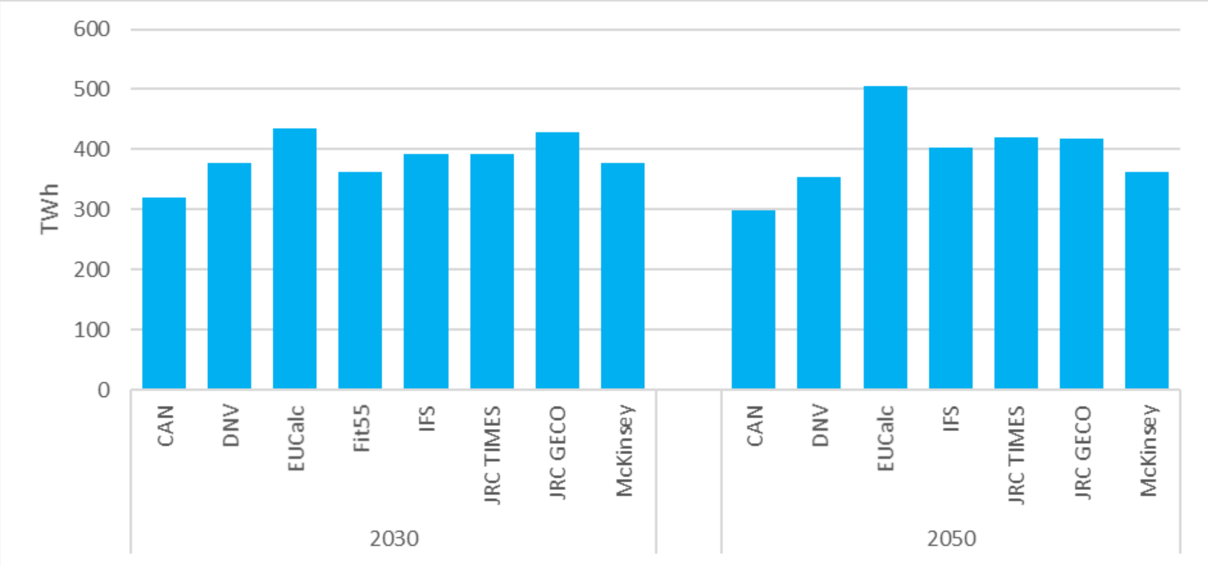
The situation remains similar towards 2050. **Globally**, the majority of scenarios see a slow growth of 5-40 GW per year. Only *Shell* shows a small decline in global installed capacity of hydropower plants. IEA has the highest installed capacity of around 2 600 GW, and *Shell* the smallest at 1 203 GW, followed by *IFS* at 1 523 GW, but in all cases, due to the rapid development of other renewable sources, the role of hydro diminishes: globally, only 5-9% of total installed capacity is made up of hydropower plants. By 2050, hydro could provide about 5 000-10 000 TWh of electricity (*IFS* at the low end and *IRENA* estimating high), providing 8-13% of total electricity generation. The study with highest global capacity (*BNEF*) does not provide information about hydro generation, lumping it in with other renewables totalling only 5 600 TWh and providing less than 5% of total electricity generation.

Figure 37. Installed hydropower capacity in the EU



Source: JRC analysis based on scenario studies

Figure 38. Hydropower generation in the EU



Source: JRC analysis based on scenario studies

In the period 2030-2050, the **EU** follows global trends. The installed capacity stays almost unchanged: in 20 years, on average, there will only be 3 GW built, and one of the studies even sees a decrease of 3.6 GW by the end of 2050. Hydro makes up only 3% to 6% of total installed capacity in the EU. Studies that provide both generation and capacity see similar generation results (of about 350-420 TWh). There are two outliers (both without data on capacity): *CAN* sees only 300 TWh generated in 2050 (down from 320 TWh in 2030) and *EUCalc* sees a generation of 500 TWh (up from 430 TWh in 2030). In 2050, hydro could provide about 7% of all electricity generated in the EU.

By 2030 the global hydropower market could total around 20 GW per year (including new installations and refurbishments). After that, the hydropower market could decline to 15 GW per year. The EU hydropower market will be negligible, at around 0.5 GW additions per year, and less in some scenarios, which see no growth at all.

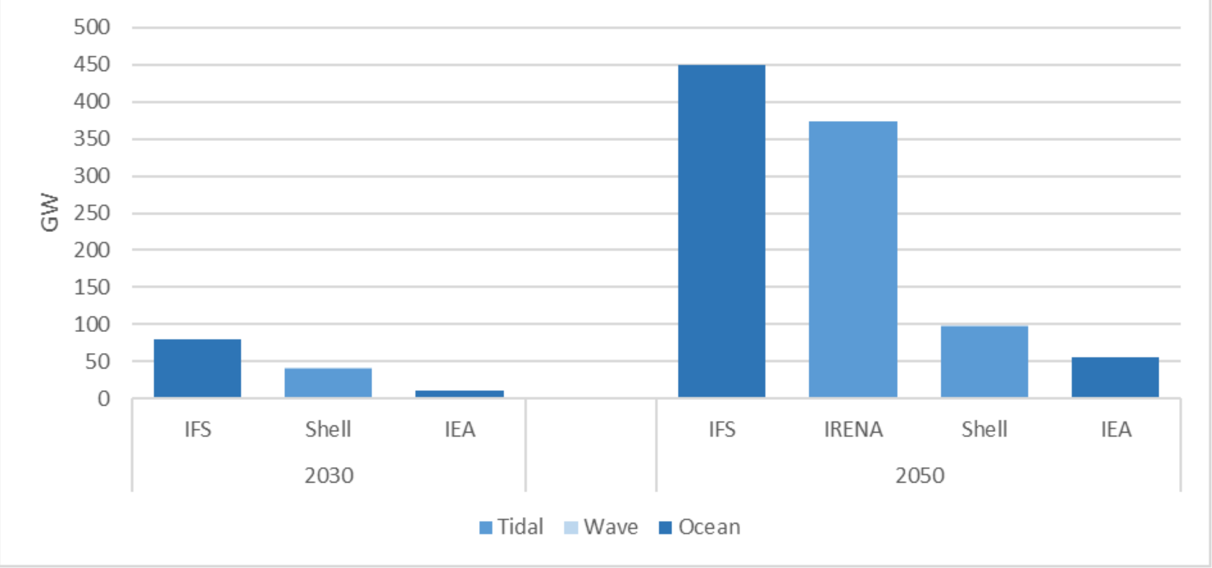
4.7 Ocean

Ocean energy (known in some literature as marine energy) is an emerging technology, used for producing electricity only in the power sector (centralised). For power generation there are two main groups of technologies: one tidal and the other using waves. Statistics (IRENA, 2022c), as well as those scenario studies which provide data on ocean energy, usually bundle tidal and wave technology under one heading. Globally, there is only 0.5 GW of ocean energy installed, almost half of it (0.22 GW) in the EU. In the last decade, there has been no progress of note in ocean energy deployment. Since 2011, only 24 MW (0.024 GW) of ocean energy has been installed globally (most of it in the UK). The CAGR of ocean energy in the period 2010-2020 was only 0.5%, and only because in 2011, the global capacity was doubled by new installations in the Republic of Korea. Moreover, in the EU in 2020, there was less installed capacity than in 2016 (221 MW, down from 227 MW). In 2019, globally, there was only 1 TWh of ocean energy generated, which translates into about 0.01% of total renewable electricity generated in 2019.

Energy scenarios still rarely provide quantifiable information on ocean energy. Only four out of 13 scenario studies included in this report provide global data points for ocean energy. For Europe, there are only studies with quantitative data. Moreover, only two of them split the data into wave and tidal (*Shell* and *JRC TIMES*). It is very likely that some other scenario studies also consider ocean energy without providing disaggregated results (for example EC FIT55), therefore these studies are not included in graphs and future analysis.

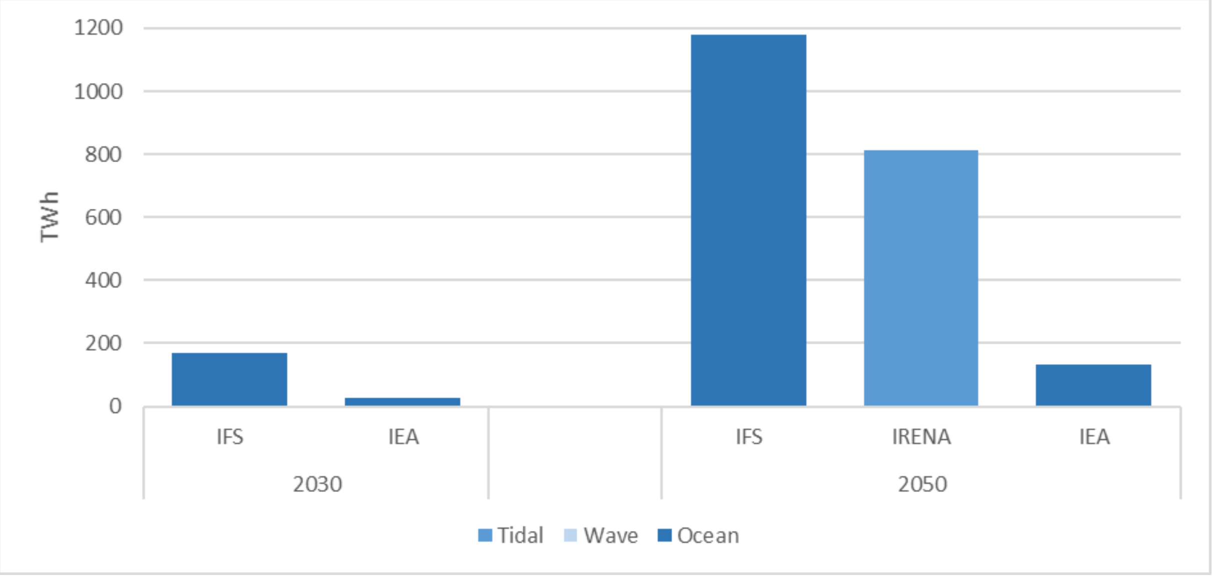
By 2030, the scenario studies that report ocean energy data see a growth in the **global** installed capacity of ocean energy of around 11-80 GW (**Figure 39**). In absolute numbers, this is negligible (compared to about 5 000 GW of solar installed in 2030), but it could signal a kick-off in the deployment of ocean energy: it translates to at least 1 GW of installed capacity per year, doubling the current total installed capacity, and shows a 20-150fold increase in 10 years. Scenarios that split results into tidal and wave see a major development of tidal energy (over 73% of new capacity). In the scenario studies selected, there are only two providing generation data on ocean energy in 2030. Ranging from 27 TWh to 168 TWh, it provides less than 0.5% of total power generation (**Figure 40**). And with a 24% capacity factor and generation which is not dispatchable, it does not contribute to security of supply either.

Figure 39. Global installed ocean power capacity



Source: JRC analysis based on scenario studies

Figure 40. Global electricity generation from ocean energy



Source: JRC based on scenario studies

In the **EU**, there are only two scenarios that provide capacity data for 2030 **Figure 41**. *IFS* sees 16 GW of ocean generation capacity installed (growing roughly 70fold), translating into 1.5 GW of new installations per year (compared to the current 0.22 GW of total installed capacity of ocean power) or about 20% of global installation, making the EU one of the leaders in the development of ocean power plants. Another study (JRC-TIMES) does not see any ocean energy installation before 2030. On the generation side, there are some studies with numerical data on ocean energy. *IFS* sees the highest growth potential, reaching 34 TWh in 2030. The remaining studies are less optimistic – ocean energy generates below 10 TWh (**Figure 42**). Despite its remarkable growth in the most optimistic scenario (70fold in *IFS*), ocean energy still generates less than 1% of all the electricity generated in the EU in 2030.

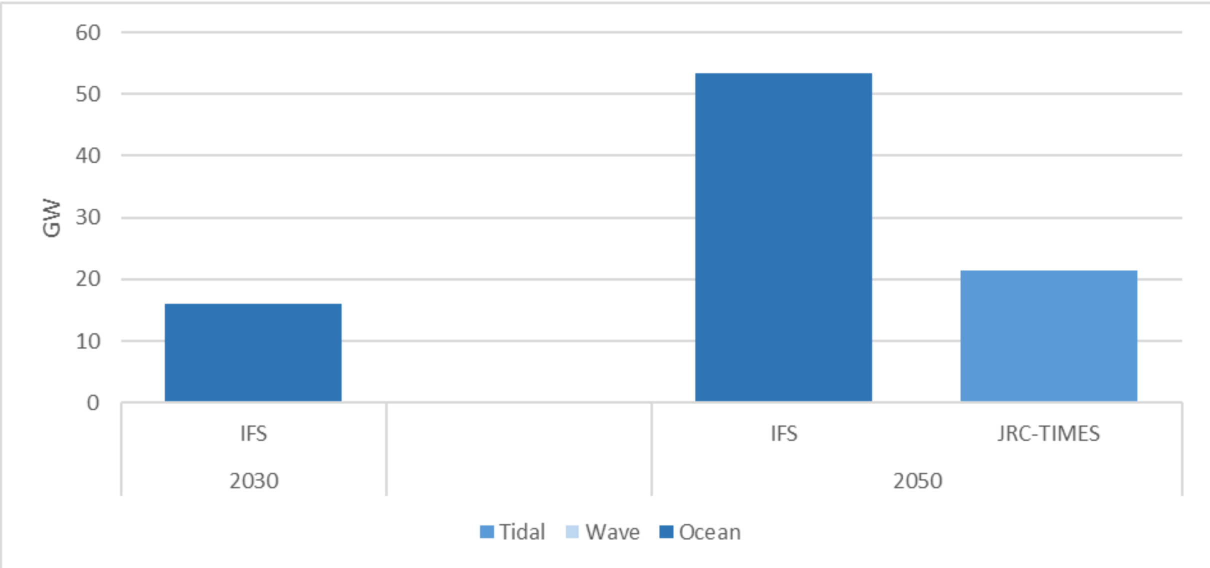
By 2050, a continuation of the rapid deployment of ocean energy can be observed. **Global** installation more than doubles, reaching 450 GW of installed capacity, but still only reaching 1.5% of total installed capacity in the most ambitious scenario (*IFS*). *Shell* and *IEA* see an ocean energy contribution of less than 0.5% of total global installed capacity. The most ambitious scenario posits figures five times the size of the least ambitious. Based on *Shell* results (the only scenario study that provides a split between tidal and wave in 2050), tidal contributes 98% of total installed ocean energy capacity. Global ocean energy generation could vary from 132 TWh (*IEA*) to 1 200 TWh (*IFS*), but in any case, it does not contribute significantly to electricity supply: even in the most optimistic scenario it accounts for less than 2% of total electricity generation.

There are only two scenario studies that quantify ocean capacity deployment in **Europe** in 2050. *IFS* projects an installed capacity of ocean energy of 53 GW. *JRC TIMES* is more specific with 21 GW of tidal installations (no wave energy installations are reported). The *IFS* projection means a tripling of the 2030 capacity and around 2 GW of new installed capacity per year. Even in this most optimistic case, the total installed capacity of ocean energy is below 1% of total installed power generation capacity in the EU (and 0.3% in *JRC TIMES*). Values are given for ocean energy power generation in three studies, ranging from 10 TWh (*CAN*) to 155 TWh (*IFS*), providing from 0.2% to 2.6% of total power generation.

There are currently no established ocean energy markets. In the last decade, only 277 MW of ocean power was installed **globally** (most of it experimental or research-driven), compared to 126 GW of PV installed in 2020 alone. Moreover, 92% (255 MW) was installed in 2011 in the Republic of Korea (one power plant). Based on the limited data from energy scenarios, it can be concluded that in the next decade between 1 GW and 8 GW of ocean energy generators could be installed per year. After that, the rate of installations could rise up to 18 GW a year (other, less optimistic, studies see only around 2 GW of new installations per year), a negligible number, even when compared to current installations of wind or solar power plants. The EU share of ocean energy could be around 10% - ranging from 1.6 GW in the period 2020-2030, and increasing to 1.9 GW afterwards.

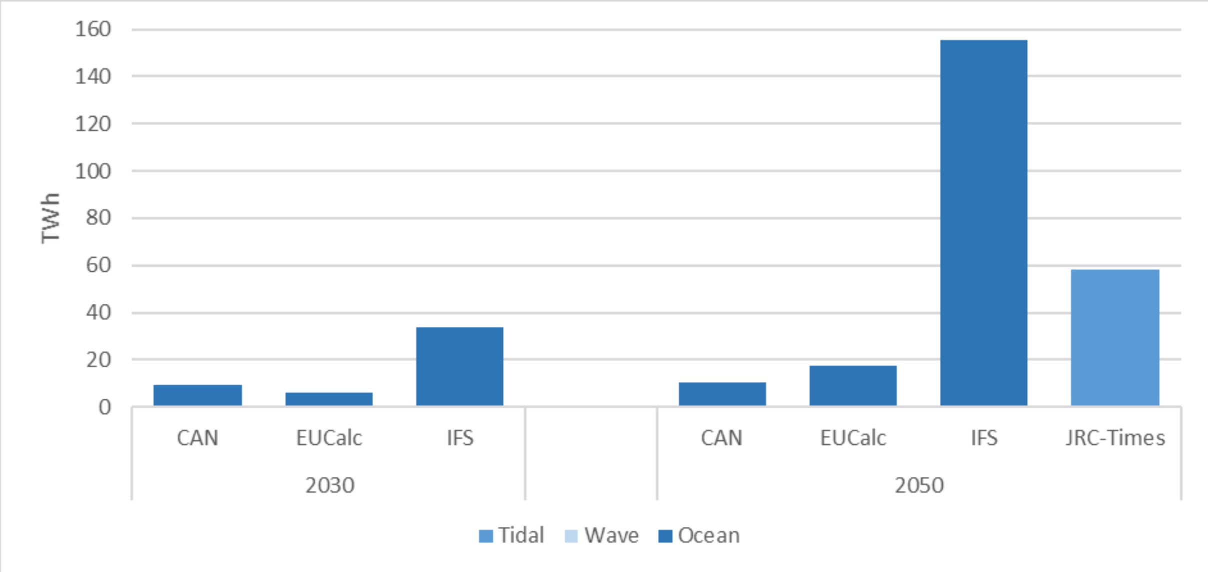
No scenario studies that provide data on ocean energy give it a significant role in electricity generation. Even *IFS*, a clear leader in ocean capacity development, sees only a marginal role for ocean power up to 2050, providing less than 2% of global electricity.

Figure 41. Installed ocean power capacity in the EU



Source: JRC analysis based on scenario studies

Figure 42. Electricity generation from ocean energy in the EU



Source: JRC based on scenario studies

4.8 Wind

Currently, wind energy is primarily used for producing electricity in the power sector (centralised). Distributed wind generation still remains a niche market (dominated by individuals and SMEs) and does not play a significant role. The market is dominated by horizontal axis, three-blade wind turbines. Although the wind turbines are similar, statistically, wind power plants are often split into onshore and offshore. The location (onshore or offshore) and for offshore turbines, the type of foundation (monopole, jacket and floating, just to name a few) significantly affects the installation costs and therefore economic efficiency. Globally, there was 698 GW of onshore wind capacity and 34 GW of offshore wind installed in 2019. In the EU, there was 162 GW of onshore and 15 GW of offshore (IRENA, 2022c).

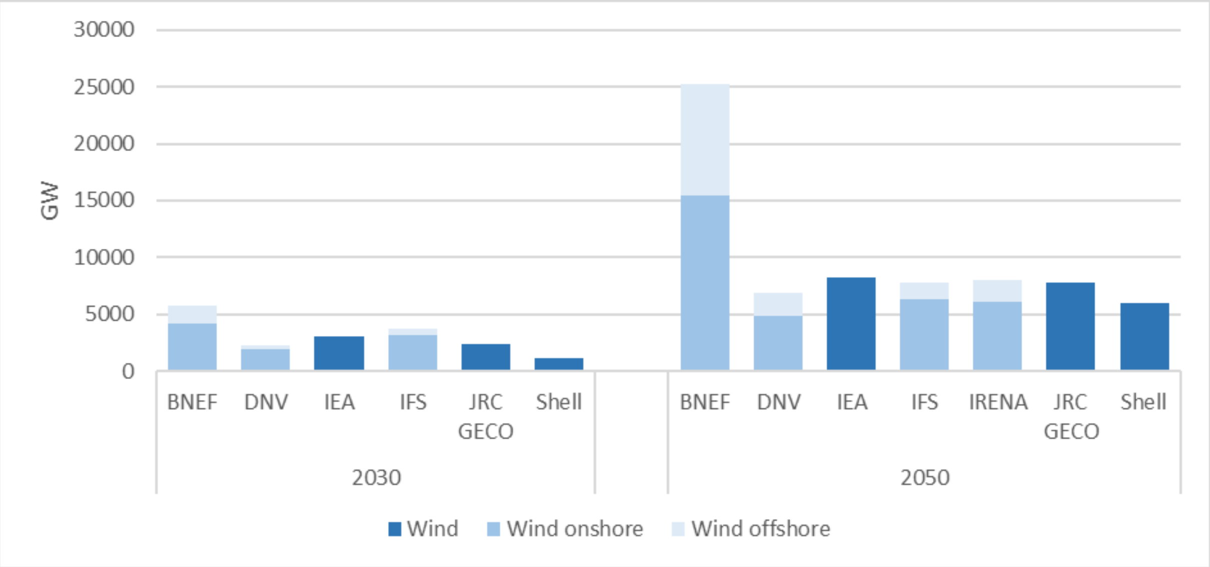
The wind power generation market is dominated by onshore wind: globally, 94% of wind power is generated by onshore (89% in the EU). Power generation from both onshore and offshore wind experienced remarkable growth in the last eight years: the global CAGR for onshore was 17% and for offshore 32% (in the EU these were 10% and 29% respectively). In 2010, the EU was the global leader, generating 40% of global onshore and 56% of offshore wind electricity, but it is currently rapidly losing its lead, with its onshore share dropping to below 24% in 2018. However, the EU is still leading in offshore wind power generation, providing around 47% of global offshore wind generation.

Trends in installed capacity are similar: the EU share in onshore dropped from 33% in 2010 to 27% in 2018, and in offshore, the EU share dropped from 52% to 45%. In 2020, the biggest market for wind energy was China, adding 72.5 GW of wind generation in one year, compared to less than 10 GW installed in the EU and 14 GW in the USA. Even in offshore wind installations, where the EU traditionally had the leading role, it was bypassed by China in 2020 when 3 GW were installed in China as against 2.9 GW in the EU.

Wind technologies are among the best represented in energy scenarios of all the renewable generation technologies. All scenario studies analysed have information on wind (either only generation or generation and installed capacities). Moreover, the majority of studies provide data separately on onshore and offshore technologies. One study (*DNV*) split offshore wind into two subcategories based on foundation: fixed and floating. As with solar power generation, the split is not always clear between power generation for end-use and power dedicated as an input for green hydrogen production. Depending on the modelling approach, solar/wind capacities/generation dedicated to hydrogen production are bundled together with electrolysers and do not appear in the power sector, but rather are reported in the energy transformation sector. For example, in the case of *BNEF*, in 2030, over 70% of offshore wind and 30% of onshore wind installations are already dedicated to hydrogen production. By 2050, dedicated installations for hydrogen production account for 80% of offshore wind and 55% of onshore wind installations. In this report we sum up (when data allows) all wind installations, both for power and hydrogen production.

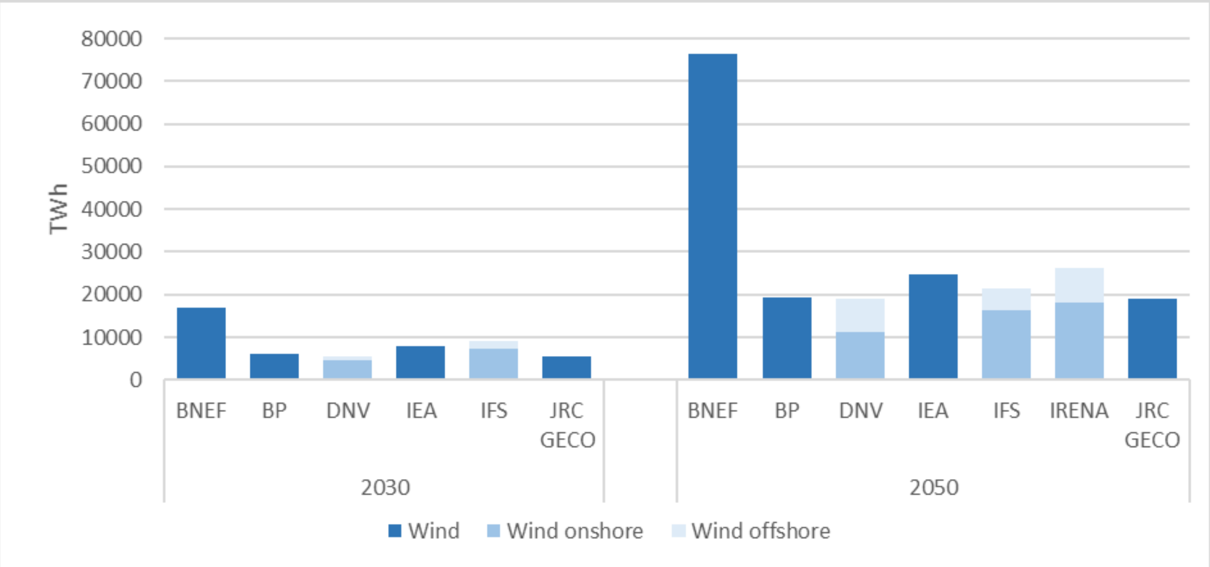
By 2030, the majority of scenarios see a **global** wind capacity growth of around 3 000 GW (**Figure 43**), with clear outliers in both directions. *Shell* does not see any major developments in global wind capacities (in this scenario, gas power plants still play a major role), and at the other extreme, *BNEF* sees almost 6 000 GW installed by 2030 (driven by hydrogen production) – an almost eightfold increase in 10 years. Scenarios that split results into onshore and offshore wind confirm current trends – the majority of new installations are for onshore wind, with the offshore share varying between 15% and 30%. The generation pattern in 2030 is similar to the installed capacity. The majority of scenarios analysed see a wind-based generation of around 5 000-8 000 TWh (**Figure 44**), an almost sixfold increase compared to 2019. There are some noticeable outliers – *BNEF* has almost 17 000 TWh of electricity produced, 40% of which is used for hydrogen production. There is no clear outlier at the lower extreme. Several studies (*JRC GECO*, *DNV* and *BP*) see generation of around 6 000 TWh, still partially relying on fossil fuels, mainly coal and gas.

Figure 43. Global installed wind power capacity



Source: JRC analysis based on scenario studies

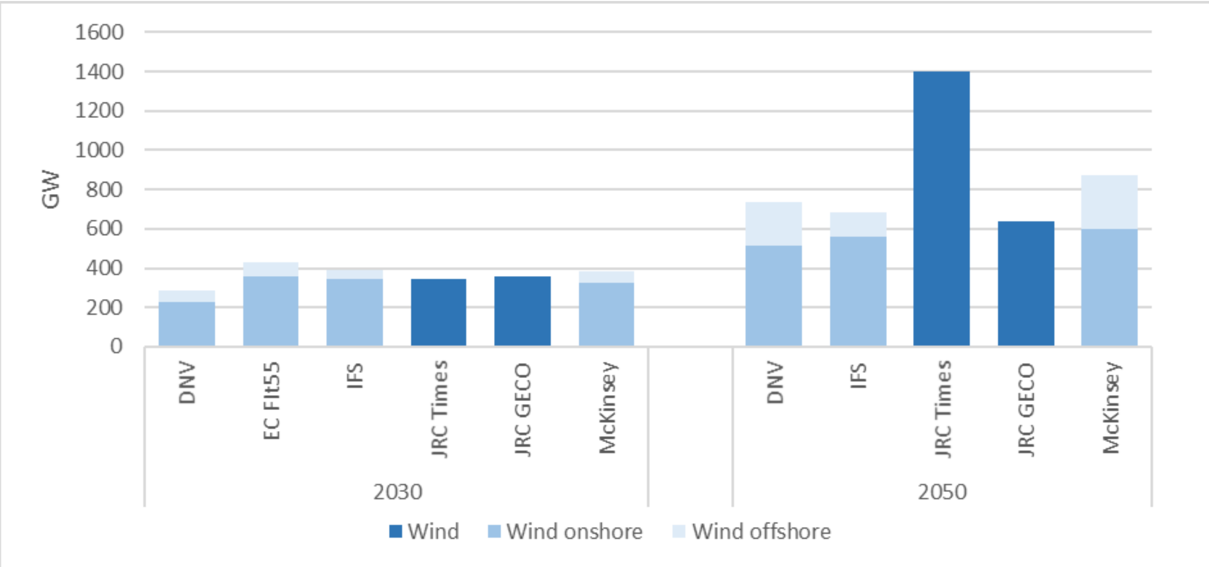
Figure 44. Global electricity generation from wind



Source: JRC analysis based on scenario studies

All scenarios agree that by 2030, the **EU** growth rate of installed capacity in wind power is slower than global trends (partly due to higher base). In 2030, the EU accounts for only 11-16% of global wind installed capacities, compared to almost 25% in 2020. Nevertheless, this does not mean there is no growth: in the period 2020-2030, scenarios see 11-25 GW of capacity installed per year compared to less than 10 GW in 2020 (**Figure 45**). By 2030, when excluding a clear outlier (*BNEF*), the total installed capacity of wind energy in the EU is on average around 300-400 GW, with a higher variability than global results. In the scenarios analysed, *EC FIT55* has the highest wind capacity (427 GW), driven by decarbonisation goals. REPowerEU mention even higher wind installed capacity: 510 GW in 2030. *DNV* has the lowest capacity due to a lower transition and the still high utilisation of fossil fuels. On the generation side, *CAN* is a clear outlier in the EU (**Figure 46**) – *CAN* (but does not provide installed capacity data). Driven by ambitious assumptions on decarbonisation, *CAN* sees more than double the wind-based generation of all the other studies and a fivefold increase compared to 2019. All other studies see only a two to threefold increase. All studies that provide a split between onshore and offshore see a very similar role for offshore wind generation technology, ranging between 170 GW and 280 GW, while onshore ranges between 470 GW and 1 660 GW.

Figure 45. Installed wind power capacity in the EU



Source: JRC analysis based on scenario studies

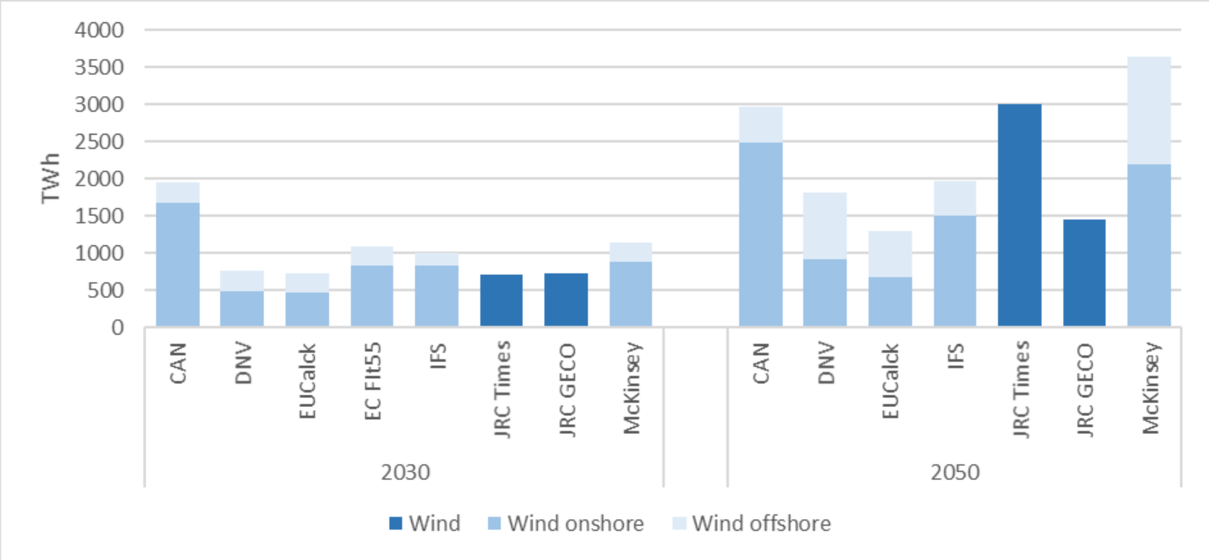
By 2050, wind, together with solar, will become the dominant source of energy in the power sector. Wind will provide over 30% of **global** electricity for final demand in the scenario studies analysed (generating from 20 000 TWh to 25 000 TWh per year). This is more than a tenfold increase compared with today's generation. The majority of scenarios see around 7 000-8 000 GW of wind power plants installed. By 2050, the role of offshore wind will be even more crucial and could amount to a third or, in some cases, up to a half of total wind capacity installed.

Of all the scenarios assessed, there was a clear outlier: *BNEF*, which is driven by market forces linked to the decarbonisation goals and anticipates a fast transition to a hydrogen economy. This scenario sees a deployment rate of wind capacity three times higher than all other studies. By 2050, almost 80% of offshore and 56% of onshore wind capacities are dedicated to hydrogen production.

In 2050, all scenario studies agree on an increasing role for wind in **Europe** (**Figure 45**). In 2050, the installed capacity of wind power plants could range from 650 GW to 870 GW, with one clear outlier – *JRC TIMES* at 1 400 GW. The main drivers behind this increase are the rapid deployment of hydrogen technologies and the use of synthetic fuel in industry and transport decarbonisation efforts. At the lower extreme, *JRC GECO* foresees only 635 GW of installed wind power due to lower electricity demand and a reliance on CCS.

Scenarios do not agree on the role wind offshore will play in 2050. *CAN* sees European offshore wind providing only 16% of total wind generation, while *DNV* and *EUCalc* put that closer to 50%. In 2050, wind energy could satisfy more than 30% of the EU's electricity demand; a substantial growth compared to about 20% in 2030.

Figure 46. Electricity generation from wind in the EU



Source: JRC analysis based on scenario studies

It is worth noting that almost all studies see a growing capacity factor for offshore wind power plants in 2030 and beyond. Based on statistical data, the capacity factor of onshore wind turbines is currently around 26% globally (and 34% for offshore). The EU has similar numbers (24% and 36%). In 2030, the onshore wind capacity factor remains around 26%, and offshore could reach 40%. In 2050, these figures will rise to 30% and 41-48% respectively. This increase could be attributed to technological improvement and solved curtailment problems (for example by using hydrogen and/or storage). The EU numbers are again very similar.

In the next decade, the **global** wind power market could rise from the current 111 GW installed capacity per year to 230 GW per year on average until 2030 (with *BNEF* seeing twice as much). From 2030, the global market could become saturated, with about 250 GW of new and refurbished capacity per year (excluding *BNEF* with almost 1 000 GW of annual installations). In 2020-2030, the share of offshore wind could be around 15-20%, increasing to almost 30% in 2050. In the **EU**, the wind market will show lower growth rates, increasing from around 10 GW in 2020 to almost 20 GW per year in the period 2020-2030 and beyond. Only *JRC TIMES* sees a rapid increase of wind installations, reaching over 50 GW of new capacity per year. Offshore wind could amount to about 20-30% of total wind installations. In the EU, from 2030, another 20 GW per year could come from replacement/refurbishment of wind power installations at end of life (compared to about 250 GW of refurbishments globally).

5 Conclusions

This report reviewed the results of 13 energy scenario studies (selected from 47 works published from January 2019 till January 2022). From each study, one scenario was selected, outlining deep decarbonisation pathways for the global and/or European energy systems. The studies selected were authored by a variety of stakeholders, ranging from industry, international and intergovernmental organisations to academia, consultants and NGOs. Based on different narratives, assumptions and modelling tools, the results cover a wide range of possible pathways to reach a net-zero future, giving insights into possible zero-carbon energy technology deployment and ways to ensure a secure and sustainable supply to meet energy demand.

The analysis focused on overall energy system developments and on the deployment of seven renewable technology groups: bioenergy, solar energy, geothermal, ambient heat, hydropower and ocean and wind energy, some of which were divided into several distinct sub-technologies. In addition to the seven main renewable technology groups, one of the enabling technologies - hydrogen – was also assessed.

Across all the scenario studies reviewed in this report, there is one common understanding: electrification plays a strategic role in the pathways to decarbonisation. Despite differences in levels of ambition, methodological approaches and transformation speeds, in the future, electrons would fuel both the global and the European economies. There are differing views on how electricity would be generated and used, but all the studies reviewed see a considerable increase in electrification in all end-use sectors, either directly or via enabling intermediate technologies, like green hydrogen and synthetic fuels. By 2030, electricity and electricity-based fuels are projected to meet above 40% of total final demand in the EU. According to some energy scenario studies, by 2050, electricity and electricity-based fuels could satisfy up to 90% of total final demand in the EU. At a global scale, electrification reaches slightly lower levels. Electricity and electricity-based fuels would meet, on average around 30% of total final demand by 2030 and almost 70% (on average) by 2050. In a transition to a full hydrogen economy, *BNEF* projects that 82% of global final demand would be met by renewable electricity or hydrogen-based fuels.

While the energy scenarios assessed see different future energy mixes, two main technologies dominate the power sector: wind (both onshore and offshore) and solar (mostly PV and some CSP). In most scenarios, these provide around 70-80% of all electricity generated. In some extreme cases, they can reach as high as 90%. Scenario studies not necessarily agree whether solar or wind will be more important. In the majority of studies, the production levels of these technology groups are comparable, with some difference in geographical scope: globally, there is a tendency to prefer solar, and in Europe, wind is preferred, but it depends on the study and the differences are not significant.

The majority of **bioenergy**, both globally and in the EU, is used in final demand sectors, and (on average) in the medium term, it shows a slight increase on current levels. Despite small changes in global bioenergy consumption in the next decade, there are noticeable shifts in sectoral demand: studies see a decreasing demand for solid biomass in the buildings sector (reduction rates vary across studies), replaced by an increase in demand from the industry and transport sectors. In 2050, global trends diverge: some scenarios see a growth after 2030, while others see a decrease (driven by electrification of the buildings sector). There is significant variation in bioenergy projections in the EU by 2030: studies see both upward and downward movement between 2021-2030. Over the longer term, the majority of the studies reviewed project that biomass utilisation in the EU would be lower in 2050 than 2030, with the most significant decrease in demand taking place in the buildings sector.

While most the energy scenarios assessed see a growing role for bioenergy in power generation by 2030, they diverge on the growth rate and the overall importance of bioenergy in the power mix, settling at a CAGR of around 7-8% on average. Solid biomass remains the main component in power production. In the EU, the growth is even slower, at around 5% CAGR. By 2050, most studies see electricity generation from bioenergy continuing to grow, but at a slower rate. By 2050, bioenergy could provide around 5% of global power generation.

Solar energy and wind are currently the fastest evolving electricity generation technologies. According to all scenarios assessed, solar and wind would dominate the market by 2050. Between 2021 and 2050, global installed solar power capacity projected to grow sevenfold on average, reaching around 5 000 GW by 2030. In the EU, growth is projected to be slower than global levels– with 'only' a threefold increase over ten years, averaging around 370 GW of installed power by 2030. Installed capacity of solar power continues to grow after 2030, reaching 10 000-15 000 GW of total installed power globally by 2050, providing 22-40% of total electricity generation. In the EU, solar grows more slowly, reaching only around 1 000 GW on average by 2050, and providing 13-22% of total power generation in the EU in 2050. PV remains the main solar technology, accounting for more than 90% of solar power installed capacity in most scenarios analysed. Besides providing electricity, solar energy can also be used to produce heat for buildings and industry, but scenario studies do not usually provide sufficient data to assess the contribution of solar technology to heat demand in end use sectors. Moreover, studies diverge on the importance of solar thermal in the future, with results ranging from almost zero to 6 500 TWh globally in 2050, which is considerably lower than solar power generation, reaching 20 000 TWh on average in 2050.

Geothermal energy is used both for electricity generation in the power sector and as a direct source of thermal energy in end use sectors. Geothermal power installations are still low in number and comparable to emerging technologies. In 2020, there was only 14 GW of geothermal power capacity installed globally. The majority of the scenario studies analysed do not provide disaggregated data for installed capacity of geothermal power plants. Globally, geothermal annual power installations are projected to grow from 1 GW to 14 GW per year, reaching around 140 GW of installed capacity in 2050. Despite a tenfold growth in installed capacity, energy scenario studies see geothermal providing only 1-2% of total global electricity generation by 2050. In the EU, scenarios assessed do not see significant additions to capacity. Geothermal energy for thermal use follows similar trends to power generation, with a negligible share even in 2050 (in the scenario studies that provide data).

Up until recently, while present in underlying mathematical models, **heat pumps** (ambient heat) was not usually directly included in energy scenario studies results: only electricity used for heat pumps was added as part of the electricity consumption. That makes proper quantitative analysis impossible. Nevertheless, energy scenario studies stress the importance of ambient heat in the future end use mix, mainly to cover heating demand in the buildings sector, but some also include heat pumps as a source of low and medium temperature heat in industry. In 2030, the projected number of heat pumps varies between 200 million and 600 million globally (providing up to 20% of final demand in the buildings sector), reaching up to 1 800 million by 2050. Scenarios projections diverge on the take-off speed of heat pumps in the EU (there are six-fold differences in figures for 2030), but by 2050, results converge at around 530 TWh of ambient heat demand. Rapid deployment of heat pumps in the EU is essential to achieving REPowerEU targets, requiring at least 30 million heat pumps to be added by 2030[22].

Hydrogen is the only intermediate (secondary) energy carrier covered in detail in this report. According to scenario projections, in the future, hydrogen would mainly be produced by intermittent renewable electricity (wind and solar) and used in hard-to-abate subsectors of industry and transport. By 2030, global hydrogen[23] demand is negligible, accounting for less than 1000 TWh. Scenario results diverge on the sectoral distribution of consumption, but buildings and transport will likely be early adopters. Between 2030 and 2050, global hydrogen demand skyrockets, with transport and industry as the main markets. Only three studies see a role for hydrogen in power generation (acting as flexibility and storage provider). In the EU, scenario studies see, on average, 150 TWh of hydrogen consumed for energy needs by 2030, with transport as the clear early adopter. By 2050, hydrogen demand in end use sectors would rise to 1 050 TWh on average, with transport still the biggest consumer in the majority of studies, and industry following closely behind. REPowerEU and its supporting legislation could at least double green hydrogen demand in the medium term, compared with previous projections.

Hydropower is currently the main renewable energy source used for power production, accounting for 50% renewable power capacity and 63% of generation globally. Taking into account low growth rates (observed in the recent past and projected in the future), its relative importance will reduce: by 2030, none of the global energy scenarios see any major development in hydropower, on average growing only 3.5% per year between 2021-2030 and reaching around 1 500 GW of installed capacity (compared to 1 333 GW today) and falling behind both wind and solar. After 2030, hydropower is projected to continue the slow growth, where in most scenarios it reaches only around 2 000 GW of total installed capacity globally and less than 10% of total electricity supply in most studies by 2050. Energy scenario studies see no significant hydropower growth potential in the EU in 2030 or 2050.

Ocean energy is the only emerging technology group included in this report, consisting of two technologies: wave and tidal. With only 0.5 GW installed globally, half of it in the EU, it does not currently play any role in the power sector. Due to low shares, energy scenarios rarely provide quantifiable data on ocean energy, but from the limited information available, it can be concluded that even with high growth potential (150-fold

[22] The European Heat Pump association translates REPowerEU numbers to 60 million heat pumps installed in the EU by 2030 (EPHA, 2022)
[23] By hydrogen we mean hydrogen and hydrogen-based synthetic fuels.

increase in some scenario studies by 2050), due to its very low base, ocean energy will not play a significant role by 2050 either globally or in the EU.

Wind energy and solar are currently the fastest growing electricity production technologies both globally and in the EU. According to all the low-carbon scenario studies reviewed, solar and wind would dominate the power market in the future. By 2030, global wind installed capacity grows to 3 000 GW on average (with some outliers projecting almost 6 000 GW) and with an almost six fold increase in generation compared to 2019. By 2050, global wind installations reach 7 000-8 000 GW and, on average, generate over 30% of the world's electricity. Wind deployment trends in the EU would be slower, adding below 20 GW on average of new capacity per year, reaching 300-400 GW in 2030 and around 800 GW in 2050. The share of installed capacity of offshore wind remains low in the future, but in some scenarios it reaches 30%, while generation is projected to reach close to 50% of total wind generation due to the higher average capacity factor. It is worth noting that in the future, almost all the scenario studies analysed see a growth in the capacity factor of offshore wind.

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List of abbreviations and definitions

PV	Photovoltaic
CSP	Concentrated Solar Power
CAGR	Compound Annual Growth Rate
EU	European Union as of February 1 2020 (27 member states) also EU27
EU27	European Union as of February 1 2020 also EU
EU28	European Union as of before February 1 2020
PSH	Pumped Storage Hydropower
BECCS	Bioenergy with Carbon Capture and Storage
OECD Europe	OECD members from Europe (Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom)
E-Fuels	Electric fuels. Hydrogen from electrolysers and its derivatives.
IRENA	International Renewable Energy Agency
IEA	International Energy Agency
BNEF	Bloomberg New Energy Finance
NEO	BNEF New Energy Outlook
LCOE	Low Carbon Energy Observatory
CETO	Clean Energy Technology Observatory
DG ENER	European Commission Directorate General Energy
DG RTD	European Commission Directorate General Research and Innovation
JRC	European Commission Directorate General Joint Research Centre
DG CLIMA	European Commission Directorate General Climate Action

List of figures

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Joint Research Centre

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