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Towards net-zero emissions in the EU energy system by 2050

Insights from scenarios in line with the 2030 and 2050 ambitions of the European Green Deal

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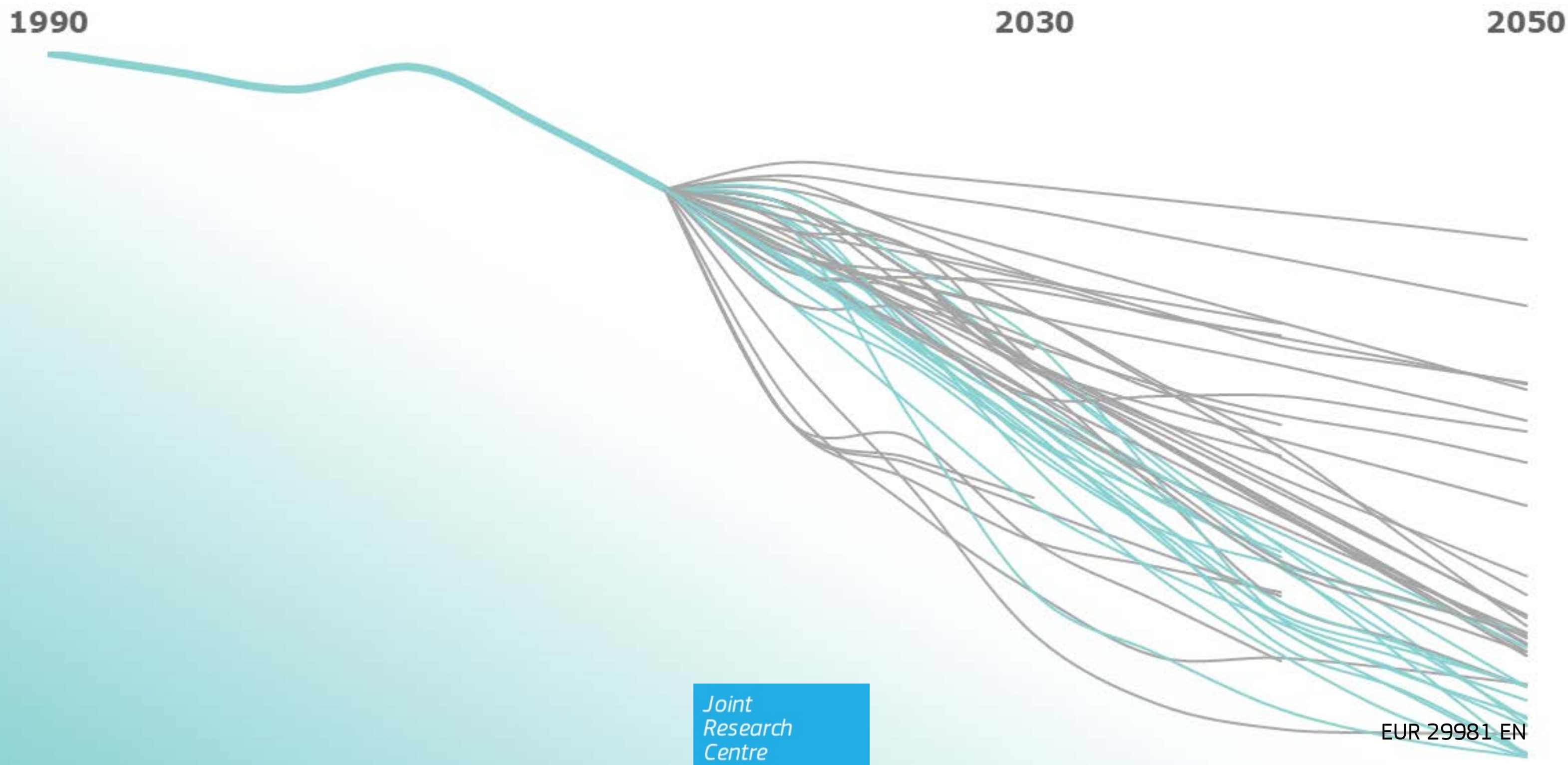

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Abstract

This report presents a comparison of 8 scenarios achieving more than 50% reduction of greenhouse gas emissions by 2030 compared to 1990, and 16 scenarios aiming at climate neutrality by 2050, similar with the ambitions of the "European Green Deal". This abstract summarises insights into similar and diverging elements of the scenarios on how the EU energy system may change by 2030 and by 2050, compared to today. The wealth of information, stemming from how different organisations see the EU energy system to evolve within their own scenario context, can provide useful input to EU climate and energy strategies.

2030 similarities

- 58-65% reduction in **ETS** and 41-50% reduction in **non-ETS** sector emissions (compared to 2005);
- 70% reduction in total **coal** use and its almost complete phase-out from power generation;
- 25-50% reduction in **oil** use and up to 25% reduction in **natural gas** use;
- Based on JRC interpretation, this implies 10-35% replacement of **oil** and **gas boilers** in **buildings** mainly by heat pumps and district heating;
- 28-55% reduction in oil use in **transport**; while mitigation efforts are required in all transport sectors, the oil reduction for cars may be larger;
- Installed capacity of **variable renewables** increases by a factor 2 to 3.

2030 differences

- The level of **energy efficiency**, influenced by the structure of the power sector and the reduction in energy demand for **heating of buildings** and for **transportation**;
- The **share of renewable energy**, influenced by the level of energy efficiency, the amount of wind and solar power, and biofuel use in transport;
- The growth of **wind** power generation varies between a factor of 1.5 and 3.5 and the growth of **solar** power between 1.5 and 4.5;
- The use of **biomass** ranges from limited growth to an increase of up to 60%;
- **Nuclear** energy provides between 20% and 30% of the electricity, unless normatively phased out;
- **Hydrogen** and **CCUS** emerges in some but not all scenarios.

2050 similarities

- A nearly complete phase-out of **coal**; a reduction of **oil** and **natural gas** use by at least three-quarters compared to today;
- **Renewables** provide 75% to 100% of the **electricity**, at least 60% of which coming from wind and solar; minimal thermal power from fossil fuels (up to 20% of the total capacity, with very limited operation);
- Increased use of **bioenergy**, from 9% of total energy today up to 20%, especially in the industry and transport sectors; increase in the use of **biofuels**, with the largest share as maritime and aviation fuels;
- Between 65% and 90% **zero-emission vehicles** in the total fleet; major uptake of electricity in **transport**, with the EU passenger battery electric vehicle fleet in most scenarios numbering between 100 and 220 million;
- Use of **hydrogen** in industry (5-20% of energy consumption, in addition to about 50% electricity), for fuel cell vehicles, and for e-fuels (mainly for aviation);
- In **buildings**; electricity meets 40-60% of energy demand, notable increase of heat supply from heat pumps;
- Necessity for natural **carbon sinks** (LULUCF) or within the energy system (carbon removal technologies).

2050 differences

- The reduction of **final energy**, ranging from 30% to 60%, compared to today;
- The share of **renewable energy**, ranging from 65% to 100%;
- The degree to which biofuels, hydrogen and e-fuels replace oil in **transport**, including the maritime and aviation sectors;
- The amount of **power**: *high* growth (a factor of 2 or 3 increase) through direct electrification and hydrogen/e-fuel output; *slow* growth through strong energy demand reduction and/or CCUS deployment instead of e-fuels;
- Related to this, the growth of **wind** and **solar** power generation each varies between a factor of 3 and 13;
- The trade-off between hydrogen and electricity as final energy carrier in **industry**;
- The extent to which enabling technologies, such as **electrolysers**, or other new technologies (e.g. CCUS) will be deployed;
- **Assumptions**, among others, on industrial output, building renovation, utilisation and occupancy of different transport modes, which are driven by disruptive societal changes such as vehicle sharing;
- Wide range for natural **carbon sinks** (LULUCF), up to 100% increase compared to today; **carbon removal** with technologies may reach the same CO_2 sequestration level as LULUCF today.

1 Introduction

Since the endorsement of the Paris Agreement in 2015, the discourse on the energy transition has been gradually shifting from "[…] *pathways consistent with holding the increase in the global average temperature to well below 2 °C* […]" [1] to efforts that limit the increase to 1.5 °C and the need to curb greenhouse gas (GHG) emissions to zero [2]. This entails that national pledges made under the Paris Agreement (National Determined Contributions) need to be strengthened since, based on current trajectories, the world would exhaust a significant part of the available carbon budget already by around 2030, making the 1.5 °C target by the end of this century more challenging [2].

In view of its commitment to the Paris Agreement, the European Union (EU) is en route to agree on higher emission reduction targets than the current ones ([1]). In the communication of the "European Green Deal" it is stated that the EC "[…] *will present an impact assessed plan to increase the greenhouse gas emission reductions target for 2030 to at least 50% and towards 55% compared with 1990 in a responsible way*" [3]. For the longer term, the EC communicated its strategic vision "[…] *to lead in global climate action and to present a vision that can lead to achieving net-zero greenhouse gas emissions by 2050 through a socially-fair transition in a cost-efficient manner* […]" and to be the world's first major economy that achieves climate neutrality by mid-century [4].

In the discourse on the energy transition, several options are communicated, usually as a result of modelling and analytical work combined in different pathways or scenarios. The technical feasibility of fully decarbonised energy systems has been discussed extensively in literature. There is a consensus on the technical challenges (such as generation/demand balance, transmission infrastructure or ancillary services) that the energy transition may face, especially regarding the feasibility and reliability aspects of fully decarbonised power sector [5], [6]. The costs and the criticality of such requirements, however, are still intensively debated. Energy transition pathways typically do not assess the technical feasibility of energy systems at a highly detailed level, but rather offer more strategic perspectives. The most prominent can be summarised as follows:

- Some pathways have a strong technological reliance, whether that is rapid deployment of renewables or deployment of carbon capture technologies at scale;
- In several scenarios, demand reduces due to increased energy efficiency (e.g. conversion efficiency of a technology), systems efficiency (e.g. circular economy, material substitution) and/or end-use efficiency measures (e.g. in-depth renovation of the building stock);
- Some opt for the deployment of new energy vectors and feedstocks, such as green hydrogen, or directly electrify end-uses as much as technically possible;
- In other pathways, disruptive innovations emerge and demand patterns change; these innovations are technological (e.g. digitalisation, automation) or behavioural (e.g. dietary preferences, car-pooling, lifestyle changes).

As there is no silver bullet for decarbonisation, these options are considered in different combinations. Ultimately, this polyphony leads to a poor or incomplete understanding of similar aspects between different scenarios, trade-offs across the several options, and conditions for decarbonisation, which are discussed in an isolated or fragmented manner.

By systematically comparing energy transition scenarios, this report aims to identify the similar elements as well as diverging scenario results towards achieving at least 50% of GHG emission reduction by 2030 (compared with 1990) and near-zero emissions by mid-century in the EU28.

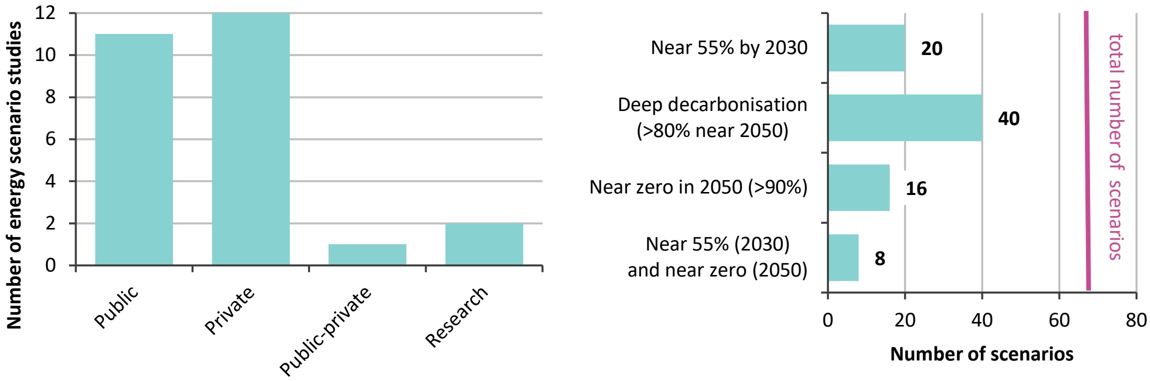
([1]) In 2018, with its so-called "Clean energy for all Europeans" package [9] the EU strengthened its policy framework to facilitate the energy transition and deliver on its commitment to the Paris Agreement. The EC impact assessment modelling shows that the updated energy strategy will lead to a reduction of GHG emissions by 46% compared with 1990, excluding emissions from Land Use, Land-Use Change and Forestry (LULUCF) [50].

2 Energy scenarios

2.1 Scenario selection

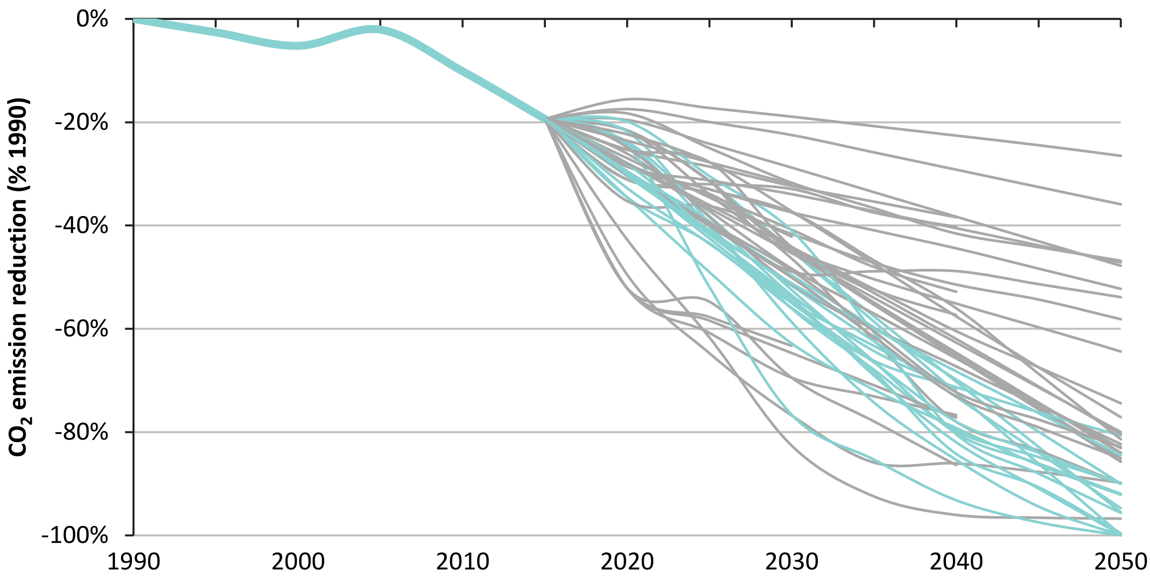
Between 2017 and mid-2019, 26 publications on energy scenarios, stemming mainly from governmental organisations or the private sector (Figure 1 (left)), present 67 scenarios for the EU energy system (Figure 1 (right), Figure 2). About two-thirds of these scenarios follow deep decarbonisation trajectories (i.e. reducing emissions by more than 80% by 2050) ([2]). One-third (20 scenarios) meet the ambition of the "European Green Deal" to reduce emissions by at least 50% by 2030 [7], and another third (16 scenarios) with the strategic vision for the EU to become a climate neutral economy by 2050 ([3]) [8] (Figure 1 (right)).

Figure 1 Overview of energy scenario studies that include the EU28, published between 2017 and June 2019



Note: This report reviews a subset of scenarios for the ambition of 2030 due to limited data availability and sectoral coverage (8 out of 20 scenarios shown in the right figure). Not all scenarios that meet the mid-term ambition (2030) meet the long-term vision (2050), and vice versa. *Source*: JRC.

Figure 2 CO_2 emission trajectories in energy scenarios for the EU28 to 2050, published between 2017 and June 2019



Note: The scenarios reviewed in this report are highlighted in blue. *Source*: JRC.

([2]) In this context, deep decarbonisation is defined as emission reduction higher than 80% by 2050 compared to 1990. The complete list of the 67 scenarios is presented in Annex 1, highlighting those that are assessed in the present study in blue.

([3]) The complete list of scenarios is in Annex 1. The assessment excludes pathways prepared for the IPCC report on Global Warming of 1.5 °C [2], due to their wide geographical scope (OECD region). These scenarios are accessible at: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/.

This report analyses two subsets of scenarios (Table 1), more specifically (4):

- Those that meet the *mid-term ambition* (i.e. emission reduction of at least 50% by 2030 compared to 1990, excluding those that exceed a 56% reduction). This group includes 8 scenarios from 7 different publications and 6 different stakeholders. Notably the EC Long Term Strategy (LTS) scenarios are not part of this selection as they do not meet the criterion;
- Those that meet the *long-term vision* (i.e. near-zero emissions or emission reduction of at least 90% by 2050 compared to 1990). This group includes 16 scenarios from 10 different publications and 9 different stakeholders, including two scenarios from the EC LTS.

Table 1 Scenarios that meet the mid-term ambition and/or the long-term vision for emission reduction in the EU28. The reduction covers energy-related and process CO_2 (including international aviation), excluding LULUCF ([a])

Publisher	**Scenario abbreviation**	**Mid-term ambition 2030**	**Long-term vision 2050**
Eurelectric	Eurelectric 90	-	**-90%** ([b, c])
Eurelectric	Eurelectric 95	-	**-95%** ([b, c])
European Climate Foundation	ECF Technology	-45%	**-90%**
European Climate Foundation	ECF Shared effort	**-52%**	**-92%**
European Climate Foundation	ECF Demand-focus	**-56%**	**-90%**
European Commission	EC LTS 1.5Tech	-45%	**-100%**
European Commission	EC LTS 1.5Life	-45%	**-95%**
International Energy Agency	IEA ETP 2DS	**-56%**	-81%
International Energy Agency	IEA ETP B2DS	-63%	**-92%**
International Energy Agency	IEA WEO SDS	**-54%** ([d])	-
International Renewable Energy Agency	IRENA GET REmap	**-51%** ([b])	-84%
Joint Research Centre	JRC GECO 1.5C	-41%	**-96%**
Joint Research Centre	LCEO Zero Carbon	**-54%**	**-100%**
Navigant	Navigant min gas	-	**-100%**
Navigant	Navigant opt gas	-	**-100%**
Oeko-Institut	Oeko Vision	**-55%**	**-99%**
Teske et al. 2019	IFS 2C	-59% ([b])	**-100%** ([b])
Teske et al. 2019	IFS 1.5C	-77% ([b])	**-100%** ([b])
WindEurope	WindEurope PC	**-55%** ([b])	**-90%** ([b])

([a]) The scenarios reviewed for 2030 and 2050 are highlighted in blue.
([b]) Proportional reduction assumed for non-disclosed CO_2 emissions (i.e. international aviation, process emissions; Annex 3).
([c]) The scenarios are designed based on 2050 targets, but data are reported only up to 2045.
([d]) International aviation emissions based on IEA ETP 2DS.

Source: JRC.

In these subsets, not all scenarios that meet the mid-term ambition lead to near-zero emissions by mid-century (5) and vice versa (6). Several scenarios do not provide adequate quantitative information to support the assertion that they achieve either the mid-term or the long-term goal (7). Furthermore, scenarios that lead to drastic emission reduction in the EU do not necessarily lead to comparable emission reduction in the rest of

(4) The analysis excludes: (a) scenarios that cover only the power sector (i.e. BNEF, ENTSO-E), because they do not cover the total energy system, although they may contribute towards the mid-term ambition and the longer-term vision, (b) scenarios that have limited data availability (i.e. FCH Ambitious, BP RT), and (c) outdated versions of scenarios (i.e. IEA WEO 2016 and 2017). The scenarios are discussed in varying degree of detail, depending on data availability. The EC LTS Baseline scenario is also used, due to its policy relevance, as it incorporates the targets of the "Clean energy for all Europeans" package for 2030.

(5) Namely, IEA ETP 2DS and IRENA GET REmap.

(6) Namely, JRC GECO 1.5C, ECF Technology, EC LTS 1.5Tech and EC LTS 1.5Life.

(7) Namely, Eurelectric (for 2030), Navigant (for 2030) (Table 1).

the world. Notably, population growth, an important exogenous assumption, is similar across all the assessed scenarios (Annex 2). Economic growth is assumed in all scenarios, with an annual rate ranging from 1.4% to 1.7% (Annex 2). Other assumptions that drive the scenario results may vary (e.g. technology costs, global energy commodity prices, renewable energy potentials, sectoral Gross Domestic Product (GDP)). Lastly, scenarios differ in their narrative, the modelling approach and the policy portfolio they include (see section 2.2). As explained further on, some scenario narratives (e.g. 100% Renewable Energy Sources (RES), EU-wide phase-out of nuclear) differ substantially from the existing climate and energy policies of the EU and its Member States. As such, these narratives are useful in their own scenario context. The analysis of all scenarios presented in this report is not an assessment of the EU climate and energy policies.

2.2 Scenario description

This section briefly describes the motivation of the studies and underlines the main elements of their scenarios that achieve the emission reduction analysed in the present report. Although all scenarios are normative with respect to their long-term emission reduction targets (i.e. forcing emissions to decline rapidly), there are important differences in the way they seek to reach that goal, whether being cost-optimal, preferential towards specific technological options or radically diverging in other key assumptions ([8]). The scenarios are grouped further into broader clusters based on selected indicators (section 2.3). An overview of the methods (models) and their scope as used in these studies is presented in Annex 1.

2.2.1 Eurelectric, 2018 – "Decarbonisation pathways"

Published by: Eurelectric in 2018. Eurelectric is the association of the European electricity industry. This study was launched following the pledge of the association to become carbon neutral well-before mid-century, in the context of the Paris Agreement.

Developed by: McKinsey, an international private consultancy company.

Storyline: The analysis shows the role of electrification in decarbonising 80-95% of the EU economy in 2050. Decarbonisation options include: switching from fossil-based generation to 94-96% carbon-free power, higher end-use efficiency due to electric mobility and electric heat pumps, and the production of hydrogen and synthetic fuels.

Modelling: *Global Energy Perspective,* a bottom-up, demand driven model. It is a model with a global scope (covering 8 regions and the EU28 plus Iceland, Liechtenstein and Norway). The results are presented for end use (transport, buildings and industry) and power generation sectors. In a first phase, a baseline and 3 EU electrification scenarios achieving 22%, 80%, 90% and 95% emissions reduction by 2050 are developed. In a second phase, the study analyses the decarbonisation pathways to drive the power sector towards climate neutrality "*well before*" 2050 at "*the lowest possible cost for each of the three electrification scenarios*".

Normative aspects and main assumptions: The *Global Energy Perspective* model is driven by links with McKinsey's *Global Energy Model,* that projects development of demand. The scenario definitions are formulated through non-quantified storylines of four sets of drivers: ambition (level of emissions reduction), technology deployment, consumer behaviour and regulation. Further normative elements of the modelling exercise are not explicitly mentioned.

Scenario description: The scenarios are formulated in reference to "*current trends*", which, however, are not provided by the study. The study covers a baseline and 3 alternative scenarios, of which only scenarios "2" and "3" achieve the long-term ambition within the scope of the present study. The scenarios reviewed in the present report are:

([8]) In this section, the elements that describe the scenarios (publisher, developer, storyline, modelling, normative aspects and key assumptions, scenario description) are not fully harmonised for the different studies. Homogenising the description of these elements across all scenarios requires access to certain information that is not systematically disclosed in the different studies. As a result, for example, scenario description may contain elements of scenario results because the distinction between inputs and outputs is not always made clear by the publisher.

- **Scenario 2, (90% CO_2 emission reduction by 2050):** For technology deployment, this scenario assumes that "*mature technologies experience steep cost reductions towards 2030*" and current technologies are "*deployed at a large scale across the economy after 2040 going beyond acceleration of current technological trends*" while "*complex industrial processes remain challenging to decarbonize and electrify*". The demand-side driver is described as "*clean technologies to progressively become mainstream and increasingly competitive for consumers*", while the competitiveness of the EU industry is safeguarded partially by adoption of electricity, given the expected electricity prices and a 38% electrification of the industry. The regulation drivers expect major shifts in policies, tariffs and taxes, driving earlier shift and removing current barriers to electrification, on top of the emission reduction targets;
- **Scenario 3, (95% CO_2 emission reduction by 2050):** "*Major technology breakthrough*" describes the technology deployment driver. It implies breakthrough technologies at an early stage of innovation reaching broad commercial scale before 2040. Consumer behaviour is set assuming high competitiveness of electricity against other energy carriers. Regulation includes the implementation of mechanisms envisioned for scenario 2 on a global scale.

2.2.2 European Climate Foundation, 2018 – "Net Zero by 2050: From Whether to How"

Published by: European Climate Foundation (EFC) in 2018. ECF is an international Non-Governmental Organisation (NGO) founded in 2008 aiming to promote climate and energy policies that reduce Europe's GHG emissions.

Developed by: ClimAct, a private consultancy company based in Belgium.

Storyline: This work aims to show how a net-zero target is technically and economically possible. It is part of ECF's "Net-Zero 2050" publication series. The reports in these series intend to create a basis for discussion with stakeholders and policy-makers on net-zero decarbonisation.

Modelling: *CTI-EU*, a simulation model of current and future European (EU28) emissions and available mitigation options. It covers GHG emissions in national inventories (including international aviation, shipping, and LULUCF). The ClimateWorks Foundation's "Carbon Transparency Initiative" presents online the results of the model (i.e. emissions, energy demand and supply, sectorial cost of supply and sector-specific consumption indicators for power, industry, transport and buildings, as well as dedicated indicators for LULUCF and biomass). Alternative sets of outputs can be accessed through user-selected ambition levels (defined on a sale from 0 to 3) for over 100 different drivers, called "*levers*".

Normative aspects and main assumptions: The outputs of the analysed scenarios are presented as the scenario results for a given set of values for all "*levers*". All pre-defined scenarios by ECF share a normative target of zero emissions by 2050. For some "*levers*", the 3 scenarios apply exactly the same values. For instance, regarding nuclear energy the scenarios assume no new investments. For EU manufacturing, all scenarios assume the current share of trade balance throughout 2050. While the "*levers*" are described to affect the economy, lifestyles, technologies and demographics, the mechanisms and the modelling arrangement through which they shape these are not available.

Scenario description: ECF presents 3 distinct pathways achieving net-zero GHG emissions by 2050. These pathways emphasise the deployment that is triggered under a given subset of "*levers*", namely technology-related, demand-oriented or their balanced mix:

- **Technology:** Emphasises on reducing emissions through energy efficiency and technological (e.g. electrification, hydrogen, Carbon Capture Utilisation and Storage (CCUS)) options pushed to the highest levels (translating to e.g. 96% of the EU building stock renovated by 2050). This scenario shows a 39% demand reduction in 2050 from 2010 levels;
- **Demand-focus:** Emissions are reduced mainly through interventions on the demand-side (e.g. recycling, product lifetime), circular economy and through social changes, for instance, by the

complete transformation of the transport sector to a service. The overall demand reduces further compared to the previous scenario (62% reduction for energy demand by 2050 from 2010 levels) while the ambition on technology change is moderate;

- **Shared efforts:** Compared to the previous scenarios, the effort is more evenly distributed across sectors and levers (e.g. between technical change and demand-side interventions). There is no particular emphasis on any specific mitigation option. The selected set of assumptions achieves a 58% reduction in the demand in 2050 from 2010 levels.

2.2.3 European Commission, 2018 – "A Clean Planet for all"

Published by: The European Commission in 2018.

Developed by: The European Commission. The corresponding impact assessment and related studies consider input from external contractors and sources.

Storyline: The EC, through its Communication "A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy" aimed to trigger a debate to feed into a long term strategy in order to "*confirm Europe's commitment to lead in global climate action and to present a vision that can lead to achieving net-zero greenhouse gas emissions by 2050*".

Modelling: *PRIMES* modelling suite. The *PRIMES* energy system model is developed by E3M Lab, a research laboratory in the Institute of Communication and Computer Systems of the National Technical University of Athens (ICCS/NTUA). The *PRIMES* model simulates the European energy system and markets, providing detailed energy balances, CO_2 emissions, investment in demand and supply, energy technology penetration, prices and costs. The *PRIMES* model covers the EU28 Member States on a country-by-country basis, simulating a multi-market equilibrium solution for energy supply and demand. *PRIMES* simulates demand and supply behaviour by agent (sector) under assumptions regarding economic development, emissions and other policy constraints, technology change and other drivers.

Normative aspects and main assumptions: Until 2030, the existing EU policy framework is assumed (among others the ones described in the "Clean energy for all Europeans" package [9]), following known Member State policies (for instance, with regard to nuclear energy and CCS) and the objective of reaching climate neutrality by 2050, including LULUCF and a limited amount of technological sequestration options (or some level of citizen involvement through lifestyle changes specifically in one scenario (EC LTS 1.5Life)).

Scenario description: The communication "A Clean Planet for all" includes 8 scenarios (electrification, hydrogen, power-to-X, energy efficiency, circular economy, combination, 1.5°C technical, 1.5°C sustainable lifestyles). From these, 5 achieve the well-below 2 °C target: 3 by switching from direct use of fossil fuels to low or zero-carbon options (which is either electricity, hydrogen or e-fuels), and 2 by focusing more on energy efficiency and circular economy. Their cost-efficient combination is assessed in a separate scenario that achieves higher emission reduction. This combination scenario realises lower deployment levels of each technology than those individually reached in the 5 scenarios. The 2 scenarios assessed in the present report (i.e. 1.5Tech and 1.5Life) are the most ambitious with respect to long-term emission reduction as they achieve net-zero emissions, including LULUCF sinks, in 2050. In these scenarios, hydrogen and power-to-X technologies become important. The differentiating elements that achieve the described targets are:

- **1.5Tech:** Increasing the contribution of all technologies by steep technology development, and relying on the deployment of biomass associated with CCS (BECCS);
- **1.5Life:** Same technological options as EC LTS 1.5Tech but relying less on these, assuming instead a more circular economy drive by EU business and consumption patterns. This translates into lifestyle changes and consumer choices that are more beneficial for the climate (e.g. less carbon intensive diets, transport sharing, limiting growth in air transport demand, a more rational demand for heating and cooling), while enhancing the incentives for LULUCF sinks compared to EC LTS 1.5Tech.

2.2.4 International Energy Agency, 2017 – "Energy Technology Perspectives"

Published by: The International Energy Agency (IEA) in 2017. The IEA is an autonomous agency under the Organization for Economic Cooperation and Development (OECD), established in 1974. The IEA has a two-fold mandate: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and to provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy.

Developed by: The International Energy Agency, Energy Technology Policy division.

Storyline: Since 2006, the IEA regularly publishes the Energy Technology Perspectives (ETP) study, providing a long-term technology outlook of the global energy system. The publication aims at identifying the most economical way for society to reach the long-term climate goals and technology options for this critical path.

Modelling: The ETP series is built on the pathways obtained from the *ETP-TIMES*, which is a *TIMES-based* bottom-up, energy system model of global scope and a technologically detailed supply side of the energy system for 11 sub-regions (28 to 39 regions are considered depending on the sector including the EU28). The ETP studies consider technologies available and in the innovation pipeline that can make their commercial scale deployment by 2060. The *ETP-TIMES* model determines the least-cost technology mix needed to meet the final energy demand. This demand is determined by the soft-linked *ETP end-use sector models* for industry, transport and buildings. The approach combines cost optimisation of an energy system model with backcasting and forecasting over the time horizon of 2014 to 2060.

Normative aspects and main assumptions: The pathways of the ETP analysis take into account policies that have already been implemented or decided at the time of the publication, such as the Nationally Determined Contributions pledged under the Paris Agreement. Besides the CO_2 emission targets, other exogenous parameters that drive the outcomes are GDP, population growth, material demand, techno-economics, CO_2 and fuel prices, demand load curves, resource potentials and their costs.

Scenario description: ETP 2017 presents 3 pathways for energy sector developments to 2060. The Reference Technology Scenario provides a baseline that takes into account existing energy and climate-related commitments by countries. This scenario is not consistent with achieving global climate mitigation objectives; nevertheless it implies a significant deviation from a business-as-usual scenario. The 2 additional scenarios assessed in the present report are:

- **2°C (2DS):** The energy system pathway is consistent with a 50% probability of limiting the global temperature increase to 2°C by 2100. From today's level, energy-related CO_2 emissions reduce by 70% globally by 2060, which means that energy and process-related CO_2 emissions must continue their decline thereafter;
- **Beyond 2°C (B2DS):** The shift from a 2°C (2DS) to a 1.75°C (B2DS) pathway requires about 35% additional CO_2 emission reduction. This scenario implies that technology development is pushed to the limit. It requires an "*unprecedented level of policy action and an effort from all stakeholders*". Net-zero emissions are achieved by 2060, with significant negative emissions through BECCS. The global temperature increases to 1.75°C by 2100 with a 50% probability.

2.2.5 International Energy Agency, 2018 – "World Energy Outlook"

Published by: The International Energy Agency in 2018 (see section 2.2.4).

Developed by: The International Energy Agency.

Storyline: Since 1977, the World Energy Outlook (WEO) is a widely disseminated report of the IEA. While ETP focuses on the impact of technology deployment in the energy system evolution, WEO aims to provide critical analysis on trends in energy demand and supply, and on their implications for energy security, environmental protection and economic development.

Modelling: The World Energy Model (WEM) is the underlying model of the WEO since 1993. It is a simulation model designed to "replicate how energy markets function and is the principal tool used to generate detailed sector-by-sector and region-by-region projections". It consists of three main modules for final energy consumption, energy transformation and energy supply. Outputs from the model include energy flows, investment needs and costs, CO_2 emissions and end-user pricing. As of 2018, the WEM covers energy developments up to 2040 in 21 regions (25 sub-regions), including the EU28.

Normative aspects and main assumptions: Main exogenous assumptions are GDP and population growth. The baseline scenario assumes that "*policies that had been enacted or adopted by mid-2018 continue unchanged*". Additional normative elements and policies are introduced to formulate alternative scenarios.

Scenario description: WEO considers 3 different scenarios: Current Policies, New Policies and the Sustainable Development Scenario, the latter being the one in the scope of this report:

- **Sustainable Development (SDS):** A normative scenario that starts from the Sustainable Development Goals (SDG) and works back to the present to see how these can be achieved. The SDS meets the Paris Agreement (SDG 13, on tackling climate change) and two complementary SDGs (SDG 7, on universal access to energy and SDG 3, on reducing severe health impacts of air pollution). The SDS uses a staggered introduction of CO_2 prices (up to 140 $ per tonne CO_2 in 2040), increased low-carbon power generation from renewables and nuclear whilst phasing-out coal (in a subset of EU Member States), extended support for CCUS, stringent emission standards in transport whilst supporting electric vehicles, alternative fuels and relying on biofuels, full adoption of best available technologies in industry, and transformation towards a near-zero buildings stock (e.g. 4% annual renovation rate post-2025), steep energy efficiency measures and demand reduction.

2.2.6 International Renewable Energy Agency, 2019 – "Global Energy Transformation"

Published by: The International Renewable Energy Agency (IRENA) in 2019. IRENA is an intergovernmental organisation supporting countries in their transition to a sustainable energy future.

Developed by: The International Renewable Energy Agency.

Storyline: The study is the second in the Global Energy Transformation (GET) series initiated in 2018, which is focused on long-term decarbonisation and on the technical feasibility and socio-economic benefits of a global energy transition.

Modelling: GET is based on *REmap*, a bottom-up excel based tool driven by statistics and stakeholder inputs. The current version covers 70 countries (and their regional aggregation, including EU28) covering 90% of the global energy demand and 4 sectors (power, industry, buildings and transport).

Normative aspects and main assumptions: Emission levels are compatible with the global temperature increase trajectories.

Scenario description: The GET report includes 2 scenarios: a Reference case and the REmap case. REmap is the scenario within the scope of the present report:

- **REmap:** The scenario builds a global pathway consistent with a 66% probability of achieving a target below a 2°C increase by 2100. This target is achieved by prioritising the deployment of renewable energy and energy efficiency. The REmap scenario for 2030 sees the EU as one of the regions with the largest emission reduction. Primary energy reduces by more than 14%, renewables represent somewhat less than 1/3 of energy consumption and 55%-renewable-electricity provides 30% of final energy consumption. Buildings and industry decarbonise the most due to electrification (about 40%) while transport sees a small increase in electrification (7% compared to the current 4%). These trends continue towards 2050, when the scenario achieves 84% emission reduction. Whilst CCS is deployed only in certain industry sub-segments (e.g. cement) and biomass CCS is not included in the REmap scenario by 2050.

2.2.7 Joint Research Centre, 2018 – "Global Energy and Climate Outlook 2018"

Published by: The European Commission, Joint Research Centre (JRC) in 2018.

Developed by: The Joint Research Centre.

Storyline: Since 2015, the Global Energy and Climate Outlook (GECO) has been a recurring publication of the JRC that provides a global picture of energy markets as they transform under the simultaneous interactions of economic development, technological innovation and climate policies. The modelling setup of the edition reviewed in the present report, provided results that were used in the EC's in-depth analysis in support of the communication "A Clean Planet for all". Earlier versions of GECO were used, for example, to support the EU negotiations in the Paris Agreement.

Modelling: The GECO analysis is built on the *JRC-POLES* and the *JRC-GEM-E3* models. Besides outputs on all energy sources, vectors and GHG emissions, the models estimate the development of international energy prices and trade that are used within the EC energy modelling framework. *JRC-POLES* has a global coverage divided into 66 regions, including the EU28.

Normative aspects and main assumptions: The main normative elements included are CO_2 emissions constrains to limit temperature rise (within a global CO_2 budget for 2011 - 2100 that depends on the scenario) and CO_2 tax. Exogenous modelling parameters include GDP, population, techno-economic assumptions, learning rates and policy constraints on subsidies and efficiency.

Scenario description: The GECO analysis considers different scenarios for emissions reduction, namely Reference, Nationally Determined Contributions and 1.5C. The 1.5C scenario is included in the present report:

- **1.5°C Scenario (1.5C):** Reduces GHG emissions within a 2011 - 2100 carbon budget of 500 $GtCO_2$ globally, in order to achieve with a 50% likelihood a 1.5°C temperature increase by the end of the century. It does so by strengthening CO_2 emission reduction (as opposed to emphasising on negative emissions or non-CO_2).

2.2.8 Joint Research Centre, 2019 – "Low Carbon Energy Observatory"

Published by: The European Commission, Joint Research Centre in 2019.

Developed by: The Joint Research Centre.

Storyline: The LCEO is an internal Administrative Arrangement of the EC being executed by the JRC for the Directorate General Research and Innovation. It aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies.

Modelling: The LCEO scenarios have been developed using the *JRC-EU-TIMES* model to assess the impact of technology and market developments into the future. The *JRC-EU-TIMES* model covers the EU28 and neighbouring countries energy system from 2010 to 2050, estimating the cost effective technology pathways for the EU to meet its climate and energy goals under different global energy scenarios. The model is open source and available through the JRC Data catalogue ([9]).

Normative aspects and main assumptions: The analysis is normative on the overall climate and energy policy goals, but exploratory for technology choices (different scenarios were defined based on additional normative elements).

Scenario description: The LCEO scenario analysis is built based on 3 scenarios (Baseline, Diversified and ProRes) that are constructed based on EU specific assumptions stemming from global development pathways and their influence on technology development parameters. Technological sensitivity scenarios are formulated within the context of the globally-derived Diversified and ProRes scenarios. The Zero Carbon scenario is the sensitivity on the emission reduction that falls in the scope of this report.

([9]) https://data.jrc.ec.europa.eu/dataset/8141a398-41a8-42fa-81a4-5b825a51761b.

- **LCEO Zero Carbon:** Designed to achieve agreed policy targets for 2030 and a 100% reduction of CO_2 emissions in the EU28 by 2050. For the longer-term, underground CO_2 storage is limited to 300 $MtCO_2$ annually and nuclear expansion is allowed in those countries with no nuclear restriction policies. The results show large amounts of RES, hydrogen and e-fuels driven by the 55% GHG emissions reduction by 2030 and by the limitation on CO_2 storage.

2.2.9 Navigant, 2019 – "Gas For Climate"

Published by: Gas for Climate, a project initiated by 9 key gas industry agents in 2019.

Developed by: Navigant Consulting Inc., a global professional services firm.

Storyline: The study aims to assess a cost-optimal way to fully decarbonise the EU energy system by 2050 and to explore the role of renewable and low-carbon gas used in existing gas infrastructure.

Modelling: The *Navigant Energy System Model cost-optimization* is the main tool, covering electricity and three end-use sectors: buildings (only heating), industry (energy demand for steel, ammonia and methanol production) and transport (passenger cars, freight trucks, buses, ships and aircrafts). The model looks into the energy system in the year 2050 for the EU28, without intermediate years.

Normative aspects and main assumptions: The study compares two scenarios, exogenously determined by renewable energy potentials, minimum and maximum technology shares in 2050 in end-use sectors, techno-economic parameters, energy efficiency and activity increase in final demand. On nuclear power, Navigant assumes normatively that it will not be an option in the long term, due to high cost combined with low capacity factors. A maximum deployment of gas-fired power plants in the power sector for dispatchable electricity generation is considered.

Scenario description: The present study assesses 2 scenarios that arrive at net-zero emissions in 2050 by assuming a significant increase in renewable electricity (wind, solar, and some hydropower). The main difference between the 2 scenarios lies in the role of renewable and low carbon (or "decarbonised") gas, and in the role of biomass power. Specifically:

- **Minimal gas:** Shows an increased role for direct electricity use in the buildings, industry and transport sectors. Within the constrained potential, biomethane use in industry is limited and diverted to other sectors. Renewable electricity is produced from wind, solar and hydro combined with solid biomass. Hydrogen is produced at industrial sites and gas networks are abandoned;
- **Optimised gas:** Includes high electrification of buildings, industry and transport sectors. Renewable and low-carbon gas is used to provide flexible electricity production, heat to buildings during peak demand, high temperature industrial heat/feedstock and fuel to heavy road transport/international shipping. Hydrogen is produced close to large-scale electricity generation sites and is transported using the current gas infrastructure.

2.2.10 Oeko Institut, 2017 – "The Vision Scenario for the European Union"

Published by: Oeko Institut, a non-profit, private sector environmental German research institute in 2017. The project was sponsored by the Greens/EFA Group of the European Parliament.

Developed by: Oeko Institut's own modelling and review of a broad range of other studies on the EU.

Storyline: The study aims to show a pathway that "*consistently combines short and medium-term objectives with long-term objectives*". It meets the EU28 GHG emissions budget consistent with a 2°C limit on the global temperature increase. It covers the aggregated EU with 28 Member States.

Modelling: The output is based on a literature review including, among others, the EU Reference Scenario 2016, studies of Frauhofer ISI and Greenpeace. Analyses for the end-use sectors and for CO_2 emissions (from industrial processes and non-CO_2 GHG emissions) are based on various deep decarbonisation projections for the EU or for single Member States for 2015-2050. The analysis for the power sector is based on an hourly modelling exercise for the EU-28. Sectorial integration is implemented through an energy balance model, which can also be used to calculate the related total primary energy supply and energy-related CO_2 emissions.

Normative aspects and main assumptions: the Vision scenario combines medium-term objectives on energy and emissions with the longer-term objective of limiting global temperature increase by 2°C, using a carbon-budget approach for the EU. The socio-economic drivers for energy consumption and GHG emissions are based on the EU Reference Scenario 2016. The scenario is formulated limiting CCS, nuclear and biomass.

Scenario description:

- **Vision:** A normative scenario that relies first on a massive roll-out of energy efficiency measures for all sectors (energy efficiency-first approach) and on early decarbonisation of the power sector. The scenario is defined through 4 main assumptions: (a) the use of nuclear power should be phased out based on the existing (at the time of the study) phase-out policies of different EU Member States or based on a technical lifetime of 40 years, (b) CCS is used only to avoid CO_2 emissions from industrial processes, (c) biomass restrictions to comply with tight sustainability criteria (15 GJ/cap) with no extensive efforts for additional carbon sinks, and as a consequence (d) all other GHG mitigation options should be used for the time horizon of 2050 so that an emission reduction of at least 90% can be reached by 2050. In addition, whilst imports of novel fuels are limited, all e-fuels deployed in the scenario are from extra-EU imports (about 1/3 of energy consumption in transport in 2050). No major behavioural changes accompany the transition towards a circular economy.

2.2.11 Sven Teske et al. 2019 – "Achieving the Paris Climate Agreement Goals"

Published by: University of Technology Sydney in 2019, edited by Sven Teske and financially supported by the Leonardo DiCaprio Foundation.

Developed by: A consortium of University of Technology Sydney, Graduate School of Energy Science, Kyoto University, German Aerospace Center (Institute for Engineering Thermodynamics and Institute of Vehicle Concepts), and University of Melbourne.

Storyline: The analysis looks towards reaching 100% renewable energy and near-zero emissions globally in order to meet the Paris Agreement goals, avoiding to rely on net-negative emissions. Emphasis is put on the power and transport sectors, including abatement of non-CO_2 emissions, mainly through sequestration by land and forests. Regional constrains and preferences are taken into account as far as possible. The solutions to decarbonisation normatively exclude nuclear power, "unsustainable" biomass use, CCS, and geoengineering due to uncertainties about the economic, societal, and environmental risks.

Modelling: An energy and Geographic Information System (GIS)-based modelling framework (of global coverage divided in 10 main sub-regions, including OECD Europe), following a hybrid bottom-up/top-down interaction of seven models with no objective cost-optimisation function:

- *Generalized Equal Quantile Walk* (*GQW*); a statistical method used to complement the CO_2 pathways with non-CO_2 regional emissions, based on a statistical analysis;
- *Land-based sequestration design*; a Monte Carlo analysis across temperate, boreal, subtropical, and tropical regions based on various literature-based estimates on sequestration dynamics;
- *Reduced complexity carbon cycle and climate mode* (*MAGICC*); a hemispherically averaged upwelling-diffusion ocean coupled to an atmosphere layer and a globally averaged carbon cycle model;
- *Transport model* (*TRAEM*); a long-term transport development model disaggregating transport into a set of different modes and providing the final energy demand;
- *Energy system model* (*EM*); a bottom-up simulation of future energy balances based on GDP, population, technology and energy intensity developments in all sectors, covering 10 world regions;
- *Power system model* (*[R]E 24/7*); an hourly balancing and electricity supply and demand in spatial resolution for sub-regional clusters;

- *Resource model* (*[R]E SPAVE*); a GIS-based approach for estimation of solar and wind potentials in space-constrained environments.

Normative aspects and main assumptions: The solutions exclude nuclear power, unsustainable biomass use, CCUS. The main exogenous modelling parameter include GDP, population, techno-economics, fuel costs (in line with IEA WEO 2017).

Scenario description: The study covers a reference scenario (based on WEO 2017) and 2 alternative scenarios. Both scenarios (2C and 1.5C) aim at deep decarbonisation see similar systemic changes towards decarbonisation, characterised by electrification of heat and transport and the parallel growth of wind, solar and geothermal. In transport, passenger and heavy duty vehicles are increasingly based on electric powertrains. The growth of electricity production is further driven by hydrogen and e-fuels production. Moreover, next to rapid deployment of efficiency measures and renewable technologies, energy inefficient behaviours are also tackled, shifting, for example, from domestic aviation to rail, are also tackled, while there is decline in the passenger kilometres driven by cars. The main difference between the scope scenarios is level of ambition:

- **IFS 2C:** global energy-related CO_2 emissions budget is about 590 $GtCO_2$. Compared to the more ambitious 1.5C scenario, it allows for delays in the transition due to political, economic and societal processes and stakeholders;
- **IFS 1.5C:** the global energy-related CO_2 emissions budget is around 450 $GtCO_2$. It assumes immediate action to realise all technically available options, without any political or societal barriers.

2.2.12 WindEurope, 2018 – "Breaking new ground"

Published by: In 2018, by the European wind industry's association WindEurope.

Developed by: DNV GL, a consultant.

Storyline: The study looks into pathways of renewable-based electrification leading to the decarbonisation of the EU energy system by electrification of industry, transport and by coupling power with heating and cooling.

Modelling: *DNV-GL-ETO* a global system-dynamics feedback model (implemented in Stella software). It covers all end use sectors (buildings, industry, transportation and feedstock) of 10 regions (including EU28, Iceland, Lichtenstein and Norway). Energy sources that meet demand are selected by a merit order-based algorithm; the evolution of technology costs over time is shaped by learning curves. The transformation sector includes electricity, heat, hydrogen and refineries.

Normative aspects and main assumptions: GDP, population, socio- and techno-economics are key exogenous parameters, though technology costs over time are being shaped through learning. The study limits future coal generation.

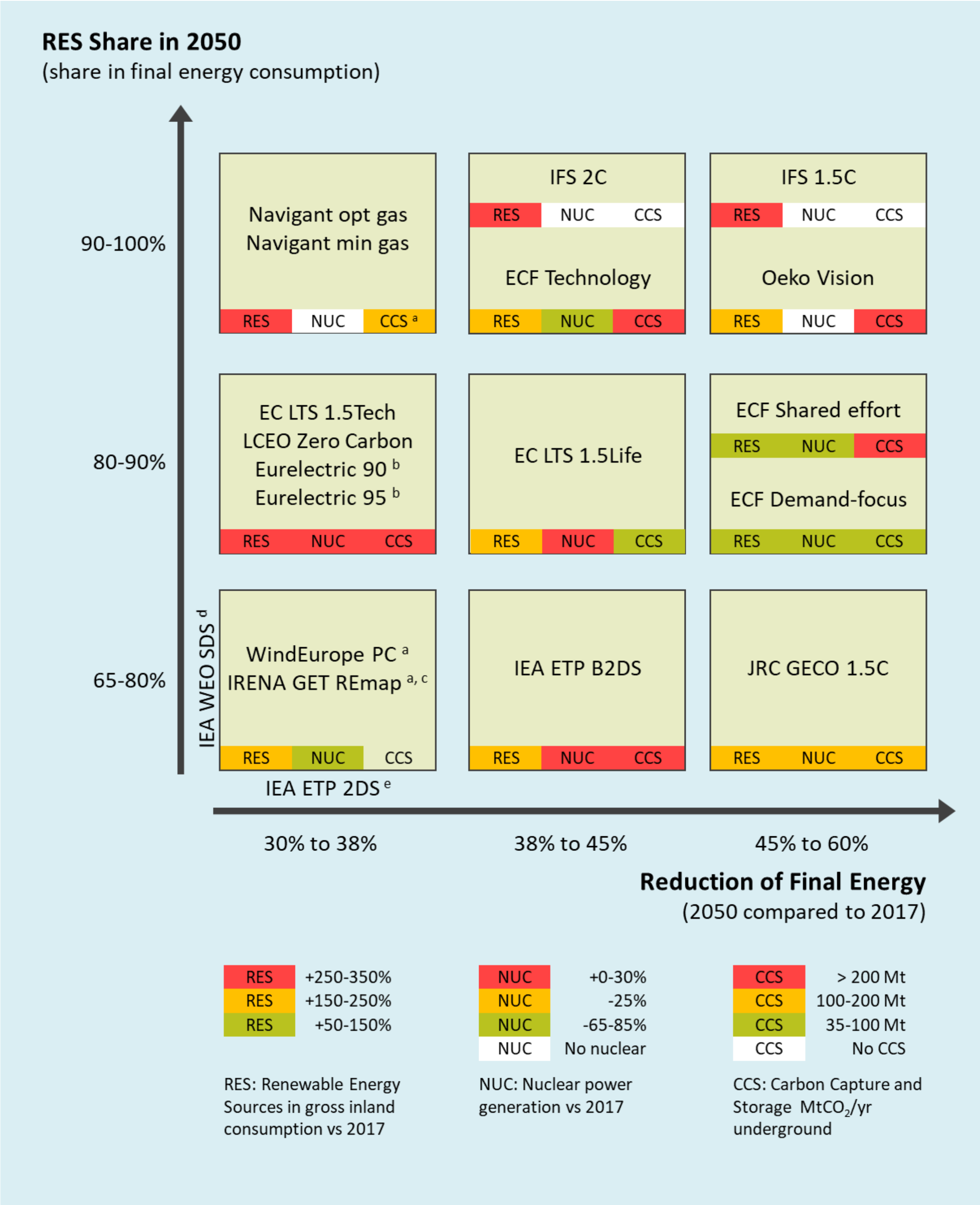
Scenario description: The study covers 2 scenarios, Accelerated electrification (which speeds up the effects of current policies by envisaging their full implementation) and a Paris-Compatible (PC) scenario. The latter meets decarbonisation criterion both for 2030 and 2050 and is thus included in the scenario comparison:

- **The Paris-compatible scenario (PC):** Limits global temperature rise to well-below 2°C and builds on additional effort in three main areas: electrification and energy efficiency, decommissioning of coal-based power generation and carbon pricing (mentioning energy users beyond those covered in the current EU Emission Trading System; EU ETS). Specifically, the uptake of electrification and energy efficiency in buildings is 1.8%/yr and 2.6%/yr in manufacturing and the passenger vehicles fleet is 90% electric (3.7% hydrogen-based) in 2050. Moreover, neither new coal plants (post-2020) nor coal-based power generation are allowed (post-2030). Finally, a carbon price of 90 €/tCO_2 in 2050 is central to the scenario.

2.3 Scenario grouping

The scenarios can be clustered on the basis of increase in the share of energy from renewable resources and the reduction of final energy consumption.

Figure 3 Scenario grouping based on results for 5 key indicators for 2050: reduction of final energy, share of renewable energy in final energy, change in the absolute amount of renewables, nuclear power and underground storage of CO_2



Note: ([a]) No data for CCS, ([b]) no data on the split between renewables and nuclear, ([c]) 84% GHG emissions reduction, no data for nuclear, ([d]) 72% GHG emissions reduction, based on 2040, reduction of final energy reaches 25% compared to 2017, ([e]) 82% GHG emissions reduction, renewable energy share reaches 50%. *Source*: JRC.

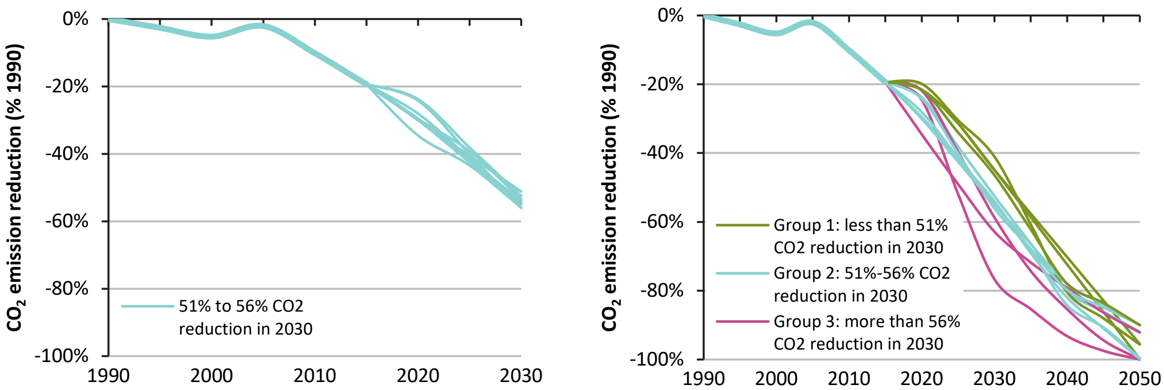
As shown in Figure 3, by 2050 the scenarios cover different combinations of reduction in final energy (x-axis) and renewable energy share (y-axis), and how these are technologically achieved. Reduction of final energy is as low as 30% to as high as 60%, compared to 2017. In the majority of scenarios, however, the reduction is between 30% and 38% (8 out of 16 scenarios). Most scenarios that meet the 2050 ambition have a renewable energy share higher than 80% (13 out of 16 scenarios). RES consumption in gross inland consumption increases with its share but decreases if energy efficiency improves (less final energy is consumed). Some scenarios show only limited increase of renewables; they require, however, very steep reduction of final energy use to reach the 2050 ambition. All except 2 scenarios use underground storage of CO_2, most with levels above 200 $MtCO_2$ per year.

3 Emissions

Between 2005 and 2015, the annual reduction of energy-related and process-related CO_2 emissions in the EU28 was 1.7% but slowed down thereafter. In order to reach the *mid-term ambition* by 2030 (Figure 4 (left)), emissions need to reduce by 2.4% per year from 2018 onwards. Among scenarios that are in line with the *long-term vision*, three groups of possible trajectories are distinguished (Figure 4 (right)):

- In the first group (green lines, Figure 4 (right)), the emission reduction temporarily slows down between 2015 and 2030 and thereafter continues at a steep rate (between 8% and 14% per year). This group includes the two scenarios developed for the "A Clean Planet for all" strategic vision (EC LTS 1.5Tech and 1.5Life);
- In the second group (blue lines, Figure 4 (right)), the rate of emission reduction is constant, showing a near-linear emissions decrease from 2020 to 2050 between 6% and 8% per year. Most scenarios follow this trend;
- In the third group (magenta lines, Figure 4 (right)), the emission reduction remains in a steep downward trajectory for the whole period 2015-2050. This group includes the scenarios with the steepest reduction before 2030 (up to 13% per year), which overshoot the reduction to levels higher than 59% by 2030.

Figure 4 CO_2 emission trajectories in the 8 scenarios that meet the mid-term ambition (left) and 12 scenarios that meet the long-term vision of the EU28 (right)



Note: 4 scenarios do not provide the emissions reduction trajectory to 2050 and are not included in the right figure. *Source*: JRC.

In the context of the EU Emissions Trading System (ETS) and the Effort Sharing Regulation [10], the energy-related and process CO_2 emission trajectories to 2030 (based also on additional information; see Annex 3) from ECF Demand-focus, ECF Shared effort, IEA ETP 2DS, IEA WEO SDS, LCEO Zero Carbon, and Oeko Vision show:

- Sectors participating in the ETS reduce emissions between 58% and 65% (currently 43%), compared to 2005. The level of ETS emissions (around 1.8 $GtCO_2$ in 2017) may need to decrease to around 0.95 $GtCO_2$ within a period of 10 years;
- Non-ETS sectors reduce emissions between 41% and 50% (currently 30%), compared to 2005.

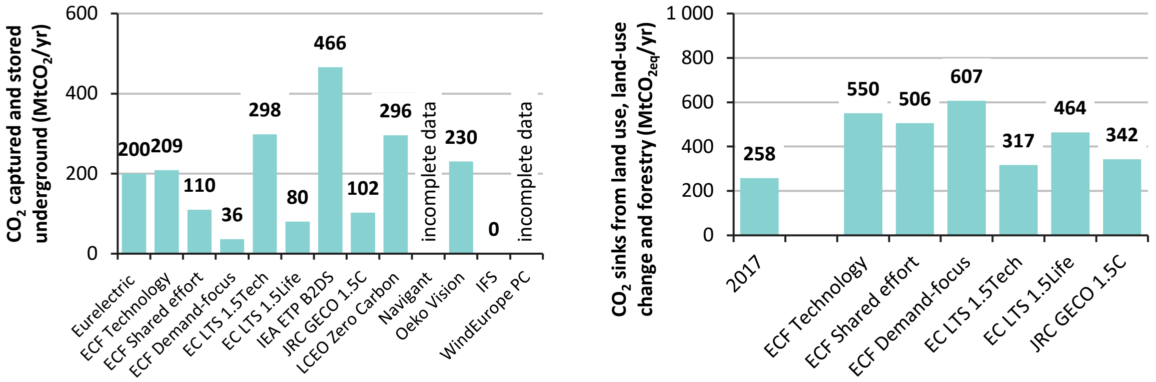
Without additional policies, the existing energy and climate framework, as reflected by the EC LTS Baseline, would achieve the same reductions only in 2040. The “European Green Deal” envisions the same reductions 10 years earlier (i.e. 2030).

Moving towards 2050 and strengthening the ambition (for example from 80% to 90% or higher) requires mitigating emissions from sectors that have more difficulty to implement abatement options (e.g. aviation and maritime, the iron and steel and cement industries) and/or the use of CCS (including carbon removal). Almost all scenarios rely on CCS to abate CO_2 emissions in 2050 (Figure 5 left). In six scenarios, CO_2 captured and stored is more than 200 $MtCO_2$ per year. Some scenarios roll out CCS already by 2030 up to a level of

85 $MtCO_2$ per year. Carbon removal by 2050 can reach up to around 260 $MtCO_2$ per year, of which around 200 $MtCO_2$ through direct air capture (EC LTS 1.5Tech) or almost entirely through BECCS (IEA ETP B2DS).

Beyond energy-related and process CO_2 emissions, which are within the scope of the present report, some scenarios assess the role of CO_2 removal by the LULUCF sector. These scenarios expect an increase of LULUCF sinks by 25% to 135%, compared to the 258 $MtCO_{2eq}$ in 2017 (Figure 5 (right)).

Figure 5 CO_2 underground storage (left) and LULUCF sinks (right) in 2050 in scenarios that meet the EU28 long-term vision



Note: JRC GECO 1.5C includes power, industry and other; in EC LTS and LCEO Zero Carbon, CO_2 is captured and reused (not shown in the figure). Navigant mentions the need for CCS in steel and cement production, with potential CO_2 supply of 113 and 179 $MtCO_2$ per annum, respectively. *Source:* JRC.

4 Gross inland consumption

In 2017, gross inland consumption in the EU28 reached 1 675 Mtoe, with oil (35%), natural gas (24%) and coal (15%), accounting for about three-quarters of the energy consumed [11]. Low or zero carbon sources, namely nuclear and renewables (biomass, hydro and other), supplied the remainder of the energy needs in roughly equal shares.

Section 4.1 and section 4.2 show how energy scenarios see the energy and fuels consumption to develop in 2030 and 2050. Note that in some scenarios, the definition of the reported quantity representing the total energy demand in a region may differ slightly. The present report harmonises it to the definition of gross inland consumption, as explained in Annex 3. The scenario results are further interpreted in the context of energy efficiency for 2030 (Box 1) [12].

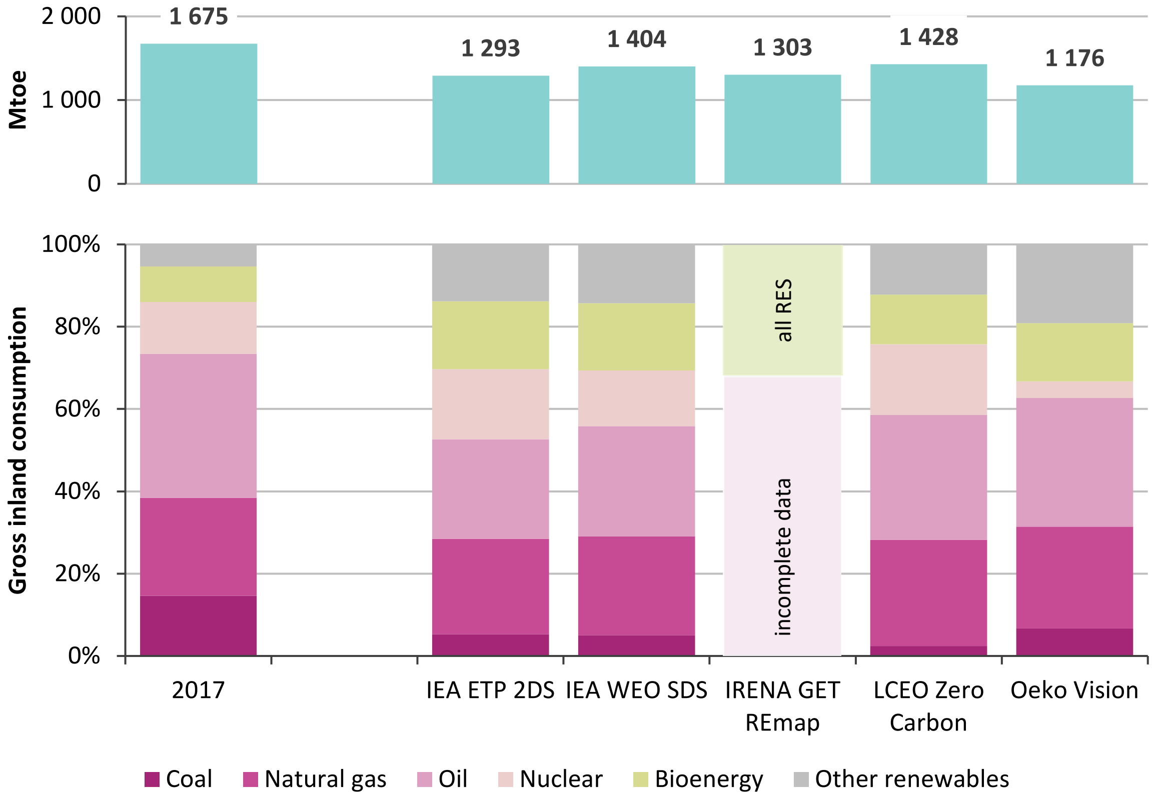
4.1 Gross inland consumption in 2030

For gross inland consumption in 2030, the analysis, due to data availability, is based on 5 out of the 8 scenarios that achieve the *mid-term ambition* by 2030 (Figure 6 - Figure 9). More specifically, the scenarios show that:

- Gross inland consumption drops within the 1 180 - 1 430 Mtoe range, which is a 15% to 30% reduction compared to today. The upper end of this range is up to 15 percentage points higher, and the low end is in line with the projections of the EC LTS Baseline scenario, which complies with the "Clean energy for all Europeans" package targets;
- About one-third to half of gross inland consumption is decarbonised, compared to about one-quarter in 2017. This is achieved with growth of renewables (including bioenergy) in all scenarios, and a relatively stable supply of nuclear energy in 3 out of 5 scenarios ([10]). Only Oeko Vision shows a decline in nuclear energy, as normatively assumed in its narrative; other scenarios maintain the nuclear capacity through 2030.
- For every unit of renewable energy (including bioenergy) deployed, the needs for energy transformation decrease, and thus between 2 and 3.5 units of fossil fuels (in energy terms) are removed from the system. As such, a large part of gains in energy efficiency are realised due to avoided transformation losses and structural change of the power sector (see section 5). More specifically, in 2030 fossil fuels account for 53% to 63% of gross inland consumption versus 73% in 2017:
    - all scenarios see drastic reduction in coal;
    - gas consumption remains similar to current levels or reduced from 7% up to 27%; its role as a transition fuel is evident, supplying about one-quarter of energy needs;
    - oil is in decline, 25% to 47% lower than today, but remains an important energy source as it supplies between 25% and 30% of energy needs; three-quarters in transport and one-quarter as petrochemical feedstock in industry;
    - despite the decrease of fossil fuels, CCS is rolled out in some scenarios already by 2030, up to a level of 85 $MtCO_2$ per year;
- The growth of biomass use ranges from being limited (additional 15%) to increasing by up to 60% compared to today.

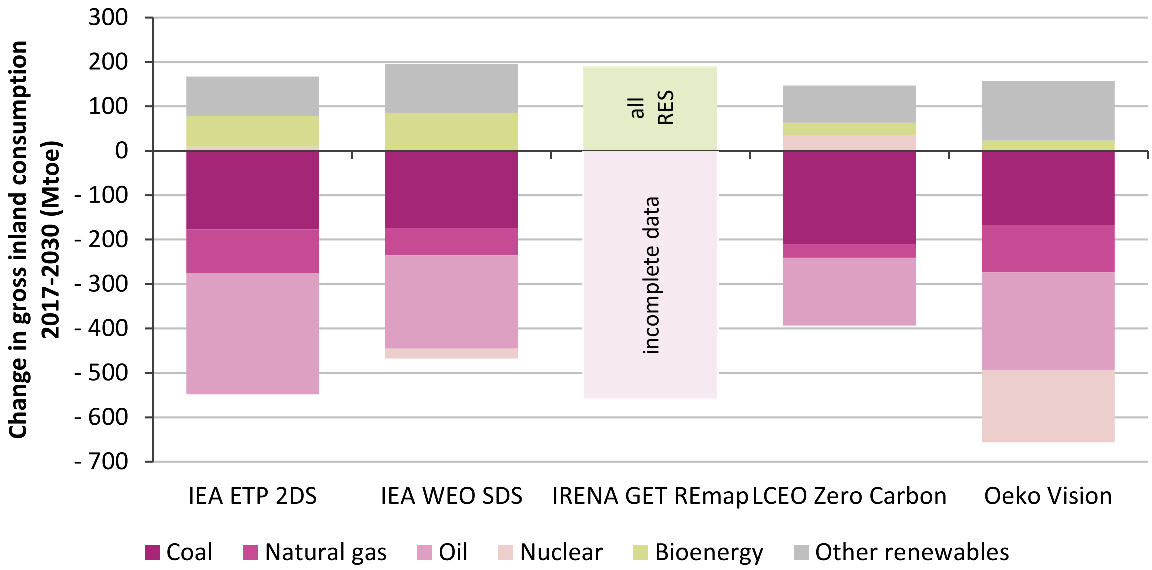
([10]) Data from IRENA GET REmap are incomplete in order to support the statement.

Figure 6 Gross inland consumption in scenarios that reach at least 50% emission reduction in 2030



Note: "Other renewables" includes hydropower, wind, solar, geothermal, ocean energy, ambient heat and imports of e-fuels. IRENA GET REmap does not provide more detailed disaggregation. *Source*: JRC.

Figure 7 Change in gross inland consumption between 2017 and 2030 in scenarios that meet at least 50% emission reduction in 2030



Note: "Other renewables" includes hydropower, wind, solar, geothermal, ocean energy, ambient heat and imports of e-fuels. IRENA GET REmap does not provide more detailed disaggregation. *Source*: JRC.

Box 1 Scenario outlook on energy efficiency and renewable energy share in 2030

Scenario outlook on energy efficiency in 2030

The strengthened commitment by the EU according to the agreed "Clean energy for all Europeans" package in 2018 is for energy efficiency to reduce by at least 32.5% [9], relative to the 2007 modelling projections for 2030, that estimated 1 887 Mtoe. In absolute terms, this means that in 2030 the EU28 primary energy consumption ([a]) should be no more than 1 273 Mtoe and/or final energy no more than 956 Mtoe. Based on own interpretation of scenario results, it is shown that (Figure 8):

- Scenarios analysed attaining a 52% to 56% emission reduction show a range of additional efforts on energy efficiency from 31% to 44%;
- In scenarios without CCUS or drastic changes to nuclear (IRENA GET REmap, ECF Shared effort, ECF Demand-focus), the energy efficiency range is between 36% and 42%. Compared to EC LTS Baseline, additional CO_2 emission reduction is achieved through further reduction in fossil fuels: 600 - 655 Mtoe compared to 755 Mtoe in EC LTS Baseline (Table 2);
- In scenarios with CCUS, either the reduction in fossil fuel use and in total primary energy is smaller (IEA WEO SDS and LCEO Zero Carbon) or the CO_2 reduction is higher (IEA ETP 2DS), compared to scenarios without CCUS and/or drastic changes to nuclear. In one scenario, with a large normative reduction of nuclear (Oeko Vision), energy efficiency reaches 44%, the highest across all scenarios.

Scenario outlook on the share of energy from renewable sources in 2030

The commitment by the EU according to the agreed "Clean energy for all Europeans" package in 2018, is for at least 32% of final energy consumption to be from renewable sources by 2030 [9]. Own synthesis of the scenario results shows that:

- The range of the renewable energy share is 30% to 40%;
- In 5 scenarios (LCEO Zero Carbon, IRENA GET REMAP, IEA ETP 2DS, ECF Shared effort and ECF Demand-focus), the gross final consumption of energy from renewable sources (b) amounts to 300 - 315 Mtoe, compared to 204 Mtoe in 2017 [11]. As shown in Figure 8 the renewable energy share of these scenarios increases proportionally with energy efficiency. This is not a result of higher consumption of renewable energy but rather a result of reduced total energy consumption. These 5 scenarios project renewable electricity generation between 1 800 and 2 000 TWh in 2030, compared to around 1 000 TWh in 2017;
- In 3 scenarios, the gross final consumption of energy from renewable sources amounts between 350 and 375 Mtoe. This is reached either through increase in biofuels in transport (IEA WEO SDS) or through increase of electricity from wind and/or biomass (Oeko Vision and WindEurope PC) with a focus on industry electrification (WindEurope PC);
- The share of electricity in transport is higher in all scenarios compared to EC LTS Baseline. Energy efficiency gains achieved mainly through this electrification of transport counterbalance a steep increase of the renewable energy share. The efficiency gains from electric motors compared to internal combustion engines ([c]) lead to a small increase in the share of energy from renewable sources and to a large reduction of primary energy.

([a]) i.e. in line with the primary energy consumption (Europe 2020-2030) definition given in Article 2 of the Directive 2012/27/EU, based on which primary energy consumption equals gross inland consumption (Europe 2020-2030), excluding gross available energy from ambient heat (heat pumps) and international maritime bunker fuels.

([b]) Gross final energy consumption from renewables (300 - 375 Mtoe) is different from primary energy consumption from renewables (323 to 399 Mtoe) mainly due to biomass transformation processes (only in primary) and due to ambient heat (not in primary).

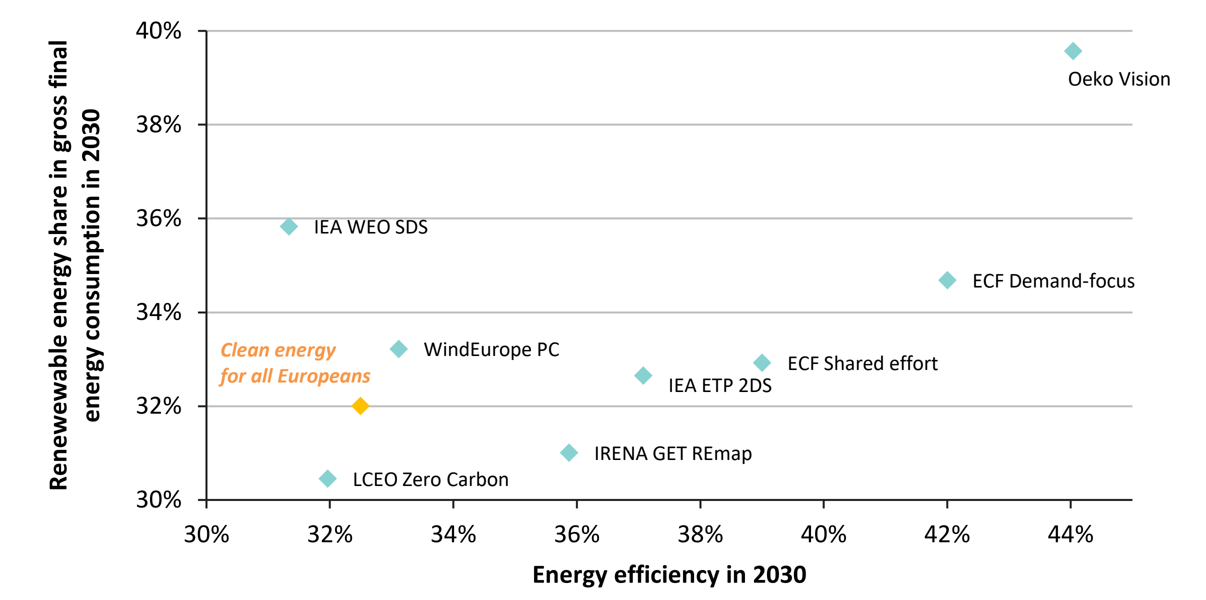
([c]) As a rule of thumb it is assumed 100 units of oil may be reduced by 25 units of electricity.

Table 2 Scenarios results for 2030 on energy efficiency and renewable energy share

	RES share %	Energy efficiency (based on the Eurostat 2020-2030 definition)					CO₂ % reduction
		Primary energy consumption				Gross final energy % reduction	
		% reduction	Fossil (Mtoe)	Renewables (Mtoe)	Nuclear (Mtoe)		
EC LTS Baseline	**32%**	**32.5%**	755	355	164	32.5%	45%
LCEO Zero Carbon	**30%**	**32%**	*(CCUS) 715*	323	246	31%	54%
IRENA GET REMAP	**31%**	**36%**	/	397	/	33%	51%
IEA ETP 2DS	**33%**	**37%**	*(CCUS) 600*	368	220	39%	56%
ECF Shared effort	**33%**	**39%**	655	333	165	39%	52%
ECF Demand-focus	**35%**	**42%**	600	330	165	42%	56%
WindEurope PC	**34%**	/	/	/	/	33%	55%
IEA WEO SDS	**36%**	**31%**	*(CCUS) 709*	399	189	32%	54%
Oeko Vision	**40%**	**44%**	635	375	47	41%	55%

Note: In LCEO Zero Carbon, both the renewable energy share and energy efficiency improvements in 2030 are implemented as policy inputs by means of minimum bounds. The calculated share based on the results is however lower due to accounting of blast furnaces and CHP in final energy consumption. Energy efficiency is also lower because JRC-EU-TIMES applies the target to European Economic Area (EEA) and not only EU28. *Source*: JRC.

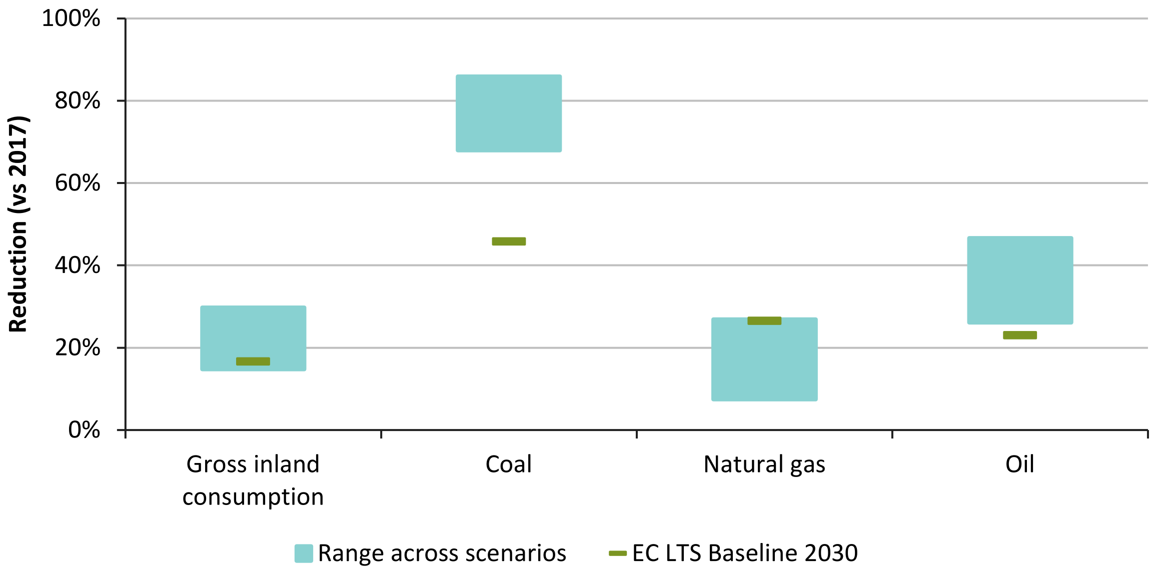
Figure 8 Scenario outlook on energy efficiency and renewable energy share in gross final energy consumption in 2030 in line with the Europe 2020-2030 definitions



Note: For WindEurope PC, due to incomplete data, the reduction of primary energy consumption is assumed to be equal to the reduction of final energy consumption. *Source*: JRC.

Compared to the EC LTS Baseline projections for 2030 (Figure 9), the scenarios achieve at least 50% emission reduction by lowering further the use of coal and oil, which are more carbon intensive than gas. Nonetheless, gas is also in decline with an observed reduction of up to 27%. The main drivers of this transformation are direct fuel switching from coal to renewables, electrification (mainly of transport, thus replacing oil) and end-use efficiency (e.g. to maintain gas use in buildings).

Figure 9 Range of reduction in gross inland consumption per fossil fuel in 2030 relative to 2017 in scenarios that meet at least 50% emission reduction in 2030 and comparison with the projected reduction under the existing policy framework



Note: The bars indicate the range of values found for 2030. The green marker indicates projections of EC LTS Baseline for 2030 and is used for comparison only, as it does not meet the required emission reduction for 2030. *Source*: JRC.

4.2 Gross inland consumption in 2050

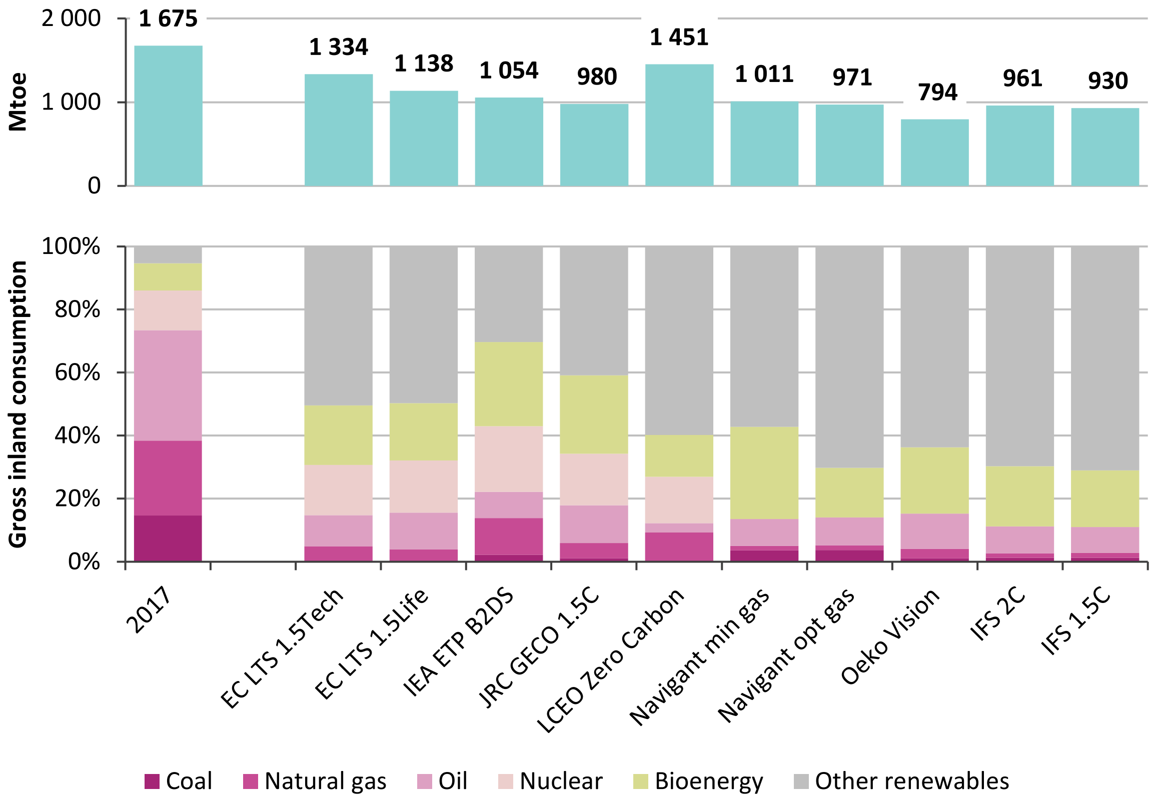
In order to realise the vision for emission reduction higher than 90% by mid-century, a major transformation of the EU energy system is required, as shown in the fuel breakdown of gross inland consumption (Figure 10 - Figure 11). More specifically, the scenarios show that the EU28:

- Decreases gross inland consumption in all scenarios, which may reach between 800 and 1 450 Mtoe by 2050; this is a reduction range of 225 - 880 Mtoe (13% to 53% compared to today), depending on the availability of new technologies such as hydrogen, CCUS (EC LTS 1.5Tech and LCEO Zero Carbon), or nuclear energy (Oeko and IFS). About half of the scenarios show a reduction by around 650 to 750 Mtoe (-1.5% to -1.8% per year or higher) over the next thirty years;
- Increases the use of bioenergy, from 9% of total energy today to 20%, in most scenarios;
- Fully reverses the fuel use; carbon-intensive fuels, representing about three-quarters of the gross inland consumption today need to contribute less than one-fifth in 2050; by then, gas may no longer be considered as a transition fuel;
- The remaining fossil fuels (mainly gas and oil) may still emit about 0.3 to 0.7 $GtCO_2$ ([11]). While this already entails a substantial emission reduction (85% to 93% compared to the 4.5 $GtCO_2$ emitted in 1990), CCS may be required. As shown in Figure 5, CCS technologies store between 0.1 and 0.45 $GtCO_2$ and have LULUCF sinks between 0.3 and 0.6 $GtCO_2$. Part of the CCS is carbon dioxide removal (in this context defined as artificial processes that sequester CO_2 from the atmosphere permanently into the underground or into materials);

([11]) Estimated by applying the emission factors of 4 tCO_2/toe (coal), 2.3 tCO_2/toe (gas) and 3.1 tCO_2/toe (oil) on the fossil fuels in the primary energy mix of each scenario [51].

- Uses some form of CCS on fossil fuels that are mainly imported. Another option for the EU is to import hydrogen or any other fuel that can be produced in a carbon neutral way. Most scenarios consider biomass imports but only a few consider hydrogen, clean gas or e-fuels imports. As such, the conclusions of this report are derived from scenarios with limited amount of imported decarbonised fuels;
- Ambient heat from heat pumps becomes an important component in gross inland consumption as it contributes 2% to 7% and can be as high as 65 Mtoe.

Figure 10 Gross inland consumption in scenarios that achieve at least 90% emission reduction in 2050



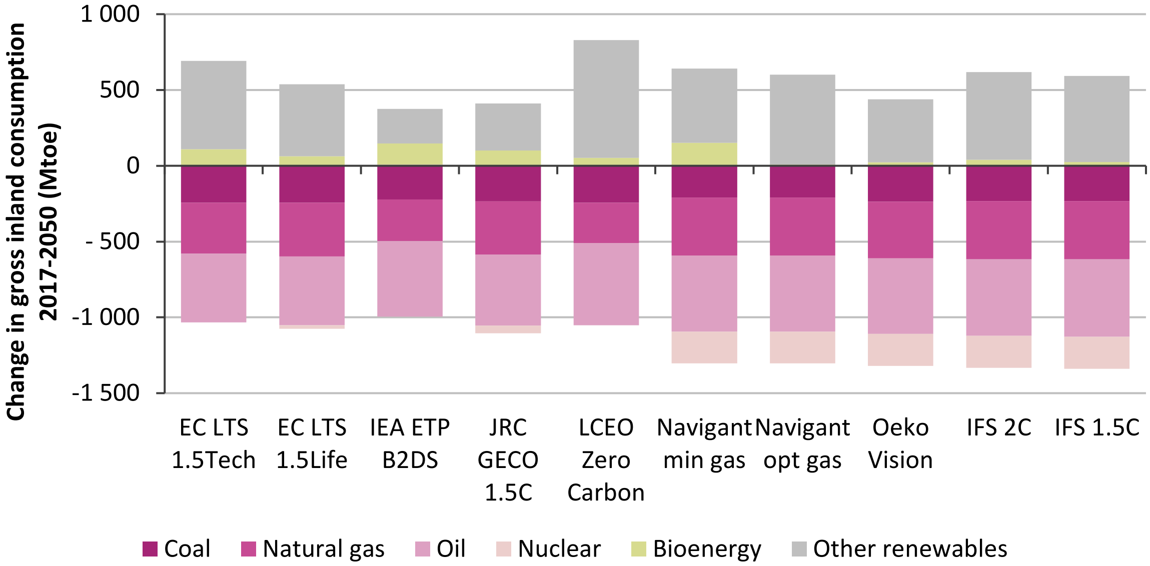
Note: "Other renewables" includes hydropower, wind, solar, geothermal, ocean energy, ambient heat, and imports of e-fuels. *Source*: JRC.

Based on these results, the three main groups of drivers that shape the future energy mix are:

- High technological reliance *and* deployment of renewables and biomass, *but* overall low energy demand (EC LTS 1.5Tech and LCEO Zero Carbon);
- Moderate technological reliance, deployment of renewables and biomass *and* energy demand (EC LTS 1.5Life, IEA ETP B2DS, JRC GECO 1.5C, Navigant);
- Low technological reliance, high deployment of renewables and biomass, *and* overall high energy demand (Oeko and IFS).

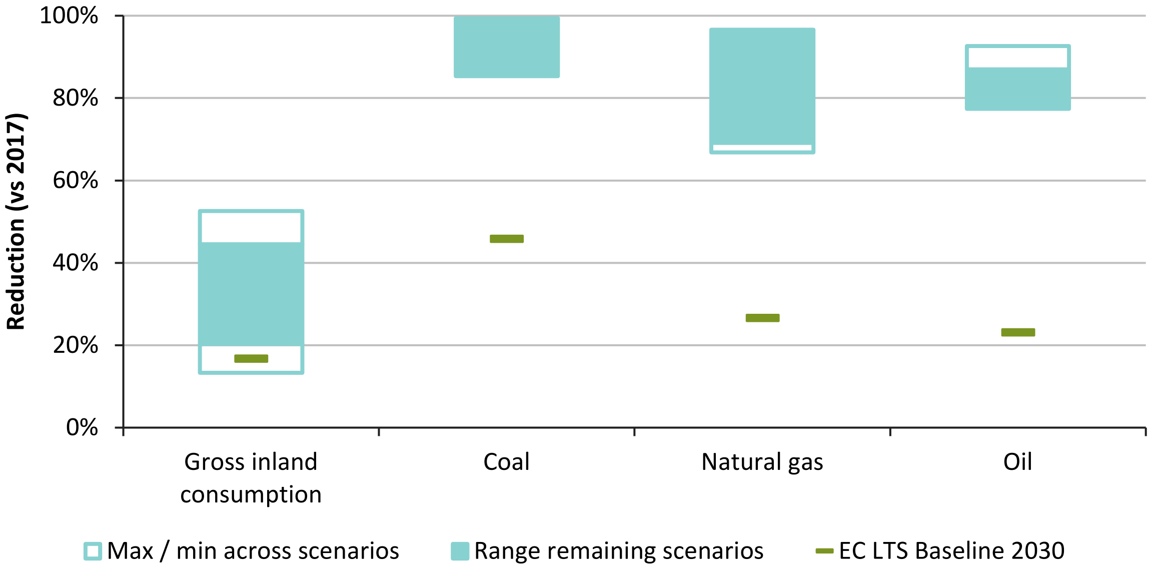
The progress towards 2030 envisaged by the "Clean energy for all Europeans" legislative package (indicated by the green markers in Figure 12) covers somewhat less than half of the ground for the desired emission reduction the EU aspires to in the long term (46% in 2030 compared to near 100% envisioned for 2050, both compared to emissions in 1990). Therefore, in the period 2030 to 2050 major transformations will be required for the decarbonisation of all sectors. The energy scenarios propose to bring forward the transition away from coal (mainly in the power sector) and oil (mainly in the transport sector) and phase out their remaining use and that of natural gas beyond 2030. While they also project a drastic reduction of natural gas beyond 2030, the results differ widely (difference of 30 percent points).

Figure 11 Change in gross inland consumption between 2017 and 2050 in scenarios that achieve at least 90% emission reduction in 2050



Note: "Other renewables" includes hydropower, wind, solar, geothermal, ocean energy, ambient heat and imports of e-fuels. *Source*: JRC.

Figure 12 Change in gross inland consumption per fossil fuel in 2050 relative to 2017 in scenarios that achieve at least 90% emission reduction in 2050 and benchmark with projections for 2030 under the existing policy framework



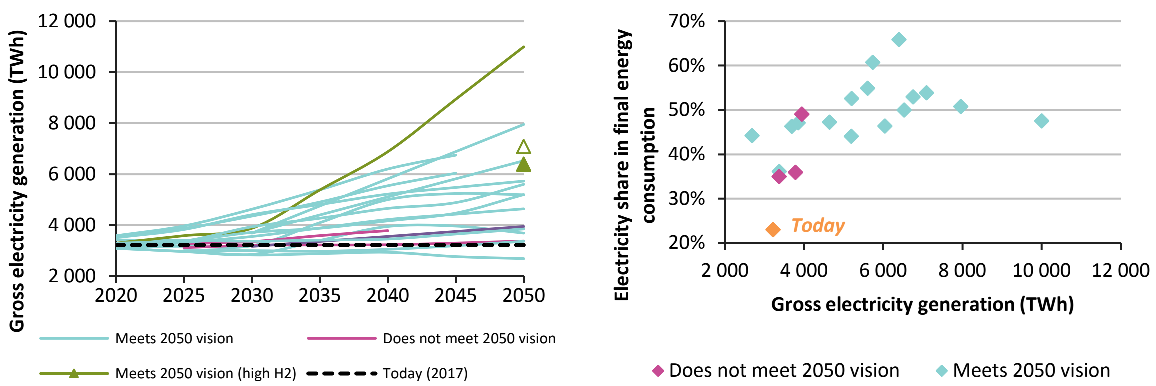
Note: White-filled boxes correspond to the maximum and minimum values across all scenarios for 2050; inner boxes include the remaining scenario values for 2050. The green marker indicates projections of EC LTS Baseline for 2030. *Source:* JRC.

5 Power sector

The gradual shift of the power sector away from coal to cleaner forms of combustible fuels and the increase of electricity from renewables has led to the reduction of the power sector's GHG emissions by 30%, despite an increase in production by 27% between 1990 and 2017. However, with a 22% contribution, the sector today is the EU28's second largest emitter after transport [11], [13]. Trajectories for power generation over time reveal a wide and increasing range of options in power production, especially when progressing towards 2050. The lowest end of the projections indicates a contraction of the sector and the higher end of the range shows a two-fold (several scenarios) or even more than a three-fold (one scenario) increase by mid-century compared to 2017 (Figure 13). The most salient observations are the following:

- The majority of scenarios show gross electricity generation between 3 850 and 6 400 TWh in 2050, which is a 20% to 95% increase compared to today;
- The higher range of projections (i.e. higher than 1% annual growth), has a rather constant rate of growth already from 2020 and is based on scenarios that:
    - o rely heavily on hydrogen to decarbonise the energy system (LCEO Zero Carbon, Navigant opt gas, EC LTS 1.5Tech, EC LTS 1.5Life, ECF Technology ([12])), combined with high energy efficiency (Oeko and IFS) ([13]);
    - o are results from power industry associations (Eurelectric and WindEurope);
    - o or, in the absence of other alternatives (hydrogen, nuclear power), aim at high electrification (Navigant min gas);
- The lower range of projections (less than 1% annual growth) is provided by JRC GECO 1.5C, the IEA (B2DS, 2DS, SDS) and the diverse scenarios of ECF (Shared effort, Demand-focus). These scenarios tend to increase the pace of growth after 2030.

Figure 13 Gross electricity generation and share of electricity in final energy consumption in energy scenarios for the EU28 in 2050



Note: Gross electricity generation except for IRENA, which is after losses. Data from Navigant available only for 2050 (represented by triangles in the left figure). In the right figure, the data of IEA WEO SDS are for 2040 and of Eurelectric for 2045. *Source*: JRC.

High *direct* electrification of final demand does not appear to be a driver for gross electricity generation nor a necessary precondition to meet the long-term vision (range from 35% to almost 70%). In several scenarios, electricity is generated to produce hydrogen (in most scenarios about one-third of the gross electricity output ([14])), which is consumed by end-users either directly or as e-fuel for transport. On the other hand, low electrification of final demand may impede the long-term goals (Figure 13 (right)). Therefore, the growth of the power sector either due to *direct* (electrification of final demand) and/or *indirect* consumption of electricity

([12]) In 2050, in these scenarios hydrogen production is higher than 1 450 TWh (including hydrogen for and e-fuels), gross electricity generation is higher than 5 200 TWh and the contribution of hydrogen or hydrogen-based fuels in final energy demand is 12% up to 20%.

([13]) The lower electricity output in Oeko Vision is partly owed to the fact that while more than 18% of final energy relies on hydrogen and synfuels, more than half are imported.

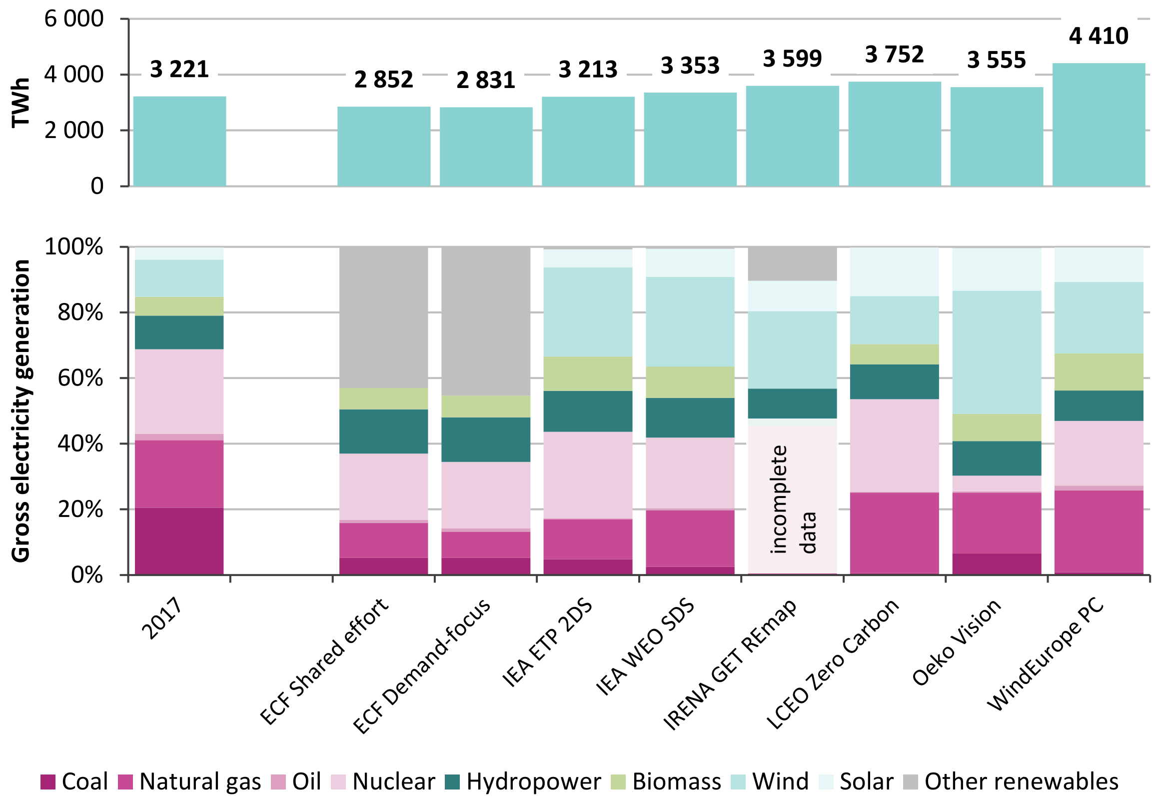
([14]) Own estimate, assuming electrolyser efficiency of 75% in 2050.

(hydrogen, e-fuels), is the preferred pathway by most scenarios to meet the long-term vision, achieving at the same time the mid-term ambition ([15]).

5.1 Power sector in 2030

The transformation of the power sector would be key to halve the emissions of the EU28 over the coming decade compared to 1990, but bears different characteristics across scenarios, in terms of the total generation output and the mix of sources used (Figure 14, Figure 15). However, the rapid expansion of renewable electricity, mainly from wind and solar, is common across all scenarios; it may double or even quadruple by 2030. In one decade from today, energy scenarios show that the share of renewable electricity in the EU28 ranges from 48% to 70%, compared to the 31% that it currently supplies. This is a 17 to 39 percentage point increase in the contribution of renewable electricity. By taking into account also nuclear energy, decarbonised power generation reaches 73% to 86% compared to 56% today. Overall, this is a 16 to 29 percentage point increase in the contribution of decarbonised power by 2030.

Figure 14 Gross electricity generation per technology in scenarios that achieve at least 50% emission reduction in 2030



Note: "Other renewables" includes ocean and geothermal energy, except from ECF, which includes variable renewables. *Source*: JRC.

In the different scenarios, this is realised as follows:

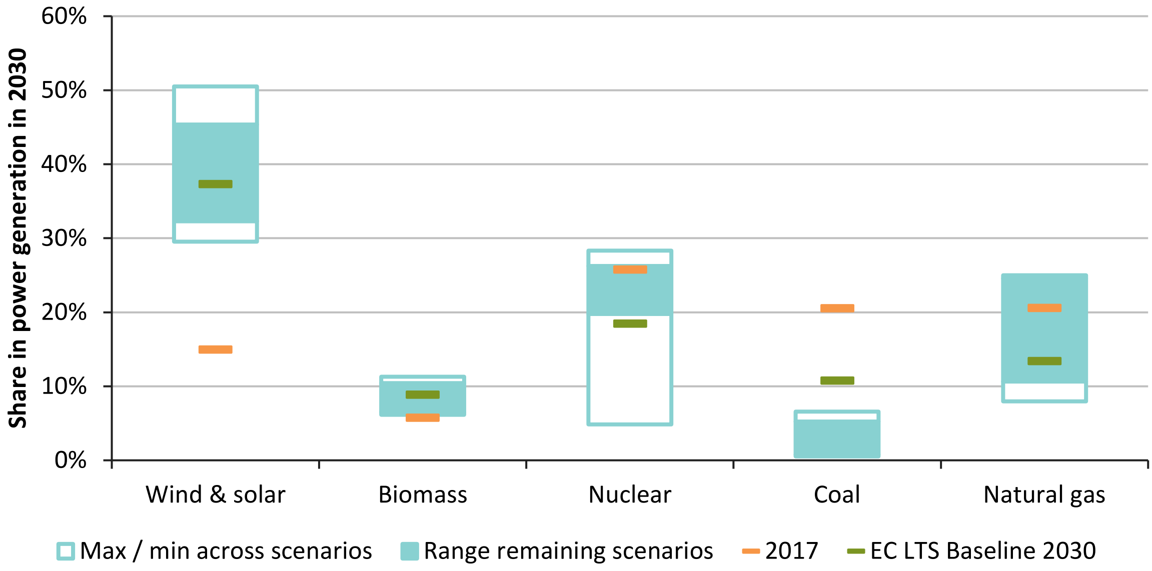
- WindEurope PC sees a *rapid expansion* of the sector's output by almost 40% compared to today (2.5% per year). Phasing out coal from power production is somewhat compensated by the increasing role of natural gas, as nuclear remains relatively stable. The sector increases its output by expanding renewable capacity by almost a factor of 3;
- In 4 scenarios electricity generation sees a comparably *moderate increase*, from 4% up to 20% compared to today (0.3% to 1.4% annually, within the range of historical growth rates between 2000 and 2010 or 2000 and 2017). In most of these scenarios, renewable capacity increases by replacing

([15]) All scenarios generating above 4 500 TWh of electricity or those that cover more than 50% of their final demand with electricity meet the long-term vision.

- the rapidly decommissioned coal plants. The growth of renewables is somewhat similar to the scenario from the wind industry association (above) as gas keeps its role as a transition fuel; ultimately, the growth of renewables depends on the assumptions for nuclear power (IEA WEO, LCEO Zero Carbon, IRENA GET REmap and Oeko);
- In the third group of scenarios, the power sector *shrinks* in terms of output by up to 12% (-1% per year). Despite the overall smaller market size, renewable electricity generation replaces coal and gas (coal and gas are also in decline), and therefore expands by 80% to 250% compared to today.

Regardless of the power sector output (gross electricity generation; TWh), the installed capacity of variable renewables (GW) increases by a factor of 2 to 3 in 2030, compared with 2017. Specifically for wind energy, growth varies between a factor 1.5 and 2.7; the growth of solar energy varies between a factor 1.3 and 4. At the same time, nuclear energy provides between 5% and 27% of the electricity in 2030.

Figure 15 Share of electricity generation per technology in scenarios that achieve at least 50% emission reduction in 2030 and benchmark with projections for 2030 under the existing policy framework



Note: White-filled boxes correspond to the maximum and minimum values across all scenarios for 2030; inner boxes include the remaining scenario values for 2030. The green marker indicates projections of EC LTS Baseline for 2030 and is used for comparison only, as it does not meet the required emission reduction. *Source*: JRC.

Scenarios that achieve at least a 50% emission reduction in the EU28 by 2030 show a reduction of coal consumption by more than 70% (as noted in Figure 9). For the power sector, this entails a nearly full coal phase out in terms of generation, bringing its current 20% share down to less than 5% (Figure 15). This is well below the projections in the EC LTS Baseline scenario for 2030. The observed reduction of gas consumption (up to 27%; Figure 9) does not affect its use in the power sector, and seems to be largely in line with the EC LTS Baseline estimates.

5.2 Power sector in 2050

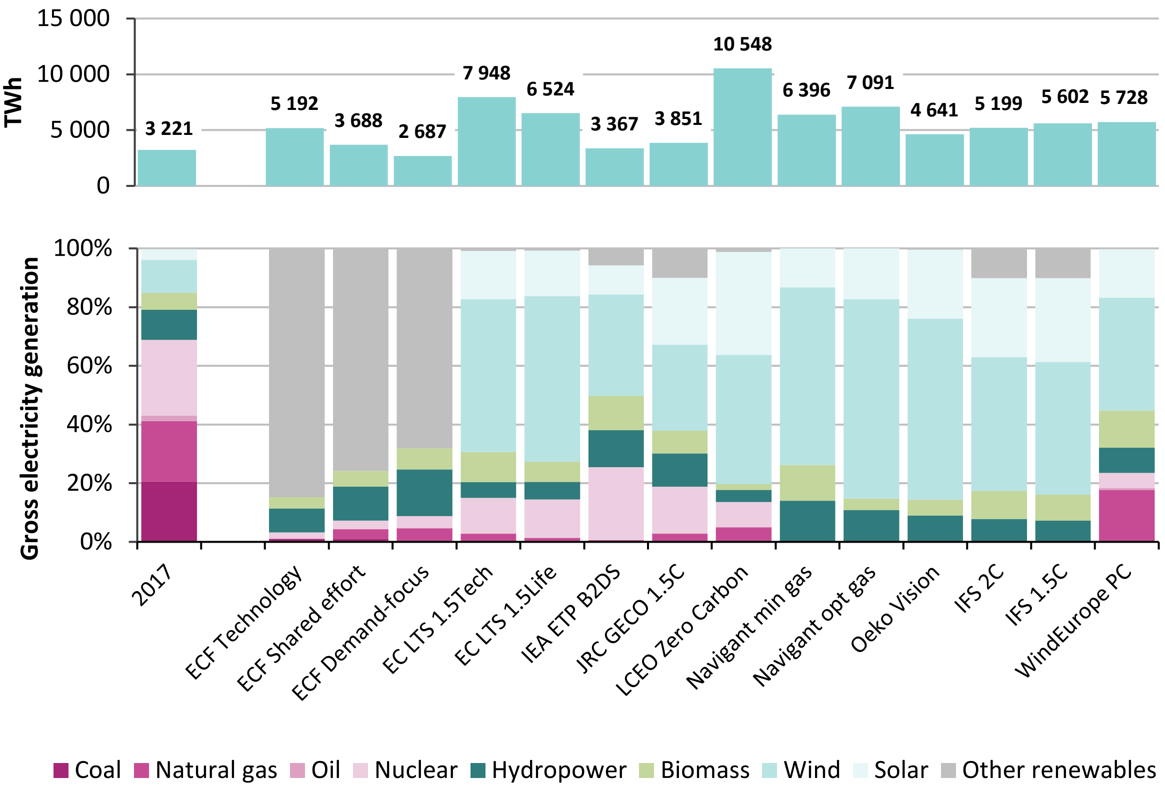
The compared energy scenarios show a complete transformation of the EU28 power sector by mid-century. The transition entails that emissions from fuel combustion for electricity production decrease from 1 $GtCO_2$ in 2017 to between 0 and 0.35 $GtCO_2$ in 2050 ([16]). The fuel mix shifts dramatically; the fossil fuel current share of 43% decreases to a maximum of 18% (almost exclusively gas) in 2050, nuclear represents a maximum of 25%, comparable to its current share, or as mandated in some scenarios, the sector transitions fully to 100% renewable power systems by mid-century, from currently 31% (Figure 16). Normative assumptions in

([16]) Estimated using emission factors of 4 tCO_2/toe (coal), 2.3 tCO_2/toe (gas) and 3.1 tCO_2/toe (oil) [51] and gross efficiency for electricity generation of 44% from coal, 60% from gas and 35% from oil, without taking CCS in the power sector into account.

scenarios with respect to the power sector are described in section 2.2. Besides these features, the scenarios differ in *size and growth rate* as follows (Figure 13, Figure 16):

- *High growth*, around 2% annually and in some cases almost 4% per year, is observed in scenarios that use renewable electricity to produce hydrogen. In these scenarios, between 1 600 and 2 700 TWh of hydrogen are produced (including hydrogen demand for e-fuels but not for industrial feedstock). Assuming an efficiency for electrolysers of 75%, this implies that between 2 100 and 3 600 TWh of gross electricity generation would be consumed for hydrogen in the various scenarios (30% to 40% of gross output; see also footnote 12). This is comparable to the size of the power sector in 2017 (around 3 220 TWh). Hydrogen is consumed in all end-use sectors. Two scenarios expect direct electrification of end-use sectors to be a driver for the sector's expansion (WindEurope, Navigant min gas), reaching almost 70% in 2050. All scenarios in this group are characterised by low to moderate efficiency improvements;
- In *mid-growth* scenarios, the annual increase of power generation ranges from 1% to 1.5%. These scenarios share the characteristic of comparably higher reduction in energy demand and moderate deployment of hydrogen (transport and in industry), while IFS and Oeko also phase out nuclear energy normatively;
- Some scenarios see *contraction* or *slow growth* (around 0.5% annually) of power generation over the coming decades. No clear drivers are identified, as these scenarios differ in characteristics and focus on a range of issues from energy efficiency and life-style changes (ECF Demand-focus) to technological diversity with several mitigation options at hand (CCS in IEA scenarios and JRC GECO 1.5C). Driven by limited demand or technological constraints, these scenarios see comparably small hydrogen deployment (except for JRC GECO 1.5C, which sees a moderate increase of around 500 TWh).

Figure 16 Gross electricity generation per technology in scenarios that achieve at least 90% emission reduction by 2050

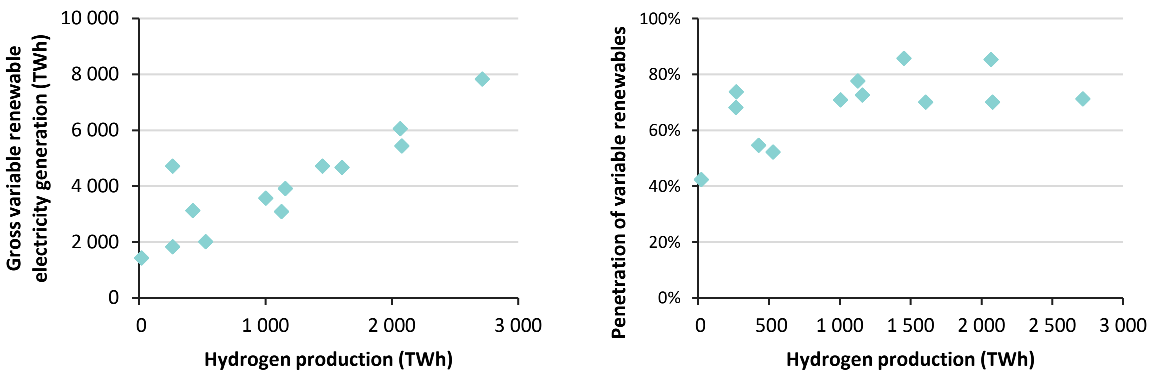


Note: "Other renewables" includes ocean and geothermal energy. In ECF it aggregates wind and solar, without specifying their respective shares. *Source*: JRC.

Looking into the power sector's technology diffusion in 2050, the following results are observed (Figure 16):

- The power sector does not necessarily phase out fossil fuels from its mix; whether to provide flexibility (e.g. gas peaking plants) or supply the system with baseload power, fossil fuel-based thermal capacity is still present in 9 out of 14 scenarios. Part of it is coupled with CCS technologies to abate much of the remaining CO_2 emissions ([17]). Power generation from fossil fuels may be as low as 20 TWh (1% of generation in scenarios with low electricity demand) to 1 050 TWh (18% of generation in scenarios with high electricity demand);
- Renewables produce the majority of the power sector's output, as they provide from 75% up to 100% of the total output:
  - o intermittent sources (wind and solar) provide 60% to 90% of the total renewable electricity (55% to 85% in gross power generation). However, there is a diverging outcome on their growth, *each* varying between a factor of 3 and 13. One scenario (LCEO Zero Carbon) sees wind and solar to produce similar levels of electricity, which translates to a growth of solar by a factor of 30, compared to 2017. The volume of wind and solar power production is driven by hydrogen (i.e. electricity generation from wind and solar in TWh; Figure 17 (left)), but not their penetration (i.e. share of electricity generation from wind and solar Figure 17 (right));
  - o supply of biomass power and hydropower is comparable across most scenarios (650 to 900 TWh in 2050, compared to 520 TWh today). Characterised by limited hydrogen production, Navigant min gas and WindEurope project high contributions of hydropower and bioenergy (1 200 to 1 680 TWh) in order to supply decarbonised electricity in a highly electrified final demand (almost 70%);

Figure 17 Electricity generation from wind and solar (left) and penetration (right) in relation to hydrogen production in energy scenarios that meet the long-term vision of the EU28 in 2050



Note: Including hydrogen demand for e-fuels but not for industrial feedstock. *Source*: JRC.

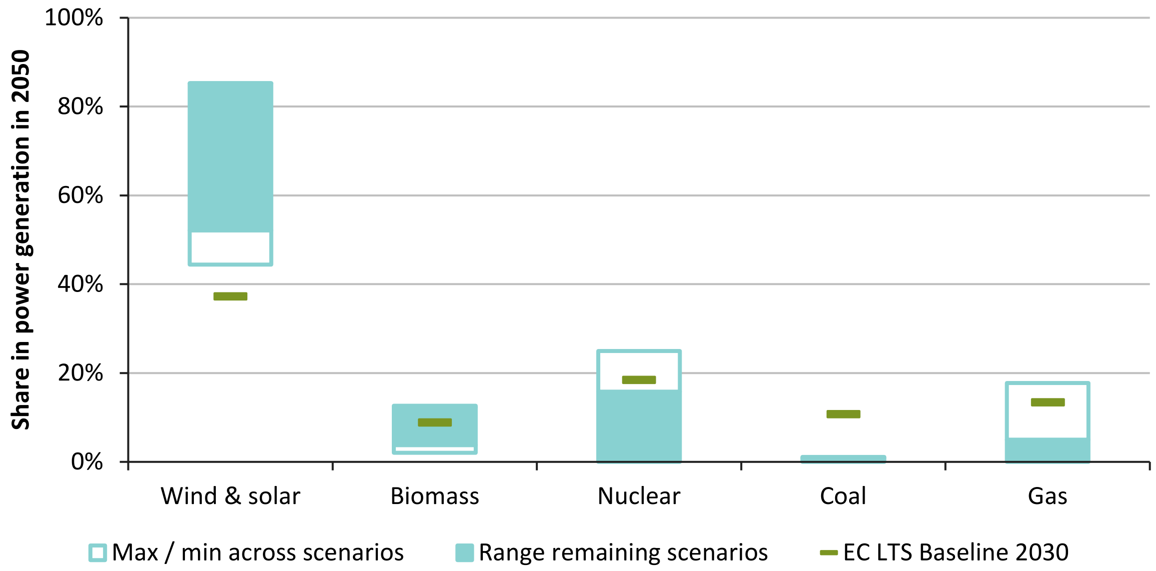
- The capacity of BECCS in power generation varies from 2.5 GW (EC LTS 1.5Life) to 50 GW (EC LTS 1.5Tech). The other two scenarios that are explicit about BECCS are IEA ETP B2DS (almost 19.5 GW) and JRC GECO 1.5C (10 GW);
- The scenarios estimate or assume different futures for nuclear power in the context of deep decarbonisation. The estimates for mid-century range from:
  - o nuclear power being normatively phased out, thereby making a case for a decarbonised power sector without using nuclear power (5 scenarios, namely Navigant min gas and Navigant opt gas, Oeko Vision, IFS 2C and 1.5C); or

([17]) In EC LTS 1.5Tech 12% (17 GW) and in EC LTS 1.5Life 2% (2.5 GW) of gas capacity is coupled with CCS [20]. The ECF scenarios require all remaining gas plants after 2030 to be equipped with CCS; Eurelectric expects CCS technologies to capture all CO_2 emissions from the remaining thermal capacity [5]; WindEurope concludes that at CO_2 prices above 90 €/tCO_2, CCS could be an economically attractive alternative to capture emissions from natural gas plants that are used to provide flexibility to the system (17% share in production) and abate remaining emissions from large power plants (about 50% of the emissions) [6].

- o nuclear power being marginalised to about one-tenth of its current supply and contribution (2% to 5% in the future mix based on 5 scenarios (ECF Technology, Shared effort, Demand-focus, JRC GECO 1.5C and WindEurope PC); or
- o nuclear power maintaining its capacity, output and/or contribution to the power mix (4 scenarios, namely EC LTS 1.5Tech and 1.5Life, IEA ETP B2DS and LCEO Zero Carbon, from 83 to 121 GW);
- o overall, relatively higher nuclear electricity production is observed in scenarios that use techno-economic partial equilibrium models (namely PRIMES, ETP-TIMES and JRC-EU-TIMES).

Based on Figure 18, it is shown that most energy scenarios cover a significant part of the transformation effort of the power sector towards full decarbonisation already by 2030 (Figure 15 compared to Figure 18). Based on the targets of the "Clean energy for all Europeans" package for 2030 (as outlined in the EC LTS Baseline scenario), the EU will need to continue at a similar pace thereafter to reach what most deep decarbonisation scenarios project for the sector (green marker versus the blue bar in Figure 18). Overall, it appears that the biggest challenge will be that of increasing shares of wind and solar, while at the same time marginalising the use of gas and coal.

Figure 18 Share of electricity generation per technology in scenarios that achieve at least 90% emission reduction by 2050 and benchmark with projections for 2030 under the existing policy framework



Note: White-filled boxes correspond to the maximum and minimum values across all scenarios for 2050; inner boxes include the remaining scenario values for 2050. The green marker indicates projections of EC LTS Baseline for 2030. *Source*: JRC.

6 Final energy consumption

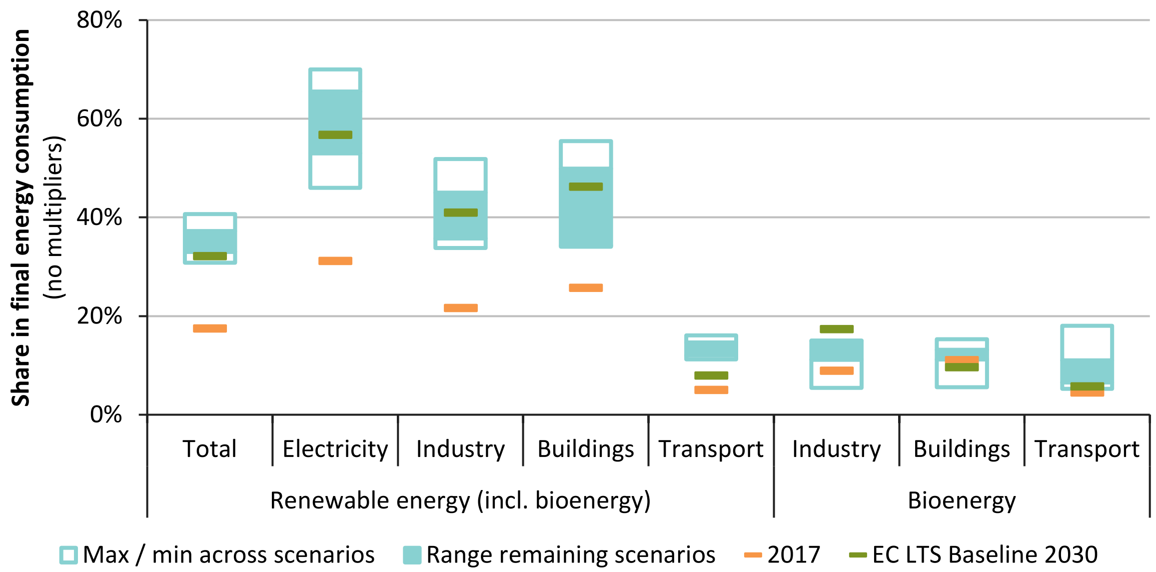
In 2017, final energy consumption in the EU28 was 1 060 Mtoe, with oil (37%) and natural gas (23%) being the fossil fuels consumed the most by the end-use sectors. Direct consumption of renewable energy was mainly biomass, representing an additional 10%. Consumption of secondary energy carriers, namely electricity and distributed heat, reached 23% and 5%, respectively. Regarding sectors, the households, commercial and public services sectors accounted for 42% of final energy consumption, industry consumed one-quarter and the transport sector about one-third. The remainder 3% was consumed by tertiary sectors (mainly agriculture and forestry) [11].

Section 6.1 and 6.2 show how final energy develops in terms of energy carriers and their consumption by industry, buildings and transport in the reviewed energy scenarios for 2030 and 2050. Note that these sections follow the definition of final energy consumption in line with the new Eurostat methodology [12]. In some scenarios, the scope of their data representing final energy consumption may differ slightly, whether in sectoral coverage or fuels. The present report harmonises them to the same definition as explained in Annex 3. The scenario results are further interpreted in the context of energy share from renewable sources for 2030 (Box 1), for which the final energy consumption definition Europe (2020 - 2030) applies [11].

6.1 Final energy consumption in 2030

In most scenarios that meet the ambition for 2030, final energy consumption is between 790 and 945 Mtoe. Compared to today, the share of energy from renewable sources increases considerably in all sectors (Figure 19). In all scenarios that reduce emissions by 53% to 56%, renewable energy supply amounts to around 300 to 375 Mtoe.

Figure 19 Share of renewable energy and bioenergy in scenarios that reach at least 50% emission reduction in 2030 and benchmark with projections for 2030 under the existing policy framework



Note: White-filled boxes correspond to the maximum and minimum values across all scenarios for 2030; inner boxes include the remaining scenario values for 2030. The green marker indicates projections of EC LTS Baseline for 2030 and is used for comparison only, as it does not meet the required emission reduction. *Source*: JRC.

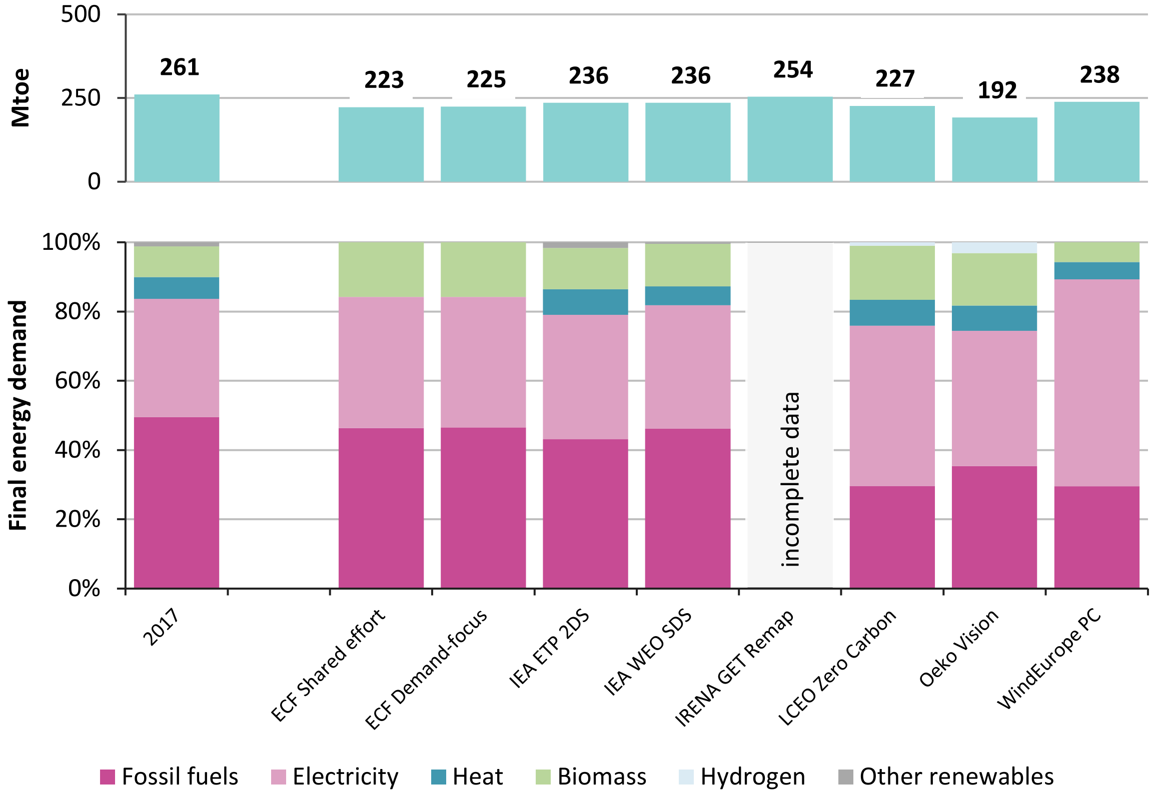
The EC LTS Baseline scenario seems to be well in line with the other energy scenarios, with the exception of the transport sector. For transport, most scenarios show considerably more effort on renewable energy supply already by 2030 (from 5 to 14 percentage points higher than the figure for EC LTS Baseline; including renewable electricity). On the other hand, the EC LTS Baseline scenario shows a higher contribution of renewable energy (and in particular bioenergy) in the energy mix of the industry sector, which, however, does not suffice in order to meet the ambition for emission reduction in 2030.

6.1.1 Industry in 2030

Across all sectors, industry has reduced its GHG emissions the most, with a decrease reaching almost 36% between 1990 and 2020 (excluding power transformation; section 5.1). Today the sector accounts for almost 20% of the EU28's emissions [13]. The scenarios show a rather consistent outlook on energy consumption and fuel mix for the industry sector in the 2030 (Figure 20):

- Most scenarios show a 10% to 15% reduction in energy demand, equally distributed among the main fuels, possibly as a result of energy efficiency measures. Part of the demand decrease may also be due to a lower output from industry;
- The only exception is Oeko Vision, which projects a higher reduction of energy demand (by almost 25%), amongst others due to electrification, optimisation of production processes, and modularisation;
- Hydrogen in industry emerges only in two scenarios (LCEO Zero Carbon and Oeko Vision).

Figure 20 Final energy consumption in the EU28 industry sector in scenarios that reach at least 50% emission reduction in 2030



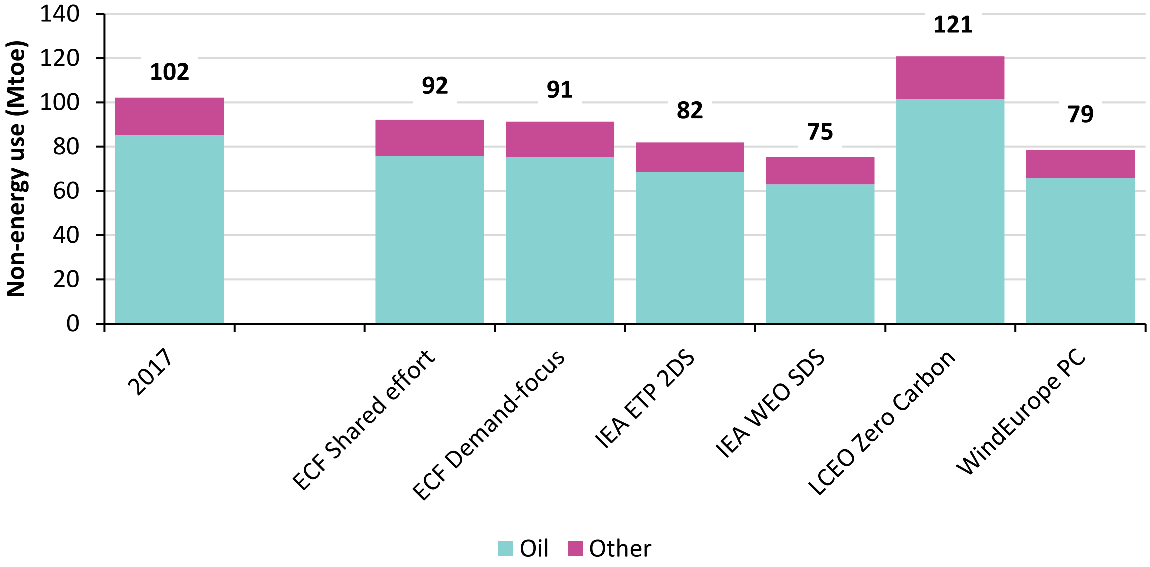
Note: "Other renewables" includes solar thermal and direct use of geothermal heat. *Source:* JRC.

The share of decarbonised energy increases from 31% in 2017 to between 43% and 53% in the scenarios for 2030 ([18]). According to the scenario results, this is due firstly to the steep progress towards the decarbonisation of the electricity sector (section 5.1) and secondly to the growth of biomass use as fuel directly by the industry sector.

([18]) i.e. renewable and nuclear electricity, distributed heat (the share of decarbonised heat in distributed heat is assumed to be similar to 2017, unless provided by the study), direct consumption of biomass and other renewables, hydrogen and e-fuels (in 2030 assumed as being exclusively produced from renewable sources) divided by final energy consumption in the industry sector. Not taking CCS into account.

Non-energy use as reported in scenarios for 2030 is presented in Figure 21 ([19]). It differs between scenarios, partly relating to different assumptions with respect to the development of the EU28's industrial output.

Figure 21 Non-energy use in scenarios that meet the mid-term ambition of the EU28 in 2030



Note: "Other" is mainly natural gas. IEA ETP 2DS includes petrochemical feedstocks, blast furnace and coke oven coke, IEA WEO SDS includes petrochemical feedstocks. *Source*: JRC.

6.1.2 Buildings in 2030

Between 1990 and 2017, the buildings sector has reduced its GHG emissions by 22%, and today it accounts for 12% of emissions in the EU28 (excluding power transformation; section 5.1) [13]. Projections of energy use in the buildings sector in 2030 show (Figure 22):

- Reduction in energy use between 4% and 23% compared to 2017; this is primarily expected in fossil fuel use, which is 30% to 55% lower than today;
- In 4 out of 7 scenarios, electricity consumption increases slightly from 4 to 11 percentage points. The share of electricity may reach 43%, compared to about 32% today. In 2 scenarios (ECF scenarios), electricity consumption decreases by about 30%, possibly due to high efficiency improvements assumed for the sector;
- District heating maintains or increases its weight in the sector. In some scenarios, the contribution of heat supply reaches up to 15%, compared with currently 7%. Due to the electrification of heating and cooling, the growth of heat from heat pumps increases by a factor of 2 to 3.5 and their contribution to the sector's demand is 5% to 7%, compared to about 2% today.

Box 2 Replacement of oil and gas boilers in buildings by 2030

Based on the reviewed scenarios, the buildings sector reduces its fossil fuel use by 30% to 55% by 2030 compared to today. It may do so, for example, by switching from fossil fuels to carbon neutral fuels for its demand for heating and cooling and by increased efforts on energy efficiency (e.g. buildings insulation). On fuel switching results are similar, apart from one scenario (WindEurope PC), biomass increase is limited,

([19]) Non-energy includes feedstock used as raw material, not for fuel purposes or transformed to fuels. In the EU28, non-energy is mainly oil and petroleum products (84% in 2017; e.g. used for the production of chemicals), natural gas (15% in 2017; e.g. used to produce fertilisers and hydrogen), and solid fossil fuels (slightly less than 2% in 2017; e.g. coke oven coke in iron and steel or coal tar for chemicals). Shifting to low carbon feedstock may further reduce process-related CO_2 emission from industry sectors (e.g. switching from coal to gas, biomass or novel processes using electricity). Energy scenarios, however, do not report explicitly on the fuel composition of non-energy.

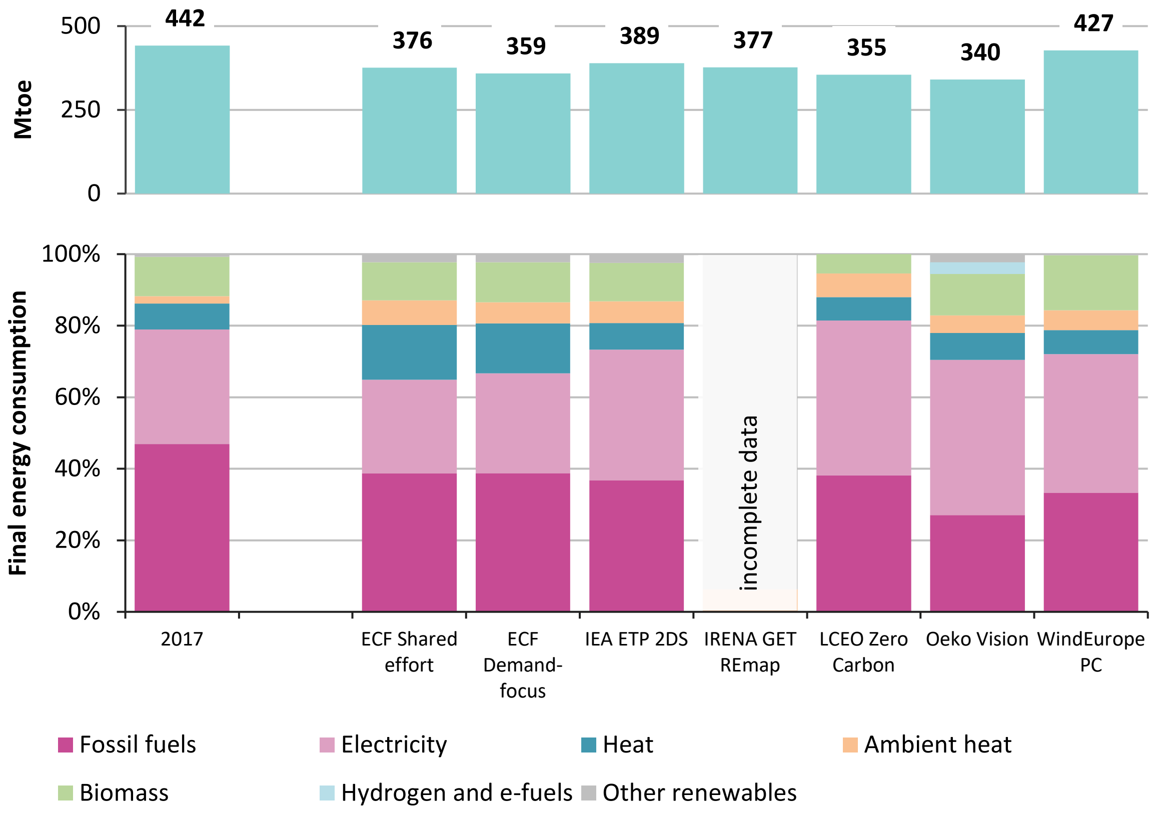
and therefore the switch towards carbon neutral fuels is mostly through electrification and supply of decarbonised distributed heat. Based on own interpretation of scenario results ([a]), the following can be concluded:

- Aiming at emission reduction higher than 50% by 2030 may require the replacement of between 10% and 35% of the individual fossil-fuelled boilers or heating stoves, mainly by heat pumps, district heating (ECF scenarios) or “other renewables”. In 5 out of 7 scenarios, the replacement of fossil-fuelled boilers and heating stoves by non-fossil fuel alternatives, is between 20% and 27%, between 2017 and 2030;
- The share of heat demand in buildings covered by individual fossil-fuelled boilers decreases from 65% in 2017 to between 42% and 58% in 2030.

On energy efficiency, there is wide range and therefore conclusions vary. The energy demand for heating reduces between 3% and 32%. To assess further these implications additional information is needed from scenarios on renovation rates of buildings, possible hurdles for the implementation of cost-efficient insulation, rebound effects or investments for energy efficiency.

([a]) The following assumptions are made: (i) direct consumption of all fuels apart from electricity in the sector is for heating purposes only, (ii) electrification of heating is achieved only with heat pumps (e.g. not with electrical resistors), (iii) thermal losses and insulation levels are independent from the type of the fuel consumed, (iv) the number of buildings built from today to 2030 is small compared to the existing building stock (in fact, 90% to 96% of the building stock in 2017 will still exist in 2030 due to low construction rate [14], and (v) the increase of electricity for heating is based on an average coefficient of performance for heat pumps of 3. Electricity consumption for heating today is based on JRC IDEES [15].

Figure 22 Final energy consumption in the EU28 buildings sector in scenarios that reach at least 50% emission reduction in 2030



Note: In all scenarios “Other renewables” includes solar thermal energy. In addition, in Oeko Vision it includes geothermal, and in IEA it also includes modern biofuels. In Oeko Vision “Hydrogen and e-fuels” refers to hydrogen and synthetic fuels (unspecified ratio). *Source:* JRC.

These pathways lead to a buildings sector in which 47% to 58% of its energy use is decarbonised by 2030, compared to about 34% today ([20]) (including the contribution of nuclear). Demand reduction, decarbonisation of power (section 5.1) and electrification of heating contribute most to that increase, as the share of biomass remains comparable to 2017 and ambient heat from heat pumps, though increasing, remains relatively small. Own interpretation of scenario results and their implication on replacement of oil and gas boilers in buildings is described in Box 2.

6.1.3 Transport in 2030

The emissions from the transport sector (including bunker fuels) increased by 28% in 2017 relative to 1990, contributing significantly to the EU28 GHG emissions (27% in 2017) [16]. Road transport accounts for about three-quarters of the sector's energy use and GHG emissions (including international bunker fuels) [11], [16]. International aviation and maritime transport consume slightly more than one-fifth of the total fuel used for transport in the EU28; in the absence of existing technological alternatives at a large scale, their emissions are hard to abate. The EU28 may need to transform radically the sector in order to reverse these trends and reach its 2030 (and 2050) goals on emission reduction. The energy scenarios indicate the following main options:

- Battery electric vehicles, plug-in hybrids and/or fuel cell vehicles are technological solutions that can reduce the environmental burden of road transport. Conventional and advanced biofuels are also examined as technologically feasible options, although there are uncertainties regarding their environmental impact, especially due to indirect land-use change effects [17], [18];
- Airplanes and ships require energy-dense fuels to cover long distances. Technological options available for road transport are less suitable for these modes (e.g. electrification of airplanes may be suitable only for short intra-EU distances, small weight and taxi mode). Therefore, advanced biofuels and synthetic fuels from hydrogen (e-fuels) or syngas (synfuels) are the most promising in view of deployment. These solutions may also find use in road transport, for example in heavy duty vehicles;
- Other scenarios explore social innovation as means to alleviate the demand for transport (e.g. modal shift, teleconferencing, car-pooling). Coupled with technological innovation, they may significantly reduce the impact of transport on the energy system and the environment.

The scenarios consistently project similar developments for transportation in 2030 in terms of final energy demand, reduction of fossil fuels and penetration shares of new technologies. They achieve the ambition of at least 50% emission reduction by 2030 by (Figure 23):

- Lower final energy consumption in transport by around 20% to 45% in 5 scenarios and about 5% to 10% in 2 scenarios, compared with today ([21]);
- Reduction in energy demand, primarily achieved by switching from oil (28% to 55% reduction compared to 2017) to electricity and biofuels. While mitigation efforts are required in all transport sectors, the oil reduction for cars may be larger. As a result, also the equivalent CO_2 emission reduction for cars may be larger than 28% to 55%;
- Scenarios agree on electric vehicles' penetration ([22]):
    - total electricity consumption in transport increases by a factor of 3 to 7 compared to today;
    - this growth is mainly attributed to road transport as energy scenarios see 7 to 90 million battery electric vehicles on EU roads by 2030;

([20]) i.e. renewable and nuclear electricity, district heating (the share of decarbonised heat in district heating is assumed to be similar to 2017, unless provided by the study), direct consumption of biomass and other renewables, ambient heat, hydrogen and e-fuels (here assumed as being exclusively produced from renewable sources) divided by final energy consumption in the buildings sector. Not taking CCS into account.

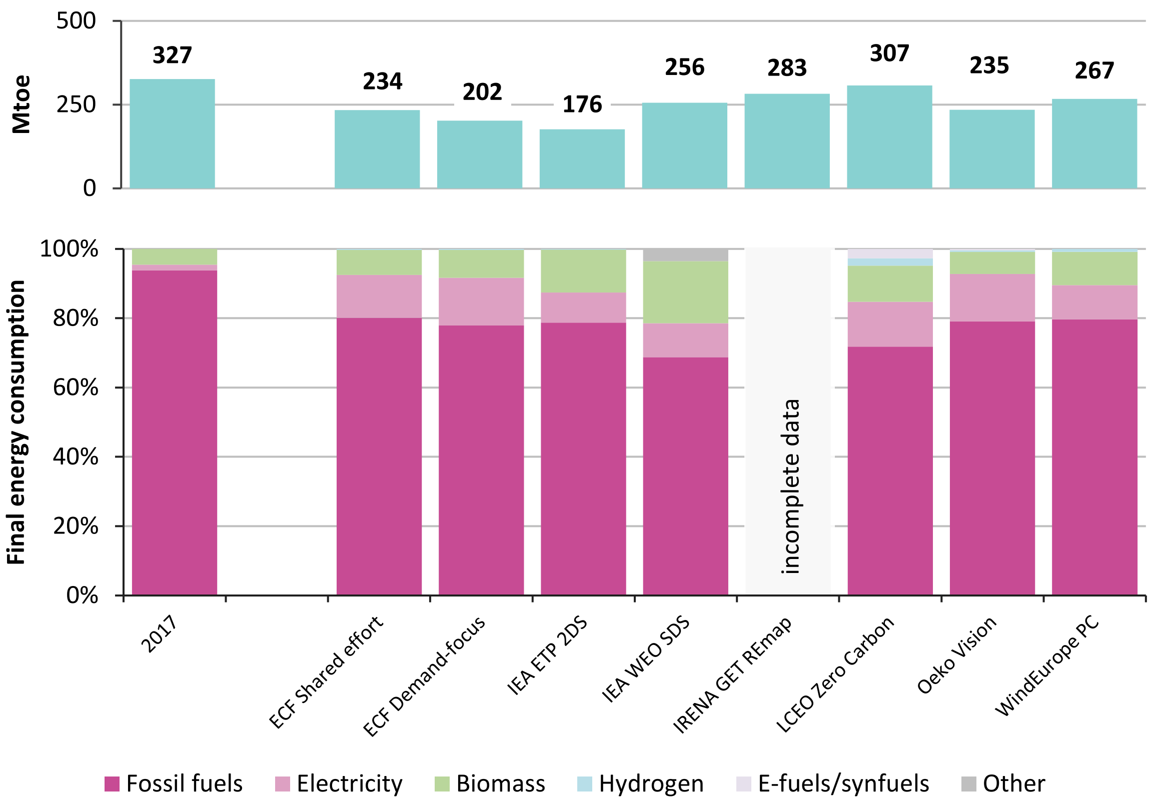
([21]) The lower final consumption entails a more efficient use of resources. Electric motors deliver significant efficiency gains compared to internal combustion engines. As a rule of thumb, every unit of electricity in final demand replaces four units of energy consumed by an internal combustion engine.

([22]) Expressed by direct electricity consumption in final energy demand for transport. Although this indicator includes electricity consumption by rail and may include modal shifts from private vehicles to public trains, it is not expected to alter this conclusion in the near-term.

- Biofuel consumption increases by 2% to 50%, although 2 scenarios expect up to a 3-fold increase;
- Most scenarios do not expect deployment of advanced fuels or hydrogen in transport, at least to a significant extent by 2030 (early deployment is expected by LCEO Zero Carbon and Oeko Vision).

The share of decarbonised energy use in transport ranges from 17% to 26% in all scenarios, compared to about 5% today ([23]). Electrification of road transport and decarbonisation of the power sector contribute the most to that increase, as biofuels maintain a share comparable to today's in most scenarios. Own interpretation of scenario results and their implication on the passenger vehicle fleet in 2030 is described in Box 3.

Figure 23 Final energy consumption in the EU28 transport sector in scenarios that reach at least 50% emission reduction in 2030



Note: "Other" is not specified in IEA WEO SDS. *Source:* JRC.

Box 3 Vehicle fleet composition in 2030

Scenarios show that already by 2030 there is a significant decrease of oil use in transport and an increase of electricity consumption. The increase can be largely attributed to the deployment of electric vehicles, as opposed to, for example, rail. However, scenarios do not provide in detail their assumptions on the composition of the vehicle fleet. Based on own interpretation of scenario results (Table 3), it can be concluded that the vehicle fleet is comprised between 30% and 50% of zero-emission or plug-in hybrid electric vehicles.

([23]) i.e. consumption of biofuels, renewable electricity (without multipliers) and nuclear electricity, hydrogen and e-fuels divided by final energy consumption in transport (i.e. excluding international aviation and marine bunker fuels). Not taking CCS in power generation into account.

Table 3 Assumptions and calculation to estimate the composition of the vehicle fleet in 2030

Scenario results	Own assumptions		Conclusions
The share of electricity use in final energy consumption of transport is between 9% and 14% (based on 7 scenarios)	Scenarios provide limited data on the split of energy use between road and non-road transport. To estimate the amount of electricity used only for road transport, electricity use for non-road transport is deducted based on Eurostat for 2017 [11].	➡	The share of electricity use in road transportation is on average 9.2% (with a range from 5.5% to 11.3%). E_{share} = 9.2%.
	The km-driven per vehicle are not fuel-specific. Each unit of electricity replaces 4.07 units of oil. The kilometers driven on electricity are estimated based on: $\frac{Eshare \times 4.07}{(Eshare \times 4.07) + (1 - Eshare)}$	➡	30% of the kilometres driven by all vehicle types on the road are on electricity.
	The electric vehicle stock in 2030 consists of 50% zero-emission vehicles and 50% plug-in hybrid electric vehicles. One-third of the kilometers driven by plug-in hybrid electric vehicles are on electricity and two-thirds on fossil fuels (utility factor of a plug-in hybrid) [19].	➡	Around 22% zero-emission vehicles and 22% plug-in hybrid electric vehicles in the total vehicle stock. Therefore, 44% are electric vehicles and 56% are internal combustion engines.
	Sensitivity analysis based on the efficiency advantage and the share of zero-emission vehicles in the total of electric vehicles.	➡	The total vehicle stock is comprised of 30% to 50% of zero-emission or plug-in hybrid electric vehicles in the total vehicle stock.

Source: JRC.

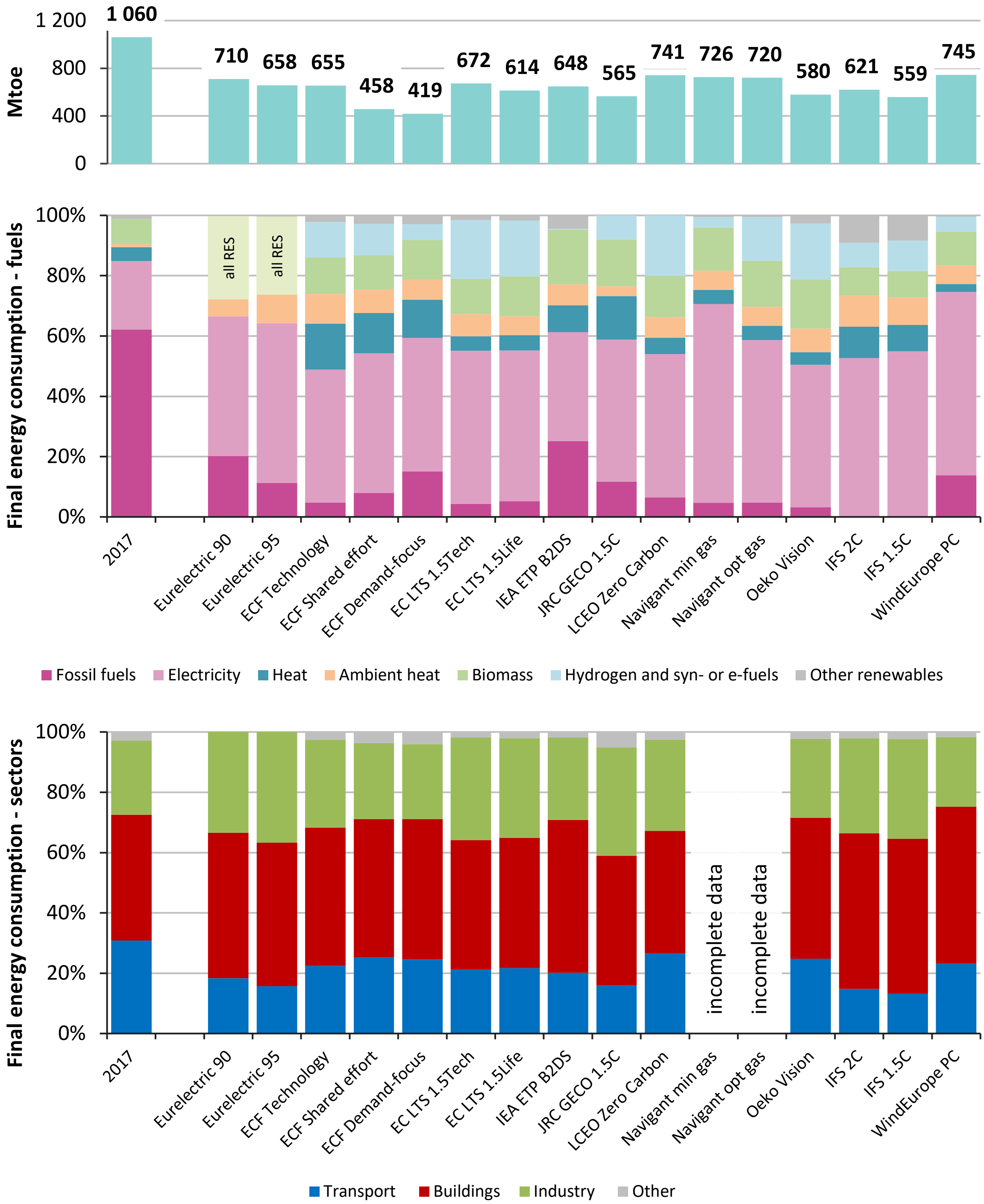
6.2 Final energy consumption in 2050

By 2050, the end-use energy consumption profile of the EU28 changes drastically. Final consumption is at least 30% and up to 60% lower when compared to 2017. Structural change is prominent in the fuel mix (fuel contribution to final demand) and less in the final consumption by sector (relative share of final energy by sector). Figure 24 shows that:

- Electricity directly contributes to between 35% and 65% of final energy consumption; this is a contribution 2 to 3 times higher than today;
- Hydrogen and hydrogen-based fuels emerge as an energy carrier, supplying from 3% to 20% of energy needs to end-users. Considering that their consumption for energy purposes is nearly zero today, considerable efforts would be required to achieve these growth and contribution levels in the coming decades;
- Direct consumption of renewable energy (e.g. geothermal heat, solar heat, bioenergy) remains similar or is a fraction of today's consumption as scenarios rely heavily on electricity and hydrogen (the growth of which inherently limits supply from other low carbon options); in the few scenarios that show an increase of direct consumption of renewable energy, it is mainly attributed to bioenergy;
- In most scenarios, direct use of fossil fuels drops to less than 20% from about 62% today;
- Lower direct electrification may entail higher consumption of combustible fuels (fossil fuels and biomass) and heat supply from district heating networks;

- Scenarios show that the relative share of energy consumption by sector in 2050 may be similar to today or characterised by a lower share of the transport sector. This implies that in most cases the overall reduction in end-use of energy (i.e. 30% to 60%) is distributed equally across sectors ([24]).

Figure 24 Final energy consumption in scenarios that meet at least 90% emission reduction in 2050



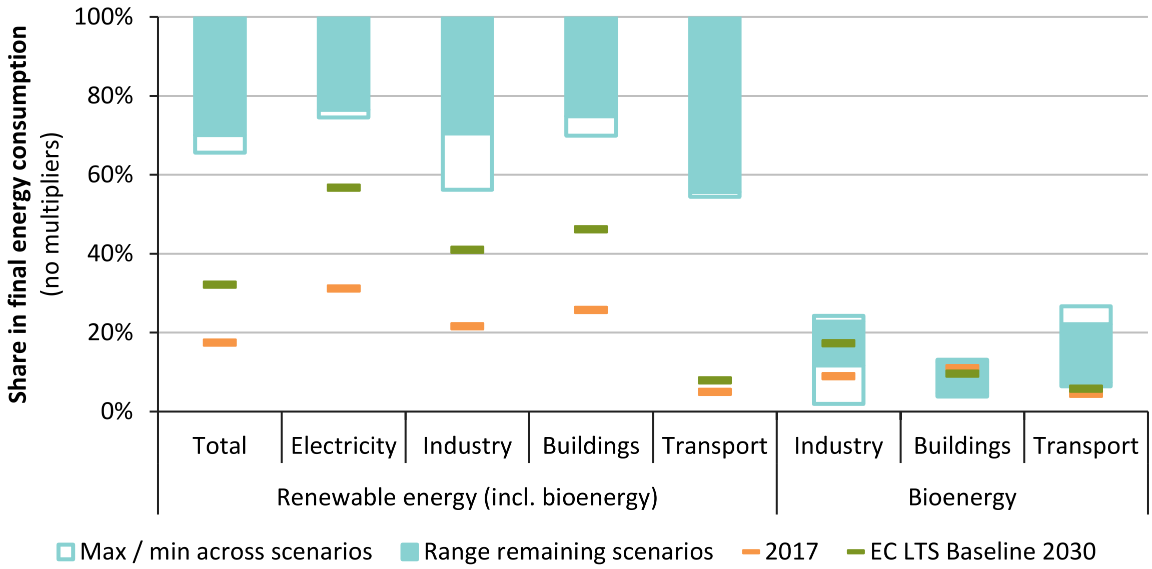
Note: In Navigant, energy use apart from electricity in industry sectors other than iron and steel, ammonia and methanol, cement and lime are not included. Agriculture is included in "Other", apart from Eurelectric which groups it under industry. *Source*: JRC.

The consumption of renewable energy by end-use sectors intensifies beyond 2030 (Figure 25). The share of renewable energy use ranges greatly between scenarios (35 percentage points, from 65% to 100% in those

([24]) 3 out of 12 scenarios estimate a higher reduction in end-use of energy by the transport sector due to widespread electrification and efficiency improvements in internal combustion engines.

scenarios that normatively deploy 100% energy from renewable sources by 2050). The difference reaches 50 percentage points in all three end-use sectors and 25 percentage points in the power sector. This is a result of the multitude and various combinations of decarbonisation options that are deployed in deep decarbonisation pathways (e.g. direct electrification, high supply of hydrogen, fossil fuels with CCS). Nonetheless, similar across all scenarios is that transportation increases its energy consumption from renewable sources mostly after 2030.

Figure 25 Share of renewable energy and bioenergy in scenarios that achieve at least 90% emission reduction in 2050 and benchmark with projections for 2030 under the existing policy framework

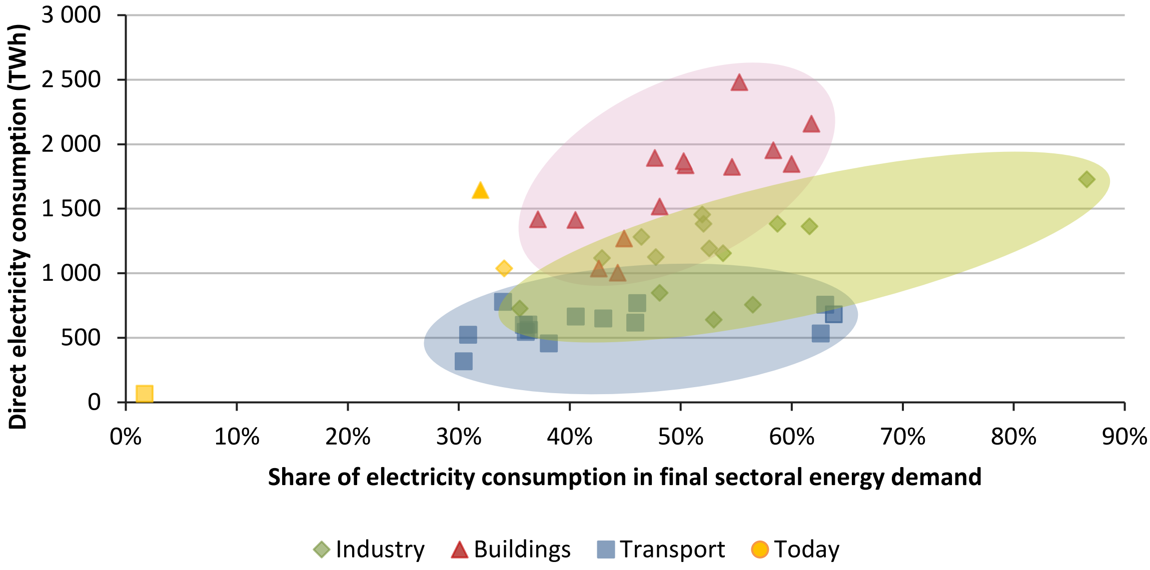


Note: White-filled boxes correspond to the maximum and minimum values across all scenarios for 2050; inner boxes include the remaining scenario values for 2050. The green marker indicates projections of EC LTS Baseline for 2030. *Source*: JRC.

The analysis of electricity consumption and its share in final energy demand per sector shows that by 2050 (Figure 26):

- About half of the industrial energy demand may be directly electrified; most scenarios show a range between 40% and 60%, with the total consumption ranging between 650 and 1 400 TWh. Notably, some scenarios expect the electricity consumption and share to remain similar to today (in 2017, 1 035 TWh contribute to 34% of final energy demand in industry), due to energy demand reduction and the constraints in the sector's electrification. The results of WindEurope are significantly higher than all other scenarios, as it relies heavily on electrification to decarbonise the industry sector;
- Buildings is the most electrified sector in absolute (1 000 to 2 500 TWh) and relative terms (37% to 62% in 2050, while in 2017, 1 645 TWh contributed to 32% of final energy demand in buildings, mostly for electrical appliances and services). The increase of electrification in the buildings sector is mostly driven by heating, which is more prominent in the projected results of the Eurelectric, the EC LTS scenarios (1.5Tech and 1.5Life) and LCEO Zero Carbon. These scenarios expect an increase in consumption due to vast electrification of heating;
- Transport consumes lower amounts of electricity compared to the other sectors (up to 780 TWh). Most scenarios expect electricity to cover between 30% and 45% of final demand for transport. The sector is the most transformed, considering that in 2017 about 65 TWh were consumed (the majority in the rail sector), covering less than 2% of demand (without multipliers). Moreover, transport is the only sector that increases its demand for electricity across all scenarios, as opposed to industry and buildings where several scenarios show that efficiency measures and other low carbon alternatives may lead to a lower electricity demand than today.

Figure 26 Direct electricity consumption and its contribution per sector in scenarios that achieve emission reduction higher than 90% in the EU28 by 2050



Source: JRC.

6.2.1 Industry in 2050

The transformation of the industry sector is evident when looking into energy scenario results over the next 30 years (Figure 27). The main trends are summarised into the following:

- The sector consumes significantly less fossil fuels (in several scenarios, one-tenth of today's consumption), though they may still provide between 3% and 35% of its energy needs (today they cover around 50%). The industry sector in IEA ETP B2DS shows 35% fossil fuel consumption, which is the highest share found in all the scenarios. About 55% of CO_2 emissions due to fossil fuel use in this scenario are captured (174 $MtCO_2$);
- The widespread electrification of the sector reaches 40% to 60% in most scenarios; there are two scenarios that show 75% to almost 100% of electrification of industrial energy needs (Navigant min gas for a part of the heavy industry and WindEurope PC);
- Hydrogen emerges as an energy carrier (between 6% and 20% of the sector's demand). In some scenarios it provides a comparable volume and share of energy needs as fossil fuels by 2050. EC LTS 1.5Tech and 1.5Life, LCEO Zero Carbon and Navigant opt gas show the highest volume of hydrogen consumption (despite the fact that the latter scenario covers only part of the sector it projects the highest hydrogen consumption in industry across all scenarios);
- There is a trade-off between hydrogen and electricity as secondary energy carriers in the energy mix; however, industry relies mostly on electricity to decarbonise, whether directly or indirectly (for hydrogen production).

As a result, in most scenarios 70% to 100% of the energy use in industry is decarbonised by 2050 ([25]). Electricity may contribute 47% to 67% to the sector's decarbonised energy profile ([26]), or almost 95% in high electrification scenarios (Navigant min gas for part of the energy intensive industry and WindEurope PC). The remaining activity will require CO_2 capture and sequestration. Scenarios in which decarbonised power in industry plays a lesser role show higher consumption of hydrogen or e-fuels by the sector. Energy demand

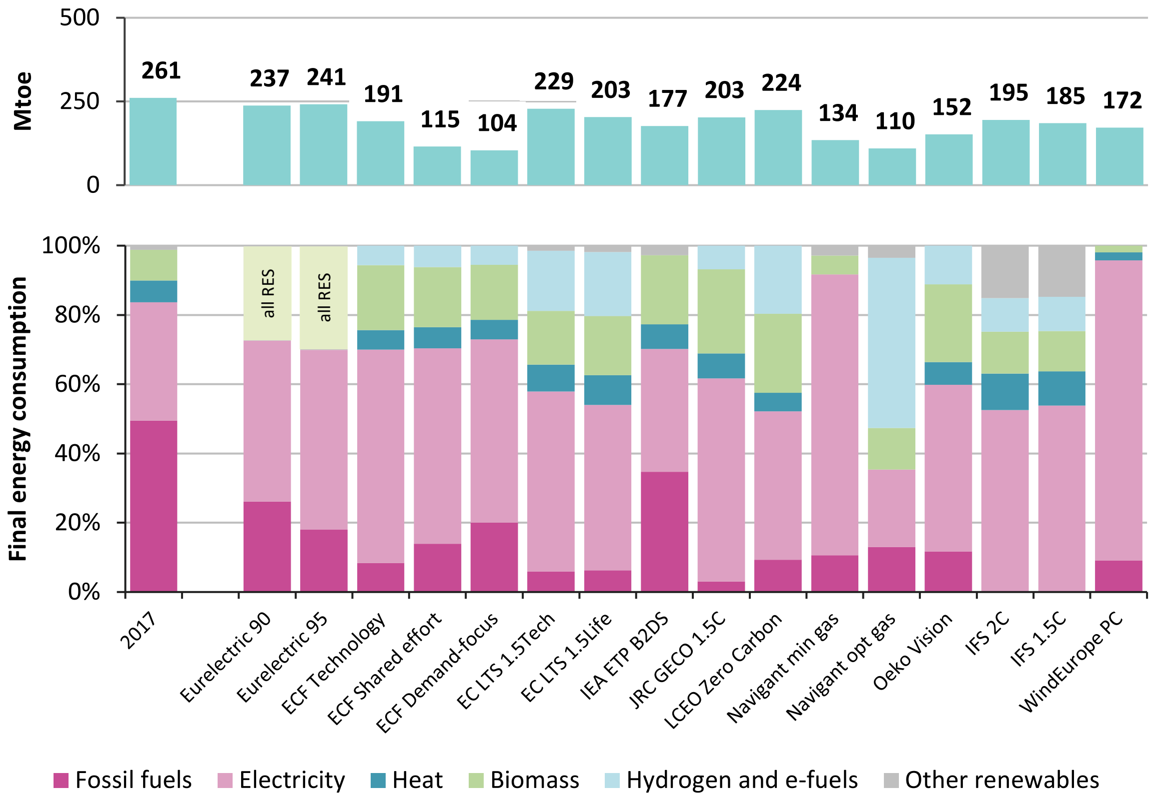
([25]) Excluding IEA ETP B2DS, which shows high shares of fossil fuels and relatively small reduction in energy demand. In these scenarios about two-thirds of the sector is decarbonised by 2050, compared to about one-third today.

([26]) i.e. renewable and nuclear electricity, distributed heat (distributed heat is assumed to be fully decarbonised by 2050), direct consumption of biomass and other renewables, hydrogen and e-fuels (assuming the share of decarbonised power for 2050) divided by final energy consumption in the industry sector. Not taking CCS into account.

decreases in all scenarios. However, there is no single trend on how the energy demand reduction develops based on the scenario definitions, as it may be lower by 3% up to almost 55% compared to today. One reason for this inconsistency may be attributed to different assumptions on the EU28 industry's production output, even though GDP, which is one of the key indicators for demand and manufacturing of materials, increases in all scenarios (Annex 2, Figure 32). The energy scenarios, however, do not report consistently on the assumed manufacturing output, which would allow for a more detailed and consistent comparison. The little available data point towards significant variations:

- Based on the ECF scenarios, total industrial output (in physical terms) is lower between 30% and 65% in 2050, compared to 2015, which depending on the sector may reach 80% (e.g. cement). For EU manufacturing, ECF assumes the current share of trade balance throughout 2050. ECF scenarios were found to have the lowest energy consumption in industry across all studies;
- In IEA ETP B2DS, total EU28 manufacturing is lower by 20% (in physical terms) in 2050 compared to 2014, but varies per sector (e.g. from 29% reduction in crude steel to 84% increase in methanol) ([27]);
- According to the Mix95 scenario of the FORECAST model used in the EC LTS [17], the industry's production output may reduce by 20% compared with 2015 (excluding refineries); in the reference scenario of the same model, the EU industry's output declines by about 12% [21];
- In LCEO Zero Carbon, the industrial production of the EU28 decreases by 12%.

Figure 27 Final energy consumption in the EU28 industry sector in scenarios that reach at least 90% emission reduction in 2050

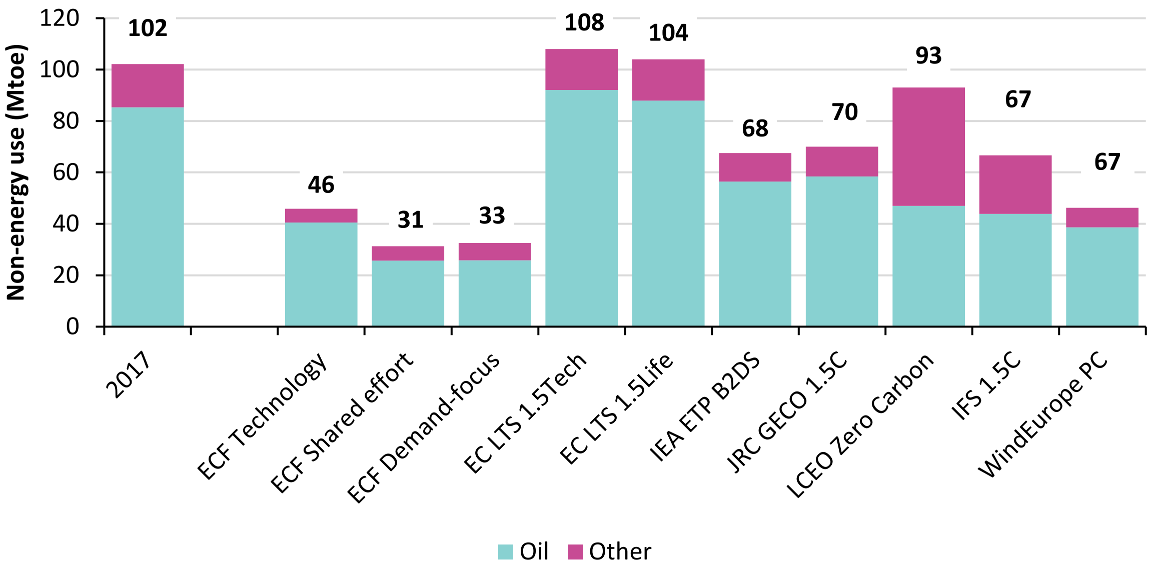


Note: Navigant scenarios cover only part of the energy intensive industry. In Eurelectric "Other renewables" includes non-emitting primary fuels/sources such as geothermal, solar thermal, biomass and secondary fuels such as biofuels, synthetic fuels, hydrogen, heat and others. In EC LTS, IEA, and IFS, "Other renewables" includes other renewable sources (e.g. solar thermal, geothermal heat) and it is not specified in Navigant. *Source:* JRC.

([27]) Estimated based on the increase of material production globally and the decreasing share of final energy consumption (including feedstock) of the EU28 industry over the global industry.

Non-energy use (Figure 28), as a proxy for sectorial output also varies in the long-term, supporting the fact that industrial output differs between scenarios and requires more transparent reporting.

Figure 28 Non-energy use in scenarios that meet the long-term vision of the EU28 in 2050



Note: IEA ETP B2DS includes petrochemical feedstocks, blast furnace and coke oven coke. The remaining scenarios include all non-energy uses. *Source*: JRC.

Next to the industrial output in physical terms, several other assumptions that affect the sector's energy demand and mix need to be reported in order to understand the degree at which energy efficiency, technology adoption and innovation in industry may contribute to the long-term vision of the EU28. Some of these assumptions are building construction rates, material substitution or material efficiency (e.g. scrap iron recycling), but also composition of the feedstocks used for non-energy applications.

6.2.2 Buildings in 2050

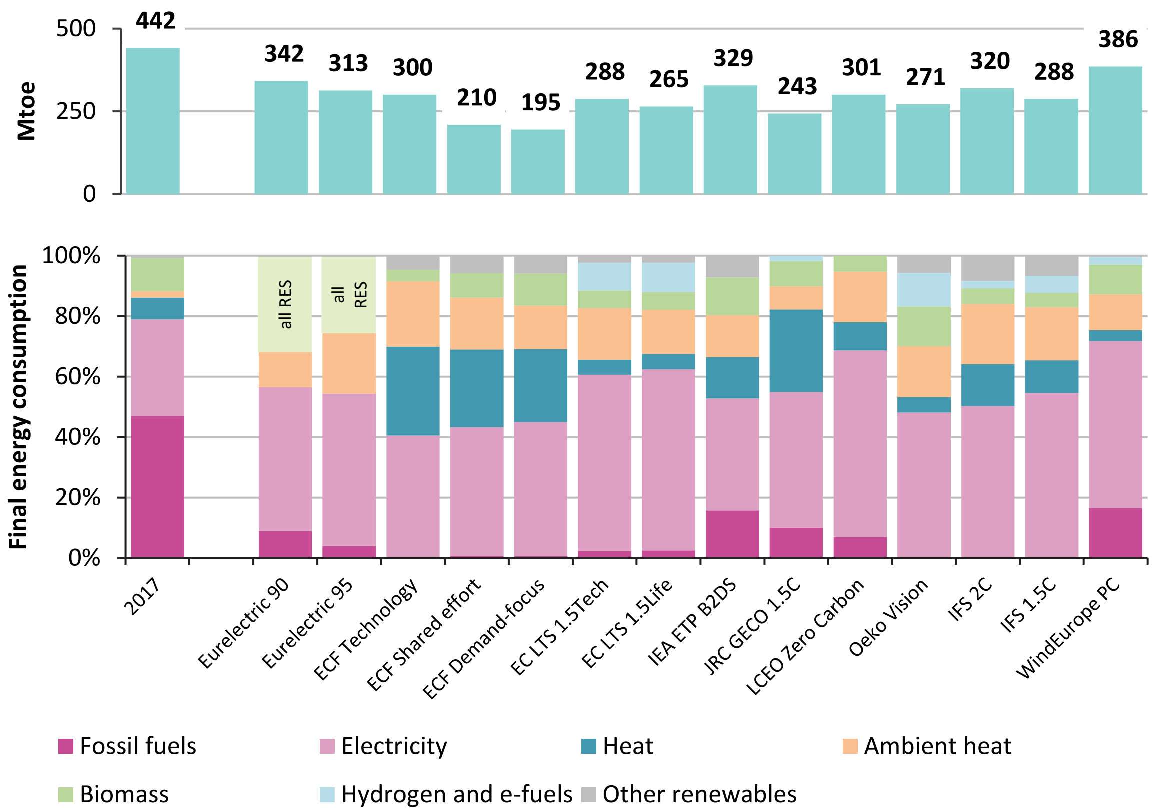
Scenarios that transition towards net-zero emissions in the EU28 by mid-century show that the buildings sector (Figure 29):

- Consumes 20% to 55% less energy than it does today; this can be partly achieved by ramping up the renovation rate of the building stock from about 1% today to between 1.4% and 1.7% (EC LTS scenarios). Other scenarios follow a 2.3% to 4% annual rate of renovation, achieving a notably higher reduction in the sector's energy consumption (ECF and Oeko scenarios). WindEurope estimates that the increase in renovation may reduce between 5% and 6% of the EU's total energy consumption;
- Practically phases out fossil fuels from its energy mix. If used, fossil fuels contribute less than 10% to the sector's energy mix (excluding the IEA ETP B2DS scenario which has a notably different profile);
- Increases its reliance on electricity (37% to 62% of final energy demand is based on direct electricity consumption);
- Increases notably its heat supply from heat pumps, by a factor 2 to 7 compared to today and may supply 10% to 20% of final demand;
- It covers 5% to 30% of its needs for heating through district heating networks, which grow in terms of supply up to 2.5 times higher than today. Some scenarios indicate a contraction by 50% (especially when heat is supplied by electricity as shown by the EC LTS scenarios). As such, with respect to district heating, transitioning to cleaner fuels seems to be more preferable than expanding their capacity significantly;

- Notably, 7 out of 12 scenarios show hydrogen and e-fuels consumption by the sector (2% to 11% of final energy demand), yet only in 4 scenarios the consumption is in relatively high volumes (between 15 and 30 Mtoe). These are in the form of e-gas (75% in EC LTS scenarios) and hydrogen (25% in EC LTS, Oeko Vision and IFS).

In most scenarios, at least 90% of the energy use in the buildings sector does not emit CO_2 [28]. While decarbonised power has a major role, other heat supply options (most prominently ambient heat from heat pumps and distributed heat from district heating networks) have similar contributions. Only two scenarios show lower shares of decarbonised energy use in buildings; WindEurope PC, due to its lower decarbonised profile of electricity generation (72%, see Figure 16) and relatively high direct consumption of fossil fuels (Figure 29), and IEA ETP B2DS due to a similar share of fossil fuel consumption (yet lower volume; Figure 29). In 7 out of 12 scenarios hydrogen and e-fuels contribute further to the sector's decarbonisation, in proportional shares to the carbon intensity of the power mix.

Figure 29 Final energy consumption in the EU28 buildings sector in scenarios that reach at least 90% emission reduction in 2050



Note: In Eurelectric "Other renewables" includes non-emitting primary fuels/sources such as geothermal, solar thermal, and biomass but also secondary fuels such as biofuels, synthetic fuels, hydrogen, heat and others. In ECF, it includes solar thermal heat. In EC LTS, Oeko Vision and IFS "Other renewables" includes other renewable sources (e.g. solar thermal and geothermal heat). In IEA, it includes modern biofuels and solar thermal energy. Navigant scenarios only partially cover the sector (only heating). In EC LTS, e-gas is 75% and hydrogen 25%, in JRC GECO 1.5C and IFS scenarios it is 100% hydrogen, while in Oeko Vision it is hydrogen and synthetic fuels (unspecified ratio).
Source: JRC.

[28] i.e. renewable and nuclear electricity, distributed heat (distributed heat is assumed to be fully decarbonised by 2050), ambient heat, direct consumption of biomass and other renewables, hydrogen and e-fuels (assuming the share of decarbonised power for 2050) divided by final energy consumption in the buildings sector. Not taking CCS into account.

6.2.3 Transport in 2050

The decarbonisation efforts for the transport sector strengthen from 2030 towards 2050:

- Most scenarios expect transport to consume around one-third of the energy it consumes today (40% to 80% reduction in most scenarios between 2017 and 2050), while the demand for mobility varies depending on the scenario:
    - by 2050, passenger road transport activity increases by about 20% in EC LTS and LCEO Zero Carbon, decreases by 20% in ECF, whilst in IEA ETP B2DS is more than halved compared to 2015;
    - however, final energy consumption in transport does not necessarily follow similar trends, as it is also affected by other underlying assumptions (e.g. on utilisation and occupancy of vehicles) and the car fleet composition;
- In most scenarios, electricity consumption increases approximately by a factor 10 and together with biofuels they cover about 60% of the sector's energy demand (i.e. excluding international aviation and maritime bunker fuels); the range, however, is rather wide across all scenarios assessed, from 40% to almost 90%;
- The electric vehicle fleet reaches 100 to 220 million battery electric vehicles in most scenarios. The ECF scenarios project as little as 5 to 10 million passenger battery electric vehicles, owing to their radically different assumptions on utilisation and occupancy of different modes of transport (in ECF the total passenger car fleet is between 10 to 35 million vehicles);
- Hydrogen and e-fuels are fully deployed and become key elements in decarbonising transport; they supply from 15% to 50% of the sector's energy needs;
- Oil is still used in transport in most scenarios (2 to 50 Mtoe, 1% to 16% of today's consumption; only 6 out of 17 scenarios phase out oil completely);
- The 10 scenarios that achieve net-zero emissions in the EU by 2050, all seem to follow a different route in decarbonising transport. The three ECF scenarios still use fossil fuels but have significant reduction in the car fleet. The two EC LTS scenarios still use oil and increase passenger road transport activity compared to 2050. The remaining five scenarios completely phase out oil (IFS 1.5C, LCEO Zero Carbon, Navigant min gas, Navigant opt gas, and Oeko Vision).

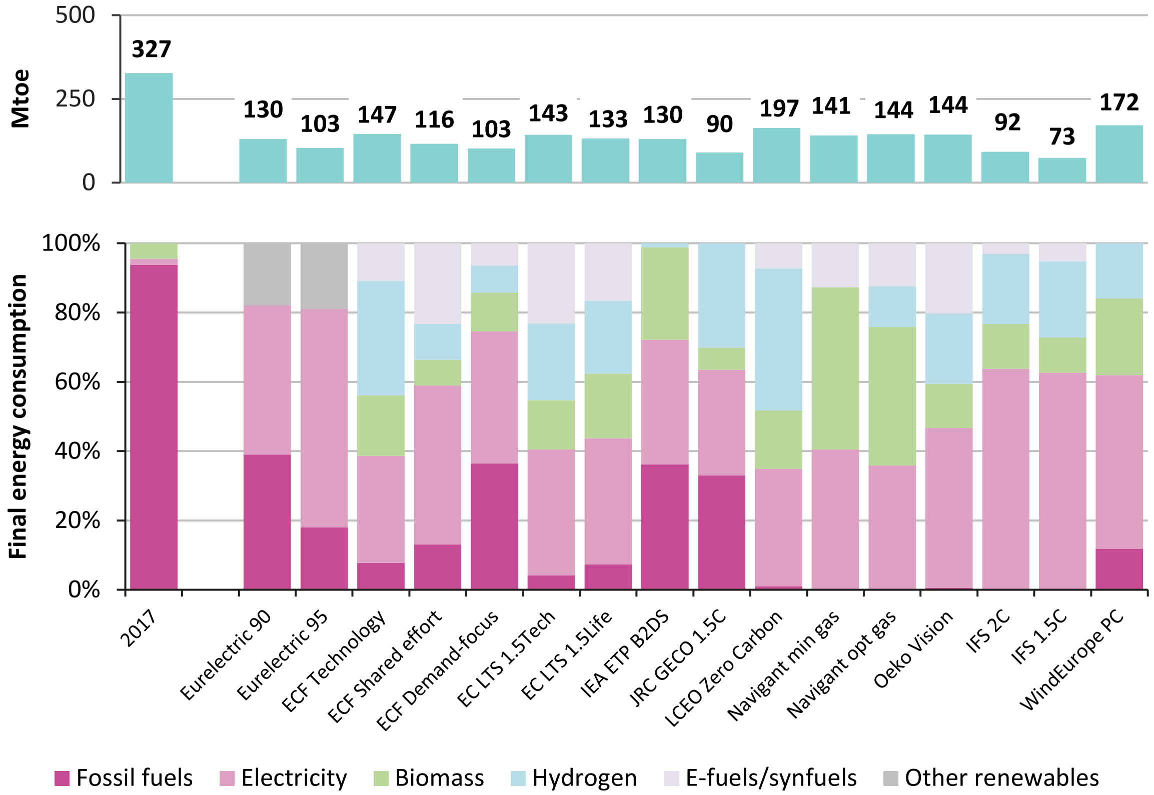
The share of decarbonised energy consumed in transport in 2050 ([29]) is around 60% in 2 scenarios (ECF Demand-focus, IEA ETP B2DS), 75% and 84% in WindEurope PC and ECF Shared effort respectively, and above 90% in all other scenarios. Own interpretation of scenario results and their implication on the passenger vehicle fleet in 2050 is described in Box 4.

Box 4 Vehicle fleet composition in 2050

The share of electricity (battery electric vehicles) and hydrogen use (fuel cell vehicles) in road transport ranges from 32% to 69% in 2050. Assuming that all electric vehicles in 2050 are zero-emission vehicles (i.e. and not plug-in hybrids) and by applying the same approach as in Box 3, then the share of zero-emission vehicles can be estimated. Based on own interpretation of scenario results, it is concluded that the total vehicle stock will be comprised of between 65% and 90% zero-emission vehicles, which are either battery electric or based on fuel cells. The remaining vehicles use mainly biofuels or e-fuels.

([29]) i.e. consumption of biofuels, renewable electricity (without multipliers) and nuclear electricity, hydrogen and e-fuels divided by final energy consumption in transport (i.e. excluding international aviation and marine bunker fuels). Not taking CCS in power generation into account.

Figure 30 Final energy consumption in the EU28 transport sector in scenarios that reach at least 90% emission reduction in 2050

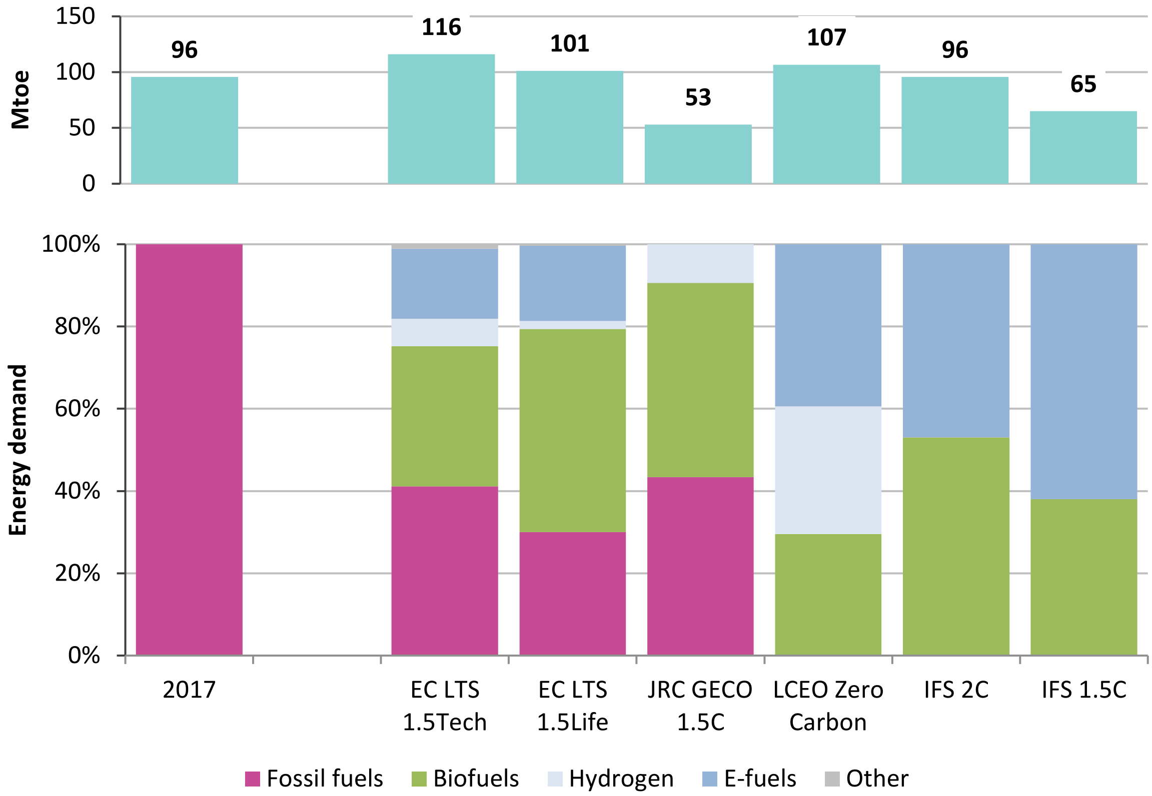


Note: "Other renewables" includes non-emitting secondary fuels such as biomethane, biodiesel, bioethanol, hydrogen and others in Eurelectric. *Source:* JRC.

International aviation and maritime bunker fuels are not part of the above analysis, as according to the new definition of Eurostat, they are reported separately from final energy consumption in transport. Due to the limited insights into the assumptions for transport but also due to the inconsistent reporting of international bunker fuels across the reviewed energy scenarios, a more detailed comparative assessment for aviation and maritime separately is not possible. Based on the available data presented in Figure 31, it is seen that:

- Final demand for international bunker fuels in energy scenarios varies by a factor 2; it can be as low as 50 Mtoe (JRC GECO 1.5C) to as high as 115 Mtoe (EC LTS 1.5C);
- Out of 6 scenarios, 3 show full decarbonisation of international aviation and maritime fuels, whilst the remaining 3 show oil consumption up to 40% of the sector's demand;
- In 5 out of 6 scenarios, biofuels are mostly consumed as international bunker fuels (60% to 80% of total biofuel consumption from Figure 30 and Figure 31). Only JRC GECO 1.5C shows that biofuel consumption is higher in road transport.

Figure 31 International bunker fuels in scenarios that reach at least 90% emission reduction in 2050



Note: For the EC LTS scenarios, the maritime bunker fuels of 1.5LIFEMar scenario is added with the international aviation fuels of 1.5Tech and 1.5Life. "Other" includes mainly electricity and small fraction from other liquids in EC LTS. *Source:* JRC.

7 Conclusions

The EU has set clear and high goals to combat climate change while leading the rest of the world to higher ambition levels. Aiming for at least 50% GHG emission reduction by 2030 compared to 1990, and zero emissions by 2050 is now part of the discourse on the EU energy transition, as framed in the “European Green Deal” and the “Long Term Strategic Vision”. This report has identified similar and diverging elements of scenarios that reach these emission reduction levels within their own scenario context.

In the scenarios reaching at least 50% emission reduction by 2030 that are analysed in this report, the energy transition is characterised by:

- A reduction of total coal consumption by at least 70% in the next 10 years;
- An increase of the installed capacity of variable renewables by a factor 2 to 3;
- Differences on energy efficiency (31% to 44% range) and the share of energy from renewables (30% to 40% range). The following factors influence that range:
    - the growth of renewables in gross final energy consumption, which varies from a factor 1.5 to 1.75;
    - the reduction of energy demand for heating of buildings and of transportation;
    - the rapid electrification of transport that reduces oil and requires proportionally smaller amounts of renewables to satisfy the same demand;
    - the scenario context on nuclear energy and the availability of CCS.

In the scenarios reaching at least 90% emission reduction by 2050 that are analysed in this report, the climate and energy transition is characterised by:

- A nearly complete phase-out of coal, oil and natural gas in all energy sectors by 2050;
- An undisputed growth of wind and solar (a growth that varies between a factor 3 and 13), heavily linked to the level of direct electrification and hydrogen/e-fuel *production*. In turn, hydrogen and e-fuel *demand* depend on the use of energy efficiency, CCS outside the power sector and/or carbon removal technologies;
- For transport, based on own interpretation, an uptake of 65% to 90% zero emission vehicles by 2050.

The analysis presented here was challenged by data availability and data boundaries (e.g. differences in sectoral coverage) across the various scenarios. The harmonisation of the different outcomes was only possible based on assumptions and interpretation of results (reported in Annex 3). As scenarios are increasingly communicated and discussed to support the debates on the energy transition, their publishers should increase the efforts towards harmonisation of results. Moreover, next to scenario results, there is a need for transparency on critical assumptions that may be pivotal in shaping the scenarios, such as technology costs, CO_2 prices, industrial output, demand for materials, renovation rates of buildings, utilisation rates of vehicles and so forth.

Methodologically, the present analysis could be complemented by investigating the differences in the structural changes induced by the various scenarios. This can be achieved, for example by indexing all scenarios against their own baseline and assessing their difference or by decomposing the CO_2 emission reduction to key drivers (e.g. Kaya identity). Additional insights could be provided by examining the degree of sector-coupling, the flexibility of the power system, the integration of hydrogen production to the system (e.g. dedicated capacity, flexibility option, market-driven output), or by providing a detailed technical feasibility of different options proposed by the scenarios. The economic dimension of scenarios (e.g. technology investment costs, infrastructure costs, avoided costs), the supply of critical materials, impacts on water resources, and other supply chains that link to geopolitics, need to be further investigated to fully grasp their economic and social implications, in order to further support the EU decision-making process in their efforts towards near-zero emissions by mid-century in a just and responsible way.

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List of abbreviations and definitions

BECCS	Bioenergy with Carbon Capture and Storage
CC(U)S	Carbon Capture (Utilisation) and Storage
EC	European Commission
ECF	European Climate Foundation
EEA	European Economic Area
ETP	Energy Technology Perspectives
ETS	Emission Trading System
EU	European Union
GDP	Gross Domestic Product
GECO	Global Energy and Climate Outlook
GET	Global Energy Transformation
GIS	Geographic Information System
GHG	Greenhouse Gas
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
LTS	Long Term Strategy
LULUCF	Land Use, Land-Use Change and Forestry
NGO	Non-Governmental Organisation
OECD	Organization for Economic Cooperation and Development
PC	Paris Compatible
RES	Renewable Energy Sources
SDG	Sustainable Development Goals
SDS	Sustainable Development Scenario
WEM	World Energy Model
WEO	World Energy Outlook

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Annex 1. Energy scenario publications and their scenarios

Table 4 Energy scenario studies and scenarios for the EU published between 2017 and June 2019. The scenarios assessed in this report are highlighted in blue

Publisher	Study	Year	Scenario	Abbreviation	Reference
Bloomberg New Energy Finance	New Energy Outlook 2018	2018	New Energy Outlook	BNEF NEO 2018	[22]
Bloomberg New Energy Finance	New Energy Outlook 2019	2019	New Energy Outlook	BNEF NEO 2019	[23]
British Petroleum	Energy Outlook 2017	2017	Various scenarios	BP 2017	[24]
British Petroleum	Energy Outlook 2018	2018	Various scenarios	BP 2018	[25]
British Petroleum	Energy Outlook 2019	2019	Evolving Transition	BP ET	[26]
British Petroleum	Energy Outlook 2019	2019	Rapid Transition	BP RT	[26]
Enerdata	EnerFuture Global Energy Scenarios to 2040	2018	Blue	Ener Blue	[27]
Enerdata	EnerFuture Global Energy Scenarios to 2040	2018	Green	Ener Green	[27]
Enerdata	EnerFuture Global Energy Scenarios to 2040	2018	Brown	Ener Brown	[27]
ENTSO-E	TYNDP 2018 Scenario report	2018	Distributed Generation	ENTSO-E DG	[28]
ENTSO-E	TYNDP 2018 Scenario report	2018	Sustainable Transition	ENTSO-E ST	[28]
ENTSO-E	TYNDP 2018 Scenario report	2018	Global Climate Action	ENTSO-E GCA	[28]
ENTSO-E	TYNDP 2018 Scenario report	2018	External Scenario	ENTSO-E EUCO	[28]
Equinor	Energy Perspectives 2018	2018	Reform	Equinor Reform	[29]
Equinor	Energy Perspectives 2018	2018	Renewal	Equinor Renewal	[29]
Equinor	Energy Perspectives 2018	2018	Rivalry	Equinor Rivalry	[29]
Eurelectric	Decarbonisation pathways	2018	80	Eurelectric 80	[30]
Eurelectric	Decarbonisation pathways	2018	90	**Eurelectric 90**	[30]
Eurelectric	Decarbonisation pathways	2018	95	**Eurelectric 95**	[30]
European Climate Foundation	Net Zero by 2050: From Whether to How	2018	Technology	**ECF Technology**	[31]
European Climate Foundation	Net Zero by 2050: From Whether to How	2018	Demand-focus	**ECF Demand-focus**	[31]
European Climate Foundation	Net Zero by 2050: From Whether to How	2018	Shared effort	**ECF Shared effort**	[31]

Publisher	Study	Year	Scenario	Abbreviation	Reference
European Commission	Long Term Strategic Vision	2018	Baseline	**EC LTS Baseline**	[20]
			Electrification	EC LTS ELEC	
			Hydrogen	EC LTS H2	
			Power-to-X	EC LTS P2X	
			Energy Efficiency	EC LTS EE	
			Circular Economy	EC LTS CIRC	
			Combination	EC LTS COMBO	
			1.5 C Technical	**EC LTS 1.5Tech**	
			1.5 C Lifestyles	**EC LTS 1.5Life**	
Fuel Cells and Hydrogen Joint Undertaking	Hydrogen Roadmap	2019	Baseline	FCH Baseline	[32]
			Ambitious	FCH Ambitious	
International Energy Agency	Energy Technology Perspectives 2017	2017	RTS	IEA ETP RTS	[33]
			2DS	**IEA ETP 2DS**	
			B2DS	**IEA ETP B2DS**	
	World Energy Outlook 2017	2017	New Policies Scenario	IEA WEO 2017 NPS	[34]
			Current Policies Scenario	IEA WEO 2017 CP	
			Sustainable Development Scenario	IEA WEO 2017 SDS	
	World Energy Outlook 2018	2018	New Policies Scenario	IEA WEO NPS	[35]
			Current Policies Scenario	IEA WEO CP	
			Sustainable Development Scenario	**IEA WEO SDS**	
International Renewable Energy Agency	Renewable Energy Prospects for the EU	2018	Reference	IRENA REmap Reference	[36]
			REmap EU	IRENA REmap EU	
	Global Energy Transformation 2018	2018	REmap	IRENA GET 2018 REmap	[37]
	Global Energy Transformation 2019	2019	Reference	IRENA GET Reference	[38]
			REmap	**IRENA GET REmap**	

Publisher	Study	Year	Scenario	Abbreviation	Reference
Joint Research Centre	Global Energy and Climate Outlook 2017	2017	Reference	JRC GECO 2017 Ref	[39]
			INDC	JRC GECO 2017 INDC	
			B2C	JRC GECO 2017 B2C	
	Global Energy and Climate Outlook 2018	2018	Reference	JRC GECO Ref	[40]
			2C	JRC GECO 2C	
			1.5C	**JRC GECO 1.5C**	
	Low Carbon Energy Observatory	2018	Baseline	LCEO Baseline	[41]
			Diversified	LCEO Diversified	
			ProRes	LCEO ProRES	
			Zero Carbon	**LCEO Zero Carbon**	
Navigant	Gas for Climate	2019	Minimal gas	**Navigant min gas**	[42]
			Optimised gas	**Navigant opt gas**	
Oeko-Institut	The Vision Scenario for the European Union	2017	Reference	Oeko Ref	[43]
			Vision	**Oeko Vision**	
Shell	Sky. Meeting the Goals of the Paris Agreement	2018	Sky	Shell Sky	[44]
Teske et al. 2019	Achieving the goals of the Paris Agreement	2019	5C	IFS 5C	[45]
			2C	**IFS 2C**	
			1.5C	**IFS 1.5C**	[45], [46]
WindEurope	Breaking New Ground	2018	Accelerated Electrification	WindEurope AE	[47]
			Paris Compatible	**WindEurope PC**	

Source: JRC.

Table 5 Overview of the methods deployed and their scope in energy scenario studies

Organisation	Study	Method/model	Scope (to compare the scenarios, this report harmonises the scope based on the method described in the Annex 3)			
			Geographical	Temporal	Sectoral	Emissions
Eurelectric	Decarbonisation pathways (2018)	McKinsey's Global Energy Perspective bottom-up simulation model, driven by links with their Global Energy Demand Model that projects development of demand	Global, covering 8 regions and the EU28 plus Iceland, Liechtenstein and Norway. Aggregation based on 146 country results	Annual projections up to 2050	Power Industry Buildings Transport	Energy-related CO_2 (incl. international aviation)
European Climate Foundation	From Whether to How (2018)	Techno-economic simulation model (CTI Roadmap tool extended for Europe), which simulates emissions and mitigation options. Similar calculator tools are used in several projects (e.g. EUCalc, DECC-UK, CLIMACT-BE)	EU28	5-year time step, up to 2050	Power Industry Buildings Transport	Energy-related and process CO_2 (incl. international aviation), LULUCF and non-CO_2
European Commission	A Clean Planet for all (2018)	PRIMES (partial equilibrium optimisation model for the energy system), POLES-JRC (for the global context on fossil fuel prices), GEM-E3 and E3ME (for macro-economic analysis) GLOBIOM and CAPRI (for LULUCF) GAINS (for non-CO_2 GHG emissions and air pollution)	EU28, country level (results presented at an EU28 level)	5-year time step, up to 2050 (optimisation up to 2070), results available for 2030 and 2050	Power Industry Residential Transport Tertiary (i.e. services, agriculture, fisheries and other)	Energy-related and process CO_2 (incl. international aviation), LULUCF and non-CO_2

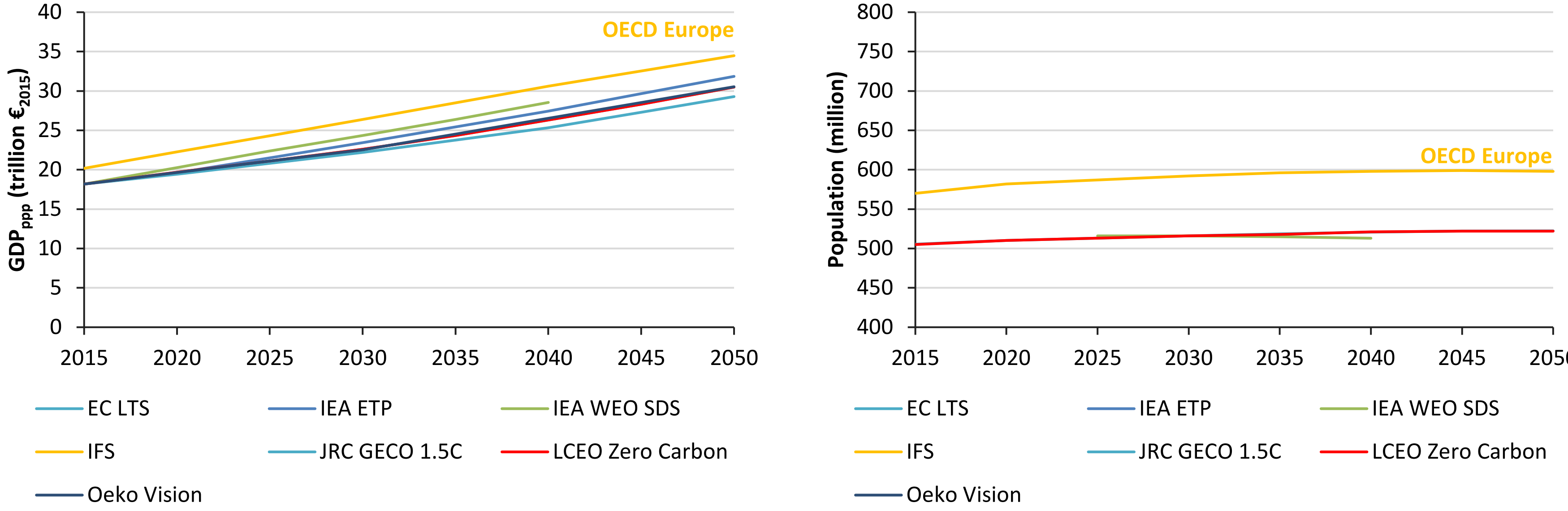
Organisation	Study	Method/model	Scope (to compare the scenarios, this report harmonises the scope based on the method described in the Annex 3)			
			Geographical	**Temporal**	**Sectoral**	**Emissions**
International Energy Agency	Energy Technology Perspectives (2017)	4 technology-rich models: optimisation model energy supply (ETP-TIMES), industry, mobility and buildings	Global, public results on 11 sub-regions, including EU28 (the framework covers 28 to 39 regions depending on the sector)	5-year time step, up to 2060	Power Industry Transport Residential Services Other	Energy-related and process CO_2 (incl. international aviation)
International Energy Agency	World Energy Outlook (2018)	World Energy Model (WEM), a large-scale simulation model consisted of three main modules (final energy consumption, energy transformation and energy supply)	Global, public results on 21 regions, including the EU28 (model has 25 sub-regions)	Annual steps up to 2040	Power Industry Buildings Transport Other (agriculture and other)	Energy-related (incl. international aviation at global level) and process CO_2
International Renewable Energy Agency	Global Energy Transformation (2019)	Bottom-up excel-based tool as a dynamic accounting framework that creates and evaluates energy system developments and costs at sector and technology level	70 countries (and their regional aggregations) covering 90% of global energy demand, including EU28	2030, 2040 and 2050	Power Industry Buildings Transport	Energy-related (excl. international aviation)
Joint Research Centre	Global Energy and Climate Outlook (2018)	POLES-JRC, partial equilibrium simulation model on energy system and GHG forecasting and the computable general equilibrium model RC-GEM-E3 on the economic impacts of the developed scenarios	Global, 66 countries/regions including the EU28	Annual steps, up to 2050/70	Power Industry Buildings Transport Agriculture Other	Energy-related and process CO_2 (incl. international aviation at global level), LULUCF and non-CO_2

Organisation	Study	Method/model	Scope (to compare the scenarios, this report harmonises the scope based on the method described in the Annex 3)			
			Geographical	**Temporal**	**Sectoral**	**Emissions**
Joint Research Centre	Low Carbon Energy Observatory (2019)	JRC-EU-TIMES, partial equilibrium optimisation model for the energy system	EU28, country level (and neighbouring countries)	Gradually increasing from 2 to 10 years up to 2050	Power Industry Residential Services Transport Agriculture	Energy-related and process CO_2 (incl. international aviation)
Navigant	Gas for Climate (2019)	Navigant Energy System Model, a cost-optimisation model built using Analytica software with various dedicated modules on renewable and low-carbon gas supply, end-use sectors, power transformation and infrastructure	EU28	Results only for 2050	Power, Industry (steel, ammonia and methanol production), Buildings (heating), Transport (passenger cars, freight trucks, buses, ships and aircrafts)	Energy-related and process CO_2 (incl. international aviation)
Oeko Institut	The Vision Scenario for the European Union (2017)	Top-down analysis of energy consumption and GHG emission dynamics for final energy, process CO_2 emissions, and non-CO_2 emissions (except transport). Bottom-up analysis for power and transport. Oeko Institute uses the ELIAS (in-house lowest capital cost model for the power sector) combined with the PowerFlex electricity market model. Unclear if they were also used in the 2017 exercise. Economic optimisation on a qualitative basis (not based on analytical modelling)	EU28	2030, 2040 and 2050	Power Industry Residential Transport Tertiary	Energy-related and process CO_2 (incl. international aviation) and non-CO_2

Organisation	Study	Method/model	Scope (to compare the scenarios, this report harmonises the scope based on the method described in the Annex 3)			
			Geographical	Temporal	Sectoral	Emissions
Sven Teske et al.	Achieving the Paris Climate Agreement Goals (2019)	GQW (non-CO_2 GHG statistical analysis) MAGICC (climate change) TRAEM (transport) EM (simulation energy system) [R]E 24/7 (power system balancing) [R]E SPAVE (regional wind and solar potential) Land-based sequestration design (Monte Carlo carbon sequestration) No cost-optimisation objective functions	Global, 10 main sub-regions, including OECD Europe (energy system model)	Up to 2050	Power Industry Residential and other (aggregated) Transport	Energy-related CO_2 (incl. international aviation at global level), LULUCF and non-CO_2
WindEurope	Breaking New Ground (2018)	DNV GL ETO system-dynamics feedback model (based on Stella)	EU28 plus Iceland, Liechtenstein and Norway	Up to 2050	Power Industry Residential Services Transport Other	Energy-related CO_2 (incl. international aviation)

Annex 2. Macro-economic assumptions in energy scenarios

Figure 32 Gross Domestic Product (left) and population (right) in energy scenarios that meet the mid-term ambition and long-term vision for emission reduction in the EU28



Note: GDP corresponding to annual growth rates between 1.4% and 1.7%. Sectoral GDP may differ. *Source*: JRC.

Annex 3. Definitions and harmonisation approach of scenario results

1. Definitions used in the report

This report applies the new Eurostat methodology, disseminated in January 2019 [12], with the exception of Box 1 (see Annex 3.2, below). Specifically:

Gross inland consumption is the total energy demand of the EU region. It represents the quantity of energy necessary to satisfy inland consumption of the EU. It covers consumption by the energy sector itself, distribution and transformation losses, final energy consumption by end users and statistical differences. This new methodology is consistently applied in Section 4 which, different from the old methodology, includes now ambient heat for heat pumps. Similar to the old methodology, international maritime bunkers are excluded.

Final energy consumption. According to the new Eurostat methodology, it includes the final energy consumed by end-use sectors (industry, transport and other). As such, it explicitly excludes international aviation and marine bunkers, and it includes ambient heat from heat pumps. In the present report, this definition is used consistently (Section 6).

2. Definitions used in Box 1

To compare with the EU targets for 2030 on energy efficiency and share of renewable energy on gross final consumption of energy, the previous version of Eurostat methodology, which was in place at the time the targets were established, was applied. Specifically:

Gross inland consumption (2020-2030). In the old Eurostat methodology, gross inland consumption does not include international maritime bunkers and ambient heat from heat pumps (for 2017 the latter flow is negligible).

$$\begin{aligned}
&\textit{Gross inland cosumption}\ (\textit{Europe}\ 2020\text{-}2030)\\
&\qquad = \textit{Gross available energy}\ [\textit{All products total}]\\
&\qquad - \textit{Gross available energy}\ [\textit{Ambient heat}\ (\textit{heat pumps})]\\
&\qquad - \textit{International maritime bunkers}\ [\textit{All products total}]
\end{aligned}$$

Final energy consumption (2020-2030). Is defined as final energy consumption by end-use sectors, including international aviation but excluding maritime bunkers and ambient heat from heat pumps, as below:

Final energy consumption (Europe 2020-2030) [All products total] =
+ Final energy consumption [All products total]
– Final energy consumption [Ambient heat (heat pumps)]
+ International aviation [All products total]
+ Transformation input Blast furnaces [All products total]
– Transformation output Blast furnaces [All products total]
+ Energy sector Blast furnaces [Solid fossil fuels]
+ Energy sector Blast furnaces [Manufactured gases]
+ Energy sector Blast furnaces [Peat and peat products]
+ Energy sector Blast furnaces [Oil shale and oil sands]
+ Energy sector Blast furnaces [Oil and petroleum products]
+ Energy sector Blast furnaces [Natural gas]

Primary energy consumption (2020-2030) is used in line with the definition in Article 2 of the Directive 2012/27/EU and can be used to assess the Directive and Europe 2020 targets, as well as tracking the progress towards Europe 2030 targets. According to the definition of the old methodology, primary energy includes gross inland consumption excluding final non-energy consumption. In the present report, primary energy consumption, complies with the formula:

$$\begin{aligned}
&\textit{Primary energy consumption}\ (\textit{Europe}\ 2020\text{-}2030)\\
&\qquad = \textit{Gross inland consumption}\ (2020\text{-}2030) - \textit{Final non-energy consumption}
\end{aligned}$$

In the present report, primary energy consumption is used in order to provide an indication on the progress that could be anticipated with respect to the energy efficiency targets for 2030 based on energy scenarios of organisations other than the EC.

Gross final consumption of energy. This definition is used to estimate the share of renewable energy in gross final consumption for 2030 in Box 1 is defined in line with the revised Renewable Energy Directive 2018/2001/EU [48]:

$$Gross\ final\ consumption\ of\ energy\ (GFCoE) = Final\ energy\ (2020\text{-}2030)$$
$$+\ the\ consumption\ of\ electricity\ and\ heat\ by\ the\ energy\ branch\ for\ electricity$$
$$,heat\ and\ transport\ fuel\ production$$
$$+\ losses\ of\ electricity\ and\ heat\ in\ distribution\ and\ transmission\ +\ ambient\ heat$$

3. Harmonisation of sectoral boundaries of energy scenario results

Non-energy use. In 2017, non-energy use in the EU28 reached 102 Mtoe, of which 85 Mtoe were oil and 17 Mtoe non-oil carriers (mostly natural gas). This split is used to distribute non-energy use in scenarios that do not report a full breakdown of fuels used for non-energy applications (IEA WEO, IEA ETP, JRC GECO and WindEurope). One scenario (IRENA GET) aggregates non-energy use with total primary energy supply (similar to gross inland consumption), while other scenarios exclude it from their reported figures in gross inland consumption (Oeko, Navigant, Eurelectric). In the latter case, to harmonise total gross inland consumption across scenarios, non-energy use is assumed to equal Eurostat values for 2017, which are comparable to the EC LTS values for 2050.

Table 6 Data availability of non-energy use in energy scenarios

	Euro-stat	Eur-electric	ECF	EC LTS	IEA ETP	IEA WEO	IRENA GET	JRC GECO	LCEO Zero Carbon	Navi-gant	Oeko	IFS	Wind Europe
Oil		/			/		/	/		/	/		/
Non-oil		/			/	/	/	/		/	/		/
Total		/				/	/			/	/		

Source: JRC.

Aviation and marine bunker fuels are not consistently accounted across energy scenarios for the EU28, whether in total energy consumption of the energy system, final energy use in transport or gross inland consumption. In 2017, 96 Mtoe of fuels were in bunkers for international aviation and the maritime sector (in roughly equal shares), while 327 Mtoe were domestically consumed for transport (road, rail, inland navigation and domestic aviation). Bunker fuels represent more than 20% of the total transport fuel demand. To put this into perspective, inland navigation and domestic together accounted for less than 3% of total energy for transport. When scenario projections are not aligned to the definitions used in this report and data are not available from the original source (Table 7), then aviation and marine fuels are harmonised assuming their absolute Eurostat values in 2017 for 2030, and their 2017 share in the total for 2050.

Table 7 Data availability on aviation and marine bunker fuels in energy scenarios

	Euro-stat	Eur-electric	ECF	EC LTS	IEA ETP	IEA WEO	IRENA GET	JRC GECO	LCEO Zero Carbon	Navi-gant	Oeko	IFS	Wind Europe
International aviation bunkers		/			/	/	/	/		/	/		/
International marine bunkers		/			/	/	/	/		/	/		/
Total bunker fuels		/			/	/	/			/	/		/

Note: In their scope of energy balances, Eurelectric, IEA ETP, Navigant and WindEurope aggregate international bunker fuels with the total reported energy balance but do not provide decomposition. Oeko aggregates international aviation bunker fuels in its total energy balance but does not provide decomposition. *Source*: JRC.

Ambient heat. In 2017, the ambient heat used by heat pumps reached 11 Mtoe, three times as much as 2007. The majority of scenarios report ambient heat used by heat pumps. For 4 scenarios, ambient heat is derived indirectly from other available data:

- For EC LTS 1.5Life and 1.5Tech, it is derived from Figures 39 and 43 assuming that new electricity for space heating in buildings is based only on heat pumps and not, for example, on electric resistors;
- For IEA WEO SDS, ambient heat in 2030 is assumed to be a factor 3 higher compared to 2017, as an explicitly stated requirement in the original source to be in line with the IEA WEO SDS scenario;
- For Oeko Vision, the ambient heat for 2030 is estimated based on following statement in the report: "if ambient heat used with heat pumps is included in the accounting approach, the share in 2030 would increase by approx. 2 percentage points".

For scenarios with data, ambient heat amounts to between 35 and 65 Mtoe. For scenarios without data, the average of all other scenarios is used, amounting to 24 Mtoe in 2030 and 46 Mtoe in 2050. Data availability on ambient heat in energy scenarios is described in Table 8.

Table 8 Data availability of ambient heat in energy scenarios

	Euro-stat	Eur-electric	ECF	EC LTS	IEA ETP	IEA WEO	IRENA GET	JRC GECO	LCEO Zero Carbon	Navi-gant	Oeko	IFS	Wind Europe
Ambient heat used by heat pumps				*Indirect*	/	*Indirect*	/				*Indirect*		/

Source: JRC.

Regional scope. Two studies (namely, Eurelectric and WindEurope) have EEA as geographical coverage (EU28 and the 3 EEA countries, Iceland, Liechtenstein and Norway) (Table 5). Results from these scenarios are harmonised for each sector separately, assuming the 2017 share of the EU28 within EEA, based on the IEA World Energy Balances [49]. One study, namely Teske et al. 2019 (the 2 IFS scenarios) has OECD Europe as its geographical scope. The results from this study are harmonised separately for each sector, assuming the 2017 share of the EU28 in OECD Europe, based on the IEA World Energy Balances [49]. Note that IFS scenarios are used only for 2050. For the scope of this report, and in line of the overall uncertainty in the long term, the implications that may arise specifically from the different economic structure between the EU28 and OECD Europe are considered less relevant.

4. Estimation of the emission reduction by ETS and non-ETS sectors by 2030

The estimates of emission reduction by ETS and non-ETS sectors by 2030 is based on 6 scenarios (out of the total 8 that reach 52% to 56% emission reduction by 2030), namely ECF Demand-focus, ECF Shared effort, IEA ETP 2DS, IEA WEO SDS, LCEO Zero Carbon, and Oeko Vision. Based on the availability and granularity of results in these scenarios, the distribution of the emission reduction effort between ETS and non-ETS sectors is not as straightforward. EU ETS covers all GHG emissions, however, most scenarios report only on energy-related CO_2 emissions (Table 5). Moreover, most energy scenarios do not cover all non-ETS sectors (but mainly transport, buildings and services).

The assessment presented in this report relies on the following assumptions:

- Emissions by *ETS sectors* are estimated by deducting from energy-related and process CO_2 the CO_2 emissions of non-ETS sectors. Specifically for international aviation (domestic, intra-EU and extra-EU), 5 out of the 6 scenarios include international aviation in their reporting of CO_2 emissions. Only IEA WEO SDS does not include them, and for this scenario CO_2 emissions from international aviation in IEA ETP 2DS are assumed. As such, the scope of ETS sectors in all scenarios for 2030 includes emissions from domestic, intra- and extra-EU aviation. Non-CO_2 emissions are not taken into account from the estimated reduction achieved by ETS sectors.
- Emissions by *non-ETS sectors* (agriculture, buildings, transport excluding aviation, industry and energy supply, product use and waste) are estimated as follows:

- CO_2 emissions:
  - by buildings and transport, as reported in the studies;
  - in agriculture, if not reported, then they are derived from fossil energy use based on Eurostat balances for 2017 and fuel emission factors (amounting to 57 $MtCO_2$) [11];
  - for industry (excluding ETS), energy supply and product use, the reduction is assumed to be proportional to that of the other sectors;
  - from waste, they are typically not reported in other scenarios, and therefore the reduction achieved in EC LTS is assumed [20];
- Non-CO_2 emissions, if not directly reported in the energy scenarios then the emission reduction reported in EC LTS is assumed [20].

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