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Authors: Maria Papadopoulou[1], Roberto Passalacqua[2], Domenico Rossetti di Valdalbero[3], Elena Righi Steele[4]

Affiliations: European Commission, Directorate-General for Research and Innovation, Euratom Research, CDMA, B-1049 Brussels, Belgium[1]

Orcid ids: 0000-0003-4914-8383[1]

Contact e-mail: papmara@gmail.com

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Preprint statement: This article is a preprint and has not been peer-reviewed, under consideration and submitted to UCL Open: Environment Preprint for open peer review.

Links to data: No new data were generated and all data analyzed were downloaded from public sources and all references are indicated in the paper.

DOI: 10.14324/111.444/000110.v1

Preprint first posted online: 13 December 2021

Keywords: EU Green Deal, Electrification, Decarbonisation scenarios, Nuclear energy, Socio-economic costs, EU energy policy, Energy system costs, Power sector, Systems modelling, Energy and policy, Energy and climate, Climate change

Decarbonising the EU Power Sector: a Technological and Socio-economic Analysis and the Role of Nuclear

Maria Papadopoulou,* Roberto Passalacqua, Domenico Rossetti di Valdalbero, Elena Righi Steele

* Corresponding author: European Commission, 1049 Brussels, Belgium - Tel. +32 229-62228, Maria.PAPADOPOULOU11@ec.europa.eu.

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Abstract

Low-carbon electricity is a key enabler in combating climate change. Decarbonising the power sector is now at the centre of global and European policies. As the IPCC highlights, pathways where the power sector rapidly decarbonises by 2030 have higher chances of keeping global warming below 1.5°C. The electricity sector should be fully decarbonised by 2050 to meet either the 1.5°C or 2°C targets. This means that EU policy efforts should focus on supporting a maximum reduction of emissions per unit of electricity by 2030 and net-zero emissions by 2050. Reaching these targets is one of the most pressing questions EU policymakers face today. In light of the COVID-19 crisis, EU policies should guide a cost-effective, reliable and environmentally sound transition of the power sector, benefiting EU research and innovation and its citizens. This meta-analysis provides a novel view on historical data and compares data from modelling scenarios identified in the literature. It assesses the current and future role of nuclear energy in decarbonizing the EU power sector, while reviewing socio-economic implications that could arise if limited public support nearly excludes nuclear fission electricity from the future EU power mix. This work highlights relevant socio-economic policy implications and actionable policy recommendations.

Keywords: EU energy policy; Electrification; power sector decarbonisation; Nuclear energy; Socio-economic costs

1 Introduction

Low-carbon electricity has been recognised as a key enabler to support efforts to combat climate change. As the Intergovernmental Panel on Climate Change (IPCC) highlights, pathways where the power sector shows rapid decarbonisation by 2030 have higher chances of keeping global warming below 1.5°C. Furthermore, the sector would need to be essentially fully decarbonised by 2050 so as to meet either the 1.5°C or 2°C targets. As result, decarbonising the power sector is now at the centre of global and European policies. This means that the EU policy efforts should focus on supporting a maximum reduction of emissions per unit of electricity already by 2030 and a net-zero emissions per unit of electricity by 2050. Reaching these targets has become one of the most-pressing questions that EU policymakers face today and in-light for the COVID-19 crisis it is imminent that policies guide a cost-effective, reliable and environmentally-sound transition of the power sector, bringing an added value to EU research and innovation and its citizens.

This work aims to complement the understanding of the policy implications of the EU energy and climate policy framework by highlighting possible emerging economic, social and environmental aspects while focusing on the growing importance of the mid- and long-term decarbonisation targets of the EU power sector. It provides a novel view of past and future decarbonisation efforts in the EU, through a meta-analysis of historical data (i.e. Eurostat, UNFCCC, World Bank, Eurostat, EEA), and a comparison of modelling data from scenarios identified in literature (i.e. the EC 2030 and 2050 scenarios and technical reports, IPCC, OECD, EC communications, scientific papers). The results shed light on the central role of electricity in decarbonising the EU economy and the contribution of nuclear power as a low-carbon energy source, while identifying relevant socio-economic policy implications and supporting actionable policy recommendations.

After the literature review (section 2), Section 3 describes the modelling scenarios and data sources analysed in this work. The results of the analysis of the EU historical trends to date are presented in the next section (Section 4), focusing on the dimensions of energy security, emissions and decarbonisation costs. Possible medium- and long-term implications are then analysed and compared along these dimensions for policy pathways where nuclear power could have a less, or more prominent role in the provision of electricity in the EU (Section 5). Additional socio-economic implications that could emerge with respect to the full-system costs of electricity generation technologies are discussed in the following section (Section 6). The main conclusions and relevant policy recommendations that are drawn from this analysis are summarised in Section 7.

2 Literature Review

The Paris Agreement¹ represents the global effort to mitigate and adapt to climate change with a central aim to keep global warming this century well below 2°C above pre-industrial levels, while pursuing efforts to limit warming to 1.5°C. A recent IPCC report has however revealed that the current post-2020 pledges of the signatories deviate from the 2°C-consistent pathways and are broadly aligned with a warming of about 3°C by 2100 (Intergovernmental Panel on Climate Change, 2018) and a potential global emissions peak at 51 GtCO₂e/year as early as 2025 (Kitous et al., 2017). More importantly, the report states that if the 2030 global emissions estimated under the current pathways are reached, limiting warming to 1.5°C would not be possible thereafter, even with additional steeper emissions reductions. Global emissions should start declining well before 2030 in order to avoid overshoot. Delayed action risks cost escalation, lock-in carbon-emitting infrastructure, stranded assets, and reduced flexibility in the long-term response options (Capros et al., 2014; European Commission, 2018). This message is especially important for the European Union (EU), where future dependence on large-scale deployment of carbon capture and storage (CCS) technologies whose cost-effectiveness is yet to be demonstrated at commercial scale (European Court of Auditors, 2018).

The IPCC report further highlights that pathways with higher chances of keeping warming this century to below 1.5°C show a rapid decarbonisation of the power sector by 2030 and around mid-century the sector should be fully decarbonised to meet either the 1.5°C or the 2°C target (Intergovernmental Panel on Climate Change, 2018). Consequently, this means that the EU should target a net-zero emissions

¹ Adopted December 12, 2015 and entered into force November 4, 2016:
https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.

electricity by 2050 and at the same time prioritise efforts to maximize the sector's emissions reduction by 2030. Reaching these targets has become one of the most-pressing questions that EU policymakers face today and in-light of the COVID-19 crisis, it is imminent that policies guide a cost-effective, reliable, energy-efficient and environmentally-sound transition of the power sector, bringing an added value to research and innovation and society at large.

To date, the EU has set some of the most ambitious energy and climate policy frameworks (European Commission, 2016a) and aims to commit to climate-neutrality by 2050 (European Commission, 2020), an objective that is at the heart of the EU Green Deal (European Commission, 2019a). The European Commission (EC) has therefore developed a set of medium- and long-term scenarios to allow policy makers to assess the potential medium- and long-term impacts of the current policy framework and assess policy proposals for achieving the EU's climate and energy targets for 2030 and 2050 (Capros et al., 2016; E3MLab, 2019; E3MLab and IIASA, 2016). However, aside from these technical reports, there exists no in-depth analysis of the economic, energy and environmental impacts of the EC medium-term scenarios. In addition, there is no analysis that compares the EC medium-term scenario projections to the EU's historical trends to date.

On the contrary, there exist comprehensive socio-economic analyses (including investment needs and energy-system costs and prices) for the long-term projections under the current EU policy framework reflecting specific policy pathways (Capros et al., 2016, 2014; European Commission, 2018; Knopf et al., 2015). However, the assumptions and boundary conditions of both the medium- and long-term EC scenarios reflect technology-specific energy and climate targets and consider particular policy incentives for renewable energy sources (RES), such as feed-in tariffs or green certificates, which can influence the interplay of technologies in the modelling and in turn the cost-effectiveness of the resulting power-mix.

It has been shown that policy routes designed to achieve a cost-effective medium- and long-term decarbonisation of the EU power sector while supporting less technology-specific targets and excluding RES policy incentives, would yield substantially different EU power-generation mixes (Simoes et al., 2017). The study found that policy routes where social acceptance for nuclear electricity was assumed higher have the highest impact on the cost-effectiveness of decarbonising the EU power. In addition, policy routes that assume a higher potential for solar and wind power generation were found to have the second highest impact on decarbonising the EU power-mix. However, as the authors discuss, these policies depend on increasing the number of available RES sites and improving the reliability of transmission and distribution. These imply that there exist socio-economic aspects and policy incentives with an exogenous influence on the cost-effectiveness of the EU power sector decarbonisation pathways that have implications for the role of nuclear power and warrant further investigation.

In addition, socio-economic externalities (European Commission, 2003), such as those related to human health-related impacts (cf. toxicity or accidents), the availability of land, public acceptance, or the competitiveness of local power generation, are not fully captured by modelling scenarios.² Many studies have highlighted that wide and contrasting estimates exist for electricity generation costs for the various technologies due to the inconsistent usage of terms and the differences in the assessed cost elements (Bustreo et al., 2017; D'haeseleer, 2013; NEA, 2018). These inconsistencies prevent a coherent

² It should be noted that macro-economic modelling was also undertaken to estimate the impacts of the scenarios on GDP growth and jobs (E3MLab, 2016; Lewney et al., 2017).

comparison of the decarbonisation technologies which as a result could over- or under-estimate the efficiency of the EU power system in terms of cost, environmental and social performance, as well as its flexibility, reliability and resilience.

3 Modelling Scenarios and Data

The analysis of the historical trends of decarbonisation and energy transformation to date in the EU (Section 4) is based on data retrieved from the official databases of Eurostat, European Commission, United Nations, World Bank, International Energy Agency and Potsdam Institute for Climate Impact Research (European Commission, Directorate-General for Energy, 2020; Eurostat, 2020; Gütschow, et al., 2019; International Energy Agency, Organisation for Economic Co-operation and Development, 2020; United Nations, Department of Economic and Social Affairs, Population Division, 2019; World Bank, 2020). The data that were collected were energy consumption, Gross Domestic Product (GDP), emissions and net-imports across energy fuels³ and sectors. In order to maintain data consistency and be in-line with the EU policy framework, the period of analysis that was selected was 1990 to 2017, with a one-year step, across the EU-28 member states⁴. Complementary data on electricity prices and costs are derived from official EC documents and supported studies (European Commission, 2019b, 2016b)(Rademaekers et al., 2018).

The different EU28 medium- (by 2030) and long-term (by 2050) decarbonisation scenarios were analysed with data collected from published EC modelling studies (E3MLab, 2019; E3MLab and IIASA, 2016; European Commission, 2019c). These scenarios represent trend projections⁵, with the EU Reference Scenario 2016 (REF2016) acting as a benchmark of policy and market trends against which several policy proposals were assessed. This scenario has the longest modelling horizon, up to 2050, with projections starting in 2015 using a 5-year-step, while assuming that the legally binding targets of the 2020 Climate and Energy Package are achieved and that the EU and Member State policies agreed until December 2015⁶ are implemented (Capros et al., 2016).

The seven mid-term scenarios (2030) analysed that include additional policies and incentives across all Member States are as follows (E3MLab, 2019; E3MLab and IIASA, 2016):

- The EUCO27 and the EUCO30 target an at least 40% reduction in GHG emissions compared to 1990, with a 27% RES share in final energy use and a 27% and 30% energy efficiency target respectively (compared to 2007).

³ Based on Eurostat terminology: <https://ec.europa.eu/eurostat/web/energy/data>.

⁴ At the time of the analysis and for the chosen data period, the United Kingdom is one of the EU Member States.

⁵ Trend projections that represent hypothetical, “what-if” scenarios, as a set of assumptions are made to address several unknowns ranging from population growth, macroeconomic and fossil fuel price developments, technology improvements, as well as the degree of policy implementation across the EU. On the contrary, forecasts would represent best estimates of future results and the most-likely scenario assumptions.

⁶ Include the legally binding 2020 targets and EU legislation, the EU Emissions Trading System Directive (including the Market Stability Reserve), the Energy Performance of Buildings Directive, Regulations on eco-design and on CO₂ emission standards for cars and vans, as well as the revised F-gas (i.e. fluorinated greenhouse gases) Regulation. It also takes into consideration the Member States’ explicit phase-out policies and ongoing projects at the time of modelling but does not incorporate the, at the time, politically agreed but not legally adopted, 2030 climate and energy targets.

- The EUCO3030 and the three EUCO+ scenarios built on the EUCO30 to assess the potential impacts of more ambitious targets: EUCO3030 assesses a higher penetration of renewable energy of 30%, hence achieving a 43% GHG emissions reduction and the EUCO+33, EUCO+35 and EUCO+40 explore more ambitious energy efficiency targets of 33%, 35% and 40% respectively with a 28% RES share, thus reaching a GHG emissions reduction between 43% and 47%.
- The EUCO3232.5 is the most recent scenario that assess a raised 2030 target of energy efficiency to 32.5% and a RES share of 32%, as agreed in the ‘Clean energy for all Europeans package’, thus reaching one of the highest reductions in GHG emissions of 46%.

The eight long-term scenarios analysed are considered comparable to the EUCO3232.5, because they were developed based on a “Baseline” policy framework keeping pre-2015 Member States policies of the REF2016, but updating the technology pathways (De Vita et al., 2018) and projecting the achievement of the 2030 energy and climate targets (European Commission, 2018):

- Five scenarios target an 80% reduction of GHG emissions by 2050, of which **Electrification (ELEC)**, **Hydrogen (H2)** and **E-fuels (P2X)** focus on switching fossil fuels to zero/carbon-neutral energy resources, whereas the **Energy Efficiency (EE)** explores more ambitious energy savings measures and the **Circular Economy (CIRC)** a transition to a circular economy.
- The **Combo** scenario, combines the above five scenarios without any predefined emissions reduction target for 2050, thus achieving close to 90% reduction in emissions by 2050.
- The **1.5TECH** and **1.5LIFE** scenarios target net-zero GHG emissions by 2050 (including land-use, land-use change and forestry), with the former relying more heavily on the intensification of the above technologies including the deployment of carbon-capture and storage technologies whereas the latter relies less on technological options and more on sustainable lifestyle changes e.g. increased climate awareness, carbon intensive diets, limiting growth of air transport demand etc.

As highlighted in the literature review, the above EC scenarios reflect technology-specific energy and climate targets and consider particular policy incentives for renewable energy sources (RES), which influences the interplay of technologies in the power-mix and impacts the cost-effective decarbonisation of the EU power-system. To explore such implications, the EC scenario data are complemented with data from a recent modelling study that assessed the role of nuclear power in the EU power mix (FTI Consulting, 2018).⁷ The study’s modelling scenarios were based on the 2050 decarbonisation targets of the ‘Clean energy for all Europeans package’ 2030 targets of at least 40% and 85% reduction in GHG emissions by 2030 and 2050 respectively, compared to 1990, which are similar to the EUCO33 scenario. The modelling data from two nuclear capacity scenarios by 2050 that reflect policy pathways of low and high social acceptance for nuclear power are selected and analysed both in the mid- and long-term:

- a) **the low nuclear capacity scenario** represents a case where most of the existing plants close without further extensions and new projects fail to conclude, resulting in 36 GW of nuclear installed capacity by 2050;

⁷ Assumes technology improvements based on the EC reference assumptions on electricity costs and performances, capital and operational expenditure based on latest data from EC and E3M, fuel commodity prices from IEA World Energy Outlook 2017, the CO₂ EUA to converge to EUCO33 by 2025 and EUCO30 by 2030/5, as well as outlook for new and existing Interconnections from the ENTSOE TYNDO 2018 Outlook.

- b) **high nuclear capacity scenario**, models long-term operation extensions and building new plants in line with current advanced projects, as well as considers the commissioning of a number of additional plants (including about 5GW of SMR and <1GW of Gen-IV) that replace thermal baseload power plants, resulting in 150 GW of nuclear installed capacity by 2050.

4 Analysis of the EU Decarbonisation and Energy Transformation Trends

Emissions, Energy Consumption and Import Dependency in the EU

As illustrated in Figure 1, in contrast with worldwide trends, the EU economy has already started to modernise and transform, having experienced a growth of over 60% since 1990, while reducing by 23% its greenhouse gas (GHG) emissions. However, the strongest reduction in emissions coincided with the period of 2007-2014 of the global financial and eurozone crises and from 2014 annual emissions have remained relatively constant. Furthermore, decoupling energy use and economic growth has shown to be a greater challenge. Since 1990, annual energy consumption has mostly displayed an upward trend, except again the period coinciding with the financial crises. In addition, looking at the four sectors responsible for over 95% of EU's final energy use (Figure 2) reveals only industry has reduced its final energy use (-23%) since 1990, while in the same period transport and services increased by 1.3 times their overall energy use and households marginally by +3.4%. Similarly, as of 2014, energy consumption has been experiencing an upward trend in all sectors, except the residential one.

Figure 3 clearly shows that EU's import dependency has been mostly rising with the EU turning into a net-energy importer in the early 2000s and a dependency of nearly 56 % in 2017. From the figure it can be drawn that this trend is linked to the increase in natural gas dependency, as net imports of natural gas have more than doubled since 1990 and consumption increased by 32%.⁸

⁸ Taking into consideration that both oil and petroleum as well as solid fossil fuel net-imports remained at close to 1990 levels but their consumption dropped.

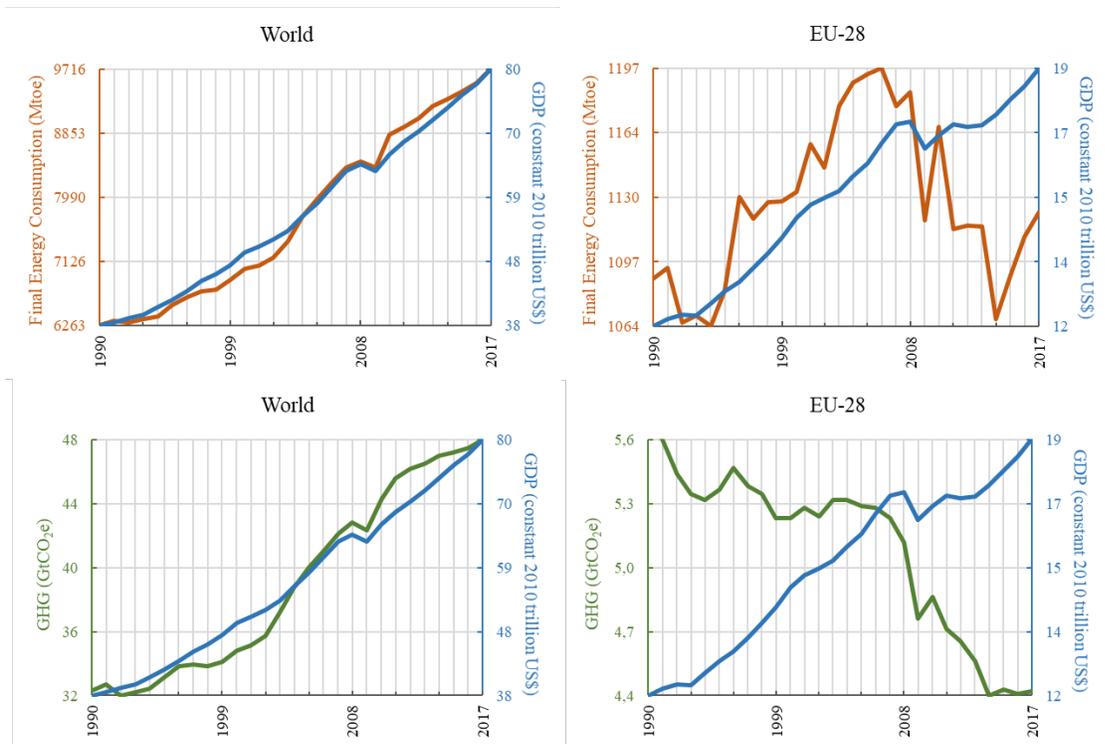


Figure 1: The global and EU28 annual change of energy consumption and GHG emissions compared to GDP growth for the period of 1990 to 2017 [based on data for GDP (World Bank, 2020), for emissions (Gütschow, et al., 2019) and for energy consumption (Eurostat, 2020; International Energy Agency, Organisation for Economic Co-operation and Development, 2020)]

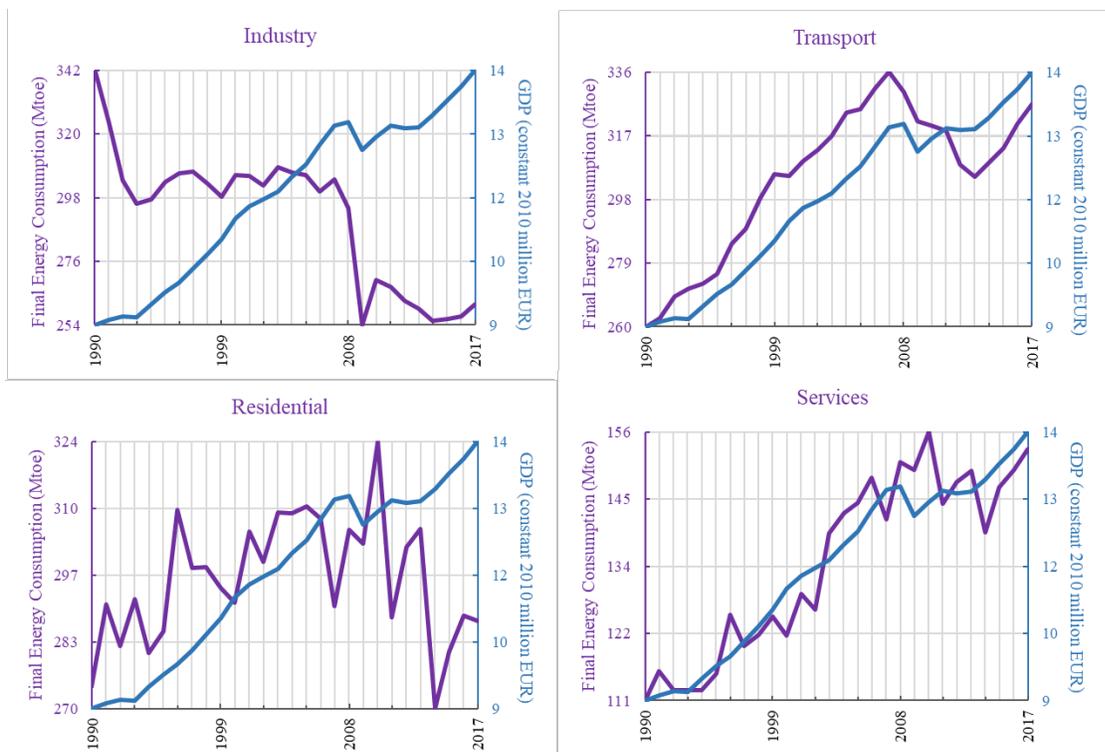


Figure 2: The EU28 annual change in final energy consumption and GDP by sector between 1990 and 2017 [based on data for GDP (World Bank, 2020), and for energy consumption (European Commission, Directorate-General for Energy, 2020)]

Electrification and the Role of Nuclear

Since 1990, the shares of electricity, natural gas and renewable heat & biofuels in the final energy use have increased, whereas those of fossil fuels decreased (Figure 4). Electricity is now the second most important energy fuel,³ together with natural gas. Electricity has also experienced the second-highest growth during this period (after renewable heat & biofuels) as a result of its increased use in the industry and buildings (Figure 5), indicating the strong electrification of these two sectors. The industry sector was also the only sector that experienced a large drop in GHG emissions compared to 1990⁹ (Figure 6), yet it is still the largest contributor of GHGs emissions (50%), with the majority attributed to electricity and heat production activities.

The decarbonisation of electricity has been slower than the decarbonisation of manufacturing and construction and the decarbonisation of fuel and petroleum refinement, despite electricity being increasingly generated by low-carbon technologies, with shares up to 56% in 2017, compared to 43% in 1990 (Figure 7). Nuclear technologies remain the most important source of low-carbon electricity, contributing almost half of it (45%) and accounting for only 11% of the total installed power capacity. The remaining half of low-carbon electricity is generated by RES that add-up to four times the installed capacity of nuclear power. Looking at the overall trends between 1990 and 2017, the shares of installed capacity of low-carbon generation technologies increased by 136%, owed, almost entirely, to new wind and solar power capacities (Table 1), yet the generation of low-carbon electricity increased by just 65%. This can be explained by variable and intermittent power generation by RES (i.e. solar and wind) which is highly depended on climate-related conditions. According to the data, the installed solar and wind capacities together with hydropower, operated 1/3 to 1/6 of the time compared to nuclear and the remaining time were idle.¹⁰ As a result, the above translate to a smaller production of decarbonised electricity per area (i.e. the installed capacity representing a proxy of the area required) and represent a possibly higher underutilisation of facilities and hence investments.

⁹ Referring to the GHG emissions resulting from the combustion of fossil fuels, which comprise $\frac{3}{4}$ of EU's GHG emissions. They include the GHG emissions from international aviation but exclude those from land use, land-use change, and forestry (LULUCF), as well as from international maritime

¹⁰ It should be noted that the operation of dispatchable power plants, and hence their capacity factors (also called load factors), can be further constrained by market forces, as the distribution system operator might give priority to generating installations using renewable energy sources, waste or CHP, according to Regulation (EU) 2019/943 (European Parliament and Council of the European Union, 2019). Among the typical dispatchable generating plants are natural gas and hydro, while nuclear and coal-fired plants are theoretically dispatchable yet designed as baseload plants.

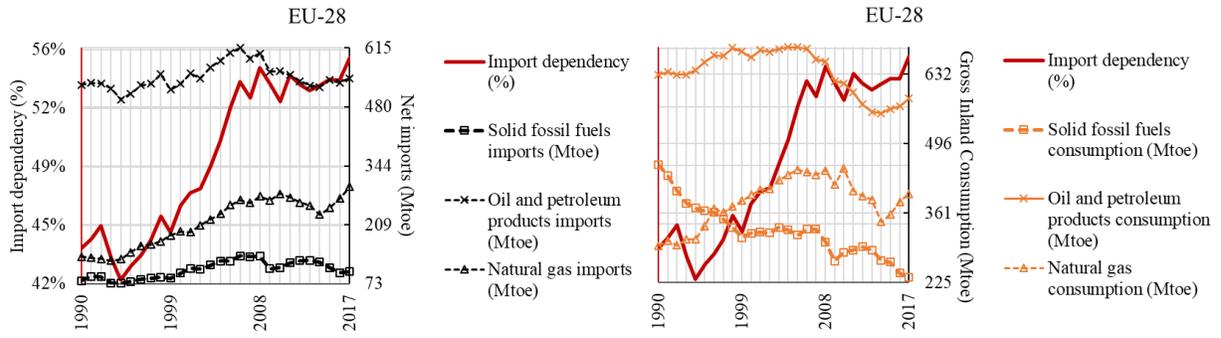


Figure 3: The EU28 annual change in import dependency compared to the net imports (left) and gross inland consumption (right) by energy source between 1990 and 2017 [estimated based on data from (European Commission, Directorate-General for Energy, 2020)]

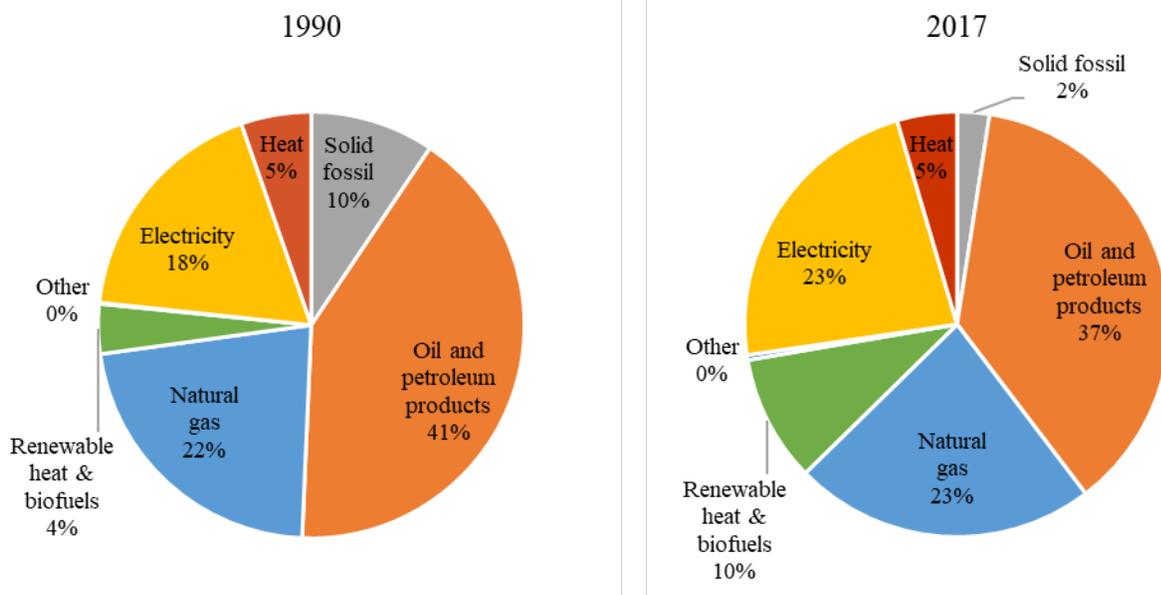


Figure 4: Comparison of the 1990 and 2017 shares (%) of energy fuels (i.e. resources and carriers) in the total final energy consumption of the EU28 [estimated based on data from (European Commission, Directorate-General for Energy, 2020)]

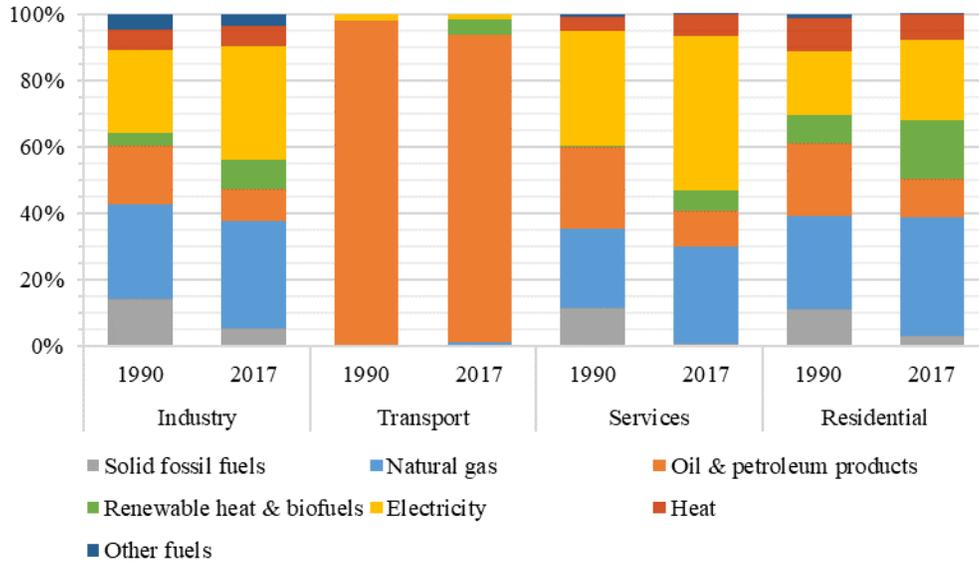


Figure 5: Comparison of the EU28 sectoral shares (%) of final energy consumption between 1990 and 2017 by fuel type [based on data from (Eurostat, 2020)]

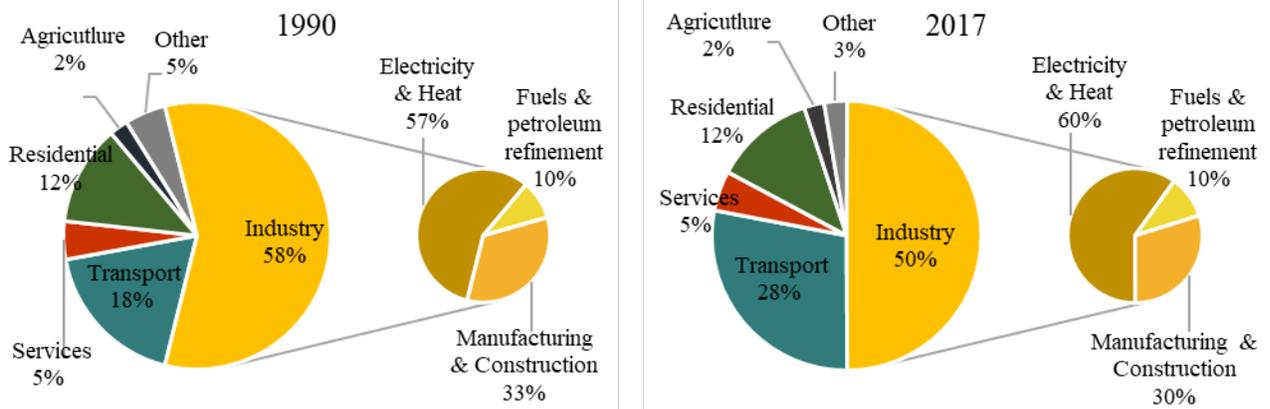


Figure 6: Comparison of the 1990 and 2017 sectoral shares (%) of GHG emissions in the EU28 [estimated based on data from (European Commission, Directorate-General for Energy, 2020)]

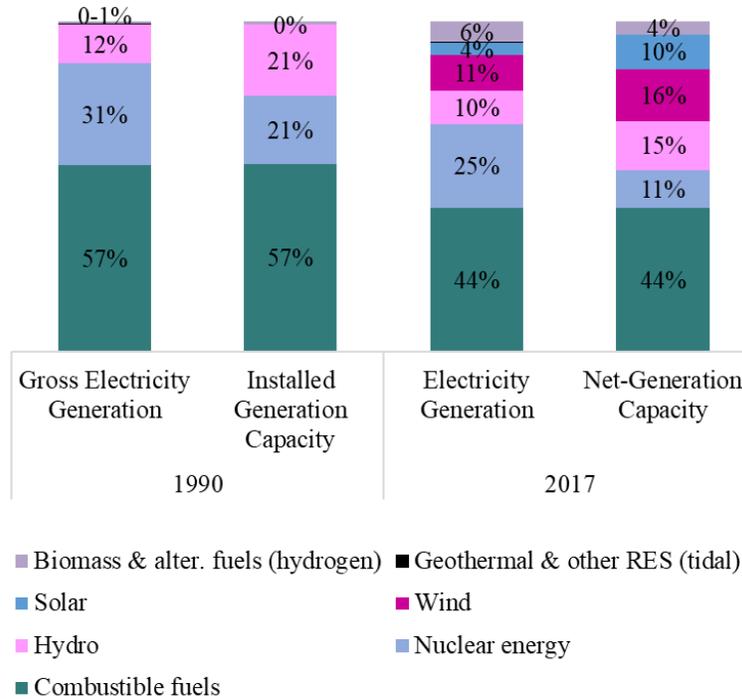


Figure 7: Comparison of the EU28 shares of gross electricity generation and installed generation capacity by source between 1990 and 2017 [estimated based on data from (European Commission, Directorate-General for Energy, 2020)]

Table 1: Comparison of the EU28 gross electricity generation, installed generation capacity and operating hours by resource and technology between 1990 and 2017 [estimated based on data from (European Commission, Directorate-General for Energy, 2020)]

	Gross Electricity Generation (GWh)		Installed Electricity Capacity (MW)		Operating hours	
	1990	2017	1990	2017	1990	2017
Combustible fuels	1467060	1433590	331479	461069	4426	3109
Nuclear	794860	829720	121770	120885	6528	6864
Hydro	308710	331240	125327	155256	2463	2134
Wind	780	361940	454	168514	1718	2148
Solar	20	119400	11	109001	1818	1095
Geothermal & other RES (tidal)	3730	7250	739	1091	5047	6648
Biomass & alter. fuels (hydrogen)	19620	208860	4674	42231	4198	4946

Electricity Costs and Prices

According to published figures (European Commission, 2016b), electricity has held on average the highest share in energy-related household expenditures,¹¹ which has been roughly half of the energy bill

¹¹ In comparison with gas, solid and liquid fuels, and heating but excluding transport expenditures, based on.

of an average EU household (European Commission, 2019b).¹² Wholesale electricity prices, have displayed significant volatility over the last decade (e.g. 30 EUR'17/MWh in spring 2016 and 60 EUR'17/MWh in August 2018).¹³ These have been attributed to seasonality (i.e. wintertime vs. summertime) and variations in the generation mix,¹⁴ and as a result also to electricity production subsidies that influenced the electricity generation mix, since without these subsidies less RES capacity would have been installed in many EU countries over the past 10 years (European Commission, 2019d). On the other hand, and with exception large industrial consumers, retail prices grew by almost 20% for households and medium-sized industries between 2008 and 2017 (from 166 and 87 to 195 and 103 EUR'17/MWh respectively) (European Commission, 2019b).¹⁵ Similarly, these were heavily impacted by policy support costs and fiscal instruments, which changed significantly the price composition since 2008, in particular with respect to the share of taxes that almost doubled. The main driver for this increase in taxes was the support towards RES and combined-heat and power (CHP) generation¹⁶, which, depending on the consumer's status, represented about 30-64% of the taxes and 12-24% of the average total electricity price, whereas the support for the nuclear sector was less than 1% of the price. Furthermore, the annual energy-related subsidies increased by 12% between 2008-2016, of which half were dedicated to support RES (with a threefold increase, reaching 76 billion EUR'17), 1/3 to fossil fuels and just 3% to nuclear (among the lowest at approximately 5 billion EUR'17); the remaining were dedicated to electricity, energy efficiency measures and heating and cooling (Rademaekers et al., 2018).

¹² Since these are average values, it is important to note that large differences are observed across the EU on both the absolute expenditures, the share of energy in the total expenditure and the role of different household energy products.

¹³ All prices are expressed in constant EUR of the year 2017.

¹⁴ Since the marginal costs of generation technologies have been dominated by the higher coal and natural gas prices. Marginal costs refer to the incremental cost of producing one more unit of electricity and reflect the change in the total cost.

¹⁵ Large industry consumers pay lower taxes due to partial exemptions from levies according to the Energy and Environment State Aid Guidelines (EEAG).

¹⁶ This considers only policy support costs that directly impact retail prices and not every tax sub-component existing in each Member State.

5 Comparison of Medium- and Long-term Decarbonisation Scenarios and Possible Socio-economic Implications

5.1 The 2030 Scenarios and the Role of Nuclear

Energy Security of Supply and Emissions Reduction

All EC mid-term scenarios model a drop in the gross energy demand, with RES playing a more significant role driven by the 2030 targets, while the importance of natural gas and nuclear is projected to remain relatively stable and of fossil fuels to decrease (Figure 8). As expected, a reduction in the gross energy demand would reduce net energy imports, yet the EU is projected to remain a net importer until 2030, with import dependency above 50%, even in the EUCO3232.5 scenario. This can be attributed to the projected increase in natural gas imports to 1.2-2 times above the 1990 levels, accounting for 1/4 to 1/3 of the total net imports by 2030, depending on the scenario.

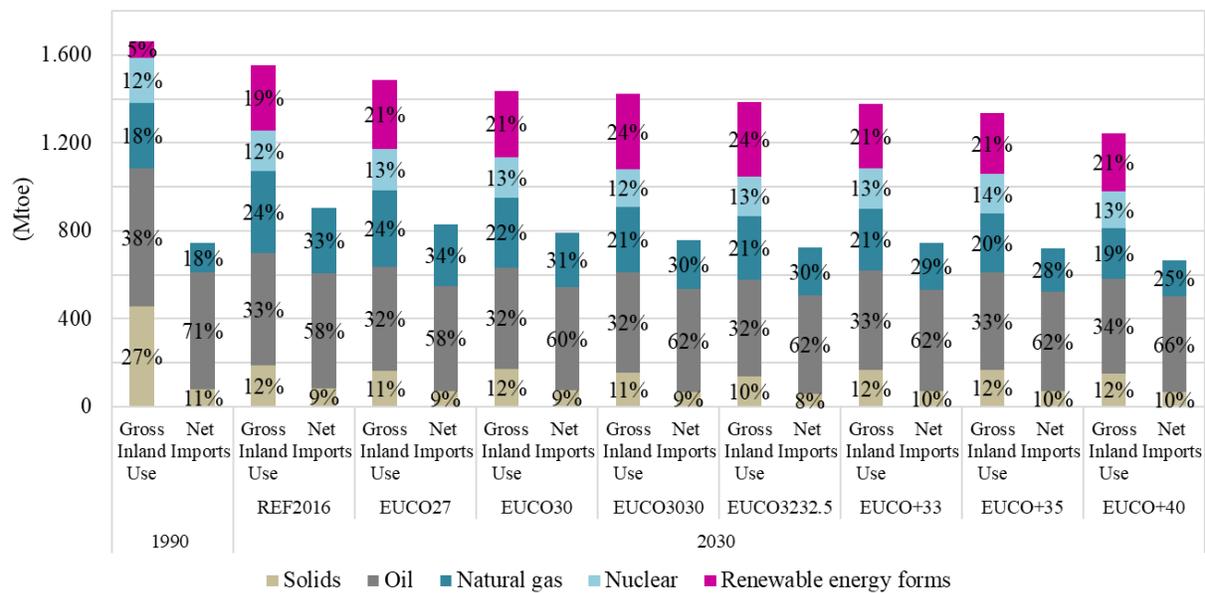


Figure 8: Mid-term projections (in 2030) of the gross inland consumption (excluding non-energy uses of energy resources and the consumption of the energy sector itself) and the net imports compared to 1990 in the EU28 [estimated based on data from (E3MLab, 2019; E3MLab and IIASA, 2016; European Commission, Directorate-General for Energy, 2020)]

Electricity is the only energy fuel projected to further increase its share in the final energy use, remaining the second most important energy fuel (Figure 9 compared to Figure 4). Focusing on the EUCO3232.5 scenario, which represents more closely the current EU current policy framework, electricity is expected to continue decarbonising: low-carbon generation would increase by 30% by 2030 compared to 2017, yet low-carbon power capacity would increase by 125% (Figure 10 and Figure 7). The role of nuclear power in decarbonising electricity would remain significant, being its second largest contributor despite a projected reduction of nearly 10% in its installed capacity compared to 2017. It can be estimated from the figure, that by 2030 the projected installed capacity for RES would be 4 times that of nuclear, to generate an equivalent amount of low-carbon electricity. This observation is in line with the historical trends analysed in Section 2 and no significant change in the operating hours has been noticed since 2017.

Moreover, despite the significant changes in the power-generation mix that target a large drop in emissions by 2030, electricity & heat is projected to be the second largest emitter, accounting for about 27% of all energy-related CO₂ emissions (Figure 12).

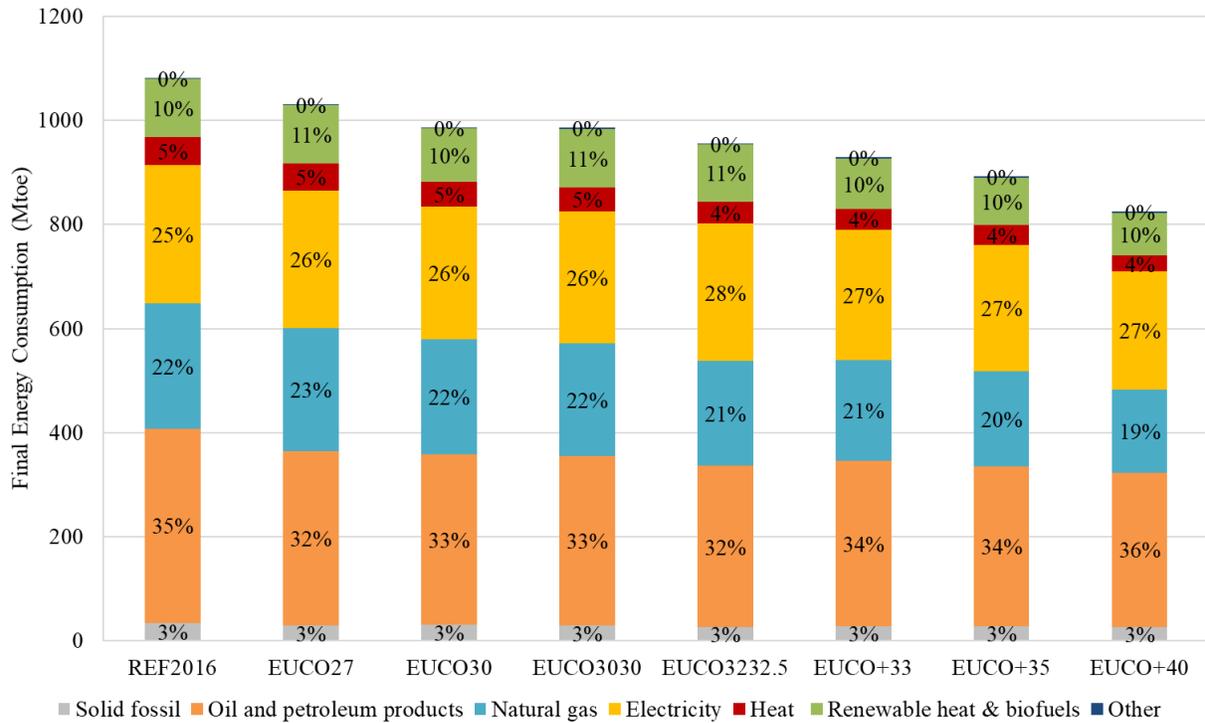


Figure 9: Mid-term projections (in 2030) of the shares of energy fuels (i.e. resources and carriers) in the final energy use in the EU28 [based on data from (Capros et al., 2016; E3MLab, 2019; E3MLab and IIASA, 2016)]

Analysing the potential medium-term implications of a policy pathway of low social acceptance for nuclear power as compared to a pathway of high social acceptance (FTI Consulting, 2018), indicates a required increase in thermal installed capacity of 27 GW in order to compensate for the loss in nuclear installed capacity, of which about 2/3 would be for new infrastructure and the remaining extensions to existing carbon-intensive units. This change in the power generation mix is projected to bring an increase in fossil-fuel consumption of 5'112 TWh, (53% natural gas and 47% coal) and result in a missed opportunity to achieve an additional reduction in CO₂ emissions of 1971 Mt by 2030. Such differences in infrastructure investments would risk carbon lock-in, stranded assets and heighten EU's energy dependence for the coming decades, whereas reaching a higher level of emissions in the mid-term, would not allow the EU to achieved its full potential by 2030, and at the same time could hinder EU's long-term decarbonisation transition before the roll-out of RES and storage, putting an upward pressure on EU ETS prices and end-customer costs.

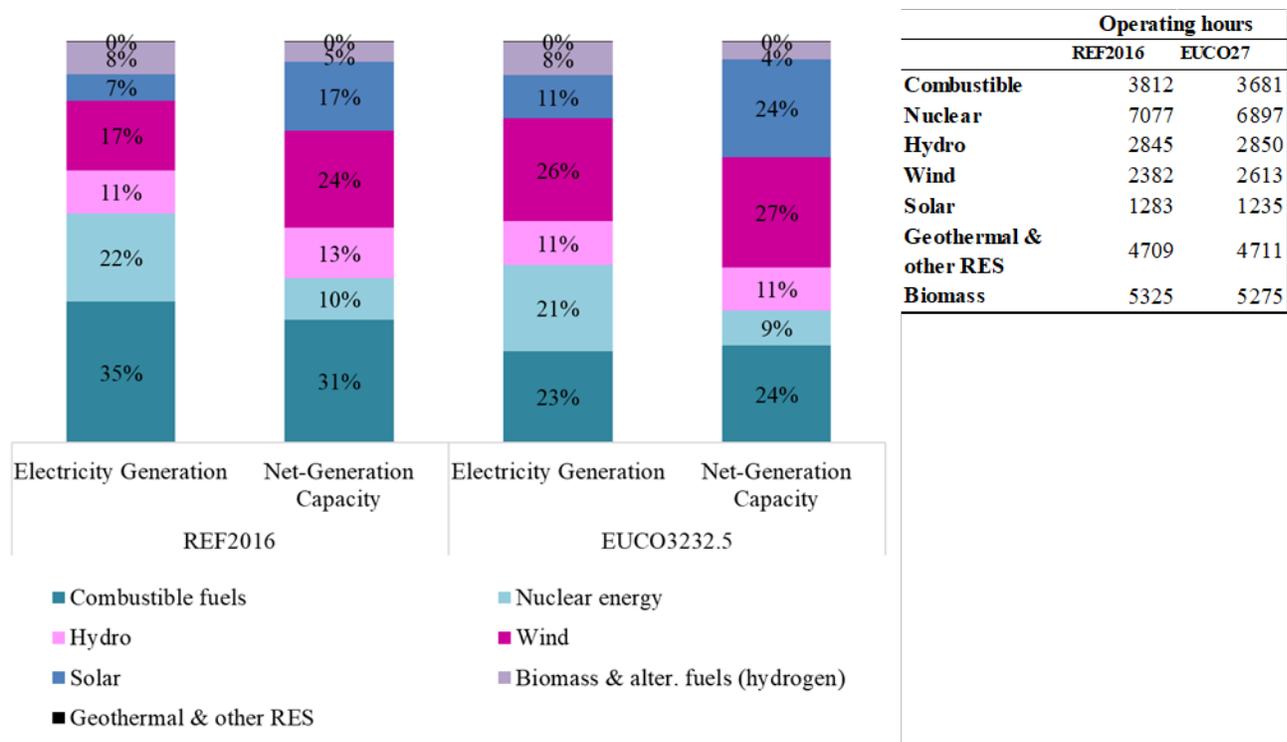


Figure 10: Mid-term projections (in 2030) of the electricity generation and net-generation capacity by technology in the EU28 [estimated based on data from (Capros et al., 2016; E3MLab, 2019)]

Decarbonisation Costs

In terms of electricity production costs, all scenarios project them to peak in the 2020s¹⁷ and subsequently slightly drop in the 2030s (Table 2).¹⁸ Yet, electricity production costs are expected to display a much higher daily variability in the future, with average values continuing to be driven by fossil fuel plants, but also increasingly by biomass-fired plants. The price of electricity is projected to keep rising, although at a smaller pace that observed by the historical trends (Section 2) and is expected to increase by another 10% compared to 2020, with total energy-related costs increasing by 22% in the same period. Compared to all mid-term scenarios, the EUCO3232.5 scenario requires the largest amount of investments by 2030, with solar PV and wind power capacities projected to continue dominating new investments, accounting for roughly 90% of new installed capacity between 2015 and 2030 (Figure 10). The scenarios project a significant decrease in fossil-fuel-fired power capacities (-92%) and a nearly 10% drop in nuclear and natural gas power capacities by 2030, since it is projected that increases in electricity needs would be satisfied by achieving the RES 2030 targets. This is expected as the current gas-fired power plant fleet is relatively young and would still be operational by 2030 (European Commission, 2019b).

¹⁷ The analysis is not directly comparable with the historical figures discussed in Section 3 as the modelling focused on trends and relative changes and only average values were included in the technical reports in constant EUR of the year 2013. In addition, the costs for storage and additional interconnections are not accounted for in the projections.

¹⁸ Projections are similar to those of the Central Scenario developed by the Commission's JRC energy model POTEnCIA (Mantzou et al., 2019).

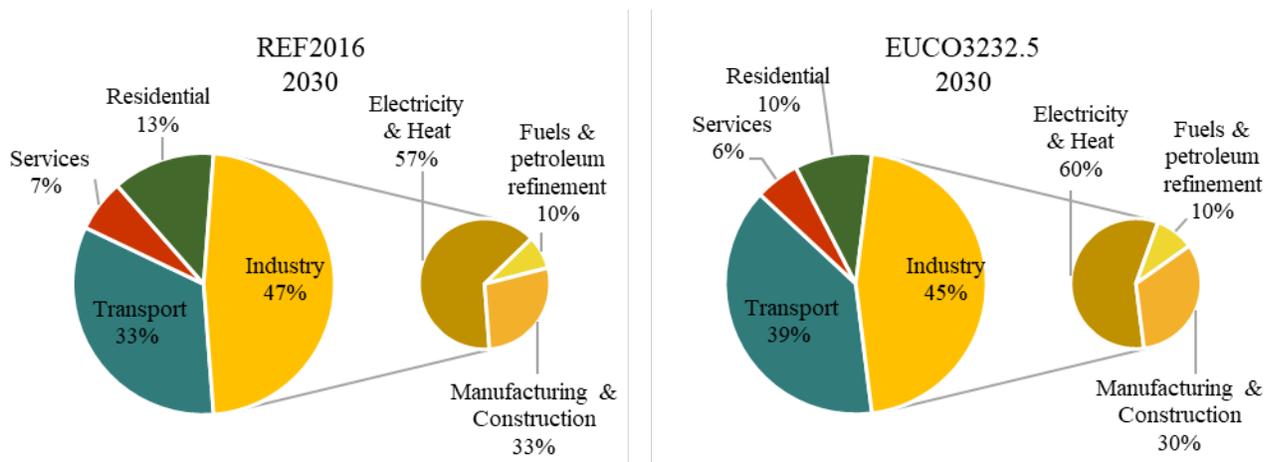


Figure 11: Mid-term projections (in 2030) of the energy related CO₂ emissions by sector in the EU28 [estimated based on data from (Capros et al., 2016; E3MLab, 2019)]

Table 2: Mid-term projections (in 2030) of the electricity and energy-related costs in the EU28 [based on data from (Capros et al., 2016; E3MLab, 2019)]

	2010		2020		2030		'10-'20		'20-'30	
	REF2016	EUCO3232.5	REF2016	EUCO3232.5	REF2016	EUCO3232.5	REF2016	EUCO3232.5	REF2016	EUCO3232.5
	Average Cost of Gross Electricity Generation (€/13/MWh)	65	65	94	93	91	89	3,8	3,7	-0,4
Average Price of Electricity in Final demand sectors (€/13/MWh)	136	136	153	151	161	163	1,2	1,1	0,5	0,7
Total energy-related costs* (in billion €13)	1468	1467,9	1791	1782,9	2032	2166,6	2,0	2,0	1,3	2,0
as % of GDP	11,4	11,4	12,3	12,3	12,2	13,0				

* Includes the capital, operating expenditures and efficiency investment costs, excluding costs related to auctioned emissions. Capital expenditures and energy efficiency investment costs have been discounted at a 10% rate.

Analysing the potential medium-term implications of an policy pathway of low social acceptance for nuclear power as compared to a pathway of high social acceptance (FTI Consulting, 2018), indicates that an early closure of NPPs closure and limited nuclear investments would trigger an additional increase in electricity prices of 20 EUR/MWh in the medium-term. This is associated with the increased use of gas- and coal-fired plants that set wholesale prices in the mid-term, whereas the losses in end-user savings¹⁹ are estimated at 206 billion EUR'17 (undiscounted), because cheaper nuclear baseload is replaced by more expensive gas and coal generation. In terms of capital investments, although temporary gains are

¹⁹ The end-user costs include all costs associate with providing electricity at the end point (electricity generation cost, generation capacity cost and subsidy costs), and are comparable to the total energy system costs.

expected in the medium term due to the lack of commissioning and retrofitting of NPPs, these are projected to be outweighed in the long-term and will therefore be discussed in the subsection below²⁰.

Potential Socio-economic Externalities

Rough estimates of possible medium-term implications with respect to externalities indicate that an early closure of nuclear power plants could translate into a missed opportunity to create 204'000 high skilled job-years in the nuclear generation sector by 2030 in the EU, as nuclear power is the most job intensive technology in terms of direct employment per site and the second most direct job intensive technology (i.e. 0.5 Jobs/MW based on (NEA, 2018)). Moreover, by replacing nuclear power with less energy-dense power technologies, could result in land-use²¹ losses of approximately 2852 km² by 2030, an area almost equivalent to the total area of Luxembourg. Finally, the increase in additional thermal generation in order to compensate for limiting low-carbon nuclear power generation, could exacerbate EU's air pollution by almost 10 Mt of SO_x and NO_x emissions, and 3230kt of PM by 2030.

Future investments beyond 2030 depend on the assumed lifetimes of the current power plants and as already mentioned, the majority of the current power plant fleet would still be operational by 2030. In the long-term, the influence of policy pathways on the power mix would become more evident, since a substantial part of the current power plants (about 1/3 of the capacity installed prior to 2005) would reach the end of their lifetime operation between 2030 and 2040. This means that a faster pace of phase-out policies with deeper decarbonisation and electrification, could substantially change investment needs, and different policy routes could have a varying-level of impact on the future technology deployment, while at the same time, most of the assumed techno-economic developments take effect, as scenarios presume storage and CCS technologies to become cost effective from 2040 onwards (Capros et al., 2016; Simoes et al., 2017). These changes are expected to trigger rapid investments that, depending on the policy pathways that would translate into a fundamentally different power mix by 2050.

²⁰ This applies also to flexible sources, i.e. batteries and long-term storage including P2G, which the models assume to be cost-effective after 2035-2040, as well as grid and balancing costs, which appear after 2030 (Capros et al., 2016).

²¹ Land-use costs are difficult to be estimated and are approximated using the geographic footprint.

5.2 The 2050 Scenarios and the Role of Nuclear

Energy Security of Supply and Emissions Reduction

By 2050, gross inland energy use is projected to show large variations depending on the policy pathway followed and the decarbonisation ambition. Compared to the pathway based on existing policy measures (i.e. Baseline), on one hand energy use could be lower driven by efficiency developments, electrification, the circular economy and by an increased decarbonisation ambition relying on sustainable lifestyle changes (i.e. EE, ELEC, CIRC and 1.5LIF). On the other hand it could also be at similar levels (i.e. H2 and COMBO) or even increase to meet the growing needs for the production of hydrogen and e-fuels (i.e. P2X and 1.5TECH) (Figure 13). The Baseline projects the EU to remain a net-energy importer in 2050, whereas the EU's import dependency is expected to improve significantly in all other scenarios, with renewables followed by nuclear becoming the prevalent energy resources. Moreover, the higher the decarbonisation ambition (i.e. COMBO, 1.5TECH and 1.5LIFE) the higher increase is projected for the consumption of renewables and nuclear energy and the lowest for natural gas and other fossil fuels (compared to the EUCO3232.5).

All scenarios project electricity to become the dominant energy fuel by 2050, representing half of the final energy demand (Figure 14), however, individual scenario projections on the shares of energy technologies in electricity generation are not provided (European Commission, 2018), and so no analysis could be performed on the differences in the power-mix and decarbonisation ambition. At the same time, discrepancies were found between the reported values for nuclear electricity generation and its share in the final energy use that require further clarification before including them in such an analysis.²² Nevertheless, the power sector is projected to have the most potential, displaying the steepest reduction in emissions across all 2050 EC pathways, which is mostly achieved through improved energy efficiency, a circular economy and deepening of electrification (i.e. CIRC, EE, ELEC).

All EC 2050 policy scenarios project a striking increase in installed power capacity compared to 2030, which more than doubles in the scenarios achieving 100% reduction in emissions (Figure 15). Similar to the mid-term projections, this trend is linked to projected increase in the installed capacities of solar and wind power compared to nuclear, that is expected to require massive investments in electricity infrastructure and storage technologies, especially in deep decarbonisation pathways and despite adopting policies to support energy efficiency, circular economy and sustainable lifestyle choices (i.e. COMBO, 1.5TECH and 1.5LIFE) (Figure 16). Specifically, and regardless of the EC policy pathway, solar and wind power capacities are projected to continue dominating new investments (77-88%), compared to new nuclear power capacities (5-7%),¹⁸ whereas the highest investment needs in conventional storage (i.e. pumped hydro and batteries) would take place in the scenarios assuming less significant development of e-fuels (i.e. EE, CIRC and ELEC).

²² Specifically, only an averaged decarbonisation scenario is provided in the supportive data (i.e. across all long-term scenarios), where nuclear power shares drop to 13% of electricity production, which is much lower than its projected share in the final energy consumption (i.e. 17-19% in Figure 13). On the contrary, the average share of RES in electricity generation is projected at 83% of which 69% is wind and solar, and the average fossil-fuel shares is at 4% (Figure 23 in (European Commission, 2018))

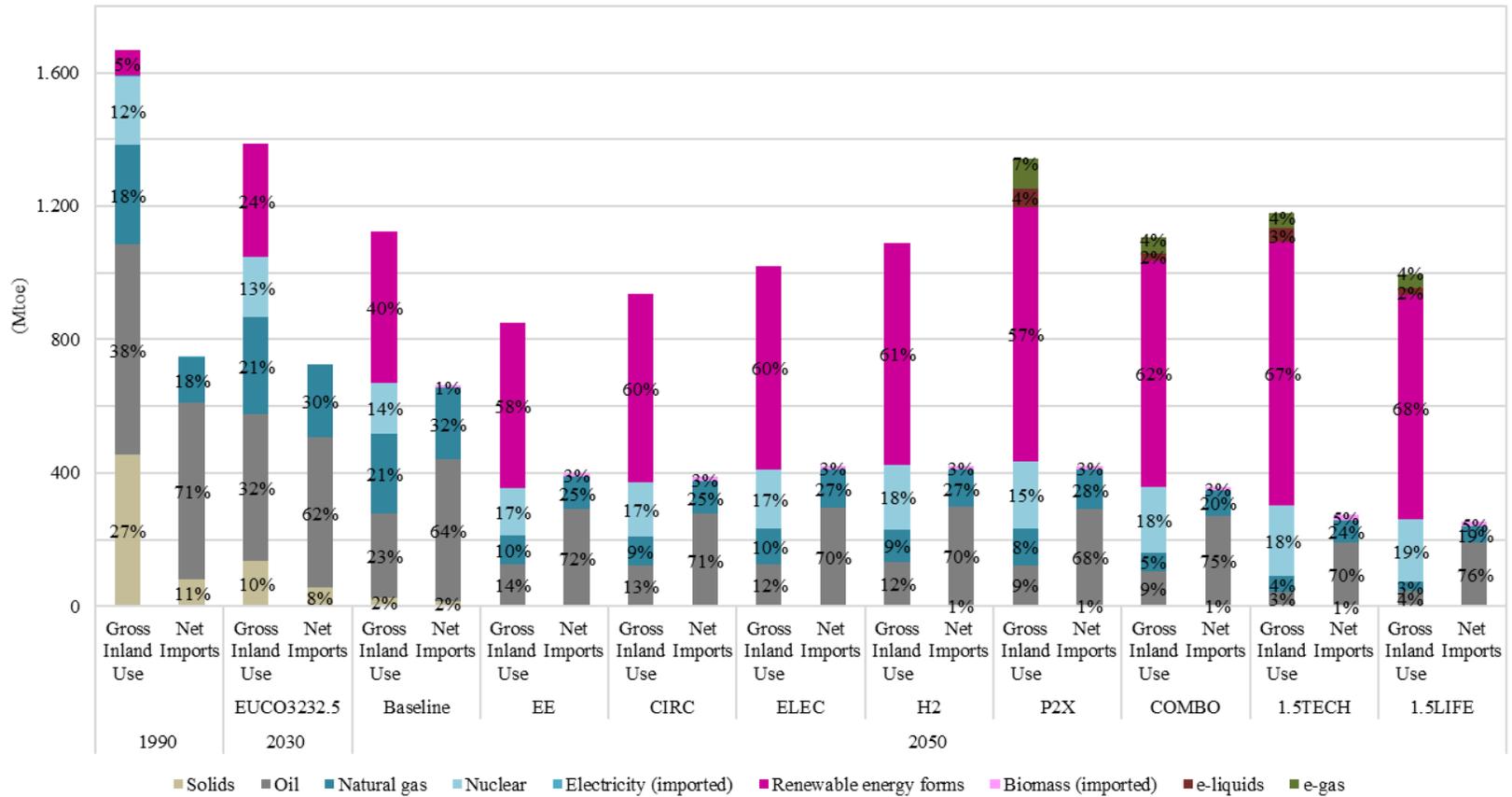


Figure 12: Long-term projections (in 2050) of the gross inland consumption (excluding non-energy uses of energy fuels and the consumption of the energy sector itself) and the net imports compared to 1990 in the EU28 [estimated based on data from (European Commission, 2019c; European Commission, Directorate-General for Energy, 2020)]

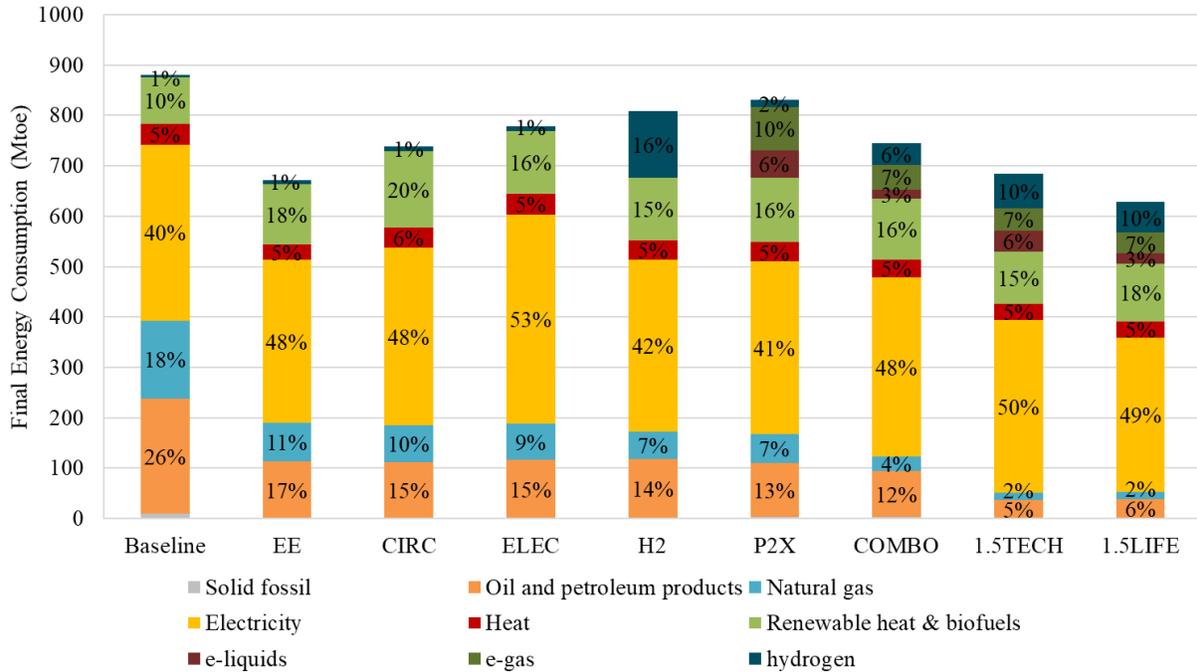


Figure 13: Long-term projections (in 2050) of the shares of energy fuels (i.e. resources and carriers) in the final energy use in the EU28 [estimated based on data from (European Commission, 2019c)]

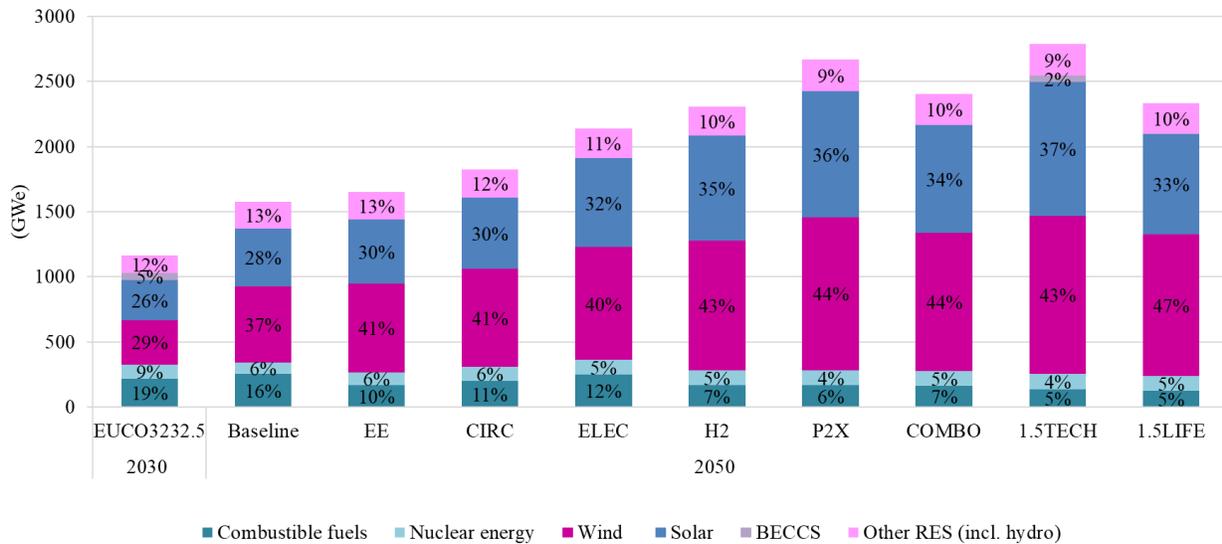


Figure 14: Long-term projections (in 2050) of the installed generation capacity by technology in the EU28 [estimated based on data from (E3MLab, 2019; European Commission, 2019c)]

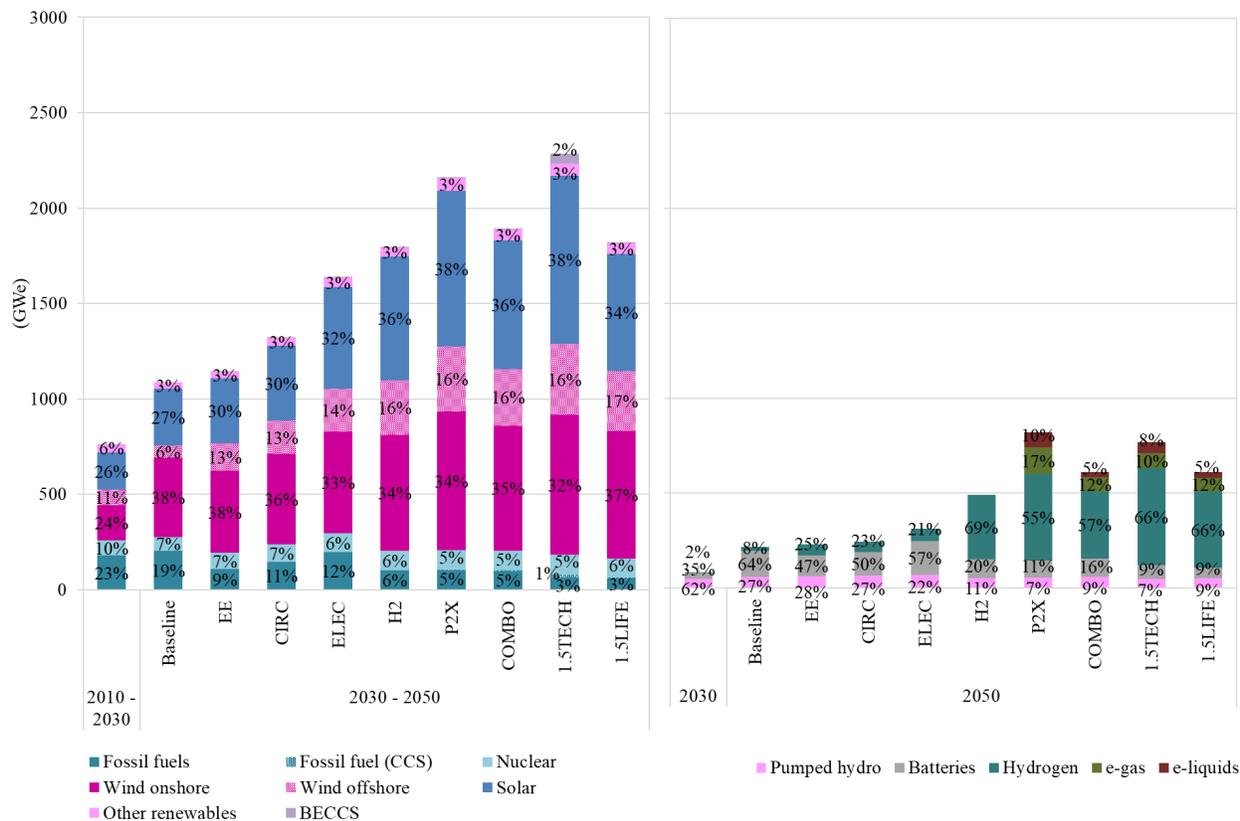


Figure 15: Projections of the (left) new, total, generation capacities by source, including new constructions, life-time extensions, refurbishment and retrofitting, and (right) capacities in electricity storage technologies, needed between 2030 and 2050 in the EU28 [estimated based on data from (European Commission, 2019c)]

Analysing the potential long-term implications of a policy pathway of low social acceptance for nuclear power as compared to a pathway of high social acceptance (FTI Consulting, 2018) indicates that in order to compensate for the potential loss of 114 GW of nuclear capacity, aside from the 25 GW of additional thermal capacity already required by 2030, additional investments in alternative technologies equivalent to 533 GW between 2020 and 2050 would be required (about 415GW of RES and 93 GW in battery and power-to-gas storage). These trends could induce an additional curtailed energy by RES of about 66TWh (or 1% of their total power) and give rise to fossil-fuel power generation (+36 % in natural and +18% of coal) to ensure security of supply, of which 80% would be consumed by 2030. Moreover, the EU's power system would rely more heavily on yet-to-be-proven storage technologies (European Commission, 2019e), of which 36 GW would need to be operational already between 2035 and 2040, while at the same time risking a higher import dependency on battery materials and generating large volumes of end-of-life batteries that currently have an average 10-year lifetime (Bobba et al., 2018). As a result, and despite the increased RES penetration, these would translate into a missed opportunity to further reduce CO₂ emissions by 2270Mt that would bring an additional 17% cut in the power sector emissions by 2050 and support EU's path towards clean electrification. Moreover, 95% of the total emission-reduction potential occurs by 2030 (see Section 4.1), which is projected to be an important worldwide tipping point for limiting worldwide warming to 1.5°C (Intergovernmental Panel on Climate Change, 2018), hence justifies the urgency for early action to reach EU's fullest potential and strengthen its role as a global leader in climate action.

Decarbonisation Costs

Depending on the policy pathway, investment costs are projected to increase at a different pace, mostly owed to differences in the technology deployment and decarbonisation ambition (Figure 17): the 1.5TECH pathway would require the largest amount of investments, followed by P2X, COMBO and H2, with energy-related costs increasing by 16 to 30% from 2030. Electricity prices however, follow diverging trends compared to 2030, forming seemingly three policy scenario groups by 2050: a) electricity prices drop with a low decarbonisation ambition, as costs are mitigated by improved efficiency and circular economy measures and intensified electrification (i.e. BL, ELEC, CIRC EE), b) electricity prices increase moderately (12-19%), either with a high decarbonisation ambition that relies on sustainable lifestyle choices (i.e. 1.5LIFE) or with a low decarbonisation ambition that relies on specific technological options (H2, P2X, COMBO), or a), and c) electricity prices increase drastically (almost 50%) with a high decarbonisation ambition that relies extensively on specific technological options, including CCS (1.5TECH).

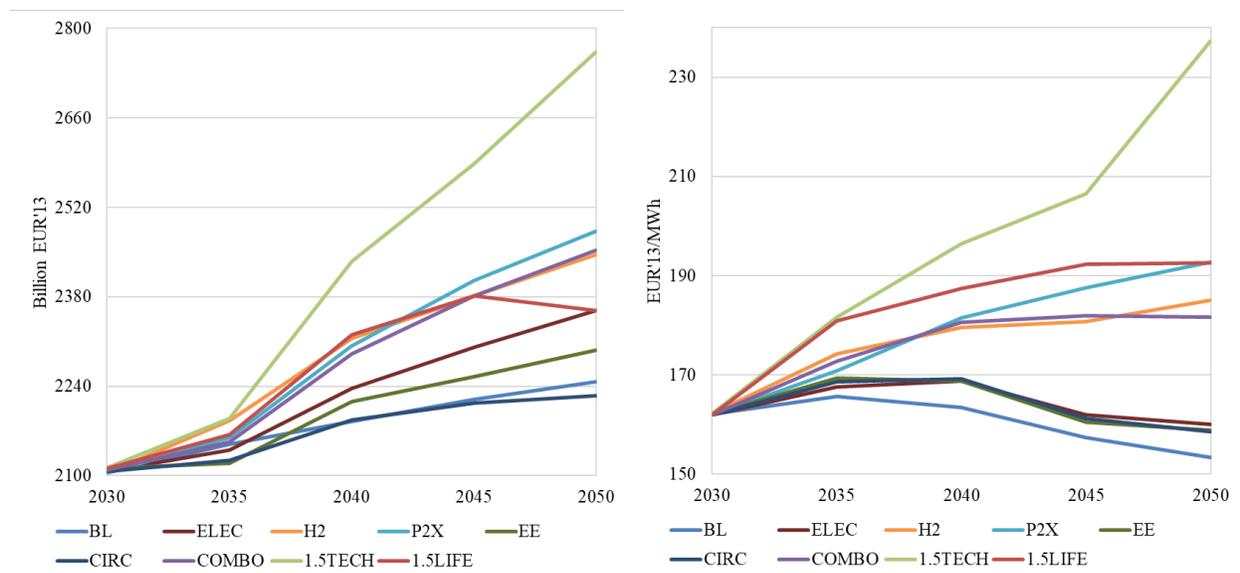


Figure 16: The evolution of the total (left) energy-related costs and (right) price of electricity by scenario up to 2050 in the EU28 [estimated based on data from (European Commission, 2019c)]

Analysing the potential long-term implications of a policy pathway of low social acceptance for nuclear power as compared to a pathway of high social acceptance (FTI Consulting, 2018) indicates that although power prices converge over time, price volatility would increase significantly due to the increased RES penetration. In addition, a peak in power-price losses is expected by 2030 (20 EUR/MWh) that could hamper the competitiveness of electricity against other energy fuels and slow down the electrification of sectors, such as transport. Furthermore, the overall losses for the end-users¹⁹ are estimated at 350 billion EUR'17 (undiscounted), of which 90% would occur before 2035. Finally, although an early nuclear closure and limited investments, would save 75 billion EUR'17 by 2035, a doubling in investment losses is expected thereafter, which could result in an overall investment loss of 85 billion EUR'17 between 2020 and 2050. It is important to note that these economic figures were based on the assumption that the nuclear CAPEX would decrease by 37% by 2050, and although end-user costs were shown to be robust to changes in the CAPEX reduction, investment costs were highly sensitive (FTI Consulting, 2018), which

further justifies the importance of recognising the contribution of nuclear power to decarbonisation and planning long-term financial support schemes to leverage the technological benefits of the nuclear power sector.

Potential Socio-economic Externalities

Rough estimates of possible medium-term implications with respect to externalities indicate that an early closure of nuclear power plants could translate into a missed opportunity to create 1 million high-skilled job-years in the EU nuclear power sector over 2020-2050. In addition early nuclear closure is expected to escalate the RES capacity and as a result both transmission & distribution (T&D) costs and balancing costs would increase from 2030 onwards: T&D grid costs could rise by €160 billion EUR'17, of which almost half (€70 billion EUR'17) are due to offshore grid cost, while balancing costs could rise by 13 billion EUR'17. Furthermore, this would escalate land-use requirements²³ to approximately 15790 km² to meet the needs of electricity generation over 2020-2050, which is equivalent to half the area of Belgium. Finally, the additional thermal capacity used to compensate the early NPP closure would heighten air pollution, of which 95% would occur by 2030 (see Section 4.1). Missing the long-term benefits of achieving lower air-pollution levels by 2030 should not be underestimated, as this would be critical point for the EU to display its global leadership role in tackling climate change and limiting global warming to 1.5°C (Intergovernmental Panel on Climate Change, 2018).

²³ Land-use costs are difficult to be estimated and are approximated using the geographic footprint.

6 Discussion on Full System Costs of Electricity Generation

The most common element to compare technology costs is the levelised cost of electricity (LCOE), which usually incorporates what can be categorised as internal costs over the operational lifetime of the plant, including investment costs, operation and maintenance costs and fuel-cycle costs, taking into account discount rates and inflation (Bustreo et al., 2017; D’haeseleer, 2013; NEA, 2018). Here a distinction is made for nuclear compared to other electricity generation technologies, as decommissioning, waste management and disposal costs are already included in the nuclear LCOE, which are borne by the operator and hence reduce profit. In addition, comparisons based on LCOE, commonly represent *plant-level costs* excluding the influence of *grid-level costs*, i.e. transmission and distribution, balancing and utilisation (or back-up) costs that organise reliable supply (NEA, 2019), which in the end are born either by the grid operator or the end-consumers through taxes or electricity tariffs. Although rough estimates of such costs have been discussed in Section 4.2, in order to properly estimate these costs, they would need to be internalised in the costs of electricity generation technologies and subsequently in the modelling scenarios. This becomes increasingly important as the penetration of variable and intermittent RES in the energy market deepens and as electrification of the economy intensifies; especially when the goal is to decarbonise the power sector at the least cost.

Moreover, except for certain taxes such as the CO₂ allowances under the ETS, it has been conventional practice to neglect the external costs, also known as externalities, of power generation technologies (Bickel and Friedrich, 2005; European Commission, 2003). Although accounting for externalities in full system costs is not an uncontroversial topic, as it can be understood as an attempt to reduce human-well-being into a question of euros, electricity generation technologies incur different environmental and social external costs, which are borne by the society at large and should therefore be critical indicators in future policies and decision making. Drawing attention to these understudied issues could facilitate public discussion and policy making by means of integrating the most pressing issues in a meaningful way (NEA, 2018) and in the end positively impact the power sector transformation from a socio-economic perspective.

An example is the share of electricity from nuclear fission, which could increase significantly in the 2050 power mix when incorporating external costs and increasing the decarbonisation ambition (Sangiorgi et al., 2019). Looking beyond 2050, a preliminary analysis suggests that nuclear fission power plants could also act as bridge for fusion deployment by potentially preventing deep and costly changes to the power system, which would thus be ready to accommodate future fusion generation (Cabal et al., 2016). Moreover, internalising externalities could also accelerate fusion penetration, even though a higher decarbonisation ambition would be a more determinant factor in this case (Cabal et al., 2017b; Entler et al., 2018).

Assessments of the external costs of electricity generation technologies have for instance revealed the relatively high external costs of fossil-fuel technologies with respect to human health and climate change impacts, but also revealed the depletion of energy resources and nuclear accidents as the most important parameters driving costs in the case of fission technologies (Alberici et al., 2014; Cabal et al., 2017a). Specifically concerns over risks of accidents and waste management could affect social acceptability and the pace of technology deployment, as is the case in many countries with nuclear energy, even though comparative risk assessments show that health risks are low for nuclear energy (Bruckner et al., 2014; Hirschberg et al., 2016). It is important to highlight here that, such assessments are highly technology-

and country-specific and uncertainties in estimates depend on the availability or lack of historical data, as is the case with some new technologies (e.g. biogas), or future technologies (e.g. some advanced nuclear reactors or fusion technologies). Considering the severity and heterogeneity of energy-related past accidents (Hirschberg et al., 2016), there is a need to improve consistency in analysing health impacts (i.e. related to mortality and morbidity) across all energy-chain stages for all energy technologies, including renewable energy technologies, while taking into consideration not only normal operation but also severe accidents and even hypothetical terrorist threats and health crises. Assessing human health-related impacts, like accidents and toxicity, across all energy technologies and life-cycle stages in a consistent manner would be vital support in managing the political debates around future technological choices and their environmental impacts.

7 Conclusions and Policy Implications

By 2050 and compared to 2018, electricity could double its share in the final energy consumption. Electricity will play a crucial role in the decarbonisation and energy transformation in the EU, with the scenarios projecting a fully decarbonised power sector by mid-century. This paper has explored the role of nuclear in the EU policy pathways towards decarbonisation and energy transformation focusing on the power sector and highlighting possible socio-economic implications that could arise when limited social acceptability could virtually exclude the provision of nuclear electricity from the future power mix.

Historical trends reveal that electricity has already become the second most important energy carrier in the EU and the most important one for industry and services. Yet, despite having experienced a large drop in its emissions over the past decades, it still remains EU's largest emitter together with heat. At the same time, the pace of its decarbonisation has been slower than the rate of increase of low-carbon electricity capacity, as a result of the vast majority of new investments being dedicated to new variable and intermittent RES capacities that need four times the installed capacity of nuclear power to produce the same amount of low-carbon electricity. In addition, electricity has held the largest share of energy-related expenditures in EU households. Retail prices grew by almost 20% for households and small and medium-sized industries within the past decade, largely owed to the rise in taxes to support RES and CHP. Electricity production prices were also influenced by RES subsidies that increased their volatility as a result of variations in the generation mix and the marginal costs of generation technologies, which were dominated by the higher coal and natural gas prices.

The EC decarbonisation scenarios reflecting closely the current policy framework, projects electricity to become the second most important source of emissions by 2030 and the share of low-carbon electricity is projected to increase by another 30%. However this would require a remarkable 125% increase in low-carbon power capacity compared to 2017 as a result investments continuing to be dominated by variable and intermittent RES technologies. On the contrary, nuclear capacity would drop by 10% for the first time since 1990, considering the Member States' explicit phase-out policies and ongoing projects at the time of the scenario modelling. The variability of electricity production costs is projected to increase further and retail prices to rise by approximately another 10% compared to 2020. Between 2030 and 2040, a substantial change in electricity infrastructure investments is expected as a large part of the current EU power plants would reach the end of their lifetime operation. The EC 2050 scenarios, project electrification to deepen with increases in decarbonisation ambition and expect a doubling in power capacity investments, continuing to be dominated by variable and intermittent RES technologies, whereas investments in new nuclear power capacities would account for 6%. The overall investments costs are projected to grow even further, particularly in scenarios with a higher deployment of hydrogen and e-fuels that would trigger another rise in electricity prices, even though impacts could be partially mitigated by improved energy efficiency, circular economy and sustainable lifestyle changes to lower consumption.

An alternative scenario where nuclear phase-out policies evolve at a faster pace, would bring the 2050 nuclear power capacity to about 25% of the current levels (36GW), resulting in an additional increase in mid-term investments for variable and intermittent RES and yet-to-be-proven storage technologies, but more importantly for carbon-intensive units (i.e. natural gas and coal). This would thus risk carbon lock-in, stranded assets and potentially heighten EU's energy and material dependence for the coming decades. Compared to a scenario where NPP deployment is not constrained, an early nuclear closure would represent a missed opportunity to cut the power sector CO₂ emissions by an extra 17% by 2030 and

further boost EU's path towards carbon-free electrification and long-term decarbonisation, putting an upward pressure on EU ETS prices and end-user costs. Indeed, although electricity prices would converge in the long-term, if nuclear baseload phase-out is intensified, power price losses are projected to peak by 2030, which could hamper the competitiveness of electricity against other energy fuels and slow down the electrification of sectors, such as transport. This underlines the urgency for considering long-term economic benefits of lifting restrictions to nuclear power generation that would largely depend on an assumed reduction in the nuclear CAPEX by 2050. Consequently, among the factors that will influence the future role of nuclear in the power mix is not only the ability to be flexible and appropriately located throughout Europe, but also achieve future cost reductions, reactor design and material improvements (e.g. Small Modular Reactors, High Temperature Reactors), as well as design decarbonisation policy actions that recognise the environmental and societal benefits of all low-carbon energy technologies while ensuring a level-playing field across low-carbon technologies. The contribution of nuclear power towards decarbonising the power sector is substantial. Long-term financial support schemes to promote research and technological innovation would allow to leverage its technological benefits and support EU's climate and energy targets. As recommended by authors (Buongiorno et al., 2019), market-oriented economies like the European Union should be able to compete with e.g. in China and Russia to promote technological advancement and investments, with governments adopting an important, yet more limited, role in the development and deployment of nuclear technologies, which could involve establishing sites where companies could test the operation of prototype reactors for regulatory licensing, as well as establish funding programs around prototype testing. The commercial deployment of advanced reactor designs is in the hand of industrial actors and national authorities.

Moreover, decarbonisation exercises evaluating power system costs, assess inconsistently the cost elements across generation technologies and energy-chain stages, and often concentrate on plant-level costs, while disregarding grid-level costs and social and environmental implications, even though these costs are still paid by the society at large. Socio-economic issues that could arise from the energy transition could be with respect to the security of energy supply and import dependency, as well as possible risks of carbon lock-in and issues related to the availability of land, to public acceptance, which could develop as electrification deepens, hindering EU's long-term decarbonisation transition and putting an upwards pressure on end-user costs. A full-system-costs approach could have positive impacts on the long-term socio-economic efficiency of the power sector, while looking beyond 2050, it could facilitate fusion penetration by potentially preventing deep and costly changes to the power system. Incorporating full system costs in future assessments of power-sector transition is especially relevant for technologies most sensitive to policy routes, such as nuclear energy technologies, whose future technological progress and deployment pace is shown to be constrained by social acceptability in many countries, which in turn influence the pace of technology development and cost reduction through economies of scale, thus having the potential to restrict important benefits to be reaped by industries and citizens.

8 Acknowledgements

This work was undertaken during the European Commission's Blue Book Traineeship programme, as part of the Euratom Research Unit of the Clean Planet Directorate of the Directorate-General for Research and Innovation. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

The views expressed in this work are purely those of the authors and may not under any circumstances be regarded as stating an official position of the European Commission.

The authors would like to thank the following colleagues for providing reports, data and other types of information: a) the Euratom Research Unit of DG RTD, b) the Energy Efficiency and Renewables Unit and the Energy Security, Distribution and Markets Unit of the Joint Research Centre and c) the Economic Analysis and Financial Instruments Unit of the DG Energy.

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10 Terms and Acronyms

BECCS	Bio-energy with carbon capture and storage.
CAPEX	Capital Expenditures.
CCS	Carbon Capture and Storage technologies.
CHP	Combined Heat and Power.
EC	European Commission.
e-fuels	Are synthetic fuels produced from decarbonised electricity, according to COM(2018) 773.
Energy carrier	According to ISO 13600:1997, it is a "substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes." It is produced from a primary energy source.
Energy resource	Refers to a primary energy resource, a.k.a. natural resource which according to ISO 13600:1997 is a "substance or phenomenon appearing in nature which can be used as input to the technosphere." It has not been not subjected to any human engineered conversion process.
ENTSO-E	European Network of Transmission System Operators for Electricity.
ESR	Effort Sharing Regulation (ESR) establishes binding annual greenhouse gas emission targets for Member States up to 2030 for most sectors not included in the EU ETS, such as transport, buildings, agriculture and waste.
EU ETS	The EU Emissions Trading System (EU ETS) is EU's greenhouse gas emissions trading scheme, covering the sectors of power and heat generation, energy-intensive industry and commercial aviation.
EU28	Also referred to in the text as EU, is the European Union of 28 Member States.
Eurostat	European statistics, the statistical office of the European Union.
Final energy consumption	The total energy consumed by end users, excluding the consumption of the energy sector itself (in tonnes of oil equivalent).
GDP	Gross Domestic Product (US\$ or EUR).
Gen-IV	Generation IV nuclear reactors.
GHG	Greenhouse gases covered by the UNFCCC/Kyoto Protocol, which are carbon dioxide (CO ₂), methane (CH ₄), nitrous oxide (N ₂ O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF ₆), and nitrogen trifluoride (NF ₃) (in CO ₂ e).
Gross electricity generation	The amount of electricity produced over a period of time, i.e. the electricity measured at the outlet of the main transformers, plus the amount of electricity used in the plant auxiliaries and in the transformers (in Watt hour).
Gross inland energy consumption	Abbreviated as gross inland consumption, represents the quantity of energy necessary to satisfy the total energy demand of a country or region (i.e. inland consumption), including the consumption of the energy sector itself, losses during transformation and distribution of energy, and the final consumption by end users. It excludes energy fuels provided to international maritime bunkers (in tonnes of oil equivalent).

IEA	International Energy Agency.
Import dependency	Also known as energy import rate, is defined as the net energy imports (i.e. imports minus exports) divided by the gross inland energy consumption plus fuel supplied to international maritime bunkers (in %).
Installed power capacity	Also used as generation capacity, is the maximum output of electricity that a generator can produce under ideal conditions including the consumption of power stations' auxiliary services and transformers (in Watt).
IPCC	Intergovernmental Panel on Climate Change.
LCOE	Levelised Cost Of Electricity.
Load factor	Electricity generated over maximum potential generation based on net power capacity (in %).
LULUCF	Land use, land-use change, and forestry.
NEA	Nuclear Energy Agency.
Net energy imports	The amount of energy imports minus the amount of energy exports expressed in tonnes of oil equivalent (in tonnes of oil equivalent).
Net-generation capacity	Also used as net-power capacity, is the installed power capacity excluding the consumption of power stations' auxiliary services and transformers (in Watt). Gross-electricity generation is defined as the amount of electricity produced over a period of time, i.e. the electricity measured at the outlet of the main transformers, plus the amount of electricity used in the plant auxiliaries and in the transformers (in Watt-hour).
NO _x	Nitrogen oxides.
NPP	Nuclear power plant.
OPEX	Operational expenditures.
PM	Particulate matter (in thousand tonnes, kt).
Primary energy use	Also, primary energy consumption, measures the total energy demand of a country or region, including the consumption of the energy sector itself, losses during transformation and distribution of energy, and the final consumption by end users. It excludes energy fuels used for non-energy purposes (e.g. petroleum used for producing plastics) (in tonnes of oil equivalent).
RES	Renewable Energy Sources.
SMR	Small modular reactors, a type of nuclear fission reactor that is smaller than conventional reactors, allowing to bypass financial and safety barriers.
SO _x	Sulphur oxides (in Megatonnes, Mt).