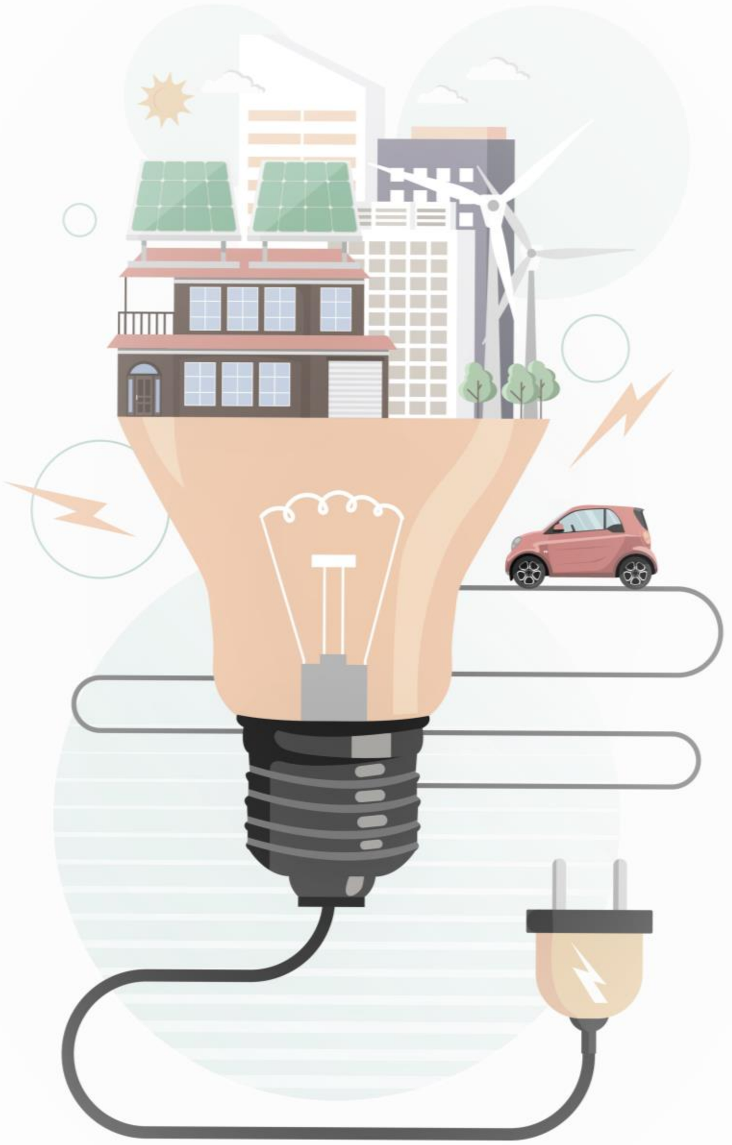
European Commission

ASSET Study on

Energy Outlook Analysis



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About ASSET

ASSET (Advanced System Studies for Energy Transition) is an EU funded project, which aims at providing studies in support to EU policymaking, including for research and innovation. Topics of the studies will include aspects such as consumers, demand-response, smart meters, smart grids, storage, etc., not only in terms of technologies but also in terms of regulations, market design and business models. Connections with other networks such as gas (e.g. security of supply) and heat (e.g. district heating, heating and cooling) as well as synergies between these networks are among the topics to study. The rest of the effort will deal with heating and cooling, energy efficiency in houses, buildings and cities and associated smart energy systems, as well as use of biomass for energy applications, etc. Foresight of the EU energy system at horizons 2030, 2050 can also be of interests.

The ASSET project will run for 36 months (2017-2019) and is implemented by a Consortium led by Tractebel with Ecofys and E3-Modelling as partners.

Disclaimer

The study is carried out for the European Commission and expresses the opinion of the organisation having undertaken them. To this end, it does not reflect the views of the European Commission, TSOs, project promoters and other stakeholders involved. The European Commission does not guarantee the accuracy of the information given in the study, nor does it accept responsibility for any use made thereof.

Authors

This study has been developed as part of the ASSET project by E3 Modelling.

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1. Introduction

In 2019, the European Commission announced the EU Green Deal[1] as its strategic plan to achieve climate neutrality by mid-century, protect the environment and boost the region's economy. To transition to a net-zero greenhouse gas emissions economy over the next decades, a vast transformation of the EU energy system will need to take place, in both supply and demand sectors. Therefore, it is important to identify the technologies that may enable the transition from an energy-system perspective, better understand what drives their development and their role in the future energy mix. This suggest the need to explore the relationship between research and innovation activities for those technologies that can help meet the EU Green Deal objectives.

For this purpose, the present study looks into assumptions and results of different deep decarbonisation outlooks that stem from entirely independent studies, frameworks and storylines. A first goal of the present analysis is to support with evidence the clean and low carbon technology solutions and innovation that are needed for 2030 and 2050. By identifying the role of technological evolution within the transition outlooks as well as possible technology gaps, the study outlines the directions of investment both in technological development and infrastructure. Ultimately, the aim of comparing the different outlooks presented in this report is to identify and bring together ideas and findings that are common regarding key technologies and policies and which may offer useful guidance ahead of the EU Green Deal.

[1] COM(2019) 640 final. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

2. Energy system analysis and energy systems models

2.1. Energy system analysis

To understand the likely development of the energy system in a complex transformation such as the "energy transition", the use of a discipline called energy system analysis often applied.

Energy system analysis is a multi-disciplinary applied scientific field based on economics, operations research and engineering. Its distinguishing feature is that is considers the energy sector as a whole – as a system – contrary to sub-sector approaches, like power economics, petroleum economics, etc.. The goal of energy system analysis is to support decision-making: energy policy analysis, impact assessments, cost-benefit evaluation, pricing and investment planning. Energy system analysis often considers the interactions with other systems, such as the economy or the environment, leading to an energy-economy-environment (E3) analysis. The aim is usually to provide quantified results, which makes energy system analysis data-intensive (depending on the resolution of the models). Usually the approach is to use mathematical models as a way of approaching complex problems, emphasizing on comprehensive rather than partial analysis. The main objectives of energy systems analysis include:

- Understanding inter-fuel substitution;
- Performing a closed-loop energy demand and supply through market competition, to analyse the effects of changes on both demand and supply;
- Trade-offs between demand-side and supply-side energy investment;
- Understanding behaviour of agents and the influence of policy instruments;
- Understanding the developments and effects of energy carriers and their production chains (e.g. hydrogen economy versus electricity economy);
- Understanding the loop between energy and the economy by closed loop simulations.

Energy systems analysis is about problem solving:

- Systems simulation: to understand complex systems and training;
- What-if questions and the resulting analysis for policy analysis feeding into impact assessment and investment evaluation;
- Normative analysis based on system optimization for policy and investment recommendation;
- Forecasting – projections of demand, prices, technology penetration: forecasting for the short term and projections for the longer term;
- Scenario construction and comparison of scenarios to explore uncertain futures and policy analysis.

2.2. Energy system models

Energy system models include models of many different methodologies and sectoral scope; each has a specific use and can provide quantifications for different types of problems.

A first level classification of modelling approaches for the energy sector can be based on their scope:

- Sectoral energy approach: covering the supply and/or demand for specific fuels or energy forms;

- Industry market approach: including both supply and demand relationships and their interactions but for a specific fuel or energy form;
- Energy System Analysis approach: encompassing supply and demand relationships and their interactions for all kinds of energy fuels and forms;
- Energy – economy approach: focusing on relationships and interactions between the energy system and the entire economy.

Looking into different methodological approaches, further classifications of models may be defined:

- Considering the *energy system coverage*, we can identify the **partial equilibrium** approach and the **general equilibrium** approach. A partial equilibrium approach would consider the energy system assuming that the macro-economy remains unaltered with changes in the energy system. In contrast a general equilibrium approach considers the impact on the macro-economy from changes in the energy system and vice-versa. In order to close the loop of the energy system with the macro-economy, a general equilibrium modelling approach can integrate both energy and economy in the same model; alternatively, a linkage of an energy system and a macro-economic model can handle the energy-economy analysis via an iterative process;
- Regarding the *mathematical structure* of a model, two general approaches are practiced: system-wide **optimization** and **market equilibrium**. The former optimises the entire energy sector via a single objective function, which aggregates all sectors. The latter, simulates the behaviour of each sector separately, in various mathematical forms including optimisation at the sectoral level, and performs equilibrium of quantities and prices at the overall, system-wide, level of the energy system;

The overall optimisation approach can be very useful, for example:

- It allows to identify the least-cost pattern of resource use and technology deployment over time;
- It can inform about priorities of constraint relaxation, e.g. new investment, new networks or resources, through the marginal costs and values derived from the optimization process;
- It quantifies the sources of emissions from the associated energy system;
- It quantifies the system-wide effects of changes in resource supply, technology availability and energy and environmental policies;
- It provides a framework for exploring and evaluating alternative futures, and the role of various technology and policy options;

The main drawbacks of this approach are that:

- There are technical difficulties integrating both energy supply and demand due to mathematical complexity of optimization. It is often the case that optimization models include a very simplified representation of the demand side sector, if at all;
- Due computer solution and time difficulties, the overall optimisation models are usually applying linear programming. The linear approach is a severe simplification of reality and presents serious undesirable solution difficulties, such as the flip-flop (instability) of solutions;
- Optimization cannot represent imperfect market competition;
- The major drawback is the lack of representation of prices explicitly.

Under a market equilibrium approach, the model is organized in demand and supply modules which are solved independently, they are however coordinated through a market equilibrium module. This modular approach is iterative. A simplified description is the following: step (1) the demand side module solves for a specific energy prices level, step (2) the supply side module solves so as to meet the demand defined in step (1), step (3) through step (2) a new level of energy prices is defined and we move back to step (1) and repeat the approach, iterating on energy prices until an equilibrium is reached. It is also possible to integrate the sectoral modules in a single model if all modules and equilibrium conditions are expressed as mixed complementarity problems; in this case, the overall model solves as an Equilibrium Problem with Equality and Inequality constraints (EPEC). The advantages of this approach are that it encompasses the optimisation approach and it also provides with flexibility: each sub-model may be fairly detailed and complex, can also be non-linear, and also adapted to the specificities of each sub-sector of the energy system. In addition, the sub-models may be selected from a library according to the particular needs of a study. Moreover, because it allows for representing different market competition regimes and handles prices and their formation explicitly, being able to represent regulatory approaches for tariffs and prices. The drawback of this approach is the modelling complexity and if the modules are large computer time and computer resource size.

The market equilibrium energy models can be further classified in reduced-form models and in structural models:

- The reduced-form models employ equations, instead of complex modules, to represent the causality between drivers and outcomes, for example regarding demand for energy in a sector and fuel substitutions. Usually, these equations are estimated econometrically. The overall model is then a system of non-linear and often dynamic (with lags) equations, and is solved using non-linear simultaneous equation solvers. Sometimes, the simultaneity applies over time, rather than on every single year, to simplify the model solution. The reduced-form models can include formulations which mimic optimisation to represent capacity and fuel mix in a sector, e.g. in power generation. But the optimisation is not full and the models use mathematical tricks to be able to embed them in the structure of simultaneous equation model while preserving optimisation features. Examples of reduced-form models are POLES, PROMETHEUS and the World Energy Outlook model of IEA;
- The structural market equilibrium models are modular and represent the behaviour, as well as capacity and fuel mix in each sector, as a fully-fledged microeconomic problem, meaning that it includes the structural details of this problem and often embeds in it both engineering and economic features. Irrespective of the mathematical form of the module, i.e. solved as optimisation or mixed complementarity, the distinguishing feature is the structural representation of the decision-making problem and not a simple causality relationship between drivers and outcomes. As mentioned above, the overall mathematical solution of structural models may rely on iterations or on mixed-complementarity problem algorithms. Examples of structural energy system models are NEMS and PRIMES.

The reduced-form models are often classified as top-down models because of the direct formulation of causalities between drivers and outcomes, which may imply a poor representation of engineering features. Complex reduced-form models, such as those mentioned above, do include engineering features at a significant detail, as well as concrete policy instruments, and so the top-down characterization is not appropriate for them. Also, the overall optimisation models have been often classified as bottom-up models because they include engineering and policy features at a significant detail. However, the characterisation bottom-up is somehow misleading because these models are not able to represent the specificities of decision-making in each at an appropriate degree of detail. The structural market equilibrium models have been often classified as hybrid models because they are top-down as they represent price formation and market equilibrium explicitly, as the reduced-form models also do, and at the same time are bottom-up because they represent in detail engineering and policy features.

The overview presented in Table 1 (energy models) and Table 2 (economic models with energy component), is a list of existing models and their classification based on the characteristics described above.

Table 1 Overview of selected energy models

Model name	General category	E3 system coverage	Mathematical structure	Engineering and policy features	Regional coverage	Builder
EFOM	Energy System Model	Partial Equilibrium	Optimisation	Bottom-up	Single country	Various in the EU and IER
MARKAL TIMES	Energy System Model	Partial Equilibrium	Optimisation	Bottom-up	Single country	ETSAP
MESSAGE	Energy System Model	Partial Equilibrium	Optimisation	Bottom-up	World	IIASA
MEDEEs	Energy System Model	Partial Equilibrium	Simulation	Simple accounting model	Single country	ENERDATA
POLES	Energy System Model	Partial Equilibrium	Market Equilibrium	Reduced form	World	IEPE and JRC-IPTS
PRIMES	Energy System Model	With limited macro feedback	Market Equilibrium	Structural form, hybrid model	Individual countries	E3MLab/ NTUA and E3Modelling
ENPEP	Energy System Model	Partial Equilibrium	Market Equilibrium	Simple energy balance model	Single country	IAEA
WASP	Power Sector Model	Supply model	Optimisation	Bottom-up	Single country	IAEA
MAED	Energy System Model	Partial Equilibrium	Simulation	Simple accounting model	Single country	IAEA
IEA model	Energy System Model	With limited macro feedback	Market Equilibrium	Reduced form	World	IEA World Energy Outlook
LEAP	Energy System Model	Partial Equilibrium	Accounting	Simple energy balance model	Single country	Stockholm Institute
Prometheus	Global energy system model	Partial equilibrium	Market Equilibrium	Reduced form	World	E3MLab/ NTUA and E3Modelling

Table 2 Overview of selected economic models with energy component

Model name	General category	E3 system coverage	Mathematical structure	Economic vs engineering	Regional coverage	Builder
HERMES	Macroeconomic model	With energy focus	Econometric	Top-down	European countries	European Commission
NEMESIS	Macro and energy model	With full energy sub-module	Econometric	Top-down	European countries	ERASME, France

Model name	General category	E3 system coverage	Mathematical structure	Economic vs engineering	Regional coverage	Builder
E3ME	Macro-econometric model	With energy focus	Econometric	Top-down	World	Cambridge Econometrics
GEM-E3	Macro and energy model	With full energy sub-module	General Equilibrium	Top-down	EU and World	E3Mlab/NTUA and KUL
PACE	Macroeconomic model	With energy sub-module	General Equilibrium	Top-down	EU and World	ZEW
WorldScan	Macroeconomic model	With energy focus	General Equilibrium	Top-down	World	CPB (NL)
Gemini	Macroeconomic model	With energy focus	General Equilibrium	Top-down	World	IDEI (FR)
PANTA RHEI	Macroeconomic model	With full energy sub-module		Top-down	Germany	IER (DE)
G-Cubed	Macroeconomic model	With energy focus	General Equilibrium	Top-down	World	Australian Nat. University
Green and EPPA	Macroeconomic model	With full energy sub-module	General Equilibrium	Top-down	World	OECD and then MIT
WIAGEM	Macroeconomic model	With energy sub-module	General Equilibrium	Top-down	World	DIW
AMIGA	Macroeconomic model	With full energy sub-module	General Equilibrium	Top-down	World	Argonne Nat. Lab. and EPA
Kiel-DART	Macroeconomic model	With energy focus	General Equilibrium	Top-down	World	Kiel Institute (DE)

3. Brief overview of selected studies and selection of outlooks

For the purpose of this analysis the following studies were selected in collaboration with the European Commission services[2]:

- *EU Long-Term Strategy* (EC LTS): In-depth analysis accompanying the Communication "A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy"[3];
- *IEA World Energy Outlook* (IEA WEO) version 2019[4];
- *JRC Global Energy and Climate Outlook* (JRC GECO) 2019[5];
- *Bloomberg New Energy Finance* (BNEF), New Energy Outlook 2019[6];
- *IRENA* Global Renewables Outlook: Energy Transformation 2050, 2020 Edition[7];
- *Greenpeace* (GP): Energy revolution – A sustainable world energy outlook 2015[8].

The tables Table 3 through Table 8 presented in the following pages (section 3.1), provide an overview of the key features of the studies, with respect to:

- *Official name* of the study;
- *Organizations*, involved in the study. The publisher does not always coincide with the analyst;
- *Publishing date*;
- *Scenarios*, included the study, with information on climate mitigation ambition;
- *Geographic resolution*;
- *Time horizon*;
- *Model(s) used*.

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[2] Other recent energy transition outlooks found in the literature but not analysed in this study include the following:

1. "Global Energy System based on 100% Renewable Energy - Power Sector", Author: LUT university of Technology, funded by DBU, Stiftung Mercator, November 2017
2. "Energy Transition in Europe across Power, Heat, Transport and Desalination Sectors", Author: LUT university of Technology, funded by DBU, Stiftung Mercator, December 2018
3. "100% Renewable Europe", Author: LUT university of Technology, funded by Solar Power Europe, 2020
4. Paltsev, Sergey. 2020. 'Projecting Energy and Climate for the 21st Century'. Economics of Energy & Environmental Policy 9 (1). Also, in: https://globalchange.mit.edu/publication/17394
5. "A comparison of three transformation pathways towards a sustainable European society - An integrated analysis from an energy system perspective", Korkmaz Pinar et al., Energy Strategy Reviews 28 (2020)
6. "The Vision scenario for the EU", Oeko institut, funded by Greens/EFA Group in the European Parliament, February 2017
7. "Energy Transition Outlook", DNV-GL, 2019
8. "Decarbonizing the EU's Energy System", SET-NAV H2020 project, Authors Pedro Crespo del Granado et al., April 2019
9. A comparison of outlooks is also presented in the JRC publication "Towards net-zero emissions in the EU energy system by 2050".

[3] https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

[4] https://www.iea.org/reports/world-energy-outlook-2019

[5] https://ec.europa.eu/jrc/en/geco

[6] https://about.bnef.com/new-energy-outlook/

[7] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_Global_Renewables_Outlook_2020.pdf

[8] https://www.greenpeace.org/canada/en/press-release/1555/energy-revolution-2015-the-latest-documentation/

3.1. Tabular overview of studies analysed

Table 3 Brief overview of the EC LTS study

<table>
<tr><td>Outlook name</td><td colspan="5">EC LTS, In-depth analysis accompanying the Communication "A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy"</td></tr>
<tr><td>Organisation</td><td colspan="5">European Commission</td></tr>
<tr><td>Publishing date</td><td colspan="5">November 2018</td></tr>
<tr><td rowspan="2">Scenarios</td><td colspan="2">Base scenario</td><td colspan="2">2°C compliant</td><td>1.5°C compliant/climate neutrality</td></tr>
<tr><td colspan="2">LTS Baseline</td><td colspan="2">ELEC
H2
P2X
EE
CIRC
COMBO</td><td>1.5TECH
1.5LIFE</td></tr>
<tr><td rowspan="2">Geographic resolution</td><td colspan="2">Global</td><td colspan="2">EU</td><td>Other geographic regions</td></tr>
<tr><td colspan="2">Partial -no results
(for economic modelling global)</td><td colspan="2">EU only: published results only EU level
Modelling: at MS level individually</td><td>NO</td></tr>
<tr><td rowspan="2">Time horizon</td><td>2050</td><td>2070</td><td>2100</td><td>Intermediate time steps</td><td>Other</td></tr>
<tr><td>✓</td><td>✓</td><td>-/-</td><td>5-year time steps</td><td>-/-</td></tr>
<tr><td>Model(s) used</td><td colspan="5">Modelling Suite of the EUCLIMIT consortium:
• Energy system modelling: PRIMES
• Non-CO_2: GAINS (with agricultural outlook based on CAPRI)
• LULUCF: GLOBIOM
• Economic modelling: GEM-E3, E3ME, QUEST</td></tr>
<tr><td>Link</td><td colspan="5">https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf</td></tr>
</table>

Table 4 Brief overview of the IEA WEO study

Outlook name	**IEA World Energy Outlook 2019**				
Organisation	International Energy Agency (IEA)				
Publishing date	November 2019				
Scenarios	***Base scenario***		***2°C compliant***		***1.5°C compliant/climate neutrality***
	Stated Policies Scenario (STEPS)		Sustainable Development Scenario (SDS)		
Geographic resolution	***Global***		***EU***		***Other geographic regions***
	YES		YES		
Time horizon	***2050***	***2070***	***2100***	***Intermediate time steps***	***Other***
	✓	✓	-/-	5-year time steps	-/-
Model(s) used	IEA WEM Model				
Link	https://www.iea.org/reports/world-energy-outlook-2019				

Table 5 Brief overview of the JRC GECO study

Outlook name	**Global Energy and Climate Outlook 2019: Electrification for the low-carbon transition**				
Organisation	JRC				
Publishing date	2020				
Scenarios	***Base scenario***		***2°C compliant***		***1.5°C compliant/climate neutrality***
Geographic resolution	***Global***		***EU***		***Other geographic regions***
	YES				66 countries/regions
Time horizon	***2050***	***2070***	***2100***	***Intermediate time steps***	***Other***
	✓	-/-	-/-		-/-
Model(s) used	POLES-JRC, JRC-GEM-E3				
Link	https://ec.europa.eu/jrc/en/geco				

Table 6 Brief overview of the BNEF study

<table>
<tr><td>Outlook name</td><td colspan="5">BNEF New Energy Outlook 2019</td></tr>
<tr><td>Organisation</td><td colspan="5">Bloomberg</td></tr>
<tr><td>Publishing date</td><td colspan="5">June 2019</td></tr>
<tr><td rowspan="2">Scenarios</td><td colspan="2">Base scenario</td><td colspan="2">2°C compliant</td><td>1.5°C compliant/climate neutrality</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td rowspan="2">Geographic resolution</td><td colspan="2">Global</td><td colspan="2">EU</td><td>Other geographic regions</td></tr>
<tr><td colspan="2">YES</td><td colspan="2">YES</td><td></td></tr>
<tr><td rowspan="2">Time horizon</td><td>2050</td><td>2070</td><td>2100</td><td>Intermediate time steps</td><td>Other</td></tr>
<tr><td>✓</td><td>-/-</td><td>-/-</td><td>Annual</td><td>-/-</td></tr>
<tr><td>Model(s) used</td><td colspan="5">To add names</td></tr>
<tr><td>Link</td><td colspan="5">https://about.bnef.com/new-energy-outlook/</td></tr>
</table>

Table 7 Brief overview of the IRENA study

<table>
<tr><td>Outlook name</td><td colspan="6">Global Renewables Outlook: Energy transformation 2050</td></tr>
<tr><td>Organisation</td><td colspan="6">IRENA</td></tr>
<tr><td>Publishing date</td><td colspan="6">April 2020</td></tr>
<tr><td rowspan="2">Scenarios</td><td colspan="2">Base scenario(s)</td><td colspan="2">2°C compliant</td><td colspan="2">1.5°C compliant/climate neutrality</td></tr>
<tr><td colspan="2">Planned Energy Scenario (PES)
Baseline Energy Scenario (BES): policies in place in 2015 Paris Agreements</td><td colspan="2">Transforming Energy Scenario (TES)</td><td colspan="2">Deeper Decarbonisation Perspective (DDP)</td></tr>
<tr><td rowspan="2">Geographic resolution</td><td colspan="2">Global</td><td colspan="2">EU</td><td colspan="2">Other geographic regions</td></tr>
<tr><td colspan="2">YES</td><td colspan="2">YES</td><td colspan="2">East Asia, SE Asia, Rest of Asia, European Union, Rest of Europe, Latin America and the Caribbean, the Middle East and North Africa, North America, Oceania, and Sub-Saharan Africa</td></tr>
<tr><td rowspan="2">Time horizon</td><td>2050</td><td>2070</td><td>2100</td><td colspan="2">Intermediate time steps</td><td>Other</td></tr>
<tr><td>✓</td><td>-/-</td><td>-/-</td><td colspan="2">5-year time steps</td><td>-/-</td></tr>
<tr><td>Model(s) used</td><td colspan="6">“The report builds on IRENA’s REmap approach, which has formed the basis for a succession of global regional, country-level and sector-specific analyses since 2014 as well as IRENA’s socio-economic analysis that captures an increasingly comprehensive picture of the impact of the energy transition on economies and societies.”
Macro-economic modelling: E3ME</td></tr>
<tr><td>Link</td><td colspan="6">https://www.irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020</td></tr>
</table>

Table 8 Brief overview of the Greenpeace study

<table>
<tr><td>Outlook name</td><td colspan="7">Energy [R]evolution: A sustainable world energy outlook 2015</td></tr>
<tr><td>Organisation</td><td colspan="7">Greenpeace</td></tr>
<tr><td>Publishing date</td><td colspan="7">2015</td></tr>
<tr><td rowspan="2">Scenarios</td><td colspan="2">Base scenario(s)</td><td colspan="3">2°C compliant</td><td colspan="2">1.5°C compliant/climate neutrality</td></tr>
<tr><td colspan="2">Reference scenario (REF): Current Policies scenarios published by the International Energy Agency (IEA) in World Energy Outlook 2014 (WEO 2014)</td><td colspan="3">energy [r]evolution scenario (e[r])</td><td colspan="2">Advanced energy [r]evolution scenario (adv e[r])</td></tr>
<tr><td rowspan="2">Geographic resolution</td><td colspan="2">Global</td><td colspan="3">EU</td><td colspan="2">Other geographic regions</td></tr>
<tr><td colspan="2">YES</td><td colspan="3">OECD Europe</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Time horizon</td><td>2050</td><td colspan="2">2070</td><td>2100</td><td colspan="2">Intermediate time steps</td><td>Other</td></tr>
<tr><td>✓</td><td colspan="2">-/-</td><td>-/-</td><td colspan="2">5-year time steps?</td><td>-/-</td></tr>
<tr><td>Model(s) used</td><td colspan="7">Mesap/PlaNet simulation model (DLR)</td></tr>
<tr><td>Link</td><td colspan="7">https://storage.googleapis.com/planet4-canada-stateless/2018/06/Energy-Revolution-2015-Full.pdf</td></tr>
</table>

3.2. Selection of outlooks for detailed analysis

In December 2019, the European Commission announced the EU Green Deal[9], which is the EU's roadmap to transform its economy so as to reach climate neutrality. The following objectives are highlighted in the Communication:

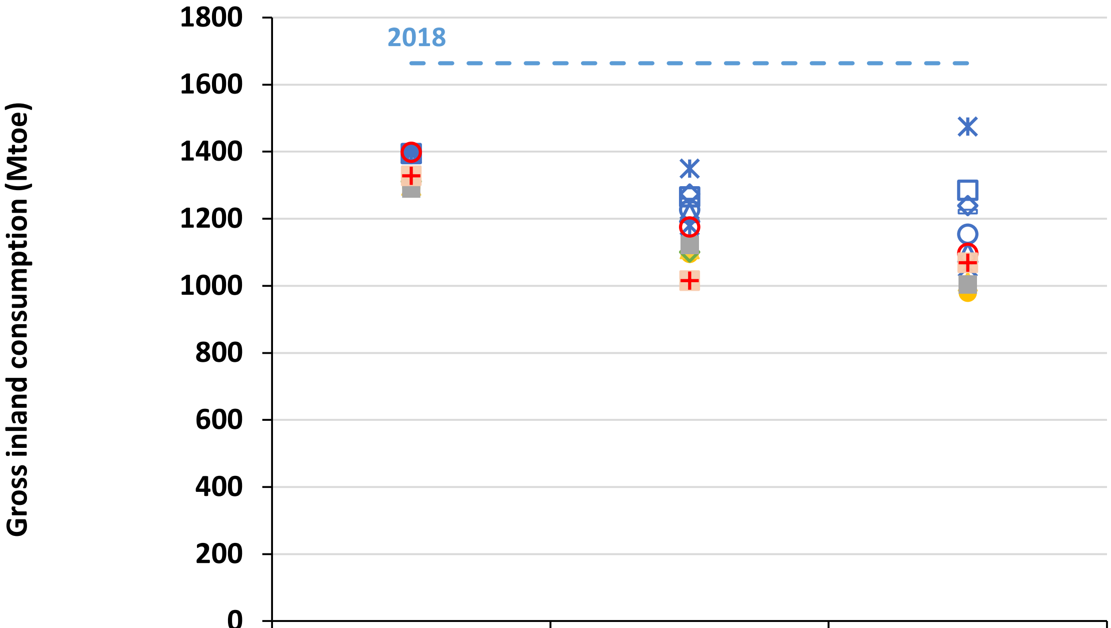
- no net emissions of greenhouse gases by 2050;
- decoupling economic growth from resource use;
- no person and no place left behind.

This context implies a strong focus on the relationship between research and innovation activities and technologies that enable the achievement of the EU Green Deal objectives. To provide evidence on clean and low carbon technology solutions, it is important to capture the role of technological evolution within the transition outlook and identify possible technology gaps. For this purpose, we analyse different projections of the energy system and the technology mix based on the reviewed outlooks included in the preselected studies (section 3.1).

The studies include detailed results for 14 decarbonisation scenarios in total (Figure 1), and 1 scenario from BNEF NEO which is not a deep decarbonisation outlook (not depicted in the graph). The scenarios differ with respect to the mathematical modelling approach, the emission reduction trajectories, the regional scope (global such as JRC GECO as opposed to EU models such as PRIMES, or higher regional clustering for Europe such as BNEF and GP, as others offer results for the EU28) and the temporal scope (see Table 3 - Table 8, Table 9). From the 15 scenarios we select 7, which we analyse in more detail in section 4.

[9] COM(2019) 640 final. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

Figure 1 Gross inland consumption in decarbonisation scenarios in the EU28 (Mtoe)



	2030	2040	2050
EC LTS EE	1395	1146	983
EC LTS CIRC	1395	1179	1056
EC LTS ELEC	1395	1227	1154
EC LTS H2	1395	1254	1222
EC LTS P2X	1395	1350	1475
EC LTS COMBO	1395	1274	1239
EC LTS 1.5TECH	1395	1265	1285
EC LTS 1.5LIFE	1395	1219	1099
GP ER	1294	1096	979
GP ADV	1299	1109	1013
IEA WEO SDS	1311	1101	
IRENA GRO TES	1290	1123	1003
JRC GECO 2C_M	1399	1176	1097
JRC GECO 1.5C	1328	1016	1069
Eurostat 2018	1664	1664	1664

Note: The regional coverage of the GP scenarios is OECD Europe.

Despite their significant differences, the scenarios show a similar trend, pointing to a reduction of gross inland consumption[10] especially in the medium-term. For comparison, gross inland consumption was 1 664 Mtoe in the EU28 in 2018, while the outlooks foresee a range of about 1 300 - 1 400 Mtoe in 2030 and 980 - 1 475 in 2050. As seen

[10] For EC LTS, we show results for gross inland consumption, which is in accordance with the old Eurostat definition that was applicable at the time of the COM(2018) 773 publication. For the remaining scenarios, the scope of the presented indicators is not necessarily aligned, and small differences may be observed due to non-energy use, aviation fuels and international maritime bunker fuels. The figure presents for the Greenpeace scenarios the indicator Primary Energy Demand, for IEA WEO scenario the indicator Total Primary Demand, for the JRC GECO scenario the indicator Primary Energy Demand and for the IRENA scenario the indicator Total Primary Energy Supply.

in Figure 1, the differences across the projections for 2050 are rather large (see section 4.1). The differences are due to two main factors: the level of ambition for CO_2 emission reduction and the projected use of hydrogen and synthetic fuels. The latter are assumed to be required to achieve carbon neutrality in a number of scenarios (e.g. EC LTS 1.5C scenarios, P2X scenario, JRC GECO 1.5C) and are inefficient from an overall system effienciency perspective as they require additional transformation steps.

Given the aim of this study and the objective of the EU to become carbon neutral by 2050, from each study we select *projections with ambitious emission reduction*, which are, however, *distinctly different in terms of their decabonisation storylines*. As such, we assess the following:

- *European Commission – Long-Term Strategy 1.5°C* scenario based on lifestyle changes (*EC LTS 1.5LIFE*)[11], which leads to carbon-neutrality by 2050. In addition to low-carbon technology development, the scenario also relies on circular economy development influencing industrial and domestic consumption patterns. In this scenario lifestyle and consumption behaviours that are climate-friendly add to the effects of the circular economy. Examples are less carbon intensive diets, transport vehicle sharing, rational energy use for heating and cooling and others. In addition, the scenario includes enhanced incentives for CO_2 emission sinks from land use, land-use change and forestry;
- *European Commission – Long-Term Strategy 1.5°C* scenario as a technology-oriented decarbonisation scenario (*EC LTS 1.5TECH*), which leads to carbon-neutrality by 2050. The scenario reached net-zero GHG emissions also through the development of negative emission technologies. In general, the scenario includes development of carbon-neutral hydrogen and hydrocarbons based on a zero or negative emissions power system expanded considerably to accommodate production of hydrogen which in its large majority is based on renewables;
- The *IEA WEO Sustainable Development Scenario* (*IEA WEO SDS*), which in addition to tackling climate change, also seeks to address other energy-related SDGs (achieving universal access to energy (SDG 7) and reduce the severe health impacts of air pollution (part of SDG 3)). The SDS scenario is on track to limiting global CO_2 emissions to 10 $GtCO_2$ by 2050, and to net-zero emissions by 2070. Note, however, that the time horizon of IEA WEO scenarios (and thus reported data) spans until 2040;
- *JRC GECO 2°C* medium scenario (*JRC GECO 2C_M*), which is based on a global GHG trajectory consistent with a likely chance of maintaining global temperature rise below 2°C by 2100[12]. It includes adoption of ambitious mitigation strategies globally. In the JRC GECO 2C_M, the transition mainly relies on electricity enabled by appropriate public policies. Electric mobility is promoted by a dynamic deployment of recharging infrastructure; actions are taken to limit the use of

[11] The European Commission is currently updating the scenarios of the Long-Term Strategy in the context of the EU Green Deal to analyse the effects of an increased emission reduction target for 2030 (i.e. 50-55%). The new scenarios are being quantified on the basis of the EC LTS 1.5TECH scenario, however, they include some updates of the assumptions to keep the scenarios in line with the current state of the art knowledge (and some minor modelling updates). The changes include some updates of techno-economic assumptions based on a review of the data both within the EC and through a stakeholder consultation (Autumn 2019) as well as an update of the policy context (cut-off date for policies December 2019 therefore including coal phase out policies in a number of countries) and the update of the macro-economic context (based on the ageing report of Autumn 2019) and of the statistical database of the model (the LTS included preliminary statistical data until 2015, whereas the new scenarios include statistical data up to the year 2017). While the updates cause some changes to the shorter-term projects and the year 2030 due to the changed assumption on the 2030 targets, the overall messages on technological options for the longer term as analysed in this report remain unchanged. The updated scenarios may show the requirement of an earlier uptake of technologies in order to meet the stricter targets, therefore enhancing the urgency of technological developments.

[12] This scenario was chosen because the JRC GECO publication offers more details with respect to its 2°C scenario rather than its 1.5°C scenario.

fossil fuel combusting equipment (awareness, standards, fiscal incentives, etc). High energy prices and low costs of renewables and electric technologies also encourage the move towards electricity;

- *IRENA's Global Renewables Outlook, Transforming Energy Scenario* (*IRENA GRO TES*), is IRENA's main decarbonisation scenario. It describes an ambitious energy transformation pathway based largely on renewable energy sources and steadily improving energy efficiency (though not limited exclusively to the respective technologies). The scenario sets the energy system on a path needed to keep the rise in global temperatures to well below 2 °C by 2100. This is the most ambitious scenario included in the study that provides detailed results for the EU (additional scenarios that reach zero and net-zero are also explored, however, with data only at a global level);
- *BNEF New Energy Outlook* (*BNEF NEO*), is a study that focuses on the power sector only and partly on the demand side (road transport and heating and cooling). The regional scope is EU28 including Iceland, Norway, and Switzerland. The BNEF does not include an emission reduction target. The scenario is interesting because it bases on market forces (competitiveness of renewable energy technologies) the projection of high shares of renewable energy supply, rather than on a policy push. It should be mentioned that the BNEF study also includes decarbonisation scenarios (coal phase-out, electrification and two-degrees scenarios), however the data on results are only presented at a global level;
- *Greenpeace's Energy Revolution scenario* (*GP ER*), developed in 2015, pursues a target of reducing global CO_2 from energy use down to around 4 $GtCO_2$ by 2050, which is likely to limit the increase in global temperature under 2°C. The scenario also includes the objective of phasing-out nuclear energy.

Although the scenarios differ substantially, the aim of the comparison is to derive common ideas and findings regarding key technologies and policies, that would eventually be a useful guidance in view of the EU Green Deal.

Table 9 Brief comparison of the selected energy outlooks

Outlook	CO_2 emissions by 2050 ($GtCO_2$/yr)	Climate target (implicit or explicit)	Regional coverage of Europe	Time horizon
EC LTS 1.5Life	0.026	Net-zero emissions to 2050 / 1.5°C ambition	EU28	2050
EC LTS 1.5Tech	0.025	Net-zero emissions to 2050 / 1.5°C ambition	EU28	2050
BNEF NEO	n/a	n/a	EU28 plus Iceland, Norway and Switzerland	2050
GP ER	0.33	Below 2°C	OECD Europe	2050
IRENA GRO TES	0.6	Zero emissions after 2050 / Well-below 2°C and towards 1.5°C	EU28	2050
IEA WEO SDS	0.82 in 2040	Net-zero by 2070 / below 1.8°C with 66% probability	EU28	2040
JRC GECO 2C_M	0.61	Global net-zero around 2080 / up to 2°C with 75% probability	EU28	2100

Note: Indicators for BNEF NEO are not applicable as they relate with the power sector only.

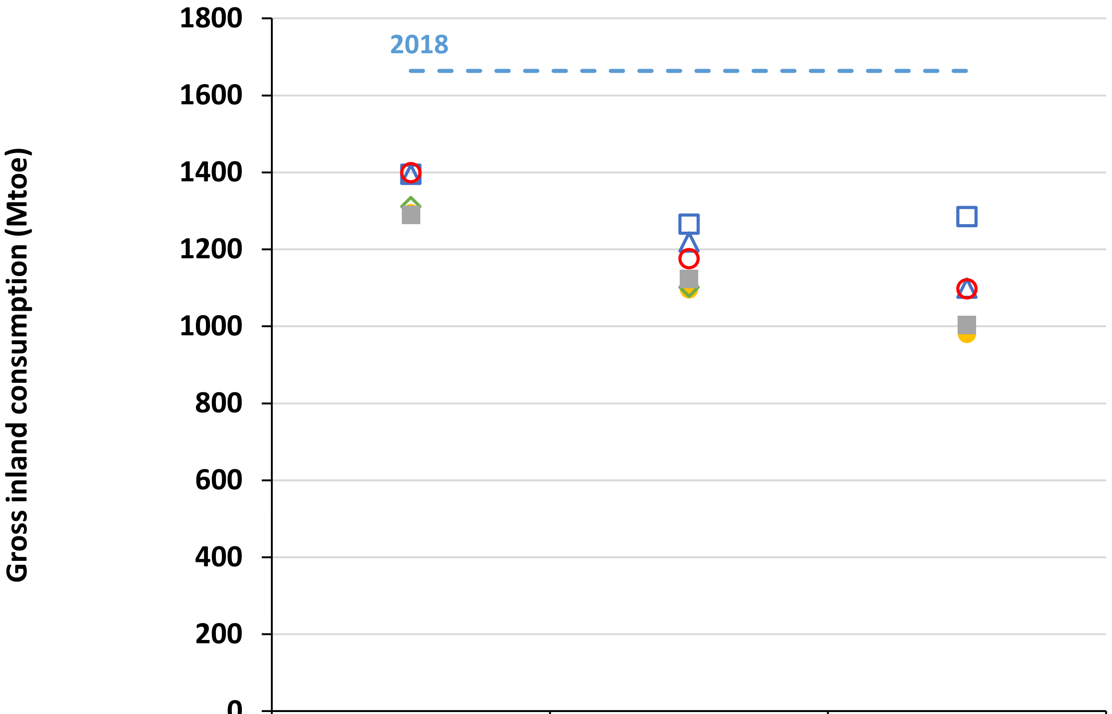
4. Analysis of the selected outlooks with focus on technology developments

4.1. Energy system developments in the selected outlooks

The selected scenarios project gross inland consumption in a range from 1 290 to 1 400 Mtoe in 2030 and between 1 100 and 1 265 Mtoe in 2040. The range of variation is much larger in 2050 (between 980 and 1 285 Mtoe) and in some scenarios, the projection shows an increase in gross inland consumption in 2050 compared to 2040 (Figure 2). As explained above, the increase in 2050 is driven in the EC LTS scenarios by the requirement to achieve carbon neutrality which includes the use of hydrogen and synthetic fuels which reduce the overall system efficiency, increasing gross inland consumption. All scenarios which include hydrogen and synthetic fuels project their significant deployment in the decade 2040-2050.

It is difficult to depict the reason for variation in projections for 2030. It is likely that the scenarios differ regarding the energy efficiency policies and ambition.
However, the scenarios have similarities in the projections until 2030 regarding the reduction in coal and the increase in renewables (mainly wind, solar and bioenergy). The similarities are less established regarding the use of oil products and natural gas. As wind and solar are rather mature technologies, the scenarios foresee similar developments. The projections are more uncertain regarding the increase in bioenergy, both regarding sustainable supply (e.g. access to feedstocks in line with the sustainability criteria of Annex IX of the Renewable Energy Directive (RED II) (EU) 2018/2001 (recast)) and the deployment of advanced conversion technologies.

Figure 2: Gross inland consumption in the selected scenarios for the EU28 (Mtoe)

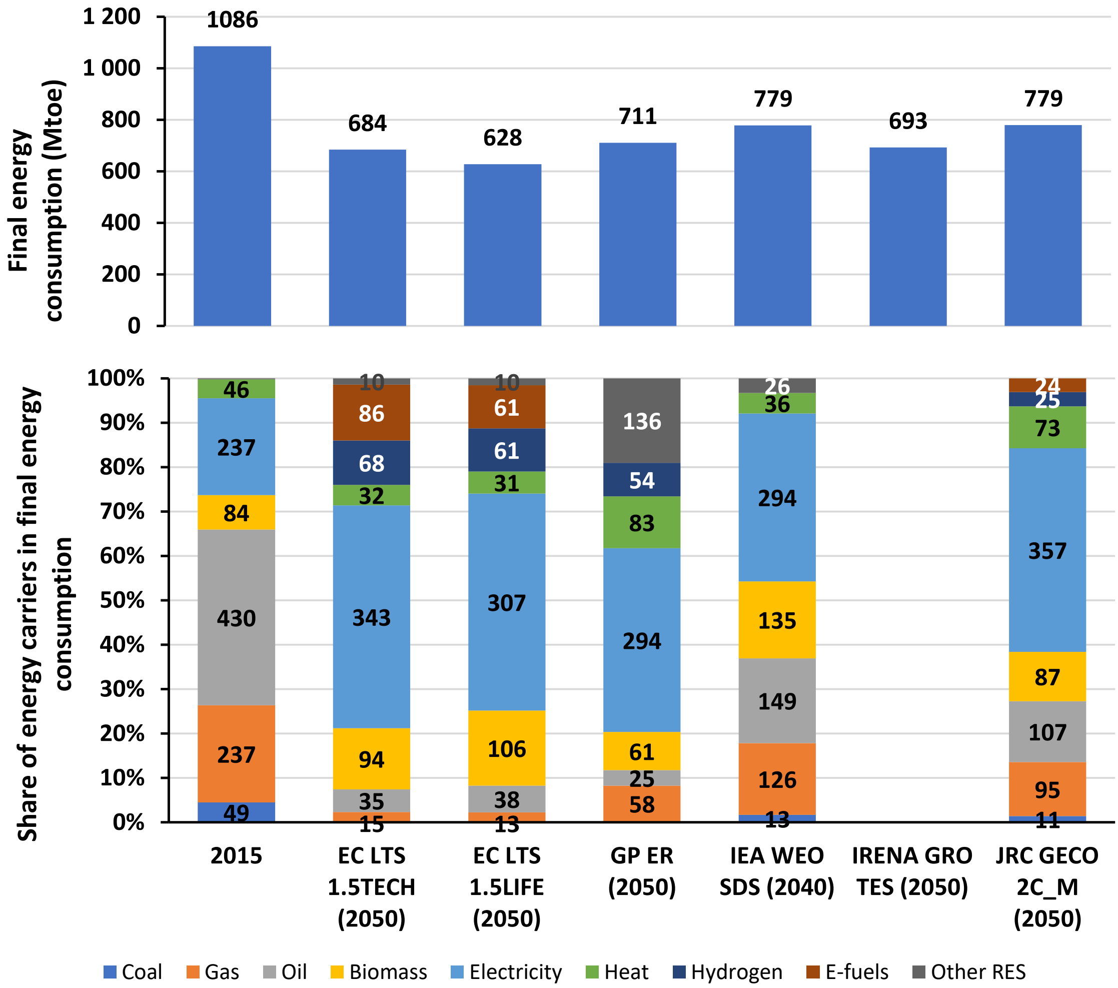


	2030	2040	2050
EC LTS 1.5TECH	1395	1265	1285
EC LTS 1.5LIFE	1395	1219	1099
GP ER	1294	1096	979
IEA WEO SDS	1311	1101	
IRENA GRO TES	1290	1123	1003
JRC GECO 2C_M	1399	1176	1097
Eurostat 2018	1664	1664	1664

Note: The results of GP ER are for OECD Europe. See also footnote 10.

The large variation of projections of gross inland consumption in 2050 is due to the development of hydrogen and synthetic hydrocarbons. On the high-end can be found the results of the EC LTS 1.5TECH scenario (1 475 Mtoe). EC LTS 1.5TECH focuses largely on new energy carriers (i.e. hydrogen and P2X), which entail intensive use of electricity for their production. On the low-end lie the results of the EC LTS 1.5LIFE projection, which relies much less on hydrogen and synthetic hydrocarbons and more on significant reductions of energy demand enabled by circular economy and behavioural changes. This scenario consumes 375 Mtoe less than EC LTS 1.5TECH (Figure 3). The other scenarios (i.e. GP ER, IEA WEO SDS, JRC GECO 2C_M), have different emission reduction trajectories (Table 9) and foresee demand for energy to stay around 1 000 to 1 100 Mtoe in 2050 (Figure 2), with production of hydrogen and synthetic hydrocarbons lower than in both EC LTS scenarios. Despite the wide variation in gross inland consumption, as indicated above, the selected scenarios show much smaller differences in final energy consumption, which ranges from 630 to 780 Mtoe in 2050 (Figure 3). It becomes clear from all the scenarios that the reduction of energy consumption in final energy demand in all sectors is a key driver to achieve emission reduction (at any level); the substantial electrification of final energy demand, by definition, leads to an increased efficiency in final demand terms. All scenarios see an increase in direct use of electricity in final energy: this is driven by the changes in the transport sector (electrification of private passenger road transport), as well as highly efficient heating (heat pumps). The scenarios vary in terms of direct use of renewables energies other than biomass (i.e. solar thermal, geothermal, etc.), with the GP ER scenario having the highest share amongst the analysed scenarios.

Figure 3: Energy mix in final energy consumption in the EU28 in 2050 (Mtoe, %)[13]



Note: The results of GP ER are for OECD Europe. The results of IEA WEO SDS are for 2040. IRENA GRO TES does not provide the energy mix of final energy consumption in detail. It reports, however, that 70% of total final energy consumption is based on renewable sources (including renewable electricity and distributed heat).

Both EC LTS scenarios and the IRENA GRO TES scenario include higher effort than other scenarios on energy efficiency improvement in final demand sectors. The EC LTS 1.5LIFE is particularly performant in energy efficiency also thanks to the circular economy restructuring and behavioural changes. The EC LTS 1.5TECH puts more emphasis on the supply side, compared to EC LTS 1.5LIFE, but nonetheless achieves a remarkable performance in energy efficiency of final demand. IEA WEO SDS mentions that economically viable efficiency options may reduce global energy intensity by 3%

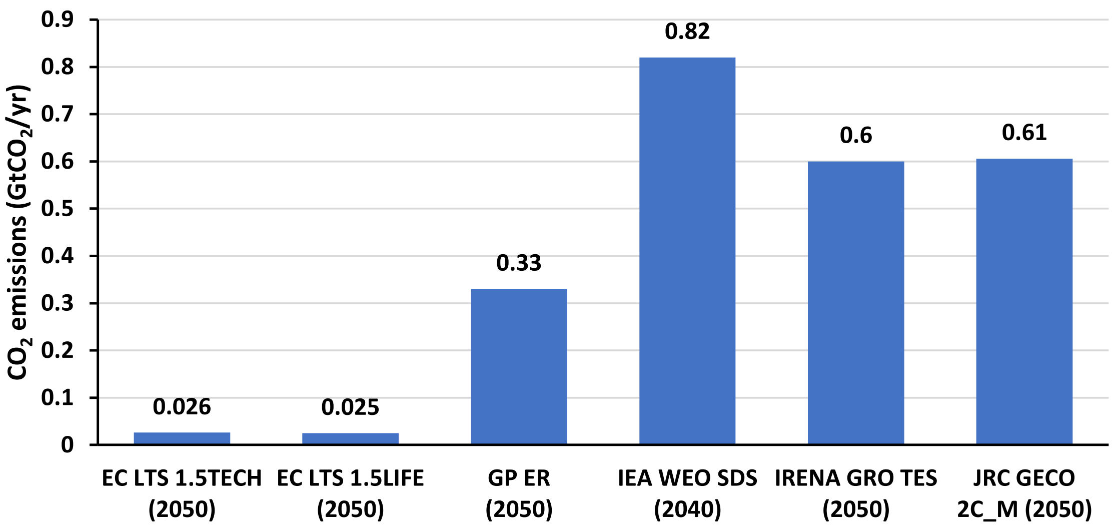
[13] Other RES includes the direct use of RES in final demand such as solar, geothermal and small-scale wind - if applicable.

annually, thus halting the growth in emissions of energy intensive industry sectors. Strong energy intensity improvements of 3.2% per year are also mentioned in the IRENA GRO TES scenario.

In the selected outlooks, the share of new fuels (i.e. hydrogen and e-fuels) ranges from 6% (in JRC GECO 2C_M) to 23% (in EC LTS 1.5TECH) (Figure 3). The share of direct electricity in final energy consumption ranges from 38% in IEA WEO SDS (n.b. results for 2040) up to 49% in EC LTS 1.5LIFE and 50% in EC LTS 1.5TECH. At the same time, IEA WEO SDS and JRC GECO 2C_M continue to rely on fossil fuels, as they comprise 37% and 27% of final energy consumption, respectively. A similar share is also projected by IRENA GRO TES (i.e. 30% of fossil fuels in final consumption, included indirectly in electricity and distributed heat). However, these scenarios that continue to involve fossil fuels in 2050 do not have the ambition to achieve carbon neutrality, and to this respect, are not directly comparable to the EC LTS scenarios.

It is important to stress that although the scenarios chosen are deep decarbonisation scenarios, not all aim at achieving carbon neutrality by 2050. As such, each outlook reaches different emission reduction levels and has different objectives with respect to climate targets (Figure 4, Table 9), , which explains the differences in the energy mix (Figure 3). However, as shown, all scenarios include: a significant increase in direct electrification of final energy uses (41% to 50% in 2050, compared to about 27% in 2017) and in the deployment of hydrogen and e-fuels in the energy sector (6% to 23% in 2050, consumption in 2017 is negligible). These shares are highest in the two EC LTS scenarios that achieve net-zero emissions in the EU28 in 2050. The use of electricity to hydrogen and e-fuels may increase the total system conversion losses, compared to today.

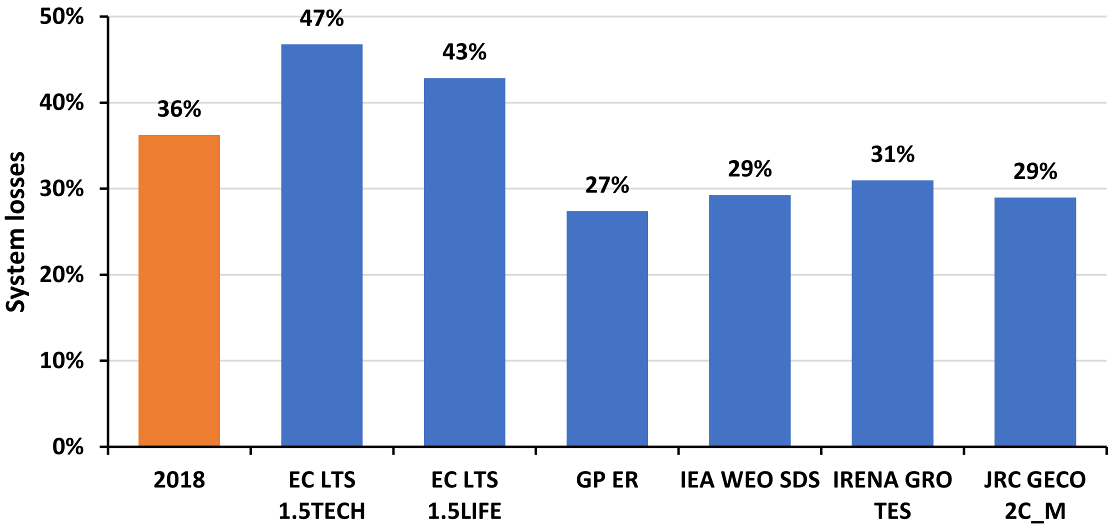
Figure 4 CO_2 emissions in the selected outlooks in the EU28 in 2050



Note: Results of GP ER are for OECD Europe. Results of IEA WEO SDS are for 2040.

The indicator of system losses (i.e. from final energy to gross inland consumption) is lower than today in scenarios that include high amounts of renewables in power generation and high electrification in final demand and no or limited amount of hydrogen and synthetic fuels. Scenarios that involve production of hydrogen and synthetic fuels from electricity increase the system losses, due to the additional energy conversion steps in electrolysis and e-fuel processes. The EC LTS scenarios project that hydrogen and e-fuels will be required in the system in order to be able to achieve carbon neutrality, as some sectors such as aviation, maritime and several industrial process will need to rely on synthetic hydrocarbons as there are limited mitigation options for these sectors. The other scenarios such as IEA WEO SDS and IRENA continue to consume fossil fuels and do not achieve climate neutrality: these scenarios have higher system efficiency but also substantial remaining emissions (Figure 4). System losses can be seen in Figure 5.

Figure 5 System losses from gross inland consumption to final energy consumption in the EU28 in 2050



Note: Not taking into account conversion losses of direct fuel consumption at the end-use. Results of GP ER are for OECD Europe. Results of IEA WEO SDS are for 2040. Data for 2018 are based on Eurostat.

4.2. Technology assumptions in the selected outlooks

The two EC LTS scenarios (EC LTS 1.5LIFE and EC LTS 1.5TECH) are technology-oriented scenarios that increase the contribution of technological options (such as direct electrification, hydrogen, e-fuels, BECCS) in order to reach net-zero emissions. While both build on the same technological basis, when compared to the 1.5TECH, EC LTS 1.5LIFE, puts more emphasis on demand restructuring and the more intense application of energy efficiency technologies in final demand sectors, as well as behavioural changes and circular economy. The restructuring of demand is not purely based on technologies but on re-engineering the organisation in industry, the transport modes and on promoting behavioural changes in the domestic sector. A key difference between the two scenarios is on the incentives (and ultimately the use) of LULUCF sinks, which are much stronger in the EC LTS 1.5LIFE scenario.

At a systems level, these differences are reflected in gross inland consumption (the EC LTS 1.5LIFE scenario shows 15% lower gross inland consumption in 2050 compared to the EC LTS 1.5TECH scenario), final energy demand (the EC LTS 1.5LIFE scenario has 8% lower final energy consumption in 2050 compared to the EC LTS 1.5TECH), final energy mix (somewhat lower shares and volumes of electricity, hydrogen and e-fuels consumption in EC LTS 1.5LIFE compared to EC LTS 1.5TECH; section 4.1). Among others, the differences also concern the deployment levels of specific technologies such as CCS and BECCS in power generation, as the EC LTS 1.5TECH scenario shows higher deployment of CCS compared to EC LTS 1.5LIFE in 2050 by a factor 6.8 and 18.9, respectively. The EC LTS 1.5LIFE sees changes in the levels of transport activity for private transportation assuming that the behavioural changes also lead to modal shifts towards increased use of public transportation particularly rail, buses and coaches.

The rest of selected scenarios are also technology-oriented. Therefore, technology assumptions play a critical role. The uncertainty surrounding technological progress of yet immature technologies explain part of the differences among the scenarios regarding technological mixes.

The EC LTS has published a detailed list of techno-economic assumptions for sectors and technologies[14]; these technology assumptions were the result of a literature review combined with a large stakeholder consultation involving interviews and a large stakeholder event with over 100 participants, as well as internal review by European Commission services[15]. The information is not directly comparable to the available data from the other studies as the level of detail is lower. IEA WEO and GP ER present data for two categories for wind (on- and off-shore), compared to the 10 categories included in the EC LTS scenarios: the values however are in the same order of magnitude. Similarly, for solar PV the categorisation published by the studies is more limited: the 2050 values for the EC LTS scenarios are lower than for the other studies. It is reminded however that the GP ER study is of 2015 and PV technology has experienced a very strong cost reduction since the publication of the study.

Readily and publicly available data from the selected studies are presented in Annex I (Table 10 - Table 16). There is difficulty in directly comparing technology cost and performance assumptions that are used in the various scenarios for the following reasons:

- In all selected scenarios, the costs are exogenously determined based on technological learning: JRC GECO reports learning rates of technologies and not absolute costs. However, some scenarios report base costs (e.g. IEA WEO reports the costs assumed for the STEPS scenario and not for the SDS). Other exogenous assumptions, e.g. on global cumulative installed capacity or learning rates are not always disclosed;
- Most scenarios incorporate technology costs specified by region. The same applies also to other techno-economic parameters. However, when reporting costs, they refer mostly to global or average figures;
- Published data is available only for technology categories such as wind offshore or only as wind: it is unclear whether this representation is the same as in the modelling i.e. if the models have only one category for wind-offshore or whether the models include a more granular representation which is not included in the technology assumptions (with the exception of the EC LTS);
- Some scenarios/studies (e.g. IRENA GRO and partly BNEF) do not report on capital investment costs, but rather on levelized costs of energy or electricity (LCOE). These are a result not only of the capital investment costs but also of other parameters/assumptions (e.g. capacity/utilisation factor, O&M costs, fuel/CO_2 prices, capital recovery factor). This reduces the comparability of modelling assumptions across the scenarios. Moreover, some studies (e.g. IEA WEO) move beyond the standardised definitions of weighted average cost of capital (WACC) or LCOE and presents costs for value-adjusted levelized costs of energy (e.g. for wind)[16];
- Studies tend to publish more information on costs of power generation technologies than for other domains, including for storage, e.g. batteries,

[14] https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

[15] Also for the scenarios of the European Commission for the 2030 analysis conducted in 2020 a stakeholder consultation was undertaken end of 2019.

[16] The value-adjusted LCOE, first presented in the World Energy Outlook-2018, assesses the value of each of the power system services (such as contributions to the bulk energy supply, to the adequacy of the system, and to the flexibility of the system (enabling supply to match demand very closely in real-time operations) and combines them with the LCOE to provide a single metric of competitiveness.

hydrogen, direct air capture, P2X, and demand sectors (industry, buildings, etc.)[17].

BNEF applies its cost projections to the NEO study, and assesses the deployment of clean energy technologies (covering, however, only the power sector) in a scenario where no targets for RES deployment or emission reduction targets are assumed; including, however, carbon pricing[18]. Cost assumptions of BNEF NEO are presented in Annex I (Table 17); however, some of the costs are reported in energy terms not as capital costs for installed capacity.

Despite the difficulties in comparing techno-economic data across the selected scenarios, the comparison confirms that for conventional renewable energy technologies for power generation (wind and solar PV) the majority of the studies assume similar cost reductions over time. This is the case for wind and solar PV technologies which typically make the bulk of the installations for RES power technologies in the time period up to 2050. For other technologies, such as geothermal and ocean (wind and tidal) technologies, the assumptions imply that high costs remain in the future rendering them less competitive than other renewables – at least in the time horizon to 2050; hence their deployment without support is comparably low, except for in specific areas with high and easy to exploit potential. Need for support is also highlighted by BNEF for the case of deep-water offshore wind based on the floating technology (Annex I, Table 17). Cost reductions over time are present in older studies such as the one of Greenpeace published in 2015 as well as in more recent ones such as that of IEA WEO published in 2019. When published, the Greenpeace study has been characterized as probably too optimistic regarding cost developments, however, the developments since that time have confirmed the strong decline in technology costs for solar PV and wind technologies (both on- and off-shore). Overall, since in the selected decarbonisation scenarios technology cost reduction in key RES technologies is in broad terms comparable, it may be inferred that the actual technology cost assumptions are not the main reason for the differences observed in the technology portfolio towards 2050. Until 2030, all scenarios foresee the largest cost reduction to occur for offshore wind (around 20% compared to today); the costs reductions are smaller for onshore wind and solar in the same period (onshore wind less than 10% cost reduction in 2030 compared to today) (Annex I).

Towards 2050, the main driver of market penetration and deployment of technologies is the stringency of the decarbonisation targets as well as the underlying policies and measures which enable the achievement of the decarbonisation objective. Therefore, the technology mix depends on factors other than the technology costs (e.g. potential availability, development of demand, etc.) for the technologies which have reached "maturity". The degree of penetration of currently not market-mature technologies depends -as discussed above- on the level of ambition of the scenarios as well as by the degree of **technology readiness and availability** assumed to be reached by the technologies: this is particularly true for fuel cells, electrolysers, carbon capture and storage (CCS) and processes for the production of synthetic fuels such as Direct Air

[17] The reasons for the discrepancy of information is uncertain. According to the estimation of the authors of the current study the reasons are multiple: the models used are more detailed in the power generation sector; the technologies of the power generation sectors are more fewer than e.g. on the demand side. The aggregation of the models on the demand side are different (some models include only external or very aggregate projections for the demand side derived from mathematical formulations rather than projections based on technologies: further the technologies on the demand side e.g. for industry are very sector specific implying many different technologies and aggregations in literature vary significantly leading to lack of comparability. Regarding "advanced" technologies and storage these are not included in all models and again the levels of aggregation vary.

[18] EU allowances increase towards 40 USD/t in 2020, they fall below 20 USD/t between 2025-2030, ultimately increasing to 32 USD/t from then onwards. BNEF states that over the long-term, Europe's carbon price becomes largely irrelevant for the power sector. Generally, such CO_2 price levels are much lower than in other scenarios.

Capture (DAC). In some scenarios, the penetration of certain technologies, such as CCS and nuclear, is restricted by non-technical reasons. For example, the GP ER scenario assumes that nuclear power is phased out by 2050 in all countries and it considers that CCS is not an acceptable technology and does not deploy. Therefore it rests more on other renewable energy technologies to cover the demand (e.g. as shown in Figure 3, solar thermal, geothermal, etc. have the highest share in the GP ER scenario). The scenarios of the EC LTS consider the national legislation in the countries with the status of 2017; this implies that nuclear phase out, possibility for new nuclear investments and deployment and possibility for national storage of carbon is dependent on Member State policies.[19]

Without ambitious climate targets as a driver for deployment, very high cost reductions would need to occur (as e.g. described in BNEF NEO), in particular for the deployment of novel technologies. In the case of baseline or reference scenarios, the absence of emission reduction targets limit the development of novel technologies, in contrast to decarbonisation scenarios. However, the reference/baseline scenarios are not the object of this assessment and may also contain different technological assumptions as slower learning may be assumed.

Overall the technology assumptions across the scenarios analysed are within the same order of magnitude; the variation of deployment of the technologies is analysed in the following chapter.

4.3. Power generation and technology mix

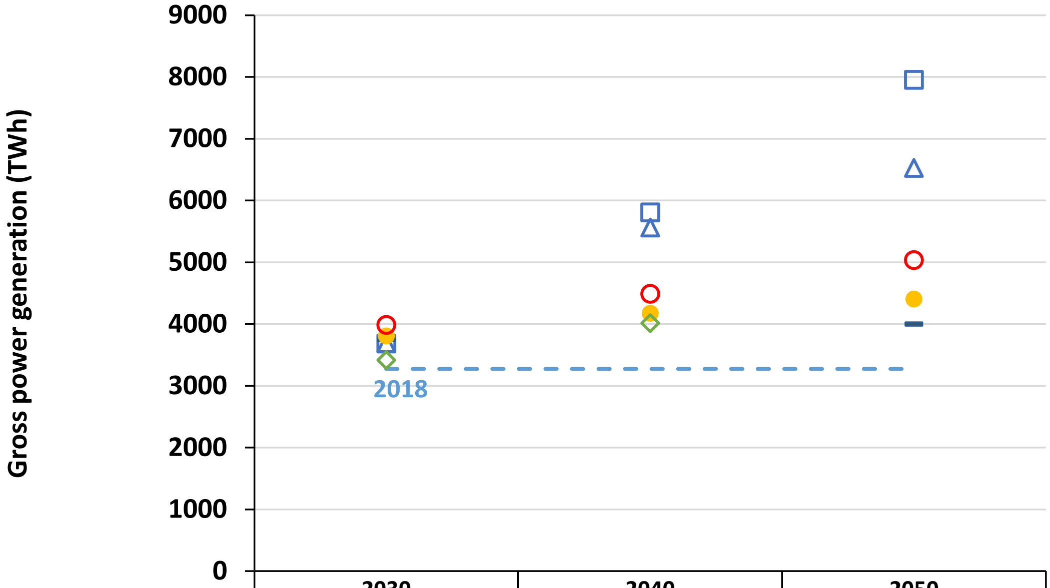
In 2018, gross electricity generation in the EU28 was about 3 270 TWh (2 941 TWh in the EU27[20]) and about 33% was produced from renewable sources (the share is similar for the EU28 and the EU27). All selected scenarios project a considerable increase in electricity generation already in 2030, and substantially higher increase by 2050 (Figure 6), driven primarily by direct electrification of demand sectors (mainly to electrify transport and heating; see section 4.4.1); in some scenarios the production of hydrogen and synthetic hydrocarbons through processes based on electrolysis further increase the demand for electricity and therefore the need for power generation (see section 4.4.2). According to the scenarios the size of the power sector expands to at least 20% by 2030-2040, and up to 70% by 2050 compared to today in the scenarios with synthetic fuels production.

In absolute terms, the scenario EC LTS 1.5TECH projects the largest gross power generation (reaching 8 000 TWh), followed by EC LTS 1.5LIFE (about 6 500 TWh). These scenarios project significant use of electricity-based production of hydrogen and synthetic hydrocarbons (section 4.4.2). It should be noted that the EC LTS scenarios are the most ambitious with respect to emission reduction, amongst the ones examined. Emission mitigation from the power sector is further supported by the deployment of BECCS in two of the scenarios (namely EC LTS 1.5TECH and EC LTS 1.5LIFE).

All scenarios project a similar increase in the share of RES in power generation (Figure 6), regardless of the size of the power sector; from 51-66% in 2030 to 75-95% in 2050 (Figure 8) compared to about 31% today. BNEF NEO represents the upper bound with RES power supply reaching high shares earlier in the time horizon: already 72% in 2030 and 86% by 2040, driven by the steeper, i.e. faster, cost reduction in renewable power supply technologies compared to other scenarios.

[19] The new scenarios exploring the increased ambition in the context of the Green Deal have update the policies to December 2019: this is particularly relevant for coal phase out policies.
[20] From Eurostat, excluding the UK.

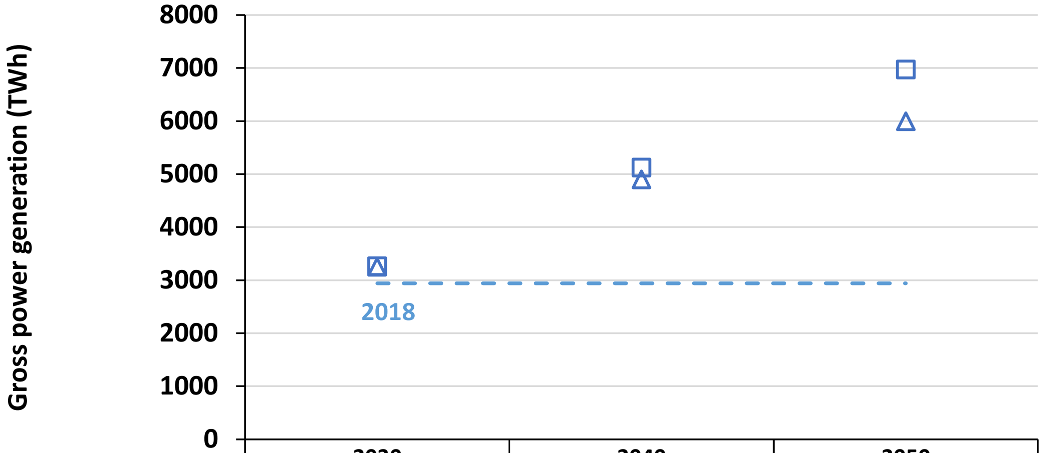
Figure 6: Gross power generation in the selected scenarios in the EU28 (TWh)



	2030	2040	2050
EC LTS 1.5TECH	3687	5810	7952
EC LTS 1.5LIFE	3692	5564	6527
BNEF NEO	3750		4000
GP ER	3809	4174	4404
IEA WEO SDS	3418	4016	
JRC GECO 2C_M	3989	4489	5035
Eurostat 2018	3272	3272	3272

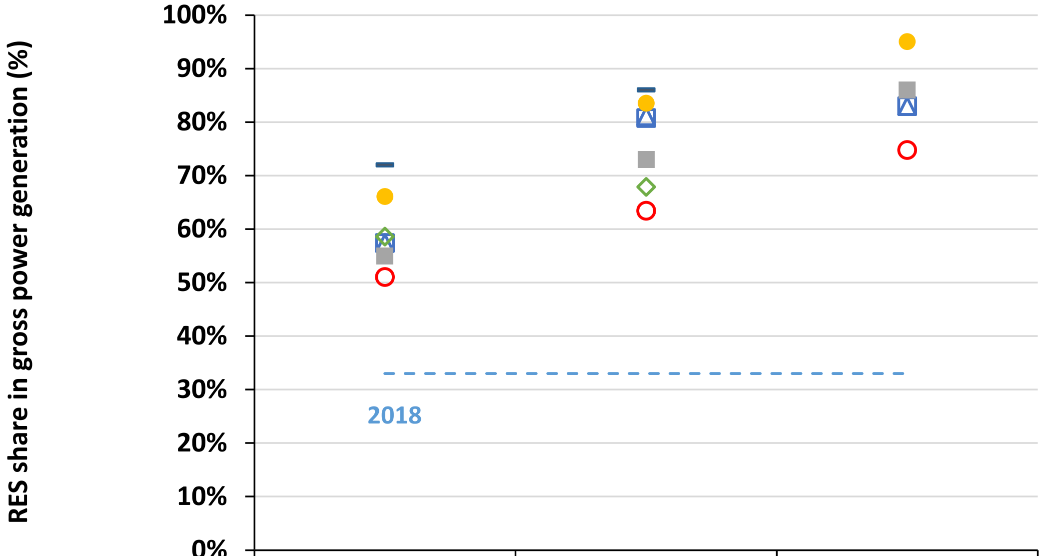
Note: Results of GP ER are for OECD Europe.

Figure 7 Gross power generation in the EC LTS 1.5C scenarios in the EU27 (TWh)



	2030	2040	2050
EC LTS 1.5TECH	3264	5124	6976
EC LTS 1.5LIFE	3253	4903	5995
Eurostat 2018	2941	2941	2941

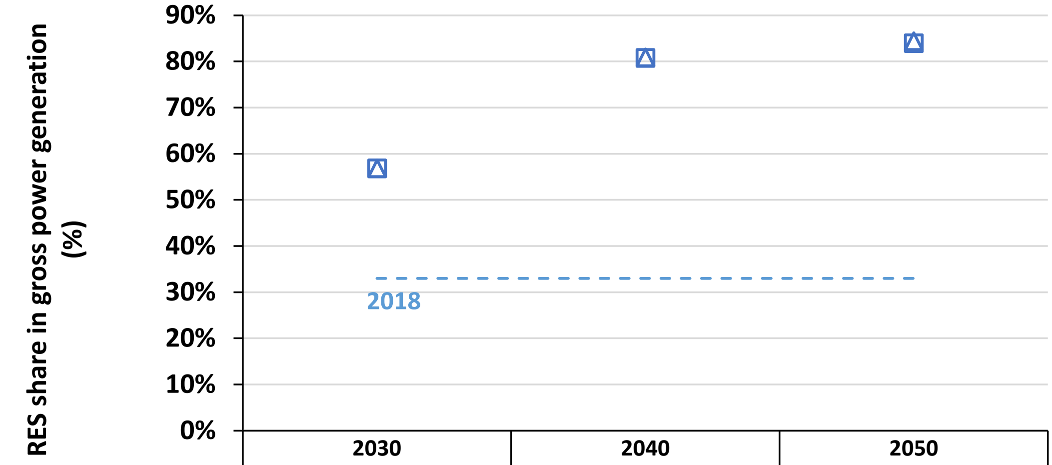
Figure 8 RES share in gross power generation in decarbonisation scenarios in the EU28



	2030	2040	2050
EC LTS 1.5TECH	57%	81%	83%
EC LTS 1.5LIFE	57%	81%	83%
BNEF NEO	72%	86%	
GP ER	66%	84%	95%
IEA WEO SDS	59%	68%	
IRENA GRO TES	55%	73%	86%
JRC GECO 2C_M	51%	63%	75%
Eurostat 2018	33%	33%	33%

Note: Results of GP ER are for OECD Europe.

Figure 9 RES share in gross power generation in EC LTS 1.5C scenarios in the EU27

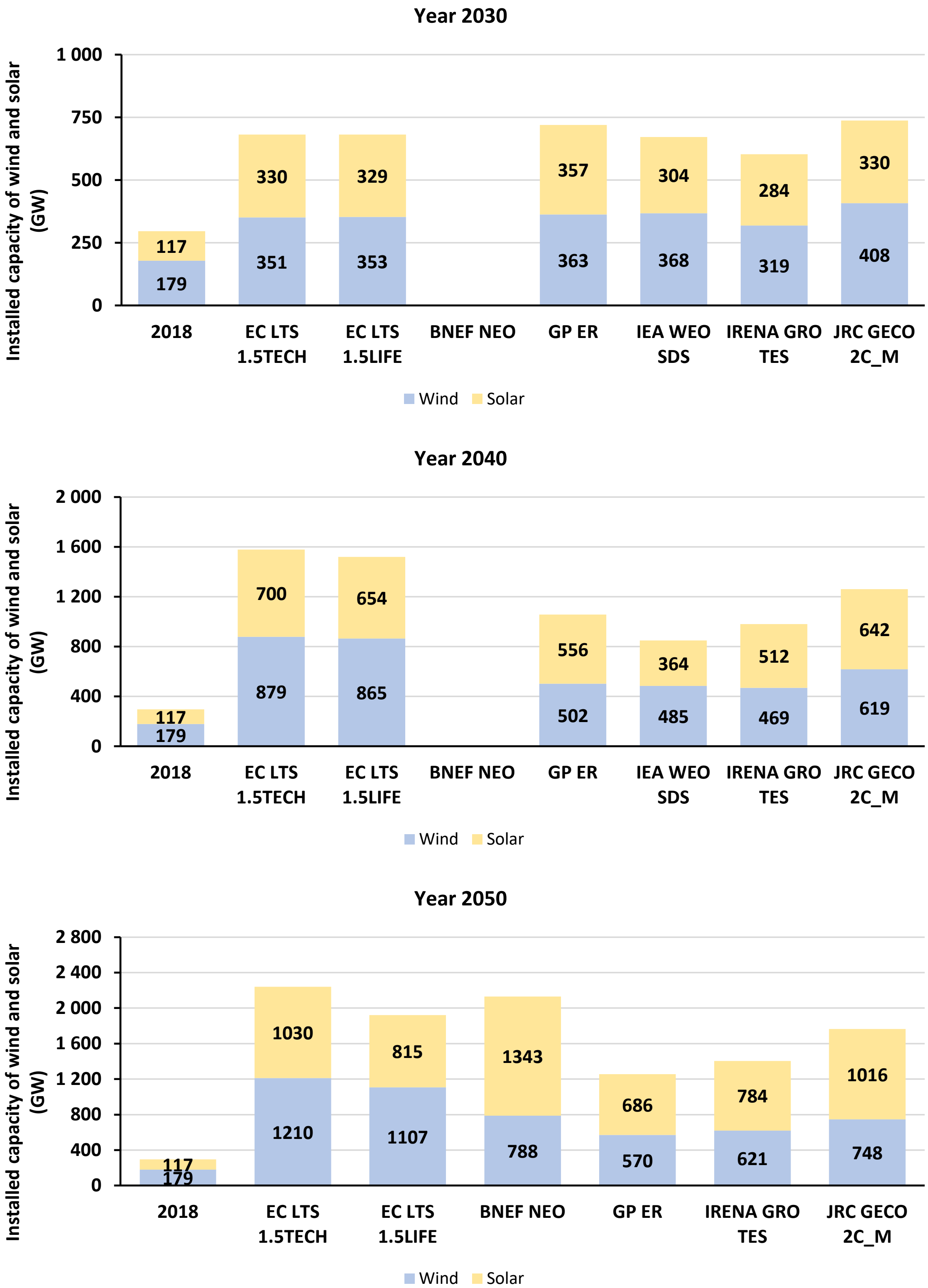


	2030	2040	2050
EC LTS 1.5TECH	57%	81%	84%
EC LTS 1.5LIFE	57%	81%	84%
Eurostat 2018	33%	33%	33%

The increase in RES generation in the selected scenarios is based on the significant increase in power production from wind and solar (e.g. almost all growth in the IEA WEO SDS by 2040 comes from wind and solar PV); comparably, hydropower and bioelectricity only increase slightly from today's levels over the projection horizon. The deployment until 2030 is comparable across the scenarios; noticeable differences emerge mainly after 2040 (Figure 10), again linked with the production of hydrogen and synthetic fuels.

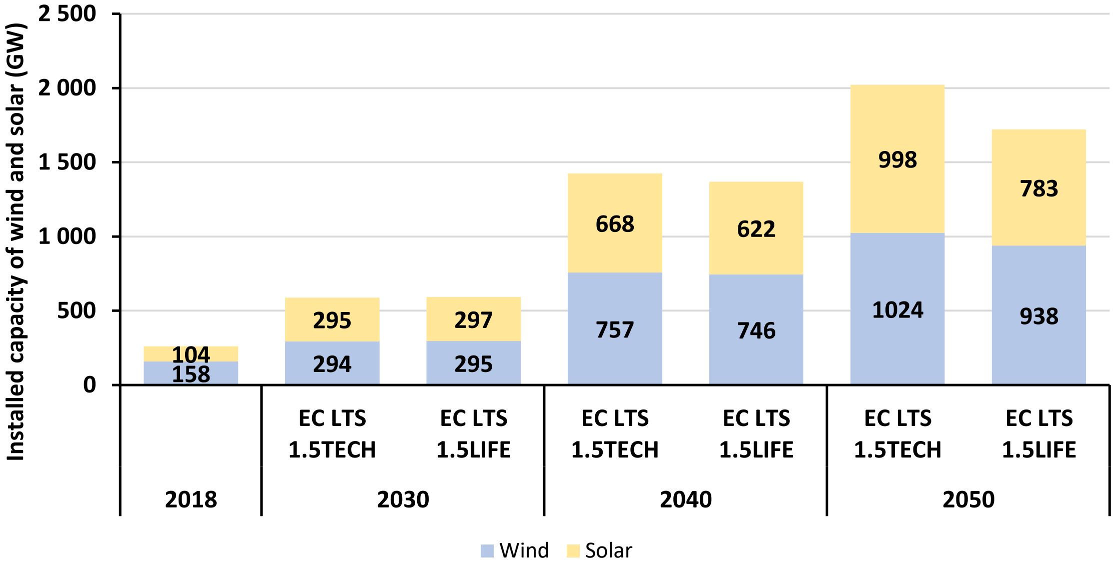
Although capacity projections are not always explicitly disaggregated between onshore and offshore wind, given the assumed cost reduction and the deployment potential of offshore wind energy in the EU, for the period after 2030 it can be assumed that large part of the growth should be attributed to offshore wind. In order to achieve the projected deployment of offshore wind, mainly after 2030, further technological improvements and cost developments are needed, as well as support structures and substations, including logistics. The development further requires streamlining of legal and regulatory procedures for the issuance of permits for off-shore wind. BNEF mentions that for deployment of offshore wind projects in deep waters (e.g. floating foundations), policy support will be required in order to induce further cost reductions. These elements are directly included in the modelling through the assumptions about the cost reductions and further through the enabling frameworks assumed.

Figure 10: Installed capacity of wind and solar in the selected scenarios in the EU28 (GW)



Note: Results of GP ER are for OECD Europe. Data for 2018 based on IRENA Renewable Energy Statistics.

Figure 11: Installed capacity of wind and solar in the EC LTS 1.5C scenarios in the EU27 (GW)



Note: Data for 2018 based on IRENA Renewable Energy Statistics.

Notably, EC LTS 1.5TECH and BNEF NEO, while distinctly different in their modelling approach and storyline, show similar deployment levels of total variable renewables (wind and solar capacity) in 2050; although the framework conditions may not be identical.

Although the difference in RES share in power generation between the scenarios is about 20% p.p. (Figure 8), the **absolute** deployment of renewable power supply technologies (in terms of installed capacity) may differ by a factor 3 (e.g. deployment of wind and solar in 2050 in EC LTS 1.5TECH reaches 2 240 GW while in IRENA GRO TES 784 GW - Figure 10); this is due to the difference in the power sector system size as explained previously. Possible implications on the absolute deployment of RES are noted:

- The continuous expansion of wind and solar implies that annual investments will also grow. However, as investment costs decrease over time, the volume of deployed technologies will play an increasing role to determine the total market size. With high absolute deployment levels within the EU (e.g. in the LTS scenarios), the EU industry may continue to capitalise on the internal market. However, somewhat lower deployment levels (e.g. as in the IRENA GRO TES scenario) suggest that, if similar underlying economies of scale apply, then substantial developments need to occur also outside of the European Union. This suggests that to maintain its competitiveness in the wind and solar industry, the EU will need to exploit and develop also extra-EU markets as these will be large. Supposing that the cost assumptions of the different models were based on curves with the same assumptions about the effect of economies of scale, the smaller the EU market, the larger the non-EU developments would need to be to achieve the same cost reductions;
- Such deployment levels of renewables across all selected scenarios point to network and infrastructure developments that need to take place to support the transition of the power supply system. For example, the IRENA GRO TES scenario projects that in the EU USD 56 billion/yr will be required for power grids and system flexibility, compared to the USD 78 billion/yr required for RES technology deployment;

- Similarly, high shares of variable renewable energy imply high demand for storage and system flexibility (section 4.4.4);
- The supply chains that will develop, will also have implications with respect to the demand for raw material required to meet the scale of the transition envisioned in these scenarios (carbon fibres, steel, etc.);
- Finally, in order to support the deployment of such volumes of wind and solar, a broad range of skillsets will need to be developed, in terms of skill types and size of the workforce, which will need to develop in a timely manner[21].

The scenarios project that gas retains a role that could also support power system flexibility, therefore developments in the direction of advanced CCGT technologies are expected to be required; there is no space left in the system for coal. The natural gas-based and residual coal-based power capacity would need to be coupled with CCS if emission reduction objectives are to be met. IRENA suggests to avoid construction of any new coal-fired capacity and implement phase out policies of coal capacities -which is currently occurring in most EU countries[22]. Finally, stringent technological and regulatory requirements for next generation nuclear power plants may also require further attention as nuclear power plant capacity ranges in scenarios between 105 and 120 GW beyond 2040[23]. However, they are not a precondition in all scenarios (e.g. GP ER, which next to fossil fuels also phases out nuclear).

4.4. Energy Vectors

4.4.1. Electricity

Electrification, defined as direct consumption of electricity in final energy demand, i.e. excluding conversion of electricity to other energy carriers (e.g. hydrogen, P2X).

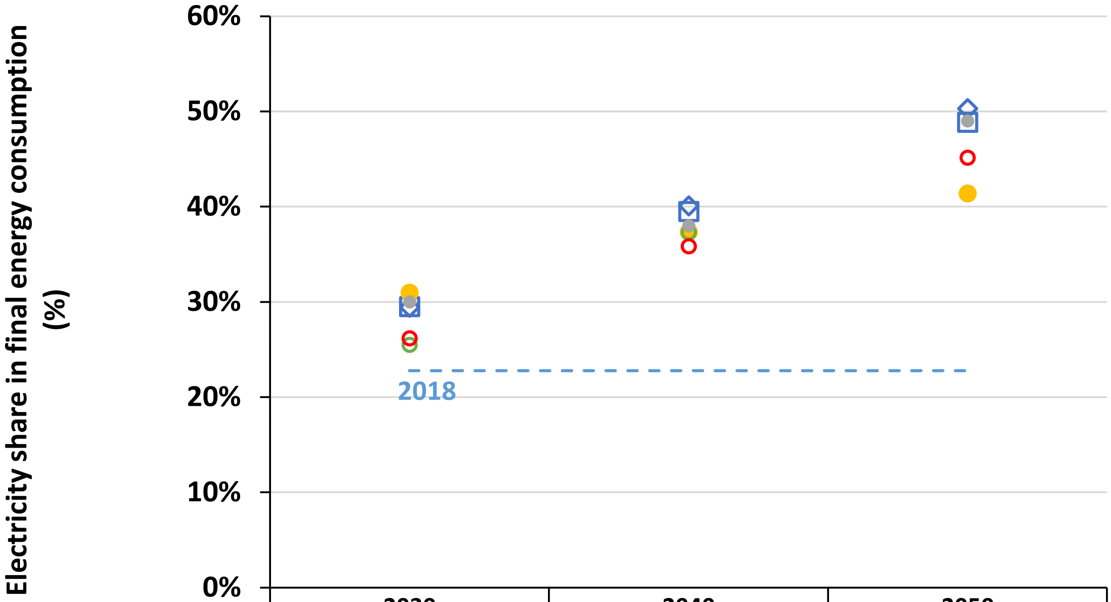
The requirement to reduce emissions in all sectors implies a strong drive towards higher electricity use in all sectors of the economy: this leads to electricity becoming a cornerstone of the future energy system. From directly covering about one-third of final energy demand in 2030, electrification progressively increases its share to about 45-50% of final energy consumption in 2050 (Figure 12). This points towards necessary transformations across all sectors. Notably, while IEA WEO SDS sees the share of electricity in a similar range with the other selected scenarios (36-38% in 2040), it expects only a moderate increase of absolute electricity demand due to increasing energy efficiency and digitalisation.

[21] An analysis of such requirements can be found in the following study: https://asset-ec.eu/home/advanced-system-studies/cluster-1/job-creation-and-sustainable-growth-related-to-renewables/

[22] The NECPs of the EU Member States include phase out policies for coal fired generation, these were not all included in the EC LTS scenarios as the modelling for those scenarios finished in Summer 2018; however the updated scenarios for the Green Deal impact assessment include this update. For the long-term projections however, the differences are not particularly large.

[23] Several EU MS have nuclear phase out policies in place and expect the retirement of significant nuclear capacity. However, some MS expect to maintain and expand their nuclear fleet. The LTS 1.5TECH scenario includes all MS policies and regulations related to nuclear phase outs and permission, as well as a detailed analysis of all existing nuclear sites on a site-by-site basis for the possibility of on-site expansion of nuclear capacity. Green-site new nuclear capacity is possible only in very few MS.

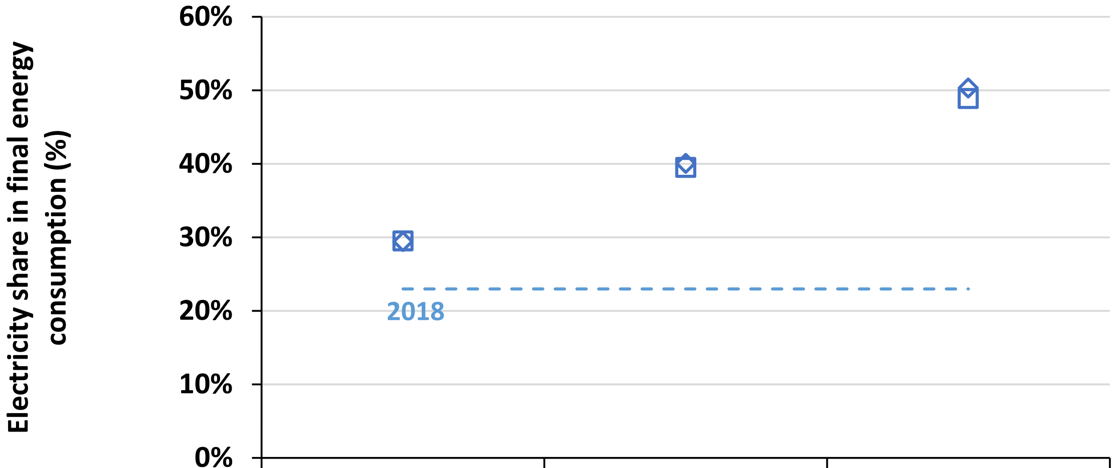
Figure 12 Electricity share in final energy consumption in the selected scenarios in the EU28



	2030	2040	2050
EC LTS 1.5TECH	29%	40%	50%
EC LTS 1.5LIFE	29%	39%	49%
GP ER	31%	37%	41%
IEA WEO SDS	25%	37%	
IRENA GRO TES	30%	38%	49%
JRC GECO 2C_M	26%	36%	45%
Eurostat 2018	23%	23%	23%

Note: Results of GP ER are for OECD Europe.

Figure 13 Electricity share in final energy consumption in the EC LTS 1.5C scenarios in the EU27



	2030	2040	2050
◇ EC LTS 1.5TECH	29%	40%	50%
□ EC LTS 1.5LIFE	29%	39%	49%
- - - Eurostat 2018	23%	23%	23%

The growth of the power sector until 2030 is driven by demand primarily from transport: in order for this development to be achieved, the cost reduction in EV battery packs (major cost component of light duty vehicles) need to follow trajectories similar to those achieved in the different scenarios, alongside the necessary deployment of recharging infrastructure, and service capacity to maintain the cars, including the development of the necessary skills.

All scenarios project electricity to be the main driver for the emission reductions in **transport**, therefore a significant part of the increase in electricity consumption is derived from the road transport sector. In the selected scenarios, systems based on direct renewable use (biofuels) and EV deployment are the main decarbonisation option for the sector. In the EU, the CO_2 standard regulation for cars and vans is a key driver to increased efficiency of ICE power trains as well as a significant push for electrification even in the already implemented legislation. The strengthening of the CO_2 standards as assumed in the decarbonisation scenarios of the EC LTS in the longer term further drives strong shift in the vehicle fleet towards electric vehicles and other clean technologies. However, already a baseline context would see a significant change in the vehicle stock (see the EC LTS supporting document section 4.4.2.2). In order to follow these development trajectories, battery costs are expected to decrease significantly as assumed in all the scenarios, also in the absence of strong policy mandates (e.g. as in BNEF NEO; Table 17), where the uptake of electric vehicles is driven by cost competitiveness compared to alternative technologies. The assumed battery costs are not explicitly available for all the scenarios analysed and this conclusion is based on the penetration levels visible from the scenarios results which would required lower battery costs for EVs to reach price parity with ICEs (or strong policy incentives, which however in the absence of battery cost decreases this would entail an increase of vehicles costs causing affordability issues and would probably lead to a reduction of vehicle purchases and activity). BNEF NEO, one of the most optimistic projections in terms of EV deployment assumes a cost reduction of more than 60% by 2030.

The higher uptake of EVs also requires developments in the performance of batteries (e.g. range and density). In addition, the deployment of recharging infrastructure is also a prerequisite to support EV deployment at large scale, as implied by the selected scenarios. In the absence of recharging infrastructure, it cannot be considered possible for individuals to choose electric vehicles, therefore the developments will need to go hand in hand. Further an issue often neglected is the development of maintenance services for the new vehicles: maintenance availability is a key requirement for the purchase of vehicles by actors and requires a workforce trained in the maintenance of the new vehicle types. In IEA WEO SDS, electric vehicles become the main source for electricity demand growth. Next to electrification, two scenarios (IEA WEO SDS and IRENA GRO TES) see significant deployment of biofuels already by 2030. With supply constrains from food-based biofuels as dictated by EU policies and the early stage of deployment of second-generation technologies, there is need to further support the development and deployment of advanced biofuels. The increased deployment of advanced biofuels requires both techno-economic improvements in conversion technologies as well as the development of the feedstock supply chain. The latter requires significant time to develop and involves the interaction and coordination between sectors which currently exist only to a limited extent: the (liquid) fuel supply industry, a conversion industry for advanced biofuels and the agricultural/forestry sectors providing ligno-cellulosic feedstock that needs to be developed.

Available scenario data for the EU do not show explicitly the split of fuel consumption by mode of transport: for example, some transport modes as road transport are considered to be relatively easy to electrify, while others such as aviation are not expected to electrified at least not for the time period under consideration[24] and will therefore be reliant on liquid fuel of biological or non-biological origin (renewable fuels of non-biological origin -RFNBOs), and/or synthetic fuels based on electricity. While scenario results for different modes could differ, electrification of LDVs is the most technologically feasible option (at current technological stage) and is expected to remain so in the future. For other modes -particularly in road transportation of heavy goods, maritime and aviation-, more advanced "drop-in" fuels are deployed beyond 2030, if strong emission reductions are to be achieved. The comparative scenario analysis is not conclusive on whether these are predominantly e-fuels or advanced biofuels, as the different studies make different assumptions which lead to different conclusions on the predominant fuel type. Both types of fuels require significant market coordination across sectors which are currently interact only to a limited extent and need to overcome a number of technical barriers for the large scale development of the technologies which are not yet at market deployment stage for the most part. In addition, scenarios project final energy demand of transport to decrease; due to the limited publicly available data, it remains unclear what this entails in terms of activity per sector. Both electrification as well as modal shifts (shift to public transportation means) allow for an improvement of the specific efficiency of the transport system (in terms of energy consumption per passenger- or tonne-kilometre). JRC GECO, the EC LTS scenarios and other key literature sources, state that road transport (passenger cars, vans, two-wheelers) and urban buses is where electrification is most suitable. This entails furthering the development of efficient and cheap electric vehicles.

Across the scenarios, the **buildings** sector sees its demand rather constant to 2030, which entails efforts on energy efficiency and renovation first as the decrease in fossil fuels becomes noticeable. Electricity consumption in buildings increases significantly post-2030, with heat pumps being a key technology deployed widely across the scenarios. In fact, electricity for space and water heating requires the development of efficient and low-energy consuming equipment, as assumed in the JRC GECO study. The extent to which the sector consumes electricity is ultimately determined by the demand

[24] Norway has plans to electrify all short term aviation by 2040:
https://www.bbc.com/future/article/20180814-norways-plan-for-a-fleet-of-electric-planes,
https://www.nordicinnovation.org/programs/nordic-network-electric-aviation-nea

drawn for heat pumps, as other direct renewable energy options such as solar thermal, geothermal and bioenergy contribute but to a lesser extent. EC LTS 1.5TECH sees more than 60% of final demand in buildings to be covered by electricity in 2050.

Industry is a very diverse sector, which should require detailed analysis on a process by process level in order to understand the possibilities of electrification, energy efficiency, fuel switching, etc.. The level of detail of coverage of the industrial sectors varies significantly across the scenarios. In industry large-scale industrial heat pumps and further use of electrical motors, increase the sector's demand for electricity. The electrification share, depends on energy efficiency in the sector and on the type of processes. Not all elements of industry can be electrified due to chemical processes and the temperatures required (although high temperature heat pumps are being developed). Given the difficulty to electrify this sector, the scenarios show that fuel switching to biomass and hydrogen/e-gas will be used further reduce emissions. Industry is also the main source for process related CO_2 emissions: these are emissions not directly related to combustion, but related to chemical processes within industry. These are particularly important for Iron and Steel production, the cement industry and the chemicals sector. Both elements of circular economy, exemplified through increased recycling (secondary recycling process are both -for the most part- less energy intensive and in some cases have no process emissions e.g. in Iron and Steel production it is the primary iron production that generates the process CO_2 emissions) and higher efficiency and fuel switching can lead to significant reductions in process emissions.

Electricity is the largest option for large-scale emission reduction in the demand side sectors, both stationary and mobile. The main technologies required to achieve the electrification are:

- Batteries for electro-mobility;
- Heat pumps;
    - Small-scale;
    - Large-scale;
    - Low-temperature;
    - High-temperature.

All scenarios analysed directly or indirectly foresee the use of these technologies and assume significant cost reductions and performance improvements.

4.4.2. Hydrogen

Hydrogen is both a final energy carrier -to be directly used in end-uses, or can be an intermediate feedstock to produce other energy carriers (e-gas or e-liquids) or for non-energy uses, as a feedstock for the chemical industry or the iron and steel sector.

Currently hydrogen is produced mainly through Steam Methane Reforming (SMR) of natural gas (or naphtha) in the chemical and refining industries: the current processes have CO_2 emissions. The alternatives for hydrogen production are SMR with CCS to minimise emissions or the production of hydrogen through electrolysis from electricity, either from renewable energy (so-called "Green Hydrogen") or from other carbon neutral electricity. Most models provide results in 5-year time-steps, and in their results, hydrogen as an energy carrier and feedstock for energy products is projected to emerge after 2030 (only small quantities deployed in 2030) in all of the scenarios analysed. All selected scenarios project the production of hydrogen through electrolysis, in the longer term as demand for hydrogen increases beyond the current uses. Today, capital investment costs of electrolysers are still very high (according to BNEF, large differences in investment costs of electrolysers are observed between the EU and the Chinese market): significant efforts are required to reduce costs by more than 50% over the coming decade so that large scale production may take place as is projected by the scenarios analysed (e.g. JRC GECO assumes costs of 560 USD/kW_{el} in 2050). In the scenarios analysed here both "green" hydrogen, i.e. hydrogen produced through electrolysis by renewable electricity[25] is considered and "blue-hydrogen" -i.e. hydrogen produced through steam methane reforming followed by carbon capture (and storage) -CCS, is considered in some studies as a mid-term option (e.g. IEA WEO SDS) or transition option (e.g. JRC GECO 2C_M) for the production of hydrogen.

The following uses of hydrogen are generally considered[26]:

- Current uses: chemical industries (e.g. fertilizers), petrochemical industry and refineries;
- Future uses: fuel for the transportation sector (various modes), for cogeneration of electricity and heat or electricity along, as a direct fuel or feedstock in industry, long and short-term storage of electricity, feedstock for the synthesis of methane and liquid hydrocarbons, direct use of hydrogen in small scale stationary end-uses.

The EC LTS 1.5TECH scenario projects the use of hydrogen in all sectors. Hydrogen is projected to be used as chemical storage of electricity (in all scenarios of the EC LTS): this implies electrolysers will produce hydrogen from (excess) electricity and the hydrogen will be stored for future use (short term, seasonal or annual storage) and will then be electrified again in gas turbine power plants which are expected to support either direct hydrogen or hydrogen blend firing. In the BNEF study, this use of hydrogen is stated as precondition to fully decarbonise the power generation sector. Further, hydrogen is assumed to be blended into the gas grid in order to reduce the emission factor of the distributed gas. The blending into the grid is expected to be within higher bounds of technical capability of the gas grids: this is the case in the EC LTS scenarios as well as the IEA WEO which sees nearly 10% blending by 2040.

In **transport**, scenarios show both the deployment of FCEVs and e-fuels that can be directly consumed ("drop-in" fuels) by all transport modes. As in the scenario results fuel consumption per mode of transport is not always available, it is assumed that e-fuels are consumed in segments such as HDVs and aviation, which have limited other emission reduction options. The supply of hydrogen to transport, requires investments in refuelling infrastructure (hydrogen refuelling stations), but also the further development of P2X technologies. With 19% of the heavy-duty fleet electrified (at a global scale), BNEF expects natural gas and hydrogen to play a role for HDVs. IEA WEO examines hydrogen as a decarbonisation option additional to electricity in all transport modes: however, the modal split is not directly available. In the EC LTS scenarios hydrogen is used for selected uses of passenger road transport (long distance transportation or taxis, but is mainly used in heavy road transport. Further in the EC LTS scenarios hydrogen is also expected to be used as a fuel in the maritime sector, together with LNG. None of the scenarios analysed project the massive scale use of hydrogen in the transport sector, but the use of hydrogen is seen as a viable option for sectors which are more difficult to electrify. The variation of scenarios in the EC LTS 2°C scenarios show the different ranges of hydrogen penetration (with the H2 scenario having the highest penetration).

[25] It is unclear in all scenarios whether only renewable electricity is used for hydrogen production or the power generation mix of the countries. As the power generation sector is assumed to be largely decarbonized with very high shares of RES in most countries, this implies that while the electricity used to produce hydrogen may not be 100% RES, it is mostly carbon neutral.

[26] The following paper contains a list of references for different hydrogen uses: Evangelopoulou, S.; De Vita, A.; Zazias, G.; Capros, P. Energy System Modelling of Carbon-Neutral Hydrogen as an Enabler of Sectoral Integration within a Decarbonization Pathway. *Energies* 2019, *12*, 2551.

In **buildings**, EC LTS 1.5TECH and JRC GECO 2C_M show deployment of hydrogen. Assumptions on transmission grids, as well as hydrogen blends in the gas grid are unclear, but to the extent that hydrogen is directly consumed in buildings this would also require upgrade of end-use equipment. The EC LTS 1.5TECH scenario projects blending in the gas grid to reduce the emission factor of the gas grid (if natural gas is still used) or decrease the reliance on e-gas (if e-gas is predominant in the grid), which is less efficient from an overall system perspective.

Finally, **industry**, as one of the most diverse sectors in terms of fuel mix in the energy scenarios, is the largest hydrogen and e-fuel consuming sector. Hydrogen is a substitute for selected processes (e.g. iron reduction) as well as a fuel enabling to reach high temperatures which are required in selected furnaces in industry. While a number of industrial processes can be electrified, today's technologies do not allow for a total electrification of all industrial processes: these include processes with requirements - from a chemical point of view- for the use of methane, or the use of very high temperatures which are today difficult to achieve through heat pumps.[27] A possible explanation is that in industrial clusters hydrogen may be more feasible to produce and supply. The IRENA GRO TES scenario calls for support of hydrogen for industrial applications.

Notably, in EC LTS 1.5TECH, hydrogen emerges in all of the above mentioned uses and sectors, as the scenario aims at achieving carbon neutrality by 2050. BNEF expects hydrogen to be required to fully decarbonise power, but for that to occur significant cost reduction of electrolysers is needed.

The scenario analysis shows that hydrogen is used in all scenarios analysed in the following uses:

- Hydrogen to balance high RES shares and provide chemical storage for the power system (EC LTS, with BNEF explicitly stating it as a condition for the high RES shares);
- Hydrogen blending in the gas transmission and distribution grid.

All scenarios therefore assume the development of electrolysers for the production of hydrogen from electricity, which seems to be an essential technology to allow both the high shares of variable RES in power generation, as well as the decarbonisation of harder to decarbonise sectors in the longer term.

4.4.3. Heat

Heat, defined as district heating and direct consumption of fuels by end-use sectors excluding transport

The heating sector is a very diverse sector because of the different heat requirements of the end-users and seasonal variation. High temperature applications are required in industry, whereas buildings require lower temperatures and have strong seasonality (space heating). The direction that scenarios propose is, however, comparable. Firstly, scenarios focus on energy efficiency (whether on the building envelope or on material efficiency and process efficiency in industry -e.g. GP ER sees energy efficiency measures to reduce demand by 33% by 2050 in parallel with economic growth). Furthermore, they project electrification and use of direct renewable potential (solar thermal and geothermal).

The scenarios rely significantly on decarbonisation of heating by using heat-pumps (domestic and industrial scale) implying a strong electrification trend (section 4.4.1).

[27] Research is ongoing into high temperature heat pumps, but as yet there is not an option to substitute all high temperature uses with heat pumps.

BNEF expects electrification of heating as a main option to decarbonise, yet for that to happen policies need to support cost reduction of heat pumps. Heat pumps have high up-front costs (high capital costs-CAPEX), and low operational costs. This is very different from the most common systems in use today such as gas boilers which have much lower capital costs while maintaining significant operational costs (most notably fuel costs) over their life time. The scenarios agree that policies will be required in order to increase the affordability of heat pumps for all users (financing options, etc. for lower income households which might have financing difficulties for technologies with high upfront capital costs). BNEF, mentions that to decarbonise the heating sector, besides the reduction of high upfront costs of heat pumps (and the required policy support to diffuse them in the market), other developments are needed in heat distribution systems and building efficiency. Other barriers include lack of skilled workers, difficulty of reaching all buildings, technical difficulties in changing the building shell. Further scenarios also suggest the need for developments in large-scale district heating networks (e.g. as also suggested by IRENA, BNEF, and GP); these could also use large-scale heat pumps. IEA WEO SDS, projects heat pumps to gain over 3% market share by 2030. In the same scenario, hydrogen fuel cells and boilers are expected to gain higher than 3% market share beyond 2030.

One point of differentiation across the scenarios is on the role and size of biomass for heating. The remaining energy demand (mainly energy for heating) is supplied from gas or liquids (mainly gas and oil -albeit in significantly lower quantities compared to today). In the EC LTS scenarios some amounts of heat remain supplied through the gas networks, however the blends in the gas grid are such that the emission factor of grid gas is very low (blending of e-gas and hydrogen). Similar structure and size for remaining fuel consumption is found across the selected scenarios, with a transition away from coal and oil.

The attitude to the use of direct solar thermal use has been changing recently according to information from experts[28]: countries with high solar thermal potential also generally have high cooling requirements, therefore recently the tendency has been to install heat pumps which have the capacity to satisfy both heating and cooling demand compared to solar thermal system which cannot satisfy the cooling demand. These may be coupled with rooftop PV systems.

The scenarios analysed indicate that:

- Energy efficiency is essential to reduce heat/steam requirements;
- Heat pumps -which require further improvements in their techno-economic characteristics- will be the main technology to supply heat in the demand side;
- Small quantities of hydrocarbons (either fossil or synthetic) will be required to supplement the remaining heat uses;
- Biomass use varies across scenarios, based on the use of biomass in other sectors and the assumptions about biomass potential.

4.4.4. Storage

The high shares of RES projected across the scenarios (section 4.3), especially of variable renewables (wind and solar) implies the need for flexible balancing and energy storage. All scenarios project usage of multiple storage options, however the mix of technologies used for storage and flexibility purposes varies (contribution and shares of different storage options are not directly quantifiable). All scenarios use pumped-hydro which is the technology used today for longer term storage and peak supply; the hydro-pumped storage available in the EU will however not be sufficient to cover the increasing

[28] Based on interviews conducted by the authors in the context of other projects.

amounts of balancing and storage needs. In all scenarios, batteries feature prominently as a storage technology (they are the primary storage/balancing technology in the IEA WEO SDS and BNEF scenarios), hydrogen and e-fuels emerge prominently along-side batteries in EC LTS 1.5TECH and EC LTS 1.5LIFE, while additionally, vehicle-to-grid storage is used in e.g. JRC GECO and IRENA GRO. As such, alongside cost reduction of batteries for EVs, costs of stationary storage also need to reduce significantly to support the deployment of wind and solar to the levels indicated by the scenarios. With one of the highest deployment level of variable renewables across scenarios, BNEF projects Europe to add 10 GW of batteries for energy storage every year to 2050, reaching 226 GW in 2045 and stabilising at such levels thereafter. More than two-thirds are utility-scale systems, while the remaining are small-scale residential systems. For that to occur, besides significant decrease of battery pack costs (about 65% by 2030 -driven by the deployment of EVs), costs of the other system components are also expected (and project ex-ante) to decrease significantly. IEA WEO STEPS scenario (not included in the scenario selection) assumes battery system costs of 200 USD/kWh in 2040, therefore it is expected that the costs in IEA WEO SDS scenario would be lower.

Different uses of storage projected by the models also depends on the type of modelling used: the PRIMES model which is behind the EC LTS scenarios includes a fully-fledged unit commitment model, aside from the capacity expansion model while solving the power and steam generation module. This implies that the model includes full technological detail of power plants (ramp-up, ramp down, etc.) for power plant operation as well as including ancillary services, etc.. Furthermore, as the model is a full energy system model including full coverage of the demand side, the hydrogen and e-fuels are projected in the EC LTS 1.5TECH scenario to aid the emission reduction in other sectors beyond the power supply. The BNEF study focuses on the electricity demand projections (unclear how overall demand for all sectors is established), and models in detail the power generation sector including detailed modelling or large and small scale battery systems as well as battery charging, etc.. The IEA model includes only a capacity expansion component in its modelling.

Besides storage, other scenarios assume innovations in power system flexibility, smart grids and demand-side management to enable integration of large RES supply (e.g. as is the case of IRENA GRO TES and GP ER). Moreover, in most scenarios, natural gas maintains a role in power generation in the long-term, with CCGT gas-peaking capacity (with or without CCS) supporting further the need for flexibility and load following.

5. Conclusions

Despite stemming from entirely independent studies using different frameworks and storylines, the scenarios analysed in the present report reveal similar trends in key technologies and end-uses of energy.

All scenarios in the current report see renewable energy technologies as essential for power generation and electrification as central to the decarbonisation of energy demand. In most scenarios these projections are driven by highly ambitious, long-term decarbonisation goals and the assumption that capital investment costs for key technologies will drop. The scenarios determine technology costs exogenously using learning rates and scenario-based dynamic conditions of global deployment. Cost data, however, are neither readily available nor in the same format to allowing cross-comparison with RES deployment on the same level. For this, the findings in the current report draw primarily on the analysis of key scenario results. Two sets of scenarios are analysed for Europe, all of which show high RES deployment. One set of scenarios, including EC LTS 1.5TECH, EC LTS 1.5LIFE, JRC GECO 2C_M, IRENA GRO TES and GP ER, aims at deep decarbonisation and achieves different emission reduction by 2050. The other scenario, BNEF NEO, assesses the development of the power system based on least costs without considering international climate targets.

The comparative analysis demonstrates that costs of power supply technologies across deep decarbonisation scenarios are similar. Therefore, a decisive factor for the trajectory and future technology mix is the size of the energy system (demand and use of electricity as a feedstock to produce fuels) and the stringency of the emission reduction target. BNEF NEO assumes that technology costs decrease significantly as a result of industrial forces which, to a large extent, suffice to drive deployment, despite retaining carbon pricing in Europe at business as usual levels. Hence, regardless of the decarbonisation context, all scenarios portray a similar direction for RES power supply technologies, one that confirms the strong expectation of dropping technology costs and increasing performance of renewables.

All studies confirm that electrification is a cornerstone of meeting end-use demand while reducing GHG emissions, primarily in sectors like transport, but also in industry (heating and/or electrical motors) and heating in buildings. More specifically, in the transport sector, electrification of final energy demand increases impressively under all scenarios. There is consensus that the transport segments of light-duty vehicles (cars, vans, two-wheelers) and buses will undergo transformation towards electrification. Assuming the accelerated reduction in battery costs, the increase in performance (e.g. range, weight), along with the rollout of re-charging infrastructure, may make the rapid electrification of the transport sector a reality. Investing towards this objective seems to be a *no-regrets* option according to all scenarios. On the heating sector, all scenarios envisage heat pumps to drive decarbonisation forward. A few scenarios assume high temperature heat large-scale pumps, which are not yet mature, and the development of which requires investing in learning-by-doing. When it comes to electricity supply, all scenarios underscore the importance of decarbonisation for achieving emissions reduction, which, in turn, implies a sharp rise in generation from variable renewables (e.g. almost all growth in the IEA WEO SDS by 2040 comes from wind and solar PV). Consequently, the demand for storage increases. Scenarios explore all options regarding storage technologies: batteries (both residential and utility scale), hydrogen and e-fuels (that also act as drivers for further increase in demand). Provided that a massive adoption of EVs takes place, few scenarios shed light on the contribution of EVs in electricity storage, where EV battery packs provide vehicle-to-grid storage services. In addition, some scenarios point prominently towards smart grids, digitisation and demand-side management. Next to electrification, energy efficiency is considered key in all sectors particularly for buildings and industry. Levels of energy intensity improvements in the selected scenarios of around 3% annually are mentioned.

The second key driver of deep decarbonisation that goes hand-in-hand with the expansion of the power sector, is the deployment of hydrogen and electricity-derived fuels (e-fuels). All scenarios stress how hydrogen (and synthetic fuels) can help decarbonise demand in sectors difficult to electrify, exemplified in specific uses of hydrogen in heavy industry and transport or as fuel blended in distributed gas. For that reason, hydrogen holds a pivotal role in achieving the emission reduction required by deep decarbonisation pathways. Production of hydrogen from electrolysers and renewable energy sources lies at the heart of technological development in all scenarios. More so, production from natural gas, coupled with CO_2 removal technologies, is a technology that some scenarios are looking at too (IEA WEO, IRENA, JRC GECO). Another use of hydrogen, highlighted in scenarios that achieve net-zero emissions by 2050, is that of an electricity storage carrier (power-to-X). The scenarios that envisage large deployment of hydrogen and e-fuels show a stark increase in electricity generation, which magnifies the total volume of renewables in the power sector. In contrast, other scenarios reflect a relatively smaller increase in the size of the power sector, despite assuming a high electrification of final demand sectors. The main reason for this is the projection of smaller volumes of hydrogen and electricity-derived fuels. E-fuels on the other hand are a key pillar of scenarios aiming at climate neutrality (1.5 degrees scenarios). This owes to the fact that only fuels produced by electricity can replace the few remaining amounts of fossil fuels in some sectors. Under less ambitious decarbonisation targets, e-fuels emerge but their deployment is less profound.

To ensure market development of hydrogen, the capital investment costs of electrolysers will need to decrease and their efficiency to increase by a lot. In the long-term, hydrogen produced by carbon-free electricity is compatible with climate targets in all scenarios. Therefore, a critical component in the cost structure of hydrogen is the cost of electricity. Producing hydrogen at times of RES abundance is simulated in few of the scenarios as a competitive way to produce hydrogen and to synthesize methane and hydrocarbons at reasonable prices. Since hydrogen is expected to become increasingly relevant for the energy system post-2030, investment in massive production and hydrogen transport infrastructure will be needed. Transport and industry are two sectors where deployment of hydrogen is anticipated. There are scenarios that meet part of the energy demand of HDVs or airplanes with hydrogen and e-fuels, which would require the set-up of refuelling infrastructure. Conversely, other scenarios decarbonise those sectors using large amounts of biofuels. Nonetheless, an uptake in biofuels entails the establishment of sustainable feedstock chains and the development of advanced conversion technologies, which have yet to reach industrial maturity.

All analysed scenarios assume improved techno-economic developments for the following technologies: electrolysers, heat-pumps, batteries - both stationary and mobile - , wind offshore, onshore wind and solar PV. For onshore wind, even though it is considered a mature technology, scenarios do anticipate some improvements in turbine size and capacity factors. Similarly for solar PV, a mature RES technology, continuing to invest in cost reduction is critical, also for leveraging the coupling with electrochemical storage systems. For less mature technologies, such as wind offshore, electrolysers, batteries and heat-pumps, most scenarios stress the need for policy support to ensure these reach sufficient levels of maturity. For offshore wind in particular scenarios foresee steep cost reduction for deep-water turbines in the long-term, which may however occur in the short-term instead. Furthermore, improvements in battery cost and performance (for EVs and for stationary storage), but also infrastructure investments in power system flexibility are considered an essential development in all scenarios.

Policy support make take different forms, ranging from research grants/incentives to deployment support. Research developments, roll-out of infrastructure, emergence of adequate business models, are all issues that require considerable time to materialize. Thus, to be available in the market by 2050, the deployment of these technologies ought to kick off well before 2040, and so research developments and clear policy signals need to be in place by 2030 at the latest. Medium term targets are important to make sure that investment in technological development and infrastructure occurs early enough, galvanizing coordination between market players and familiarizing consumers with the new technologies. The 2020-2030 decade is decisive in that respect and will affect all sectors, including RES integration in the power sector, electricity storage, electromobility, renovation of old buildings and efficient industrial technologies. The 2020-2030 should be a decade characterised by large-scale, intensive investment across sectors, including infrastructure, to allow for the harvesting of both economic and technological benefits in the period to come. Ensuring such a positive anticipation of future technology markets is the main challenge for energy policy in the 2020’s.

Annex I: Readily and publicly available data on techno-economic progress in the selected studies

Table 10 Capital costs in IEA World Energy Outlook STEPS scenario

USD/kW	2017	2040
Nuclear	6 600	4 500
Coal	2 000	2 000
Gas CCGT	1 000	1 000
Solar PV	1 090	610
Wind onshore	1 950	1 760
Wind offshore	4 920	2 580

Table 11 Capital costs in Greenpeace's ER scenario

USD 2013/kWp	2030	2040	2050
PV	1160	920	680
Ocean	4480	2870	1690
Large scale hydropower	3400	3520	3620
Solar thermal	5430	5070	4940
Wind Onshore	1650	1610	1570
Wind Offshore	3540	3100	2750
Biomass	2210	2130	2070
Biomass CHP	3770	3590	3380
Geothermal	6380	5310	4560

Table 12 Technology cost assumptions in PRIMES used for EC LTS 1.5LIFE and EC LTS 1.5TECH in 2018[29]

Technology	EUR/kW			
	2020	2030	2040	2050
Gas Turbine Combined Cycle Gas Advanced	820	770	750	750
Steam Turbine Coal Conventional	1600	1600	1600	1600
Nuclear III gen.	5300	5050	4750	4700
Wind onshore-Low	1395	1261	1110	1043
Wind onshore-Medium	1295	1161	1010	943
Wind onshore-high	1080	988	840	782
Wind onshore-very high	1200	1066	915	848
Wind small scale rooftop	2850	1850	1750	1650
Wind offshore - low potential	2223	1804	1763	1749
Wind offshore - medium potential	2778	2048	1929	1891
Wind offshore - high potential	3206	2454	2292	2240
Wind offshore - very high (remote)	3684	2843	2689	2640
Solar PV low potential	721	690	567	495
Solar PV medium potential	710	663	519	454

[29] https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

Technology	EUR/kW			
	2020	2030	2040	2050
Solar PV high potential	700	645	477	431
Solar PV very high potential	690	627	455	407
Solar PV small scale rooftop	1435	930	745	610
Solar Thermal with 8 hours storage	5500	4237	3437	3075
Tidal and waves	6100	3100	2025	1975
Lakes	3000	3000	3000	3000
Run of River	2450	2400	2350	2300
Geothermal High Enthalpy	3901	3198	2897	2613
Geothermal Medium Enthalpy	4970	4586	3749	3306

Table 13 Capital investment costs of green hydrogen production technologies in PRIMES used for EC LTS 1.5LIFE and EC LTS 1.5TECH in 2018

Technology	Investment cost per unit of capacity (EUR/kW-output)		
	2015	2030	Ultimate
Hydrogen from low temperature water electrolysis PEM centralised - Large Scale (per 1 kW or 1 MWh H2 HHV)	1400	340	200
Hydrogen from low temperature water electrolysis PEM de-centralised at a refuelling station (per 1 kW or 1 MWh H2 HHV)	2200	750	350
Hydrogen from low temperature water electrolysis Alkaline centralised - Large Scale (per 1 kW or 1 MWh H2 HHV)	1100	300	180
Hydrogen from low temperature water electrolysis Alkaline de-centralised at a refuelling station (per 1 kW or 1 MWh H2 HHV)	1650	380	300
Hydrogen from high temperature water electrolysis SOEC centralised (per 1 kW or 1 MWh H2 HHV)	1595	804	600
Hydrogen from high temperature water electrolysis SOEC de-centralised at a refuelling station (per 1 kW or 1 MWh H2 HHV)	2712	1407	750

Table 14 Capital investment costs of storage technologies in PRIMES used for EC LTS 1.5LIFE and EC LTS 1.5TECH in 2018

Storage technologies	Investment cost per unit of energy stored per year (EUR/MWh)		
	2015	2030	Ultimate
Compressed Air Energy Storage (per 1 kW or 1 MWh electricity)	125000	112500	110931
Flywheel (per 1 kW or 1 MWh electricity)	1750000	1575000	1553029
Large-scale batteries (per 1 kW or 1 MWh electricity)	600000	253000	225484
Small-scale batteries (per 1 kW or 1 MWh electricity)	270000	114000	101619
Pumping (per 1 kW or 1 MWh electricity)	100000	90000	88745
Underground Hydrogen Storage (per 1 kW or 1 MWh H2)	5340	3936	3821
Pressurised tanks - Hydrogen storage (per 1 kW or 1 MWh H2)	6000	4800	4659
Liquid Hydrogen Storage - Cryogenic Storage (per 1 kW or 1 MWh H2)	8455	6800	4000

Storage technologies	Investment cost per unit of energy stored per year (EUR/MWh)		
	2015	2030	Ultimate
Metal Hydrides - Hydrogen Storage (per 1 kW or 1 MWh H2)	12700	11430	11271
Thermal Storage Technology (per 1 kW or 1 MWh Heat)	100000	90000	88745
LNG Storage Gas (per 1 kW or 1 MWh Gas)	135	135	135
Underground NGS Storage (per 1 kW or 1 MWh Gas)	33	33	33

Table 15 Learning rates in JRC GECO 2C_M

%	Learning rate
Wind onshore	5%
Wind offshore	11%
Solar PV	20%
Solar thermal electricity	18%
Stationary storage	12%

Table 16 Costs of end-use technologies in JRC GECO 2C_M

Technology	Component	Unit	Value
Light EV battery	Battery cost (as part of vehicle cost)	kUSD/veh in 2050	7.4
Heavy EV battery	Battery cost (as part of vehicle cost)	kUSD/veh in 2050	127
Light vehicle fuel cell	Fuel cell cost (as part of vehicle cost)	kUSD/veh in 2050	6.7
Heavy vehicle fuel cell	Fuel cell cost (as part of vehicle cost)	kUSD/veh in 2050	29.4
Heat pumps	Investment cost	USD/kWel in 2050	635

Note: In addition, JRC GECO 2C_M assumes hydrogen production costs of 568 USD/kWel in 2050.

Table 17 Technology cost and performance considerations in BNEF NEO

Technology	Description of cost and performance
Solar PV (fixed-axis utility scale)	From 770 USD/kW in 2020, to 530 USD/kW in 2030, 390 USD/kW in 2040 ultimately to 330 USD/kW in 2050.
Onshore wind	Their capital investment costs develop with a learning rate of about 10%. This reduces to 7% for wind parks including balance of system. Besides CAPEX developments, BNEF expects increase in turbine size and capacity factors (potential up to 50% over the next years) ultimately leading to reduction in LCOE over time.
Fixed-bottom offshore wind	Costs decrease at a rate of 17% for every doubling of capacity after 2030. In terms of electricity production costs, these decrease from 133 USD/MWh in 2019 to 57 USD/MWh in 2025.

Technology	Description of cost and performance
	BNEF expects a much lower reduction thereafter, as offshore wind sites will need to move to deeper waters. For offshore wind e.g. with floating foundations, further policy support is expected to be needed.
Lithium-ion battery packs (for EVs and for stationary storage)	Costs decrease from 176 USD/kWh in 2018, to 94 USD/kWh in 2024 and 62 USD/kWh in 2030. BNEF estimates this cost decline assuming an 18% learning rate. Moreover, BNEF expects significant improvements in performance (e.g. density, weight, but also on scale-effects from increase in manufacturing output).
Lithium-ion battery-based energy storage systems	BNEF expects full system costs to decrease from 357 USD/kWh in 2018 to 170 USD/kWh in 2030 (energy-oriented storage systems - i.e. large-scale systems), and 742 USD/kWh in 2018 to 266 USD/kWh in 2030 for residential storage (i.e. smaller scale systems). Notably significant cost reduction comes from battery packs, gradually shifting the need for cost reduction to other system components.

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