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French nuclear power in the european energy system

Scenarios for the SFEN, using the PRIMES model

NOTE SFEN - JUNE 2018

The French Nuclear Energy Society (SFEN) is the French knowledge hub for nuclear energy.

Created in 1973, the SFEN provides a place where French and International specialists, and all those with an interest in nuclear energy and its applications, can obtain and share information. The SFEN brings together 4000 professionals in industry, education and research.

Société Française d'Energie Nucléaire

The SFEN's contribution to France's Multi-Year Energy Plan

(Programmation pluriannuelle de l'énergie)

Document prepared by the SFEN's Energy Economics and Strategy Expert Group:
Michel Berthélemy, Didier Beutier, Jacques David, Nicole Dellero,
Jean-Guy Devezeaux de Lavergne, Valérie Faudon and Boris Le Ngoc

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Executive Summary & Recommendations

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Introduction

> New European scenarios provide a complementary view to the 2017 RTE Forecast Report ('Bilan Prévisionnel RTE 2017'), and help to inform future decisions on France's Multi-Year Energy Programme (PPE - *Programmation Pluriannuelle de l'Énergie*).

Three additional variables must be considered: Europe, the long-term, and the energy system as a whole

France's Multi-Year Energy Plan (PPE - *Programmation Pluriannuelle de l'Energie*), covers changes in energy supply and demand over the next ten years, in line with the many objectives of the Energy Transition for Green Growth Law (LTECV - *Loi de Transition Energétique pour la Croissance Verte*). The context in which the latest version of this document is being drawn up is twofold.

On the one hand, the French Government stated in the 2017 Climate Change Plan (*Plan Climat*), that "the challenge of climate change is a priority", and has since set a greenhouse gas emissions neutrality goal for 2050. On the other hand, the first indicators monitored in the French National Low-Carbon Strategy (SNBC - *Stratégie Nationale Bas-Carbone*)[1] show that, instead of decreasing, greenhouse gas emissions are currently increasing[2].

France's mix of nuclear and renewable energy has resulted in an electricity production which is more than 90% decarbonised and has the lowest CO_2 emissions of all of the G7 member countries[3]. In the coming years, the electricity mix is likely to diversify, as the economic and technical performance of renewable energies improves.

The Energy Transition Law sets a goal of reducing the share of nuclear power in France to 50% by 2025. This objective is at odds with the priority given to the fight against climate change. RTE's 2017 Forecast Report (*Bilan Prévisionnel*), shows that in order to meet this objective, 23 to 27 nuclear reactors would need to be shut down, whilst continuing to operate existing coal power plants beyond 2025, and building about 20 new gas-fired power plants. Such a scenario would result in an increase in emissions of 38 to 55 million tonnes of CO_2 per year.

Even though they have abandoned the date of 2025, the French Government has recently confirmed the goal of reducing the share of nuclear power. This raises the question of the pace of diversification of the electricity mix in discussions for the Multi-Year Energy Plan. RTE's Forecast Report serves as a guidance tool for this discussion; it looks in depth at changes in the production and consumption of electricity, as well as the solutions which make it possible to balance supply and demand. As such, RTE has published five scenarios for reducing nuclear at different timescales, and the conditions required to achieve them.

The SFEN is looking to provide an additional perspective to the RTE scenarios, in line with France's national and international goals in the fight against climate change (and not on the objective of reducing the share of nuclear power). This work aims to identify the most economically efficient long-term trajectories for achieving the decarbonisation objectives of the French and European energy systems.

In this technical note, the SFEN puts forward three additional variables to those considered in the RTE scenarios.

1. **Europe:** while the Energy Transition Law focused exclusively on the French electricity mix, the 2017 Forecast Report already specifies that it is "no longer possible to consider the electricity production mix from an exclusively national viewpoint". The RTE scenarios model cross-border electricity flows, which depend on interconnection capacity constraints at an hourly level. Although these scenarios take into account projected changes in neighbouring European countries' electricity systems, they do not enable us to understand the role of French nuclear power in decarbonising their electricity production. By exporting low-carbon, flexible and dispatchable electricity to its neighbours, France supports the development of intermittent renewable energies in Europe.

2. **The long-term:** the 2017 Forecast Report explores several scenarios over the 2018-2035 time period, going beyond that of the Multi-Year Energy Plan (2019-2023 and

1 – The French National Low-Carbon Strategy provides strategic directions and sets targets for reducing France's greenhouse gas emissions.

2 – In 2016, French CO_2 emissions exceeded the target set for the end of 2015 by more than 3%, based on 2013 figures.

3 – World Bank.

2024-2028). However, it is also necessary to take the implications of longer-term trajectories into account: the French Decarbonisation (SNBC) and European Decarbonisation Roadmaps are now set for 2050, and the Paris Agreement sets a goal for 2100. Decisions on nuclear power need to consider these longer timescales: the benefits in terms of climate change and economic interests of extending France's existing nuclear fleet today, and renewing it from 2030, highlighted in earlier SFEN Technical Notes, underlines the need to maintain a core supply of nuclear power to 2050.

3. **The energy system as a whole:** the 2017 Forecast Report focuses on the electricity supply-demand balance in France. The issues of the electrification of energy uses and the potential for decarbonisation of other energy vectors are addressed exogenously via the forecasting of the overall electricity demand. The RTE scenarios, therefore, do not provide an understanding of the increasing contribution of the electricity system to greenhouse gas reductions across the entire energy system.

The European PRIMES energy model

As a Scientific Society, the SFEN does not have its own model for running energy scenarios. We have therefore chosen to use a proven simulation model, which is recognised by the different European stakeholders, and is sophisticated enough to model the role of French nuclear power in the three areas of interest (Europe, long-term and energy system as a whole).

The modelling scope adopted is that of the scenarios developed by E³ Modelling (backed by the University of Athens) for the European Commission, including as part of the 2016 'Clean Energy for All Europeans' ('Winter Package') project, using the PRIMES model.

Further to the scenarios published in 2016 for the European Commission, **the SFEN asked E³ Modelling for a set of additional scenarios,** within the scope defined for the study, **looking at different possible trajectories for the share of nuclear power in the French electricity mix.**

The PRIMES model is an energy system model which simulates the EU's energy consumption and energy supply system:

- The main input variables are hypotheses of demand, technological characteristics of supply[4] and the energy system, and decarbonisation objectives.
- The model infers coherent trajectories of carbon prices in the EU, which play a central role in adjustment.
- The main output variables are investments, electricity generation and energy mixes, greenhouse gas emissions, and electricity prices (wholesale and retail).

The model is very comprehensive:

- It includes all 28 EU Member States.
- It covers long time periods, with a timescale of 2050 (energy-climate package), and even an outlook for 2070 (recently available).
- It describes the hour-by-hour electricity balance on the markets (which enables integration of the effects related to the intermittent nature of some renewable energy sources), and takes into account interconnections and flows between countries.
- It measures the impact of the electricity vector in decarbonising the transport and heating sectors in the long-term, and thus the impact of French nuclear power on the entire energy system.

4 – Efficiency, unit capacities, flexibilities, investment and fixed and variable costs.

The model measures a wide variety of impacts through a number of evaluation metrics:

- Technical impacts within the power system (considering market rules).
- Economic impacts in terms of the costs of the electricity systems (investment and operation), the price of electricity[5], or cross-border trade.
- Environmental impacts of greenhouse gas emissions.

It should be noted that the impacts in terms of increased CO_2 emissions remain limited by the design of the model. In PRIMES (unlike the RTE or ANCRE scenarios), the price of carbon on the EU-ETS market plays a central role in achieving the decarbonisation objectives: its increase induces substitutions in all sectors in order to stay on the European path for decarbonisation, and this constraint is then reflected by increases in costs for the different stakeholders up to the end consumer.

5 – The model calculates wholesale market electricity prices for each hour of the year, for each agent, verifying that the accounts of the utilities are balanced.

The Scenarios

> The PRIMES model produced the reference scenarios that guide the choices of the European Commission. Shared throughout the EU, it does not reflect the views of specific States or private stakeholders.

Reference Framework: EUCO 'Clean Energy for All Europeans' Package Scenarios
The EUCO Scenarios were developed for the European Commission in 2016 using the PRIMES model. They meet the following objectives:

- Reduction of greenhouse gas emissions by 40% by 2030 (compared with 1990 levels), and by 80% by 2050, when the European energy system becomes deeply decarbonised.
- Renewable energy share of at least 27% in final energy consumption by 2030.
- Energy efficiency efforts to reduce the final energy consumption by 30% by 2030.

Since the Paris Agreement (COP 21), scenarios have been developed up to 2070. They look at trajectories with deep decarbonisation in the very long-term.

The hypotheses concerning energy production costs were developed by a group of economists led by the European Commission[6]. The model integrates the following specific conditions, in particular in relation to electricity generation technologies:

- A drive to reduce production costs that is highly beneficial to renewable energies via learning-by-doing effects, without integrating future reductions in construction costs of new nuclear power.
- The SFEN's position, as recently published[7], is that the construction costs of nuclear power plants can be reduced[8] by 30% through economic series effects and technical learning-by-doing effects.

The Additional SFEN Scenarios
The SFEN's aim was to study the impacts of different hypotheses on extending the operating life of France's nuclear power plants, and their possible renewal in the long-term (2050). As such, we asked E³ Modelling to run **eight additional variants of the EUCO Scenario, developing specific hypotheses for reducing the share of nuclear energy in the French electricity mix.**

6 – The hypotheses can be found in the 'EU Reference Scenario 2016: Energy, Transport and GHG emissions - Trends to 2050' report.
7 – The Cost of New Nuclear in France - SFEN Technical Note, March 2018
8 – To which a potential reduction of 50% in financing costs can be added.

The context for the hypotheses is the same as for the EUCO study, in particular the 2030 EU targets are assumed to be achieved. The shifting of the objective of reducing nuclear power in the electricity mix to 50% in 2025 is considered as confirmed, in light of the recent Government announcement.

The first four scenarios (FNS_50_2030, FNS_50_2035, FNS_50_2040, FNS_50_2045) have different dates by which the nuclear production[9] is reduced to 50% (2030, 2035, 2040 and 2045, respectively).

Two other scenarios look at possible futures up to 2050:

- An 'extreme' scenario (FNS_CONST_NU), which exogenously assumes a stable nuclear capacity[10].
- A scenario (FNS_HIGH_ELEC) which assumes a linear increase in electricity demand of up to +10% by 2030 (i.e. of the order of 1% per year).

Finally, two scenarios, developed by E^3 Modelling, looking at deep decarbonisation by 2070 are also published in this study:

- The first (FNS_2070) is an extrapolation to 2070 of the 2050 scenario: electrification rate increases in order to further reduce greenhouse gas emissions.
- The second (FNS_2070_SF) expects additional use of synthetic fuels, produced using electricity, in order to approach carbon neutrality.

9 – The nuclear production ratio has been defined using a flexible approach: nuclear production is net of exports.

10 – The investment function is then adjusted exogenously to compensate for shutdowns.

Table 1 Scenarios Summary Table (simplified).

Scenario Name	Projection Year	50% share by	Details
FNS_50_2045	2050	2045	The share of nuclear generation in the domestic electricity supply is 50% in 2045
FNS_50_2040	2050	2040	The share of nuclear generation in the domestic electricity supply is 50% in 2040
FNS_50_2035	2050	2035	The share of nuclear generation in the domestic electricity supply is 50% in 2035
FNS_50_2030	2050	2030	The share of nuclear generation in the domestic electricity supply is 50% in 2030
FNS_CONST_NU	2050	N/A	Stable nuclear capacity of about 63GW maintained throughout the projection period
FNS_HIGH_ELEC	2050	N/A	Electricity demand increases linearly up to +10% by 2030 compared to the reference Winter Package Scenario
FNS_2070	2070	N/A	Extension of EU2050 context up to 2070, with a higher rate of electrification
FNS_2070_SF	2070	N/A	As for FNS_2070, with greater use of synthetic fuels produced using electricity

Key Lessons from the SFEN Scenarios

> « Scenarios should not be considered as predictions but as analyses of the impacts and trade-offs of different technology choices and policy targets, thereby providing a quantitative approach to support decision-making in the energy sector. » **International Energy Agency**

1. All scenarios studied show both strong growth of renewable electricity and the need for maintaining a core supply of nuclear power to 2050 and beyond

1.1. In all scenarios, there is a substantial increase in renewables. In the FNS_50_2045 scenario, their installed capacity reaches 150GWe in 2050 and nearly 60% of the French electricity mix.

1.2. French nuclear, dispatchable and flexible, supports the development of electricity from renewable energies in France.

1.3. The need for maintaining a core supply of nuclear power in France, estimated according to the scenarios up to 2050 at an installed capacity of around 35-40GW, corresponding to a production ratio of 35-40%.

1.4. Beyond France, the scenarios show the need for maintaining a core supply of 70GW of nuclear power distributed across twelve other countries in Europe.

2. Comparison of scenario FNS_50_2045 (objective of 50% reached in 2045) to scenario FNS_50_2030 (objective reached in 2030) shows:

2.1. A 10% reduction in the cost of electricity, owing to the current nuclear fleet's highly competitive production costs.

2.2. Savings of €20 billion in investment requirements: the *Grand Carénage* refurbishment programme costs less than building any new production capacities.

2.3. Doubling of French electricity exports, favourable both for decarbonising the mix of neighbouring countries and for trade balance.

2.4. An additional saving of €18 billion between now and 2050, through integration of possible improvements in competitiveness of new nuclear (SFEN estimates a reduction of 30% for construction costs[11])

3. The scenarios show the key role electricity plays in decarbonising the energy system, with substantial increase in demand for electricity over the medium- to long-term

3.1. All scenarios show an increased share of electricity in the energy mix (over 40% by 2030), even as the total energy consumption drops considerably.

3.2. The FNS_HIGH_ELEC scenario shows that greater use of electricity could save €90 billion in decarbonisation of the energy system.

3.3. Even with only a very slight increase in demand (1% per year[12]), the need for nuclear power would still exceed the size of the current fleet after 2030, which calls for caution in the pace of reducing the fleet.

3.4. Beyond 2050 (FNS_2070 and FNS_2070_SF), the need for deep decarbonisation supports electricity demand growth, with a potential 'rebound effect' for nuclear power in France and Europe, and an increase in nuclear generation of around 200TWh between 2050 and 2070.

SFEN Recommendations

- France's Multi-Year Energy Plan (*PPE*) is designed to provide for the progressive taking into account of the numerous uncertainties, in 5 year periods, in terms of demand, the strategies of France's European neighbours, and expected technical and economic progress. Maintaining available nuclear power is less expensive and more consistent with the Multi-Year Energy Plan's adaptive approach; it will also make it possible for France to programme its decarbonisation more efficiently, in the face of these uncertainties. Reduction of nuclear power must be managed in line with the development of other low-carbon energies, and not preemptively.

- The need for maintaining a core supply of nuclear power to 2050, and the potential rebound of this energy in France and Europe in the long-term, in order to achieve deep decarbonisation objectives, make a public discussion essential. This discussion would be focused on the setting up of an industrial programme to bring about significant cost reductions for third generation nuclear power. Progress made during renewal of the French nuclear fleet, in terms of competitiveness, will be of benefit to the rest of Europe, where 70GW of new nuclear capacity is to be built between now and 2050.

11 – The Cost of New Nuclear in France - SFEN Technical Note, March 2018.
12 – From 2020.

Detailed version

1. All scenarios studied show both strong growth of renewable electricity and the need for maintaining a core supply of nuclear power to 2050 and beyond

1.1. In all scenarios, there is a substantial increase in renewable energies. In the FNS_50_2045 scenario, their installed capacity reaches 150GWe in 2050 and nearly 60% of the French electricity mix

Depending on the version, renewable energies in France comprise between 34% and 68% of the electricity mix in 2050. In all scenarios, their installed capacity increases substantially in both Europe and France (see Figure 1).

In the FNS_50_2045 scenario the installed capacity of renewables reaches 150GW in France, with production of 385TWh, in addition to production from hydropower (68TWh). This production comes mainly from wind (226TWh) and solar (82TWh).

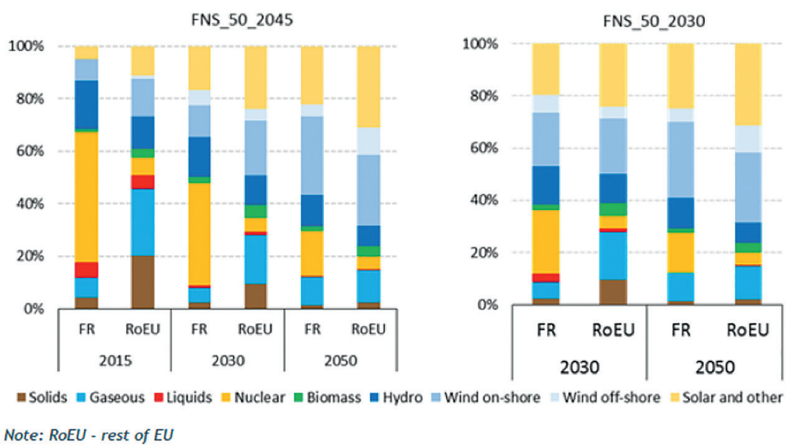

Figure 1 - Comparison of share of installed capacity in FNS_50_2030 and FNS_50_2045 scenarios.

1.2. French nuclear, dispatchable and flexible, supports the development of electricity from renewable energies in France

In the coming decades, storage technologies, that make it possible to move away from *back-up* dispatchable technologies and manage a fleet of mainly renewable energies, will not be ready. This outcome is clearly visible in RTE's 'Ohm' scenario, where fossil fuel means of production (gas-fired power plants) are required, leading to an increase in CO_2[13] emissions. Conversely, in the scenarios studied in this technical note, nuclear power contributes significantly to grid balancing in France and Europe, without emitting additional CO_2.

In France, the nuclear fleet already adapts its load profile to variations in demand. At the inter-seasonal level, unit outages are planned for the summer, corresponding to the period of lowest demand. At the daily and intraday levels, the majority of nuclear reactors can adjust their power by up to 80% in less than 30 minutes. This flexibility helps to manage the intermittency of renewable generation and limits the associated network costs[14].

The concept of a *core supply* of nuclear power also acknowledges the fact that the flexibility of the installed nuclear fleet makes it technically possible to envisage, in the short- and medium-term, the feasibility of up to 30% of French production coming from intermittent energy sources[15] with limited risk.

In E[3] Modelling's simulations, a reduction in nuclear power production benefits renewables (Figure 2). Nuclear power, whose availability factor is greater than 80% (and greater than 90% for the EPR), is used at a much lower rate (around 75%) to make way for renewable energies, which have priority access to the grid in the years 2025-2035.

13 – Up to around 20 million tonnes of CO_2 in 2025, if we want to reduce nuclear production by this deadline.

14 – This does not prevent network costs from reaching more than one third of the 'technical' cost of electricity at the end of the period.

15 – Several recent studies show that the French nuclear fleet has several drivers for responding to increasing need for flexibility in the coming years, linked to the growing integration of renewable energies into the mix. See RGN review (2017, Number 1), 'Energy Transition: Nuclear and Renewables, together for success' *(Transition Energétique : Nucléaire et renouvelables, complémentaires pour réussir).*

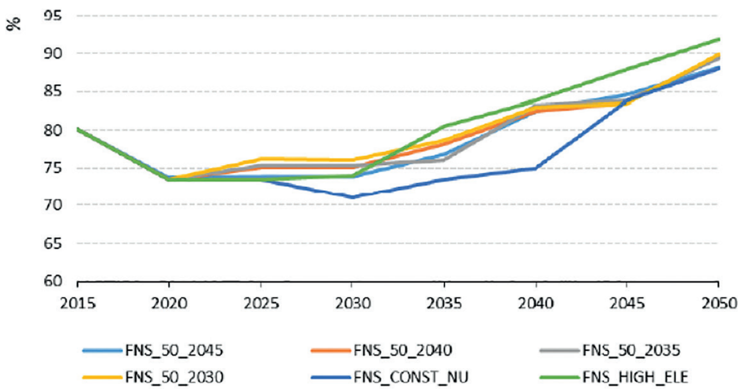

Figure 2 - Average annual load factor of the French nuclear fleet.

In the longer-term, other technologies, such as storage, become available and contribute to the *back-up* requirements of renewables. A significant share of nuclear is then used as a core supply, which increases its profitability.

All the scenarios show, in particular the FNS_50_2045 scenario, that extending use of existing nuclear power makes it possible to develop a sustainable coexistence between nuclear and renewables, under economic conditions that are of benefit to the entire energy mix. At the 2050 timescale, the scenarios demonstrate that a re-optimisation of the fleet is possible, with new proportions of the different sources of low-carbon production, and a core supply of nuclear power, indispensable but at a lower level than today.

1.3. The need for maintaining a core supply of nuclear power in France, estimated according to the scenarios up to 2050 at an installed capacity of around 35-40GW, corresponding to a production ratio of 35-40%

The scenarios make the assumption that there will be a partial renewal of the French nuclear fleet by 2050: in the FNS_50_2045 scenario, nearly 20GWe of new nuclear capacities are built in France in the 2030-50 period, with eight EPRs during the 2030-40 decade, then six EPR for 2040-50.

It is important to note that the PRIMES model does not take into account possible savings on construction costs, estimated by the SFEN at 30%[16]. This reduction in costs comes in particular from the series effect, resulting from a construction programme whose pace is consistent with the renewal of the park envisaged in scenario FNS_50_2045. We can therefore consider that the ratio used in these scenarios is conservative.

1.4. Beyond France, the scenarios show the need for maintaining a core supply of 70GW of nuclear power distributed across twelve other countries in Europe

The European Commission 2016 reference scenario plans to maintain the nuclear component at 109GW in 2050, compared to 120GW currently. This takes into account investments in new nuclear capacities by 2050, as considered in twelve Member States: Bulgaria, Finland, France, Hungary, Lithuania, Poland, Romania, the United Kingdom, Slovakia, Slovenia, Sweden and the Czech Republic[17].

Table 2 shows changes in nuclear capacities outside of France, which will increase from 57GW in 2015 to 72GW in 2050. At this point, the share of French nuclear in European nuclear capacity will be 34% (compared to 52% today). Figure 3 shows how investments in new units are distributed over time in France and the rest of Europe.

16 – The cost of third generation nuclear power is based on two factors: the cost of investment and the cost of financing. The SFEN considers that significant reductions are possible compared to the first construction projects: of the order of 30% on the cost of construction, owing to series and learning-by-doing effects, and up to 50% on the financial costs, particularly through contract design.

17 – The 6 countries that are already committed to building new units: Finland, France, Hungary, Romania, the United Kingdom, Slovakia.

	2015	2020	2025	2030	2035	2040	2045	2050
France	63.2	61.3	59.5	59.5	56.3	49.1	45.7	37.2
Rest of EU	57.6	52.9	45.6	50.4	56.2	68.7	71.0	71.9
Total EU28	**120.8**	**114.2**	**105.1**	**109.9**	**112.6**	**117.8**	**116.7**	**109.2**
Share of French nuclear in installed nuclear capacity	52%	54%	57%	54%	50%	42%	39%	34%

Tableau 2 - Total nuclear capacity in France and the rest of the EU28, in FNS_50_2045 scenario.

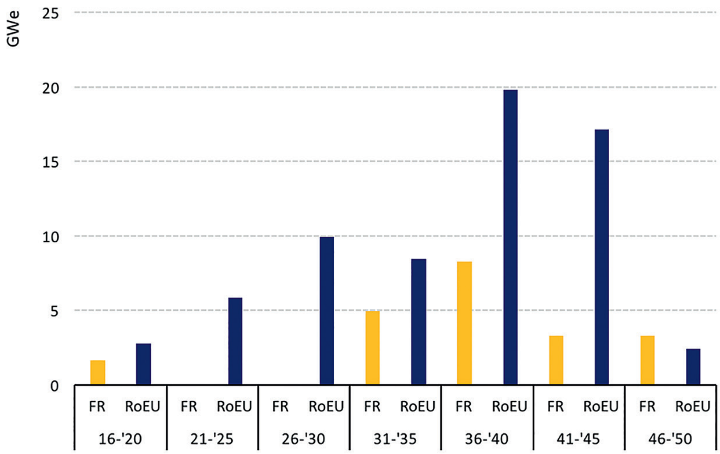

Figure 3 - Comparison of investments in new nuclear capacity in France and the rest of Europe (RoEU) in FNS_50_2045 scenario.

One of the main objectives of these twelve Member States is to reduce the greenhouse gas emissions of their electricity production.

The projections show that in 2030 France and Sweden maintain their position for decarbonised electricity, followed by Finland, the United Kingdom, Hungary and Slovakia.

Germany, however, will not be doing much better than Poland in 2030. This under-performance by Germany is due to the initial importance of their coal and lignite power plants, which still provide more than 40% of electricity generation today. It is not possible to rapidly transform an energy system, when the transformation is as radical as that involved in the Energiewende. On the other hand, the objectives of the Energiewende may be feasible for 2050.

In comparison, France is in a strong position to capitalise on past and now largely amortised investments in nuclear power. The cost of producing existing nuclear power makes it the most competitive means of low-carbon electricity generation. Elsewhere in Europe, however, production with high emissions (coal, lignite) is expected to be replaced by low-carbon units. In this context, it is necessary to prolong the operation of the French nuclear fleet, whose cost per kWh remains more competitive than the European average. By 2030, France retains an advantage of more than 40€/MWh compared to the rest of Europe.

2. Comparison of scenario fns_50_2045 (objective of 50% reached in 2045) to scenario FNS_50_2030 (objective reached in 2030) shows:

2.1. A 10% reduction in the cost of electricity, owing to the current nuclear fleet's highly competitive production costs

The postponement of the 50% target for the share of nuclear energy in the French electricity mix, from 2030 to 2045, makes it possible to limit the increase of electricity prices for end consumers (households, and especially manufacturers).

Electricity prices[18] are higher in the FNS_50_2030 scenario, where fewer nuclear reactors have extended operating lives, and additional new investments must be made to compensate for the lack of capacity. The FNS_50_2045 scenario results in prices up to 15€/MWh lower compared to FNS_50_2030 (Figure 4).

The stable nuclear capacity scenario (FNS_CONST_NU) produces upward pressure on prices in the longer-term, owing to the costs of the investments needed to replace nuclear capacity after 60 years of operation. These economic results could be improved (reducing the cost of investments) with greater consideration of the potential for reducing nuclear reactor construction costs.

18 – Final prices for consumers include production and network costs, as well as taxes.

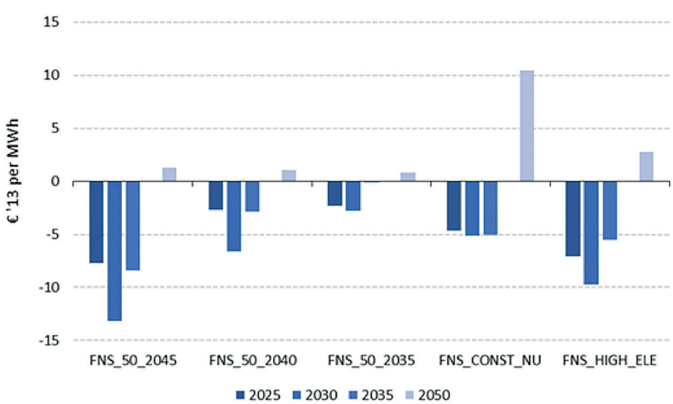

Figure 4 - Scenario electricity prices compared to FNS_50 _2030 scenario.

2.2. Savings of €20 billion in investment requirements: the *Grand Carénage* refurbishment programme costs less than building any new production capacities

The overall amount of investment in electricity system infrastructures will also be a factor in decision-making: in the different scenarios it increases substantially, reaching around €600 billion in France over the 2020-2050 period, with a fairly balanced spread between power plants and the grid. There are, however, significant differences between the scenarios studied.

In the medium-term, significant savings in capital expenditures are made in scenarios where the reduction of the share of nuclear energy is postponed. The investments required for the completion of the *Grand Carénage* refurbishment programme are significantly less than those needed for construction of new production capacities. The FNS_50_2045 scenario is thus the one which minimises total investment requirements until 2050, with an overall reduction of €20 billion compared to the FNS_50_2030 scenario.

It is interesting that the stable nuclear capacity scenario (FNS_CONST_NUC) is the one which, compared to FNS_50_2030, requires the most investment (of the order of €120 billion), but results in significant savings on network costs (of around €60 billion). Indeed, the FNS_50_2030 scenario produces a significant increase in network costs related to the integration of intermittent renewable sources.

In addition, the FNS_CONST_NUC scenario leads to development, by 2050, of a new fleet with a significant operating life in the long-term. This raises the question of the quality of the economic 'metrics' capable of measuring scenario costs, with important 'horizon effects'. More work is needed in this area[19].

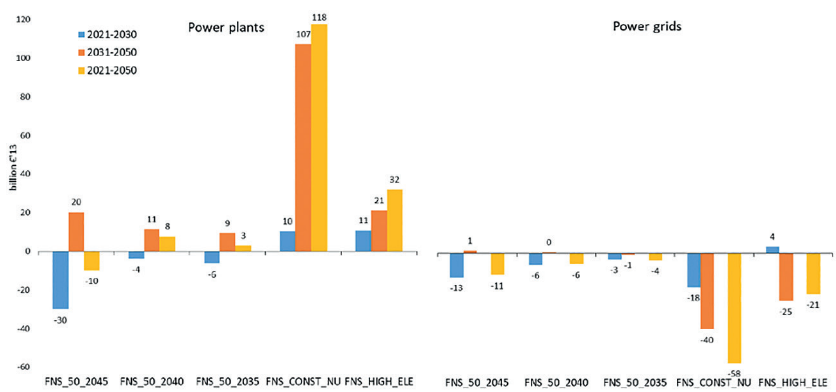

Figure 5 - Differences in capital expenditures on power plants (left) and power grids (right) in France compared to FNS_50_2030 scenario.

2.3. Doubling of French electricity exports, favourable both for decarbonising the mix of neighbouring countries and for trade balance

The European Union benefits from a significant amount of low-carbon French electricity production. Each year, France exports about 10% of production for about €2 billion a year[20].

These exports amount to 64TWh in 2030 in the FNS_50_2045 scenario, whereas they fall to less than 30TWh in the FNS_50_2030 scenario (Figure 6).

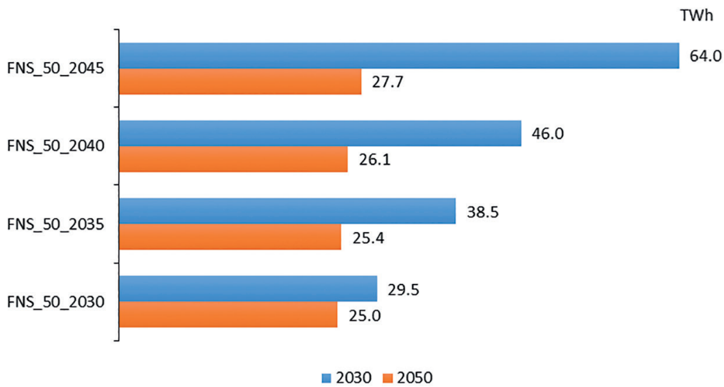

Figure 6 - Net electricity exports (France).

The importance of French nuclear energy for the EU can be seen when we look at the average unit cost of reducing CO_2 emissions at the European level. Based on the FNS_50_2030 scenario, the study shows that emission reductions of one tonne of CO_2 would cost, on average, €1.90 less than in the FNS_50_2045 scenario, over the 2021-2050 period.

19 – One option is to build very long-term scenarios and to reason in Net Present Value terms. This has not been possible in this study (and indeed, as far as the SFEN is aware, in any of the studies used to inform Multi-Year Energy Plan decisions).

20 – French Nuclear Industry Strategy Committee - *Comité Stratégique de la Filière Nucléaire* (CSFN, 2014)

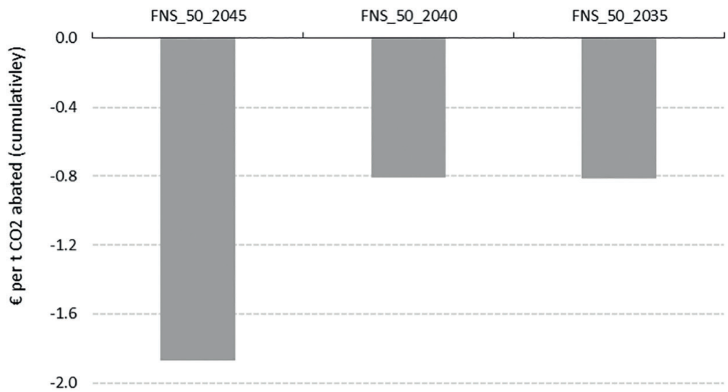

Figure 7 - Average unit cost of reducing CO_2 emissions in the EU28 over the 2021-2050 period, relative to the FNS_50_2030 scenario.

2.4. An additional saving of €18 billion between now and 2050 through integration of possible improvements in competitiveness of new nuclear (SFEN estimates a reduction of 30% for construction costs[21])

The overall positive results would be considerably strengthened by a reduction in construction costs for new nuclear power. The simulations of the PRIMES model do not take into account the potential for reducing costs that have been identified by the SFEN at around 30% compared to the current costs of new nuclear power (€5100/kWe in the PRIMES model).

On this basis, and given the prospects for renewing the fleet in the various scenarios between 2020 and 2050, investments in new nuclear power would be impacted as follows:

- **FNS_50_2030 to FNS_50_2045 scenarios:** reduction of €18.4 billion, from €89 to €70 billion.
- **FNS_HIGH_ELEC scenario:** reduction of €30.7 billion, from €148.5 to €117.8 billion.
- **FNS_CONST_NU scenario:** reduction of €45 billion, from €215 to €170 billion.

In addition to the benefits of reduced construction costs, improved financing conditions – through a lower cost of capital[22] – would enhance the economic benefit of maintaining a significant core supply of nuclear power. This effect would, as such, positively impact the other economic factors studied previously (cost and price), feeding into investment decisions for new nuclear, which has not been studied here.

3. The scenarios show the key role electricity plays in decarbonising the energy system, with a substantial increase in demand for electricity over the medium- to long-term

3.1. All scenarios show an increased share of electricity in the energy mix (over 40% by 2030), even as the total energy consumption drops considerably

The EUCO scenario involves energy efficiency efforts to reduce total energy consumption in 2030 by 30%.

As the International Energy Agency has shown, 'electricity' must be used to decarbonise other sectors of the economy. This is the case, for example, for mobility either directly by using the electrification of transport, or indirectly through synthesis of biofuels using electricity. This implies an increasing share of electricity in energy consumption.

Electricity demand, however, remains weak at the beginning of the period due to improvements in energy efficiency. It then gets going again from 2035 as decarbonisation technologies mature.

In this context, it seems necessary to look beyond 2035 in order to see significant differences between the different possible electricity system scenarios.

21 – The Cost of New Nuclear in France - SFEN Technical Note, March 2018

22 – An assumption of a Weighted Average Cost of Capital (WACC) of 8.5% is used in all the scenarios studied.

3.2. The FNS_HIGH_ELEC scenario shows that greater use of electricity could save €90 billion in decarbonisation of the energy system

In the FNS_HIGH_ELEC scenario, increased use of electricity makes it possible to substantially reduce the cost of the entire energy system, with a saving of nearly €90 billion for the electricity system. Greater demand for electricity will increase use of installed electric power capacities (nuclear and, to a lesser extent, renewables), proportionally reducing expenditures on fossil fuels.

Additional investment is needed to meet this demand for electricity, with construction of new nuclear reactors (around four units) by 2030. Electricity generation from nuclear increases to go beyond the limit of 63.2GW.

These results are mainly due to the very low production costs of existing nuclear (even when the *Grand Carénage* refurbishment programme is included) – this 'cash' cost has been estimated by the SFEN to be around 32-33€/MWh[23]. Extension of the operating life of the current fleet is, therefore, by and large the most economic option. This is also related to nuclear's extremely low CO_2 emissions[24], the fact that it is dispatchable, as well as being flexible – a core supply of nuclear power contributes significantly to the resilience of the electricity system.

In 2050, the share of nuclear decreases, as the PRIMES model does not take account of potential improvements resulting from increased competitiveness of new nuclear over the coming decades, as opposed to renewables whose construction costs continue to decrease rapidly.

3.3. Even with only a very slight increase in demand (1% per year)[25], the need for nuclear power would still exceed the size of the current fleet after 2030, which calls for caution in the pace of reducing the fleet

Availability of a nuclear fleet which is of 'sufficient size' in terms of power, is an insurance against uncertainty (demand, cost of renewables, technical and social feasibility).

The adaptive approach of the Multi-Year Energy Plan (in periods of 5 years) allows for progressively taking into account reduced uncertainties, including changing demand which plays a key role.

As such, transitioning from fossil fuels to electricity for end use sectors (industry, households, services and transport) leads to large emissions reductions, provided the electricity is low-carbon (which is the case in France). This substitution mechanism, in particular through differences in relative costs, leads to increased demand.

Conversely, energy efficiency significantly reduces energy demands, through building renovations, development of quality standards for household electrical appliances, and use of improved techniques available in industrial sectors, as well as in research into more efficient vehicles.

Despite the situation being difficult to model, attempting to resolve opposing drivers, this scenario plays a key role in decision-making for the fleet. It is important here to remember that the context is asymmetric. As the Energy Transition for Green Growth Law (*LTECV*) plans for a reduction in the share of nuclear, the decision to keep nuclear power capacities is very different to that concerning investment (in the event of a lack of power or energy). Maintaining nuclear is noticeably less expensive than developing any new means of production[26]. These mechanisms of progressive adaptation, combined with typical timescales for nuclear power, point strongly to the need for future scenarios covering several decades.

They support consideration of a scenario with continuously increasing demand for electricity (although remaining low, at around 1% per year from 2020 to 2030). This is the objective of the 'HIGH_ELEC' scenario, which as a result combines increased demand with a stable nuclear fleet at the start of the period.

This scenario highlights two types of advantage. On the one hand, electricity prices are relatively low, incremental demand being covered by new investments in power plants whose marginal costs increase only slightly. All of which occurs alongside a temporarily higher share of nuclear power, with lower production costs. On the other hand, investments in development of electricity grid infrastructures are spread across a large number of consumers. In addition, the total cumulative cost of the energy system is lowest in this scenario, despite additional investments of around €25 billion compared to the 2045 scenario, which means that the electricity sector benefits from additional economies of scale.

Overall, this scenario combines a cautious move towards reducing nuclear power (only reducing it at the end of the period) and substantial substitution of electricity by other types of energy. It makes it possible to combine decarbonisation with low electricity prices.

23 – Production Costs for the French Nuclear Fleet – SFEN Technical Note, November 2017

24 – According to the IPCC, nuclear power is one of the sources of electricity with the lowest carbon emissions: below that of wind and solar, and at the same level as hydropower.

25 – From 2020

26 – This reasoning meets its limit in the nuclear capacity factor. Keeping reactors for use only during a few hours a year is not possible in the long run. However, the principle of keeping the power margin by adjusting a few years later is the most competitive. It will be adjusted when the level of demand requires it, bridged by the intermittent renewables (for the part of the fleet involved, depending on costs, policies, social feasibility), and with improved technologies for balancing needs (smart grid, storage, demand side management, etc.). It is therefore necessary to maintain energy security and keep options open. Nuclear power is one of them, even if the field is very open by mid-Century: for the moment (the next 20 years and probably significantly more), the French core supply of nuclear is an essential asset, so we would be wise to keep it.

3.4. Beyond 2050 (FNS_2070 and FNS_2070_SF), the need for deep decarbonisation supports electricity demand growth, with a potential 'rebound effect' for nuclear power in France and Europe, and an increase in nuclear generation of around 200TWh between 2050 and 2070

The latest scenarios from the European Commission (EUCO) plan for deep decarbonisation in Europe by 2050. For this, the International Energy Agency makes it clear that it is necessary to play two cards: on the one hand, energy efficiency with an overall reduction of demand for energy in France of nearly 27% between 2015 and 2050; and on the other hand, the 'electricity' vector for decarbonising the different sectors of the economy on this timescale. For example, for mobility either directly by using the electrification of transport, or indirectly through synthesis of biofuels using electricity. This implies an increasing share of electricity in energy consumption.

This development leads to a considerable increase in electricity demand (which reaches 700TWh by 2050, then up to 1200TWh by 2070), and provides opportunities for new investment in nuclear energy in France and the rest of Europe.

Additional notes on the importance of using very long-term scenarios to inform decision-making

The results of these scenarios provide insights into the short- to medium-term comprising the decades 2020-2040, and as such inform the decisions to be made up to 2028, which are part of the new Multi-Year Energy Plan (*Programmation pluriannuelle de l'énergie - PPE*). At the end of the period in question, we have the 'economic' phase where the share of nuclear decreases as a result of reduced costs for renewable energies, coinciding with the end of programmes for extending the operating life of the installed nuclear fleet.

This period, with the assumptions of the model, sees an open world, with an 'optimum' economy including a place for nuclear (core supply), but which is smaller than today's. The scenario with 'nuclear stable up to 2050', is not therefore the least expensive, despite its increased contribution to exports.

The key question is not, therefore, to know whether we must reduce nuclear or not, but to know at what pace a particular reduction is reasonable. At this stage, we can observe that the current energy transition law pre-empts the situation and, as such, jeopardises France's climate change objectives.

Other simulations looking at a more distant future show that a nuclear 'rebound' is possible, and even likely, after 2050, which we can observe by extending the timescale studied to 2070 (Figure 8). This rebound is the result of significant increases in demand for electricity starting as soon as 2040-50, due in particular to electrification of transport and to production of hydrogen by electrolysis, and even accentuated up to 2070 by development of synthetic biofuels (FNS_2070_SF scenario). We will see a saturation of wind and solar technical potential given the level of demand (see the comparison of the two scenarios below), owing to a scarcity of favourable sites. Hence the increased nuclear production between 2050 and 2070 shown below in the SF scenario ('Synthetic Fuels').

	FNS_2070 (TWh %)			**FNS_2070_SF (TWh %)**		
	2050	**2070**	**Increase**	**2050**	**2070**	**Increase**
Nuclear	288	346	59	288	388	100
Wind	265	446	181	313	469	156
Solar	117	165	47	172	222	50
Others	119	114	-4	132	122	-10
Total	789	1072	282	904	1202	298

Figure 8 - Share of different energy sources of electricity production (TWh) in France between 2050 and 2070.

It is, therefore, important to have this potentially significant increase in electricity demand in mind when considering the future energy mix. And this has direct impacts on the nuclear fleet, owing to the long operating life of reactors (which is amortised over long periods, resulting in economic performance). Developments by 2040 and 2050 will incorporate these expectations.
An existing fleet whose economic and technical service life is reduced will not have the same value as a new fleet. Conversely, especially if demand is stable, or even decreasing, a modern fleet, regardless of its means of production, can be an obstacle ('lock-in' syndrome) to rapid adaptation, by creating significant future costs, such as stranded costs from premature shutdown of equipment. Very long-term scenarios make it possible to study the resilience of nuclear fleets, in an uncertain world.

In conclusion, the purpose of long- and very long-term scenarios is to look at outcomes for nuclear fleets over long time periods, in order to understand developments and possible structural changes in external variables (examples include electricity demand, cost of new technologies, etc.), to predict them and to highlight options in terms of future uncertainties (for which a range of scenarios can provide insights).

Nuclear, through its reliability, its predictability (especially in terms of production costs) and its programming flexibility, is one of the tools that provide improved control over these long time periods.

In this context, lessons learned from the first Generation-3 reactors, including the EPR, should encourage more Member States to re-invest in new capacities. Maintaining nuclear in Europe, outside of France (+70GWe to install by 2050) is an excellent opportunity for the French nuclear industry. In Europe's vision for mid-Century, the most reliable scenarios are based on a strong mobilisation of nuclear and an increased European fleet in several Member States. It is definitely in these countries, where industry will be most efficient, with a qualified workforce and high safety standards, that it is important to focus these developments: France has a key role to play.

Scenarios

Table of Outputs for FNS_50_2030 Scenario: Share of nuclear power reduced to 50% of electricity mix by 2030.

		2010	2020	2030	2040	2050
Energy System	**Final energy consumption (Mtep)**	155	157	131	123	113
	Electricity in final energy (%)	25%	25%	29%	37%	43%
	Energy Sector CO_2 emissions (t CO_2)	360	307	241	151	77
	EU-ETS carbon price (€/t CO_2)	11	15	28	148	502

		2010	2020	2030	2040	2050
Installed Electricity Capacity (GWe)	**Total**	**123**	**147**	**162**	**188**	**221**
	Nuclear	**64**	**63**	**40**	**42**	**34**
	Existing nuclear	64	61	38	27	13
	New nuclear	0	1.7	2	15	21
	Renewables	**32**	**63**	**100**	**120**	**157**
	Fossil fuels	**27**	**21**	**22**	**25**	**30**

		2010	2020	2030	2040	2050
Electricity Generation (TWh)	**Total**	**564**	**600**	**536**	**638**	**700**
	Nuclear	**429**	**407**	**268**	**307**	**268**
	Existing nuclear	429	396	256	199	99
	New nuclear	0	11	11	108	169
	Renewables	**80**	**163**	**260**	**325**	**424**
	Fossil fuels	**55**	**30**	**8**	**6**	**8**

			2010	2020	2030	2040	2050
Economic Results for Electricity System	**Final electricity price (€/MWh)**		101	128	147	147	142
	Cost of production (€/MWh)		63	101	86	79	62
	Net electricity exports (TWh)		60	66	30	27	27
				2010-20	**2020-30**	**2030-40**	**2040-50**
	Investments in the electricity system (€Bn_2013)	**Network**		**49**	**63**	**90**	**84**
		Power plants		**60**	**80**	**86**	**69**
		Nuclear		8	24	49	26
		Renewables		46	54	30	37
		Fossil fuels		6	3	6	7

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Table of Outputs for FNS_50_2035 Scenario: Share of nuclear power reduced to 50% of electricity mix by 2035.

		2010	2020	2030	2040	2050
Energy System	Final energy consumption (Mtep)	155	157	131	123	113
	Electricity in final energy (%)	25%	25%	29%	37%	43%
	Energy Sector CO_2 emissions (t CO_2)	360	307	241	151	77
	EU-ETS carbon price (€/t CO_2)	11	15	27	149	501

		2010	2020	2030	2040	2050
Installed Electricity Capacity (GWe)	**Total**	**123**	**147**	**160**	**188**	**217**
	Nuclear	**64**	**63**	**49**	**44**	**35**
	Existing nuclear	64	61	47	30	14
	New nuclear	0	1.7	2	15	21
	Renewables	**32**	**63**	**95**	**120**	**152**
	Fossil fuels	**27**	**21**	**20**	**26**	**30**

		2010	2020	2030	2040	2050
Electricity Generation (TWh)	**Total**	**564**	**601**	**548**	**638**	**700**
	Nuclear	**429**	**407**	**321**	**322**	**277**
	Existing nuclear	429	396	309	214	109
	New nuclear	0	11	11	108	169
	Renewables	**80**	**163**	**246**	**324**	**415**
	Fossil fuels	**55**	**31**	**8**	**6**	**8**

		2010	2020	2030	2040	2050
Economic Results for Electricity System	Final electricity price (€/MWh)	101	128	144	147	143
	Cost of production (€/MWh)	63	101	85	79	63
	Net electricity exports (TWh)	31	66	39	27	28

			2010-20	2020-30	2030-40	2040-50
Economic Results for Electricity System	Investments in the electricity system (€Bn_2013)	**Network**	**49**	**60**	**92**	**81**
		Power plants	**60**	**74**	**99**	**66**
		Nuclear	8	25	56	26
		Renewables	46	47	35	34
		Fossil fuels	6	2	8	6

Table of Outputs for FNS_50_2040 Scenario: Share of nuclear power reduced to 50% of electricity mix by 2040.

		2010	2020	2030	2040	2050
Energy System	Final energy consumption (Mtep)	155	157	131	123	113
	Electricity in final energy (%)	25%	25%	29%	37%	43%
	Energy Sector CO_2 emissions (t CO_2)	360	307	241	151	77
	EU-ETS carbon price (€/t CO_2)	11	15	27	149	503

		2010	2020	2030	2040	2050
Installed Electricity Capacity (GWe)	**Total**	**123**	**147**	**157**	**184**	**218**
	Nuclear	**64**	**63**	**49**	**44**	**35**
	Existing nuclear	64	61	49	36	30
	New nuclear	0	1.7	0	8	5
	Renewables	**32**	**63**	**89**	**115**	**152**
	Fossil fuels	**27**	**21**	**19**	**25**	**30**

		2010	2020	2030	2040	2050
Electricity Generation (TWh)	**Total**	**564**	**600**	**560**	**641**	**700**
	Nuclear	**429**	**407**	**321**	**322**	**277**
	Existing nuclear	429	396	309	214	109
	New nuclear	0	11	11	108	169
	Renewables	**80**	**163**	**232**	**313**	**415**
	Fossil fuels	**55**	**30**	**7**	**6**	**8**

			2010	2020	2030	2040	2050
Economic Results for Electricity System	Final electricity price (€/MWh)		101	128	140	146	143
	Cost of production (€/MWh)		63	101	83	79	64
	Net electricity exports (TWh)		31	66	46	28	28
				2010-20	2020-30	2030-40	2040-50
	Investments in the electricity system (€Bn_2013)	**Network**		**49**	**57**	**91**	**83**
		Power plants		**60**	**76**	**96**	**71**
		Nuclear		8	35	51	26
		Renewables		46	39	37	39
		Fossil fuels		6	2	7	7

Table of Outputs for FNS_50_2045 Scenario: Share of nuclear power reduced to 50% of electricity mix by 2045.

		2010	2020	2030	2040	2050
Energy System	**Final energy consumption (Mtep)**	155	157	131	124	113
	Electricity in final energy (%)	25%	25%	29%	37%	43%
	Energy Sector CO_2 emissions (t CO_2)	360	311	240	151	77
	EU-ETS carbon price (€/t CO_2)	11	15	27	146	500

		2010	2020	2030	2040	2050
Installed Electricity Capacity (GWe)	**Total**	**123**	**145**	**153**	**179**	**215**
	Nuclear	**64**	**61**	**59**	**49**	**37**
	Existing nuclear	64	60	58	34	16
	New nuclear	0	1.7	2	15	21
	Renewables	**32**	**63**	**76**	**106**	**148**
	Fossil fuels	**27**	**21**	**17**	**24**	**30**

		2010	2020	2030	2040	2050
Electricity Generation (TWh)	**Total**	**564**	**600**	**587**	**649**	**704**
	Nuclear	**429**	**396**	**385**	**355**	**288**
	Existing nuclear	429	385	374	247	122
	New nuclear	0	11	11	108	166
	Renewables	**80**	**163**	**196**	**288**	**406**
	Fossil fuels	**55**	**41**	**6**	**6**	**10**

			2010	2020	2030	2040	2050
Economic Results for Electricity System	**Final electricity price (€/MWh)**		101	128	132	142	143
	Cost of production (€/MWh)		63	101	79	76	65
	Net electricity exports (TWh)		31	66	64	31	30
				2010-20	**2020-30**	**2030-40**	**2040-50**
	Investments in the electricity system (€Bn_2013)	**Network**		**49**	**51**	**91**	**84**
		Power plants		**67**	**50**	**98**	**77**
		Nuclear		15	27	50	25
		Renewables		46	22	41	46
		Fossil fuels		6	1	7	6

Table of Outputs for FNS_CONST_NU Scenario: Nuclear power capacity kept stable at about 63GW up to 2050.

		2010	2020	2030	2040	2050
Energy System	Final energy consumption (Mtep)	155	157	131	123	112
	Electricity in final energy (%)	25%	25%	29%	37%	42%
	Energy Sector CO_2 emissions (t CO_2)	360	303	240	151	76
	EU-ETS carbon price (€/t CO_2)	11	15	30	149	502

		2010	2020	2030	2040	2050
Installed Electricity Capacity (GWe)	**Total**	**123**	**148**	**148**	**164**	**161**
	Nuclear	**64**	**65**	**65**	**63**	**63**
	Existing nuclear	64	63	63	58	14
	New nuclear	0	1.7	2	5	50
	Renewables	**32**	**63**	**67**	**85**	**82**
	Fossil fuels	**27**	**21**	**17**	**16**	**16**

		2010	2020	2030	2040	2050
Electricity Generation (TWh)	**Total**	**564**	**601**	**585**	**660**	**727**
	Nuclear	**429**	**417**	**402**	**413**	**490**
	Existing nuclear	429	406	392	380	107
	New nuclear	0	11	10	33	383
	Renewables	**80**	**163**	**177**	**237**	**228**
	Fossil fuels	**55**	**21**	**6**	**10**	**9**

			2010	2020	2030	2040	2050
Economic Results for Electricity System	Final electricity price (€/MWh)		101	128	140	142	153
	Cost of production (€/MWh)		63	101	88	79	80
	Net electricity exports (TWh)		31	66	68	39	33
				2010-20	2020-30	2030-40	2040-50
	Investments in the electricity system (€Bn_2013)	**Network**		**49**	**44**	**83**	**52**
		Power plants		**62**	**88**	**53**	**211**
		Nuclear		9	75	25	205
		Renewables		46	12	24	3
		Fossil fuels		6	1	3	3

Table of Outputs for FNS_HIGH_ELEC Scenario: Increase of up to +10% in electricity demand by 2030 compared to reference Winter Package Scenario.

		2010	2020	2030	2040	2050
Energy System	Final energy consumption (Mtep)	155	157	129	123	112
	Electricity in final energy (%)	25%	25%	33%	38%	44%
	Energy Sector CO_2 emissions (t CO_2)	360	303	229	148	77
	EU-ETS carbon price (€/t CO_2)	11	15	30	149	502

		2010	2020	2030	2040	2050
Installed Electricity Capacity (GWe)	**Total**	**123**	**148**	**159**	**162**	**198**
	Nuclear	**64**	**65**	**70**	**63**	**46**
	Existing nuclear	64	63	63	38	11
	New nuclear	0	1.7	7	25	35
	Renewables	**32**	**63**	**72**	**80**	**123**
	Fossil fuels	**27**	**21**	**17**	**20**	**29**

		2010	2020	2030	2040	2050
Electricity Generation (TWh)	**Total**	**564**	**601**	**640**	**677**	**714**
	Nuclear	**429**	**417**	**448**	**460**	**369**
	Existing nuclear	429	406	406	278	90
	New nuclear	0	11	43	182	279
	Renewables	**80**	**163**	**186**	**210**	**335**
	Fossil fuels	**55**	**21**	**6**	**6**	**10**

			2010	2020	2030	2040	2050
Economic Results for Electricity System	Final electricity price (€/MWh)		101	128	137	143	145
	Cost of production (€/MWh)		63	101	82	80	69
	Net electricity exports (TWh)		31	66	64	31	30
				2010-20	**2020-30**	**2030-40**	**2040-50**
	Investments in the electricity system (€Bn_2013)	**Network**		**49**	**67**	**67**	**81**
		Power plants		**62**	**91**	**83**	**93**
		Nuclear		9	74	66	36
		Renewables		46	16	13	50
		Fossil fuels		6	1	4	8

The importance of French nuclear power in the low carbon transition of Europe

FINAL REPORT

Georgios Zazias and Pantelis Capros
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Project Involvement

Project Director	Leonidas Paroussos
Project Manager	Pantelis Capros

Contents

1. Introduction

The aim of the present study is to provide insights regarding the evolution of electricity generation from nuclear power in France, given the decisive challenges the French nuclear industry will face in the medium-term, in a wider European policy context in which Europe makes a transition towards a low-carbon economy. For that purpose, a modelling approach has been adopted using the PRIMES energy systems model, an analytical and complex mathematical tool that has been historically used in a large variety of quantitative assessments for the elaboration of energy scenarios for the European Commission, national governmental agencies, international organizations and the private sector since the 1990s.

The context for the design of the scenarios used in the current study is the one of the family of scenarios that have provided key input to the preparation of the "Clean Energy for all Europeans" package of proposals. These scenarios named "EUCO scenarios" have been developed using the PRIMES model. The policy package contains proposals for binding legal targets for 2030, in a wider context of a deeply decarbonized EU energy system by 2050. ***The current study has not replicated the EUCO scenarios of the European Commission, but has developed specific scenarios for the study and has only used the framework assumptions of the EUCO exercise***. As a result, the present study assumes that the 2030 targets included in the EC policy proposals are met, and focuses on the implications of different sets of assumptions regarding the extension of the lifetime of the French nuclear power plants in the long-term (2050). In addition, given the commitments by Head of States taken in the COP21 meeting in Paris in 2015 aiming at fully decarbonizing the EU energy system by mid-century, a set of scenarios extending to 2070 have been developed, giving insights for the very long term.

2. Assumptions and context

Lifetime extensions of nuclear reactors

The evolution of nuclear power in France, which currently generates around 75% of its electricity from nuclear power plants, is very sensitive to the assumptions regarding the retrofitting and extension of the lifetime (long-term operation, LTO) of its nuclear reactors, whose average age is 33 years in 2018. There are prospects of extending the lifetime of all existing French nuclear reactors up to 60 years, after undertaking a series of retrofitting works (replacement of steam generators and other refurbishment). Previous political announcements were calling for a decommissioning schedule that would bring the share of nuclear power in domestic generation down to 50% by 2025[1]. On the other hand, several studies suggest that an ambitious refurbishment (up to 60 years) is feasible both technically and economically. The latter would lead the share of nuclear electricity generation in domestic power supply to fall below 50% much later (e.g. close to 2045). An extreme case is also modelled which would enable keeping the 63 GW of nuclear reactor capacity currently operational almost constant, but with a considerable amount, even for

[1] Energy Transition Act, 17 August 2015. http://www.gouvernement.fr/en/energy-transition

French standards, of new capacity additions. The evolution of nuclear generation in France in the long term is crucially driven by policy decisions; these however sound be based on sound economic analysis.

In the absence of official decisions and information regarding the extensions of the lifetime of the existing nuclear fleet, the current study has used a series of different assumptions ranging from “low lifetime extensions” (which would imply that 50% of nuclear in total power generation share is reached in 2030), to “high lifetime extensions” (which would imply that a 50% share is reached in 2045). The assumptions are summarized in the following table, where one can see the capacity of nuclear power plants (in GWe) that receive permissions to operate in LTO (following refurbishment works) in each case.

Table 1. Lifetime extension profiles of existing nuclear reactors in France, for different levels of ambitions in terms of GWe of capacity operating in LTO

Age of reactors in 2015	Low ambition (*FNS_50_2030*)	→ (*FNS_50_2035*)	→ (*FNS_50_2040*)	→ (*FNS_50_2045*)	High ambition (*FNS_CONST_NU*, *FNS_HIGH_ELE*)
> 30 years	10.9	17.8	20.8	30.3	33.1
20-30 years	20.2	20.2	20.2	21.5	21.5
< 20 years	6.0	6.0	6.0	6.0	6.0
Total capacity in LTO	**37.1**	**44.0**	**47.0**	**57.8**	**60.6**
No of reactors in LTO	**31**	**38**	**40**	**51**	**55**

Note: Figures represent capacity that gets permission for extended operation when aged more than 40 years. Please refer to Chapter 5 for the detailed scenario specifications.

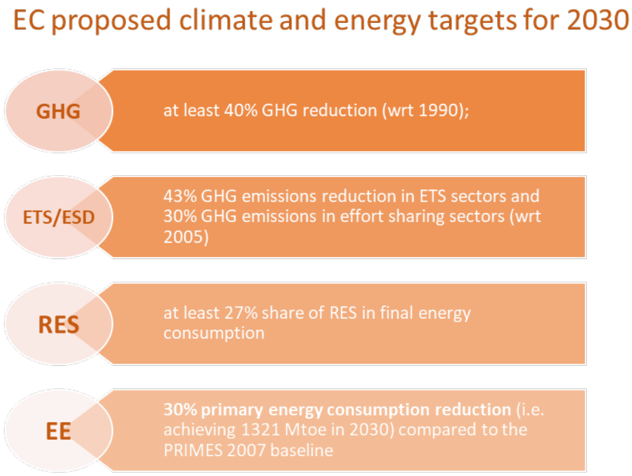
For the rest of the EU, a constant profile for the lifetime extensions of nuclear power plants has been maintained across all cases.

General context of the scenarios

As previously mentioned, the context of the scenarios developed for the current exercise relies on similar assumptions as the ones that have been used in the preparation of the recent decarbonisation scenarios for the European Commission. In other words the developed scenarios meet at the European level the targets agreed by the European Council[2] presented in Figure 1. In the long term, the scenarios achieve the long-term decarbonisation target of the EU of reducing the GHG emissions levels by 80% in 2050 compared to 1990. The power system contributes significantly to this reduction, as electricity is one of the main pillars and the first level of sectoral integration for deep decarbonisation. In the model, the emissions target is met via an iterative process during which ETS values are changed so as the desired reduction in emissions is achieved.

[2] http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/145397.pdf

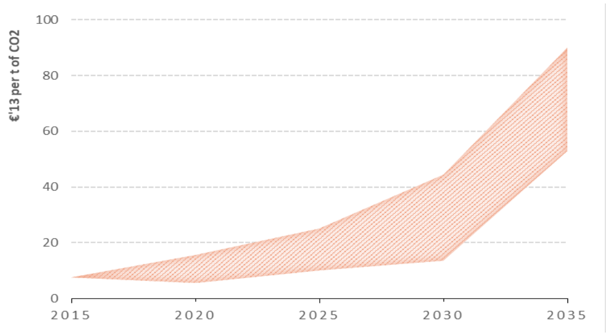
Figure 1. Energy and climate targets agreed for 2030 by the European Council.



ETS allowances prices and implications for the French power sector

A central policy instrument that is used in the scenarios and assists in meeting the aforementioned targets is the EU Emissions Trading System (ETS), including the Market Stability Reserve Mechanism (MSR). The range of ETS allowance prices that enables meeting the targets for the different scenarios are presented in Figure 2. Beyond 2035, very high prices for ETS allowances are observed, making any investments in carbon-intensive power generation unfavourable.

Figure 2. Projections of EU ETS allowance prices in the medium term



Carbon pricing not only delivers significant GHG emission reductions, but at the same time is a strong driver for the development of RES, which benefit from learning-by-doing in the medium term and beyond, and consequently require low or no out-of-the-market support for their widespread penetration.

It should be noted at this point that the PRIMES model assumes agents with perfect foresight, i.e. their decisions regarding investments in a certain time period are not dependent solely on the prevailing market and technology conditions (fuel prices, ETS prices, techno-economic costs) at this period, but also on the anticipation of future conditions in the following years. This mechanism resembles real-world behaviours, as it is highly unlikely that rational decision makers will invest in e.g. new coal-fired capacity additions in periods (e.g. 2030) when carbon prices are expected to significantly increase in the following years (after 2035), even if the economics solely in the decision year would still favour coal-fired generation.

Given the above considerations, regardless of the assumptions used for the lifetime extensions of the French nuclear fleet, very limited investments in coal-based capacity in the EU are observed, given the strong increase in the ETS allowances prices beyond the medium-term. Consequently, lack of prolongation of the lifetime of a part of the French nuclear fleet leads to the replacement of nuclear power generation with domestic RES, such as wind and solar PV, the cost of which reduces considerably over time, and leads also, to a lesser extent, to new investments in gas-fired power plants, mainly as a means to provide stability and flexibility services to the French electricity sector. The potential for CCS for replacing bulk amounts of power generation in the case of early retirement of nuclear reactors, is assumed to be relatively limited.

It should also be noted that given the targets for 2030 and for deep decarbonisation, in case a large part of nuclear reactors is not extended, the PRIMES model readjusts slightly ETS prices (if needed), so that the climate objectives are met at the EU28 level.

Other key EU energy and climate policies affecting the French power system

Besides the ETS mechanism, the context of the scenarios is built upon a number of additional pillars in order to achieve the 2030 climate and energy targets and to achieve the deep decarbonisation of the energy system in the long term.

The role of electricity is essential in the transition towards a low carbon economy, as the decarbonisation of the power sector via the wide-scale penetration of RES, the construction of new nuclear power plants in certain MS, and to a lesser extent, the carbon-free generation from plants equipped with CCS technologies, enables electricity to become as an almost carbon-free energy carrier. Thus, fuel switching towards electricity in the end-use sectors (industry, households, tertiary and transport) leads to significant emission reductions, when this is accompanied with the decarbonisation of the power sector.

Energy efficiency is also a strong pillar of all scenarios, as it strongly reduces energy demand. Reductions in energy demand are achieved via the renovation of buildings, the use of standards/labels for domestic appliances, the use of best available (higher efficiency) technology (BAT) in industrial sectors and the push towards more efficient powertrains imposed by emission standards on new vehicle sales (Table 2).

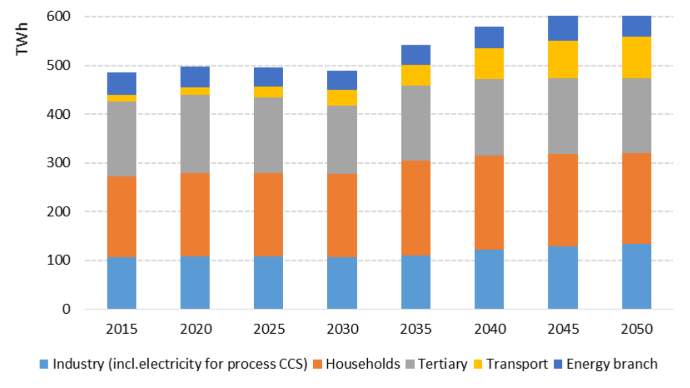
The strong energy efficiency policies in the medium term imply strong pressures on electricity demand, as renovated buildings and more efficient equipment require in general less energy input in order to provide the same output (heating a building or delivering mechanical work). Consequently, total final consumption in end-use sectors reduces significantly.

Table 2.Level of final energy consumption by sector in France in one of the main scenarios (Mtoe)

	2015	2020	2025	2030	2035	2040	2045	2050
Industry	30.3	31.3	29.9	29.0	27.7	28.5	28.4	27.5
Residential	44.2	45.1	40.1	32.7	32.0	30.4	28.2	25.8
Tertiary	30.3	29.9	27.1	23.2	23.3	23.2	22.5	21.4
Transport	50.5	50.3	47.9	46.4	44.4	41.5	39.2	37.8
Total Final Consumption	**155.3**	**156.6**	**145.1**	**131.3**	**127.5**	**123.6**	**118.3**	**112.5**

Electricity demand in the EU, including France, presents only moderate increases in the medium term, despite the growth in population and the size of economy, due to the efficiency gains. However, towards the long-term, the rapid and strong electrification of the car and van fleets, together with the economic growth and the population increase, allow electricity demand to start growing again. The transport sector provides half of the electricity demand growth in France between 2015 and 2050 (Figure 3).

Figure 3. Electricity demand by end-use sectors in France in one of the main policy scenarios



In addition, the context of the scenarios assumes the successful implementation of the reforms in the EU internal electricity and gas markets, which enhance integration of balancing and competition for generation from different Member States. The latter is supplemented by the development of new interconnection capacity.

Support to renewables is assumed to be phased-out progressively, as the reduced investment costs of renewables make them competitive without the need for further incentives.

Assumptions for the very long term

The ambition outlined by the conclusive text of the COP21 meeting in Paris in 2015[3], provides an indication that the EU should be almost carbon neutral, close to mid-century. This would become a more pressuring goal, in case the more ambitious target, to limit the global temperature increase to 1.5ºC compared to pre-industrial levels, is pursued.

In the latter case, the EU energy sector should limit its GHG emissions even below the levels achieved in decarbonisation scenarios extending to 2050. Given the scarcity in decarbonisation options existing in certain demand segments, the remaining GHG emissions (beyond the 2050 EU target of reducing emissions by 80% compared to 1990 levels), will prove the most difficult to abate. For example, despite the strong efficiency improvements in the powertrains of trucks covering long-distances, they cannot be fully decarbonised, as one of the main zero emissions pathways for this transport segment (decarbonisation using advanced biofuels) has limited potential due to the relatively small biomass resources in Europe. Consequently, other decarbonisation options should be considered. One alternative that presents important synergies with the power sector is the case of synthetic fuels (alternatively called P2X fuels or electro-fuels). The latter are carbon neutral hydrocarbons that are produced via chemical pathways, using carbon derived from captured carbon dioxide from air and hydrogen as feedstock. Both the chemical reactions used for the production of the synthetic hydrocarbons, and the electrolysis of water in order to produce hydrogen are power intensive processes. Therefore, they constitute significant new electricity demand segments that could emerge in the pursuit of a fully decarbonised EU economy, with important opportunities for the expansion of the power sector and possibly for nuclear power. This concept is assessed via the elaboration of a dedicated scenario that extends to 2070 in the present study.

3. Modelling tools

Overview of the PRIMES energy systems model

The PRIMES energy system model has been the main modelling tool that has been used for the preparation of the scenarios presented in the current study. PRIMES is an EU energy system model which simulates the energy consumption sectors and the energy supply system[4]. It is a partial equilibrium modelling system that simulates an energy market equilibrium in the European Union and each of its Member States. This includes consistent EU carbon price trajectories. The energy demand and supply modules of PRIMES interact between them through the prices of energy commodities, via an iterative sequence till equilibrium is reached. For instance, a change in the assumptions affecting the power module of PRIMES, not only affects the power generation mix, investments, ETS emissions etc., but also leads to the re-calculation of electricity and heat prices, hence providing a new stimulus to the demand modules. The latter re-adjust their energy fuel mix and the iterative procedure is repeated till equilibrium is reached.

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[3] http://unfccc.int/resource/docs/2015/cop21/eng/10.pdf

[4] A full model description can be found at: http://e3modelling.gr/images/files/ModelManuals/PRIMES_MODEL_2016-7.pdf

Decision-making behaviour is forward-looking and grounded in microeconomic theory. The model also represents in an explicit and detailed way energy demand, supply and emission abatement technologies, and includes technology vintages.

The core model is complemented by a set of sub-modules (i.e. the transport sector module and the biomass supply module). Industrial non-energy related CO_2 emissions are covered by a sub-module so that total CO_2 emissions can be projected. The model covers all EU28 MS individually, and in addition versions of PRIMES have been developed in the past for a total of 9 additional non-EU countries. It proceeds in five-year steps and is fully calibrated to Eurostat data for the years 2000 to 2010, and partially-calibrated to 2015 based on data availability at the time of calibration. The model's horizon for projections has been recently extended to 2070. Older versions have been running up to 2050.

The PRIMES model is suitable for analysing the impacts of different sets of climate, energy and transport policies on the energy system as a whole, notably on the fuel mix, CO_2 emissions, investment needs and energy purchases as well as overall energy system costs. It is also suitable for analysing the interaction of simultaneous policies on combating climate change, promotion of energy efficiency and renewable energies. It provides details at Member State level, showing differential impacts across the EU Member States.

Regarding policies for abating GHG emissions, the model can analyze various emission constraints: per sector, per country or EU-wide. The supply and demand sectors included in the model are grouped in ETS and non-ETS sectors, in order to reflect the different mechanisms available for reducing CO_2 emissions in these two control areas of the energy system.

For reducing GHG emissions from sectors that belong to the ETS, the model follows the concept described below:

- An EU-wide emission constraint is applied reflecting total volume of allowances (per year) and assumptions about permissible international credits (e.g. CDM)
- Grandfathering (free allowances) can be represented through exogenous quotas per sector and per country; carbon prices are, entirely or partially (reflecting the degree of market competition), treated as opportunity costs and price signals, but actual payments only correspond to excess emissions by sector
- Auctioning of allowances is represented by modelling carbon prices inducing true payments by sector
- Carbon prices are determined iteratively (until ETS volume of allowances is exactly met) and apply on all ETS sectors and countries in a uniform way
- Inter-temporal aspects, such as arbitraging over time within the ETS, are considered in the modelling by introducing cumulative allowances as a constraint and excluding borrowing from the future

As far as non-ETS sectors are regarded:

- The model can handle non ETS emission reduction targets either at a country level or EU-wide assuming possible exchanges between MS
- Carbon values (i.e. shadow prices associated with the volume constraint) serve to convey price signals to non-ETS sectors without entailing direct payments (only indirect costs)

- Carbon prices and carbon values act on top of any other policy measure (of specific character, for example standards, specific taxes, subsidies, performance standards, RES policies and obligations, etc.), thus carbon prices and values determined endogenously depend on the extent of other policies and measures assumed for a scenario.

The aforementioned methodology allows meeting various climate related objectives such as the overall GHG, ETS, and ESD emissions reduction targets, as well as the 2050 decarbonisation target.

The following list includes all main assumptions and inputs that are exogenous to the model. In certain instances though, the exogenous parameters are provided by other models developed and operated by E3Modelling (e.g. World prices of fossil fuels by the PROMETHEUS world energy model, economic growth by the GEM-E3 global computable general equilibrium model etc.)[5].

Inputs of the model

- GDP and economic growth per sector (many sectors)
- World energy supply outlook – world prices of fossil fuels
- Taxes and subsidies
- Interest rates, risk premiums, etc.
- Environmental policies and constraints
- Technical and economic characteristics of current and future energy technologies
- Energy consumption habits, parameters about comfort, rational use of energy and savings, energy efficiency potential
- Parameters of supply curves for primary energy, potential of sites for new plants especially regarding power generation sites, renewables potential per source type, etc.

The outputs of the model are presented below. All outputs are available in 5-year steps up to 2050 or 2070 depending on the version of the model used.

Outputs of the model

- Detailed energy balances (using EUROSTAT format)
- Detailed demand projections by sector including end-use services, equipment and energy savings
- Detailed balance for electricity and steam/heat, including generation by power plants, storage and system operation
- Production of fuels (conventional and new, including biomass feedstock)
- Investment in all sectors, demand and supply, technology developments, vintages
- Transport activity, modes/means and vehicles
- Association of energy use and activities
- Energy costs, prices and investment expenses per sector and overall
- CO_2 Emissions from energy combustion and industrial processes

[5] Further information on the modelling tools of E3Modelling: http://e3modelling.gr/index.php/products

- Emissions of atmospheric pollutants
- Policy Assessment Indicators (e.g. import dependence ratio, RES ratios, CHP ratios, efficiency indices, etc.)
- Trade of electricity, gas and other fuels between the European countries and with the rest of the world

The model has been successfully peer-reviewed[6], most recently in 2011[7].

The power sector module of PRIMES

PRIMES includes a very detailed model for electricity generation, trade and supply, and for steam generation and distribution. The model is dynamic, solving over multiple periods (until 2050 or 2070), multi-country to capture electricity trading in the European internal market, and market-oriented as it projects electricity tariffs by sector/country and closes the loop between demand and supply.

The PRIMES power and steam model applies a sophisticated optimisation algorithm to handle long-term simulation of power system operation, power plant dispatching, investment in new or refurbished power plants, supply/distribution, trading and pricing of electricity between countries and towards customers/consumers. Power market simulation is simultaneous with simulation of steam/heat market so as to capture trade-offs between cogeneration and boilers, between CHP and pure-electric plants and between self-production and distribution of steam/heat.

The PRIMES power and steam model is rich in representation of technologies, market mechanisms and policy instruments:

- The fully endogenous investment and plant operation modelling covers all known generation technologies (more than 150 distinct technologies) and very detailed representation of renewable energy sources, including highly distributed resources. Several electricity storage technologies are endogenous, including hydro with reservoir, hydro pumping, batteries, Power-2-X and hydrogen-based storage. Several CHP technologies and their technical operation limits are also included.
- Daily and seasonal variations are captured through hourly modelling of several typical days for each year. Data for typical days include power load, wind velocity and solar irradiance. Load demand is bottom-up built from projection of energy end-uses at detailed level by the PRIMES energy demand models. Demand side management possibilities are handled at detailed level based on technical potential and costs. Highly distributed generation at consumer premises is also included and is taken into account in calculating transmission/distribution losses and costs.
- Investment decisions distinguish between green-field development, construction on existing plant sites, refurbishment and extension of lifetime of plants and the building of auxiliary equipment (such as DENOX, desulphurization, CHP, CCS-ready,

[6] https://ec.europa.eu/clima/sites/clima/files/strategies/analysis/models/docs/primes_model_2013-2014_en.pdf
[7] https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1569_2.pdf

etc.). Investment decisions also distinguish between utility, industrial and highly distributed scales.

- The model incorporates in detail feed-in tariff and other supporting schemes for renewables and simulates individual investment behaviour in RES, following project-financing considerations.
- The PRIMES power model includes reliability and reserve constraints, such as reserve margin constraints to address forced outages of plants or unforeseen demand increases. The model is deterministic and handles uncertainty of load, plant availability and intermittent RES by assuming standard deviations, which influence reserve margin constraints. Ramping up and ramping down restrictions of plant operation, balancing and reserve requirements for intermittent renewables and reliability restrictions on flows over interconnectors are also included.
- Flexibility and reserve to balance intermittency from renewables is ensured simultaneously by storage (various endogenous techniques), ramping possibilities of power plants (which influence plant technology mix) and demand response.
- Regulations such as the large combustion plant directives, the (optional) emission performance standards, the best available techniques standards, the (optional) CCS-ready recommendations, the CHP directive and the Emission Trading Scheme are fully implemented in the model.
- The PRIMES power model represents the entire system of interconnectors in Europe, as well as possible AC and DC line extensions (including optional remote connections with offshore wind power in North Sea and with North Africa and Middle East).
- The model can perform simulation of different market arrangements within the internal European market, including market coupling, net transfer capacity restrictions versus load flow based allocation of capacities and others.

The **optimisation algorithm** is intertemporal (perfect foresight) and solves simultaneously:

- a unit commitment-dispatching problem
- a capacity expansion problem and
- a DC-linearized optimum power flow problem (over interconnectors).

The optimisation is simultaneous for power, CHP, distributed steam, distributed heat, district heating and industrial boilers and satisfies synchronised chronological demand curves of power, steam and heat, which result from the sectoral demand sub-models. Dynamically the model applies a full scale capital vintage formulation (keeps track of plant vintages until the end of the projection horizon). All types of investment in all types of plants including storage are endogenous, as well as their operation and consumption.

The **unknown variables** include:

- capacity additions by plant type (several types of capacity investment);
- extension of lifetime of plants after refurbishment, investment in auxiliary equipment;
- generation of electricity (or steam or heat) from plants on an hourly basis;
- consumption of fuels (use of more than one fuel or blending of fuels in each plant type is permitted under constraints);

- emissions, CO_2 transportation, and storage;
- injection or extraction from storage facilities on an hourly basis; and
- investment in storage equipment.

The **input (exogenous) parameters** include the elements included in the following list. Please note that certain elements might be exogenous to the power model, but they might be endogenous variables for other modules of PRIMES[8]:

- electricity demand* and elasticities;
- plant fleet as existing in the beginning of projection;
- planned capacity decommissioning;
- known capacities under construction in the beginning of projection;
- grid loss rates;
- ramping possibilities of power plants by technology;
- technical restrictions of CHP plant operation;
- unit costs of investment by technology[9], unit variable costs, unit fixed costs;
- fuel prices;
- site development costs;
- parameters used in non-linear cost-supply curves;
- taxes and subsidies;
- ETS carbon prices*;
- feed-in tariffs and other parameters for representing RES support schemes;
- costs and potential parameters for transportation and storage of captured CO_2;
- costs and potential parameters of storage technologies;
- unit costs of investment in grids, unit operation costs of grids;
- parameters expressing policy instruments and restrictions (nuclear, CCS, environmental, efficiency, CHP, etc.);
- parameters expressing cost of development of smart grids;
- parameters on uncertainty affecting calculation of reserve margins;
- restrictions on use of interconnectors;
- capacities and electrical characteristics of interconnectors;
- reliability parameters on flows over interconnectors.

Non-linear relationships regard the cost of access to resources, such as fuels, RES and plant sites. Such resources are represented as upward sloping cost-supply curves linking unit costs to cumulative exploitation. The cost-supply curves are country and resource specific and change over time in order to reflect changing conditions about potential and technology.

The **financial and pricing model** is a recursive model, which includes mixed complementarity formulations to solve a cost allocation problem.

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[8] These are marked with *

[9] A table with investment costs for selected technologies as used in the model is presented in Annex A.

Regarding **electricity trade**, the PRIMES power model represents the entire system of interconnectors in Europe, as well as possible AC and DC line extensions. The interconnection capacities, as they evolve dynamically, as well as the Net Transfer capacity parameters, are exogenous. The model finds the flows over the lines as a result of a DC linear power flow problem, which respect the two Kirchhoff's laws. The interconnection capacities differ by scenario and take into account the official infrastructure development plans from ENTSOE. In a decarbonisation context, the capacities increase in the long term to accommodate access to remotely located renewables (e.g. wind offshore). The NTC values change over time and per scenario to reflect assumptions about the completion of the internal market in the EU. NTC values close to thermal capacities of lines denote full completion. The latter is assumed to happen in the scenarios after 2025. The flows between countries depend on the capacities of lines but also on relative competitiveness of generation costs. Essentially the model derives the flows from a mimicked operation of a fully coupled wholesale market. The flows influence both generation and capacity expansion, simultaneously. However, capacity expansion also depends on national constraints, such as the requirements for ancillary services, replacement capacity, etc. as well as on national policies regarding renewables, nuclear, etc. The flows are endogenous based on the coupled wholesale market concept.

Net imports for EU28 include the net trade also with non-EU European countries, e.g. Switzerland, Norway, western non-EU Balkans and Turkey, as well as neighbouring states such as Russia, Ukraine, Moldova, Belarus etc. External links with Africa and Middle East can also be enabled.

Use of PRIMES in the current exercise

Regarding, the scenarios prepared in view of the current exercise, the 5th version of the PRIMES model has been used for the elaboration of the scenarios whose time horizon extends to 2050, whereas the more recent 6th version has been used for the scenarios extending the projections to 2070. Besides the extension of the time horizon, the following enhancements have taken place for the 6th major update of the model:

- Further improvement of the model's capability in simulating unit commitment in the presence of high contribution by variable RES and therefore in capturing in a more sophisticated manner of the system requirements for the operation of fast-ramping power resources (flexibility) and of the possible sharing of such resources within the EU internal market, based on cross-border trade and market coupling. The updated model can better simulate market barriers and distortions similar to the ones introduced in the study that has provided input to the Impact Assessment accompanying the proposal for revised rules for the electricity market, risk preparedness and ACER[10];
- The modelling of certain technologies, e.g. batteries, bio-energy with Carbon Capture and Storage (BECCS) has been improved;

[10] https://ec.europa.eu/energy/en/studies/modelling-study-contributing-impact-assessment-european-commission-electricity-market-design

- More analytical representation of potential pathways used to produce synthetic fuels, including updates of the techno-economic information of associated technologies, such as CO_2 capture from air, methanation, production of synthetic liquid hydrocarbons, Carbon Capture and Utilization (CCU) etc.;
- Apart from the developments in the power module of the PRIMES model, significant developments have been performed also to other modules. Most notably, a new sophisticated and analytical buildings module has been added to the modelling suite, the transport module has been enhanced in order to better reflect the potential development of synthetic fuels. Its database has been updated in terms of techno-economic characteristics of both conventional and electric vehicles, in view of the recent developments in the automotive industry and the rapid reduction in the cost of batteries etc.

All the updates mentioned above, made for the 2070 exercises, may create discrepancies when comparing scenarios that have been developed using the previous version used for the 2050 scenarios; therefore, such comparisons should be made with caution.

For most scenarios, the EU wide version of the model has been used. In the case of two additional scenarios extending to 2050 and assessing the French power system solely, only the French module of the PRIMES model has been run (see next chapter).

4. Scenarios

A total of 8 scenarios have been designed as part of the quantitative work for the current study and are presented in this report.

The **four main scenarios include projections to 2050**. The key element differentiating them is the assumption regarding the amplitude and pace of the lifetime extensions of the French nuclear reactors. Consequently, the share of nuclear generation in the domestic supply of electricity drops to 50% at different points in time; in the "high lifetime extensions" case in 2045, whereas in the "low-lifetime extensions" in 2030. The capacity of nuclear power plants going into LTO in each scenario has been presented in Table 1. Every scenario meets the 2030 targets for emissions reduction, ETS, non-ETS, renewables and energy efficiency, and the 2050 targets for greenhouse gas emissions reduction overall and in the transport sector in particular. The EU28 version of the PRIMES model (its 5th version) has been used in the preparation of these four scenarios.

Two additional scenarios with a horizon up to 2050 (using the 5th version of the model for France only) include:

- An extreme scenario assuming an exogenously controlled stable nuclear capacity in France. It has been obtained using the standard electricity demand profile of the main 2050 scenario (the "high lifetime extensions" case). Only the French module of the PRIMES model was used, with the aim to measure the impact on CO_2 emissions and to observe the consequences in terms of changes in electricity prices.
- A scenario assuming increased electricity demand in France in the mid-term. The scenario assumes a linear increase up to 10% in 2030, with respect to the "high lifetime extensions" scenario. This scenario explores the consequences of such a

demand trend for the power sector and its generation mix. Only the French module of the PRIMES model has been used.

Two additional scenarios extending the projections to 2070 have also been prepared using the most recent version of the PRIMES model.

- The first is an extended projection of the concept and logic behind the “high lifetime extensions” 2050 scenario extrapolated until 2070 with an aim to achieve close to zero emissions.
- The second one builds on the former but it also assumes the development of synthetic hydrocarbons, aiming at further reducing remaining GHG in the very long term. This development leads to a considerable increase in electricity demand and provides opportunities for new capacity investments in nuclear power in France and elsewhere in Europe.

Both of the 2070 scenarios take advantage of the enhancements of the most recent version of the PRIMES model. Even though both of them are based on the concept of the 2050 scenarios, given that all the latter had put emphasis in the mid-term (2030), they might deviate in certain elements towards the mid-century. For instance, the 2070 scenarios show a greater use of synthetic fuels already by 2050, and the electrification of light transport modes has been revised upwards due to the recent significant drops in the cost of batteries.

A table summarising all scenarios is presented below.

Table 3. Summary of all scenarios developed and presented in the current study

Scenario name	Horizon of projections	Primes version used	50% share reached in	Short description
FNS_50_2045	2050	Ver.5	2045	The share of nuclear generation in domestic electricity supply drops to 50% in 2045
FNS_50_2040	2050	Ver.5	2040	The share of nuclear generation in domestic electricity supply drops to 50% in 2040
FNS_50_2035	2050	Ver.5	2035	The share of nuclear generation in domestic electricity supply drops to 50% in 2035
FNS_50_2030	2050	Ver.5	2030	The share of nuclear generation in domestic electricity supply drops to 50% in 2030
FNS_CONST_NU	2050	Ver.5	Not applicable	A constant nuclear capacity of around 63 GW is maintained through the projection period
FNS_HIGH_ELE	2050	Ver.5	Not applicable	Electricity demand increases linearly by up to 10% in 2030 compared to the main scenario of the Winter Package
FNS_EUCO_2070	2050	Ver.6	Not applicable	Extension of the logic of the main decarbonisation scenario until 2070, involving higher electrification, which implies increase of nuclear after 2050
FNS_SF_2070	2050	Ver.6	Not applicable	Same as above but with significant further penetration of synthetic fuels produced using electricity, which implies further increase of nuclear after 2050

5. Results

This section presents the key outcomes from the modelling exercise for France and the implications for the rest of Europe.

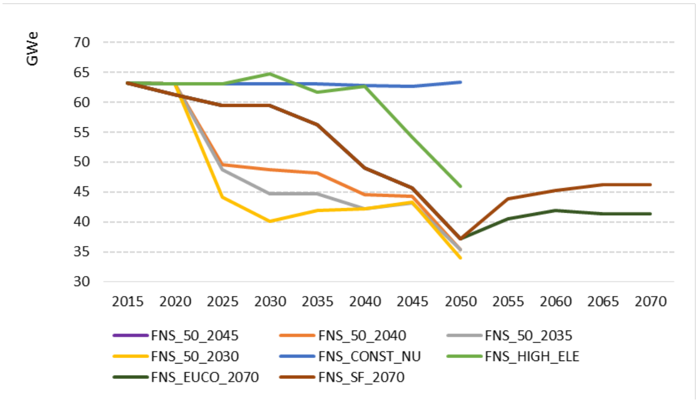
Nuclear capacity and investments

The evolution of nuclear capacity in France across all scenarios is presented in Table 4. Based on the assumptions used ***in the four main 2050 scenarios***, nuclear capacity presents a continuous drop in these four case. The pace of the decline depends on the exogenously defined assumptions of the lifetime extensions for nuclear power plants. The latter are differentiated in order to allow the share of nuclear power generation in domestic electricity supply to drop close to 50% in different time periods.

Table 4. Net installed nuclear capacity in France (GWe)

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
FNS_50_2045	63.2	61.3	59.5	59.5	56.3	49.1	45.7	37.2				
FNS_50_2040	63.2	63.2	49.6	48.7	48.1	44.5	44.3	35.4				
FNS_50_2035	63.2	63.2	48.7	44.7	44.7	42.2	43.2	35.4				
FNS_50_2030	63.2	63.2	44.1	40.1	41.9	42.2	43.2	34.0				
FNS_CONST_NU	63.2	63.2	63.2	63.2	63.2	62.9	62.6	63.4				
FNS_HIGH_ELE	63.2	63.2	63.2	64.8	61.7	62.6	54.1	45.9				
FNS_EUCO_2070	63.2	61.3	59.5	59.5	56.3	49.1	45.7	37.2	40.5	42.0	41.3	41.3
FNS_SF_2070	63.2	61.3	59.5	59.5	56.3	49.1	45.7	37.2	43.8	45.3	46.2	46.2

Figure 4. Net nuclear operating capacity in France



In scenario FNS_50_2045, nuclear plants represent almost 40% of total installed capacity in France in 2030, while this share drops to 25% in the FNS_50_2030 scenario (Table 5). The same figure for the rest of EU is 5% in all scenarios (Figure 5).

At the same time, the electricity exports of France, the largest European exporter of electricity in Europe, decrease more rapidly as nuclear capacity is retired earlier (fewer nuclear entering LTO) as shown in Figure 6. In the long term (2050), nuclear capacity in

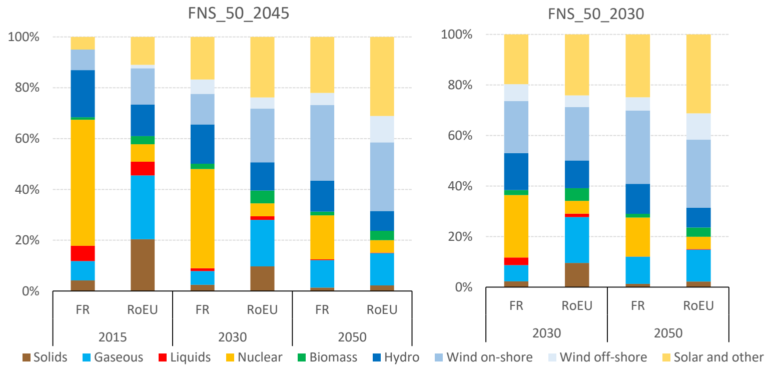
France stabilises close to 35 GWe in all the main 2050 scenarios, and net exports of electricity decrease to approx. 30 TWh, down from more than 60TWh in 2015. France is importing quantities of electricity in periods of peak demand and relatively low generation from variables RES, especially towards the end of the projection period, but the amounts are quite small relative to the bulk electricity exports that the French power system provides to the rest of Europe.

Investments in new nuclear power plants (Table 6) are required in the period post-2030 in order to replace retired nuclear capacity and meet the increasing electricity demand. The latter is mainly due to the booming penetration of EV in the transport sector - close to 65 TWh by 2050 in all these scenarios.

Table 5. Net nuclear and total power generation capacity in France

	Nuclear Capacity (GWe)			Total Power Capacity (GWe)			Share of nuclear over total power capacity (GWe)		
	2015	2030	2050	2015	2030	2050	2015	2030	2050
FNS_50_2045	63.2	59.5	37.2	127.6	152.6	215.1	50%	39%	17%
FNS_50_2040	63.2	48.7	35.4	127.6	156.8	217.5	50%	31%	16%
FNS_50_2035	63.2	44.7	35.4	127.6	159.7	217.2	50%	28%	16%
FNS_50_2030	63.2	40.1	34.0	127.6	162.5	221.2	50%	25%	15%
FNS_CONST_NU	63.2	63.2	63.4	127.6	150.6	161.1	50%	42%	39%
FNS_HIGH_ELE	63.2	64.8	45.9	127.6	161.8	199.8	50%	40%	23%

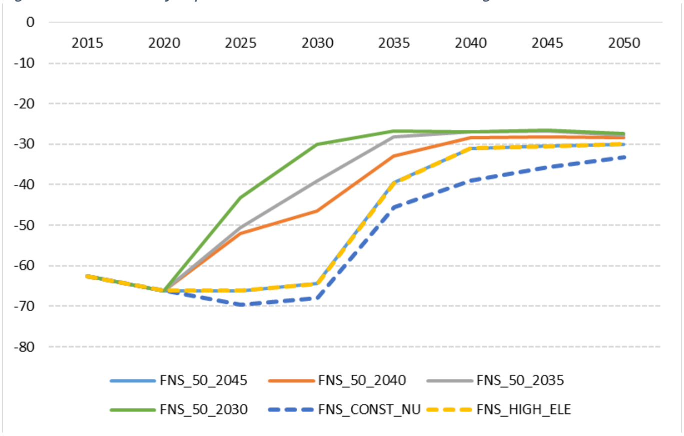
Figure 5. Net installed power capacity in France and the rest of EU by type in selected scenarios



Note: RoEU - rest of EU

In **the additional 2050 scenarios**, the outlook for nuclear capacity is more optimistic. In the ***FNS_CONST_NU*** scenario, the capacity of nuclear plants is maintained by assumption close to 63 GWe (operating capacity in 2015), via the prolongation of the lifetime of all 58 reactors for more than 40 years after their construction date and by significant investments in new nuclear capacity, mainly post-2040. At the same time, electricity exports remain at high levels in the mid-term, but they unavoidably decrease post-2030 as import requirements from neighbouring countries decline. In the ***FNS_HIGH_ELE*** scenario, nuclear capacity presents even an increase in 2030, reaching short of 70 GW, as new nuclear investments are realised in the period shortly before 2030 in order to cover the incremental electricity demand (by assumption 10% more in 2030 than in the ***FNS_50_2045*** scenario - Figure 7).

Figure 6. Net electricity imports in France in the scenarios extending to 2050

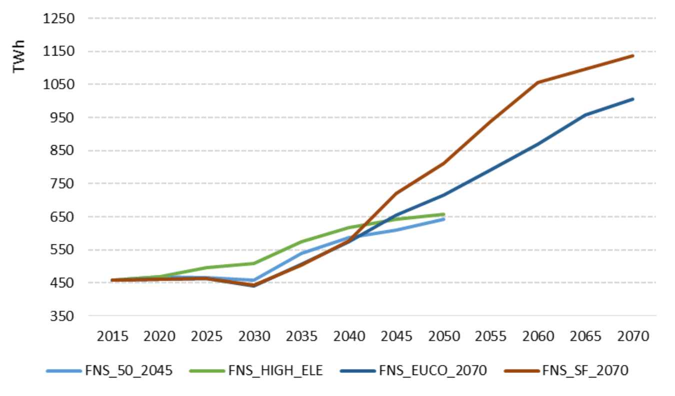


In the **two scenarios extending the projections to 2070**, a similar profile with the "high lifetime extensions" case of the main 2050 scenarios (***FNS_50_2045***) is maintained in the period up to 2050 for the retrofitting of old nuclear plants. In the period post-2050 significant investments in nuclear capacity take place as electricity demand further expands, due to the increased electrification of all demand sectors (already taking place from 2040 onwards). The need for additional capacity is more accentuated in the case of the ***FNS_SF_2070*** scenario, in which electricity demand is larger due to the need to produce additional synthetic hydrocarbons (liquids and methane), required for the (almost) complete decarbonisation of the French energy system.

Table 6. Investment in new nuclear plants per 5-year periods (GWe)

	15-20	21-25	26 30	31-35	36-40	41-45	46-50	56-60	56-60	61-65	66-70
FNS_50_2045	1.7	0.0	0.0	5.0	8.3	3.3	3.3				
FNS_50_2040	1.7	0.0	0.0	5.0	8.3	1.7	5.0				
FNS_50_2035	1.7	0.0	0.0	5.0	8.3	1.7	5.0				
FNS_50_2030	1.7	0.0	0.0	5.0	8.3	1.7	5.0				
FNS_CONST_NU	1.7	0.0	0.0	0.0	3.3	19.8	24.8				
FNS_HIGH_ELE	1.7	0.0	1.7	13.2	8.3	5.0	5.0				
FNS_EUCO_2070	1.7	0.0	0.0	5.0	8.3	3.3	3.3	13.2	3.3	3.3	0.0
FNS_SF_2070	1.7	0.0	0.0	5.0	8.3	3.3	3.3	16.5	3.3	5.0	0.0

Figure 7. Gross electricity demand for France in selected scenarios

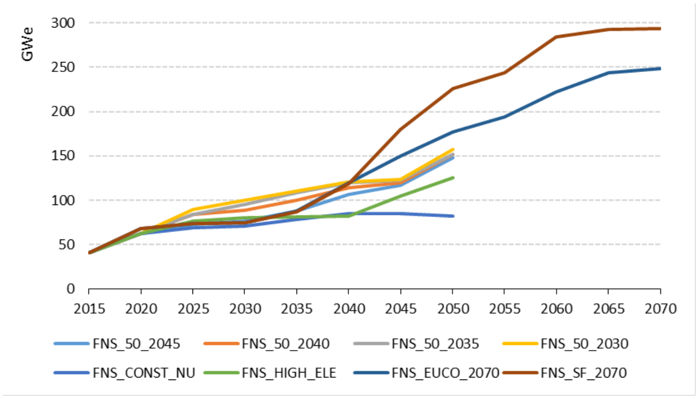


Note: Gross electricity demand in the remaining scenarios is similar to the FNS_50_2045 scenario

Evolution of RES

The outlook for power generation from RES is closely related to the developments of the nuclear power industry. As explained in the assumptions/methodology chapter, the high prices of ETS allowances post 2030 make investments in fossil-fuelled power plants scarce, with limited investments in gas-fired generation taking place in order to provide flexibility and act as reserve capacity for the stability of the electricity system.

Figure 8. RES power generation capacity in France



Given the above, the share of variable RES generation picks up as the number of nuclear reactors entering LTO drops (Figure 8). For instance, the RES-E share, which indicates the share of electricity consumption originating from RES surpasses 50% by 2045 in the ***FNS_50_2045*** scenario, whereas i***FNS_50_2030*** scenario this takes place already in 2030.

In the extreme constant nuclear case (***FNS_CONST_NU***), RES-E stays below 40% for the whole projection period up to 2050, whereas a 50% share is achieved only by 2050 in the ***FNS_HIGH_ELE*** scenario.

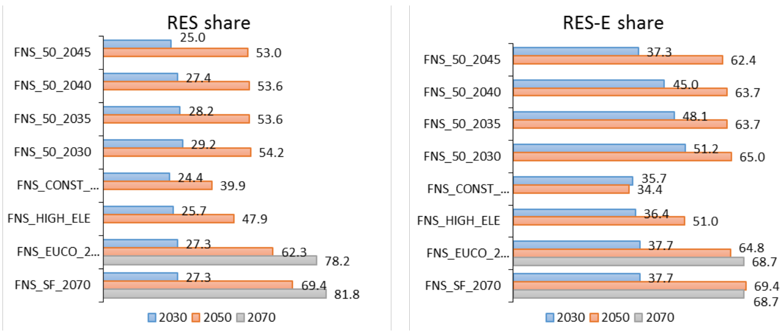
The scenarios extending the projections up to 2070 show an upwards trend for electricity produced form RES, which touches 70% in the very long-term.

Table 7. Renewable share for electricity (RES-E) in France (%)

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
FNS_50_2045	19.8	30.3	35.1	37.3	40.0	46.4	51.0	62.4				
FNS_50_2040	19.8	30.3	41.9	45.0	46.6	51.0	52.7	63.7				
FNS_50_2035	19.8	30.3	42.5	48.1	50.9	52.9	53.5	63.7				
FNS_50_2030	19.8	30.3	45.8	51.2	52.1	53.0	53.5	65.0				
FNS_CONST_NU	19.8	30.3	34.1	35.7	36.0	38.1	36.2	34.4				
FNS_HIGH_ELE	19.8	30.3	35.2	36.4	34.2	33.3	43.0	51.0				
FNS_EUCO_2070	19.8	32.5	36.4	37.7	40.3	51.5	57.1	64.8	64.4	66.3	68.7	68.7
FNS_SF_2070	19.8	32.5	36.4	37.7	40.1	50.6	60.8	69.4	67.3	68.9	69.1	68.7

The aforementioned developments also affect the total RES share for France as expected and observed in Figure 9.

Figure 9. Overall RES share (left) and RES-E share (right) in France (%)



Power generation mix

The evolution of the French power generation mix in the horizon up to 2050 is obviously affected by the lifetime extensions of the nuclear reactors currently in operation. The lower and shorter the lifetime extensions, the faster other electricity sources enter the power mix (Figure 12). For example, wind generation surpasses the threshold of 100 TWh already in 2025 in the "low lifetime extensions" case (***FNS_50_2030***), whereas this occurs only in 2040 in the constant nuclear scenario (***FNS_CONST_NU***). Power generation from nuclear at the end of the projection period ranges from close to 290 TWh in the "high lifetime extensions" case of the four main scenarios ones for 2050, down to around 265 TWh in the "low lifetime extensions" one. In the additional scenarios, electricity from nuclear rises to 490 TWh in the constant nuclear scenario, whereas it climbs up to 370 TWh in the high electricity scenario (Figure 10). The higher electricity generation from nuclear in 2050 (490 TWh) compared to 2015 (445 TWh) in the constant nuclear scenario despite nuclear capacity remaining almost identical (63 GW), is an outcome of the smoothening of the electricity load duration curve in future years, within a decarbonisation context - mainly due to smart charging of electric vehicles and demand response in the building sectors. The electricity systems under this context are assumed to have achieved a sufficient level of digitalization and have become more intelligent in order to allow better coordination between consumers and suppliers for electricity. More specifically, the emergence of EVs, the charging of which can take place during periods of low power demand, plus demand response, the penetration of smart grids, etc., leads to a load curve that is much smoother than today, and this allows more nuclear reactors to operate at base load operation, in contrast to the current situation in France where many of them operate as load followers. This translates into increasing capacity factors for French nuclear power plants over time (Figure 11).

In all 2050 scenarios, generation from wind presents the largest growth between 2015 and 2050 and touches 225 TWh by 2050 in **the four main 2050 scenarios**. It remains at low levels in the ***FNS_CONST_NU*** scenario (slightly more than 103 TWh), and presents considerable growth in the ***FNS_HIGH_ELE*** scenario (surpassing 175 TWh by the end of the projection period).

Power generation from solar also presents significant growth, the amplitude of which depends again on the assumptions regarding the evolution of the existing nuclear power plants. In the most pessimistic case for nuclear, solar generation raises above 50 TWh already in 2030 and reaches almost 95 TWh by 2050. In the ***FNS_CONST_NU*** scenario, it remains below 50 TWh for the entire projection period, while in the high electricity scenario it climbs up to 70 TWh in 2050.

The role of gas generation further dwindles and any new capacity built, serves mostly as ancillary services for the stability of the power system. Therefore, already from the mid-term (2030) generation from gaseous fuels falls below 10 TWh per year. Generation from hydro and biomass remains relatively stable, as they present limited potential for further growth.

Figure 10. Nuclear power plants generation in France

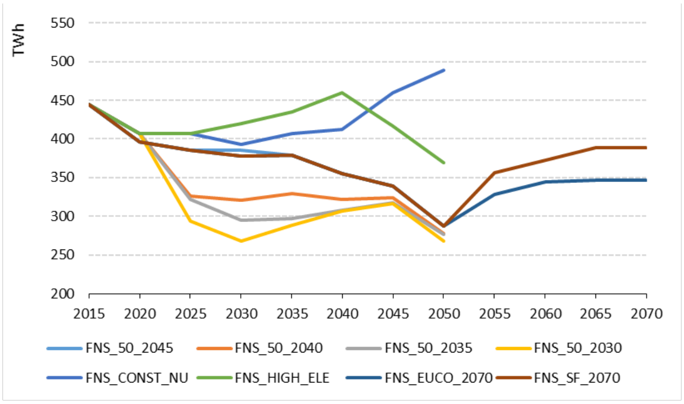
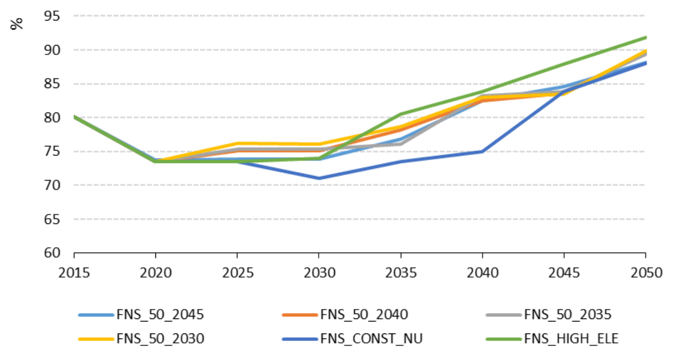


Figure 11. Average capacity factors for French nuclear power plants.



In the very long term (beyond 2050), the increased electricity demand due to higher electrification of final demand and the production of synthetic fuels offers opportunities for a further increase in nuclear power generation. Table 8 presents the generation mix in 2050 and 2070 as well as the incremental generation (by source) between 2050 and 2070. Wind energy is the most competitive source of electricity in the long term and makes up for 64% of the increment growth in the *FNS_EUCO_2070* between 2050 and 2070, reaching 346 TWh at the end of the projection period, in France. However, in the case of the ***FNS_SF_2070*** scenario, where electricity generation is 115 TWh and 130 TWh higher in 2050 and 2070 respectively than in the former scenario, only 53% of the incremental generation is provided from wind energy, as the cost of RES show strong non-linear behaviour once the relatively cheap sites are exhausted and new plants have to be installed in less attractive locations e.g. off-shore turbines at deeper seas, solar PV in places with less irradiation, etc. (Figure 13).

Figure 12. Power generation mix in France in the 2050 scenarios

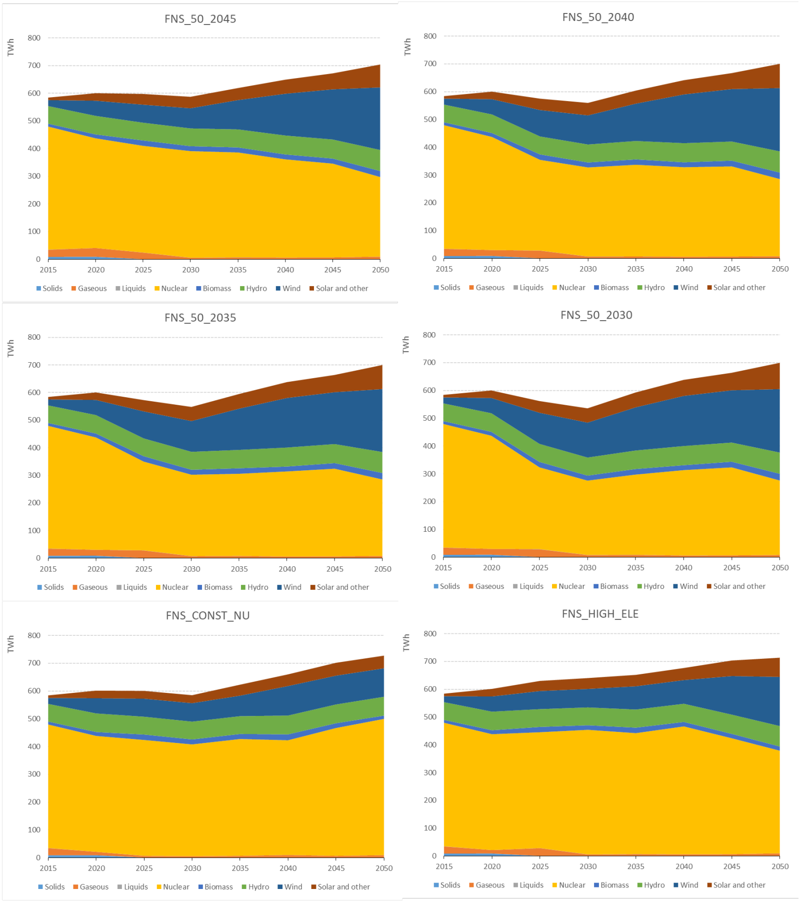


Figure 13. Power generation mix in France in the 2070 scenarios

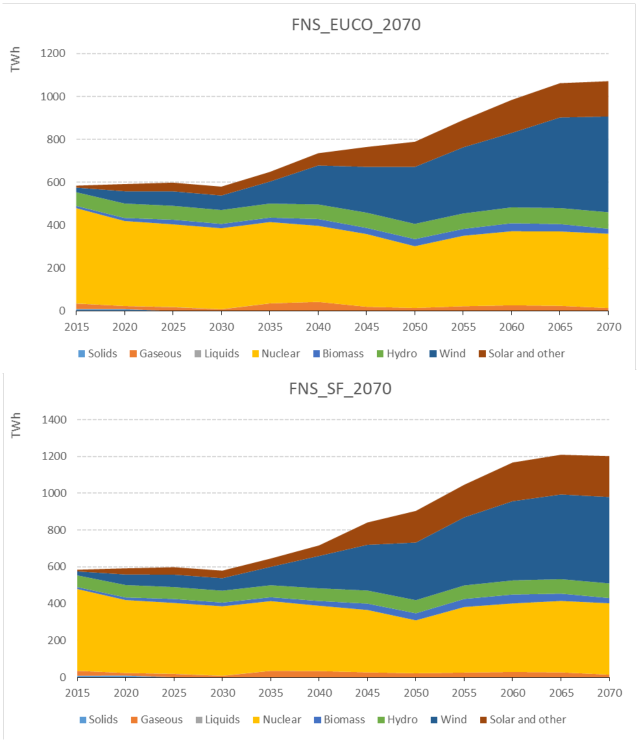


Table 8. Electricity generation by source between 2050 and 2070 in the 2070 scenarios in France

	FNS_EUCO_2070			FNS_SF_2070		
	2050	2070	Growth	2050	2070	Growth
Nuclear	288	346	59	288	388	100
Wind	265	446	181	313	469	156
Solar	117	165	47	172	222	50
Other	119	114	-4	132	122	-10
Total	789	1072	282	904	1202	298

Note: "Other" includes all other sources of electricity generation besides the ones mentioned explicitly, eg. biomass, gas etc.

Given this non-linear increase in the cost of renewables with increased penetration, nuclear energy can still provide power generation at a competitive price, when electricity demand expands significantly, as observed from the increment in generation between 2050 and 2070, in the ***FNS_SF_2070*** scenario, a scenario with a dramatic increase in electricity demand towards the very long term.

GHG emissions

Total GHG emissions in France present a continuous declining trend in all scenarios (Table 9). In all **the main scenarios extending to 2050**, the decline is similar, with little deviations between them, regardless of the pace of the retirements of French nuclear plants. The reasoning behind this trend is that by 2030, variable RES become competitive compared to carbon-intensive emitting options of power generation due to:

a) Reductions in the capital costs of RES and improvements of their techno-economic characteristics;
b) Increasing ETS prices that reduce the competitiveness of fossil-fueled generation (coal and gas).

Moreover, given that all scenarios assume that the European climate targets for 2030 and 2050 are met, any loss in nuclear capacity, results to adjustments (upwards) in the prices for ETS allowances and consequently lowering even further (although slightly) the competitiveness of fossil-fuelled generation.

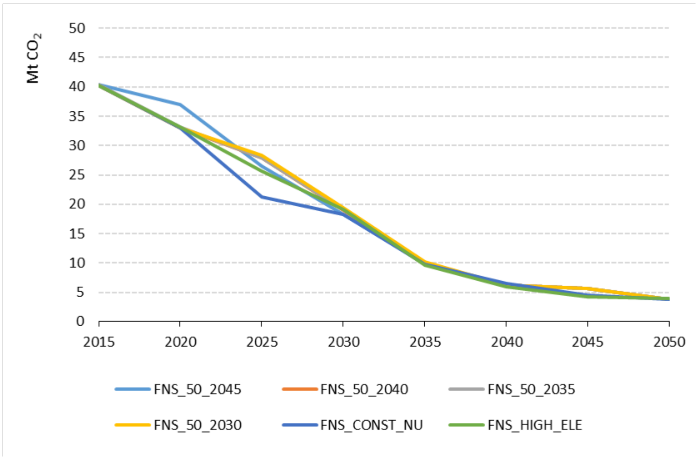
Consequently, any loss in nuclear capacity is almost entirely replaced by RES, with gas-generation acting mostly as ancillary services and providing flexibility to the French power system if and when necessary. By 2050, France emits 147 Mt of CO_2-eq per year, almost three quarters less than the respective emissions in 1990 (Table 9).

Table 9. Total GHG emissions in France (Mt of CO_2-eq)

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
FNS_50_2045	482.2	447.3	405.5	363.7	294.9	229.3	185.3	146.8				
FNS_50_2040	482.2	443.3	407.6	364.1	294.8	228.0	185.3	146.8				
FNS_50_2035	482.2	443.4	407.2	364.4	294.9	228.1	185.4	146.9				
FNS_50_2030	482.2	443.3	407.5	364.5	295.1	228.1	185.4	146.8				
FNS_CONST_NU	482.2	443.3	400.5	363.3	294.5	228.2	182.6	146.0				
FNS_HIGH_ELE	482.2	443.4	398.7	352.8	288.5	224.6	181.2	146.3				
FNS_EUCO_2070	488.1	451.5	405.5	357.8	286.0	212.9	166.3	130.0	107.4	91.9	82.3	75.2
FNS_SF_2070	488.1	451.3	405.7	357.2	287.1	213.1	167.9	123.1	95.4	77.3	74.0	68.7

In the **additional scenarios extending to 2050,** lower emissions are observed in the medium term up to 2030, as in both scenarios, the prolongation of the lifetime for all nuclear reactors avoids the necessity of some gas-fired generation that was taking place in the main scenarios. In addition, in the ***FNS_HIGH_ELE*** scenario, which assumes a higher profile for electricity demand, a drop in emissions is observed throughout the projection period, due to the replacement of fossil fuels (oil, gas) in the demand sectors by electricity (uptake of EVs, heat-pumps, fuel switching in industry). The increased electricity demand in this case, does not result in significantly higher emissions from power generation, as the incremental demand is covered by investments either in new nuclear power plants or in RES (Figure 14).

Figure 14. GHG emissions from the power sector in France



In **both 2070 scenarios**, emissions in 2050 are lower than in all the 2050 cases, due to slightly different fuel mix trajectories in the demand sectors approaching mid-century. For instance, the increasing electrification in the fleets of vans and cars significantly reduces emissions from the transportation sector. The same push for increased electrification takes place in other demand sectors such as industry and buildings, which reduces emissions and increases electricity demand at the same time. Post-2050, GHG emissions decline further, with the lowest levels observed in the ***FNS_SF_2070*** scenario which involves the introduction of significant amounts of synthetic fuels in the fuel mix. In this case, GHG emissions drop to 68 Mt of CO_2-eq by 2070, however, the pace of reduction is faster compared to the ***FNS_EUCO_2070*** scenario, as synthetic fuels[11] start to gain momentum just before mid-century, leading to considerably lower cumulative emissions in the period post-2050 (~160 Mt of CO_2-eq in the period 2051-2070).

Electricity prices

The power & heat supply module of the PRIMES model projects endogenously the prices of electricity and steam and passes them to the demand models. The prices are calculated so as to fully recover all production costs including capital costs, fuel costs, monetary and carbon-related taxes, and other fixed and variable costs.

The prices in a given year take into consideration the investments occurring at the specific period, by transforming the corresponding overnight cost to a series of equivalent annuity cash payments.

[11] The carbon required for the production of synthetic fuels is assumed to be derived from direct air capture, therefore the net GHG emissions from synthetic fuels are statistically zero.

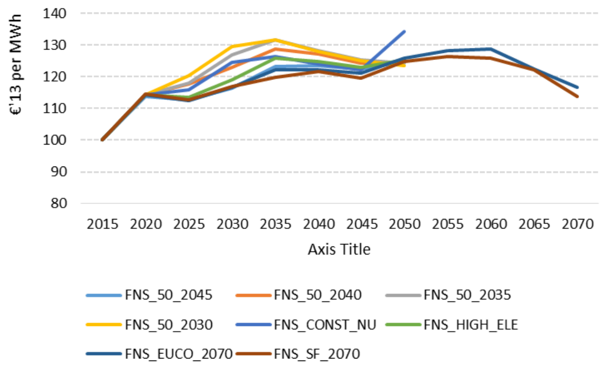
The average pre-tax electricity prices[12] for all scenarios modelled in the current study are presented in Figure 15. Electricity prices for 2030 in the main scenarios are increasing as the number of nuclear reactors whose lifetime gets extended drops (Figure 16).

Prices are higher in the ***FNS_50_2030*** scenario where less nuclear reactors get their lifetime extended, and additional new investments need to be built to compensate for the retired capacity. The opposite holds true for the ***FNS_50_2045*** scenario**,** which in general exhibits the lowest prices among all scenarios. Prices in the long-term tend to stabilise in all the main 2050 scenarios around €124/MWh.

In the extreme constant nuclear option (***FNS_CONST_NU***), significant upwards pressures on prices are observed in the long-term, in order to recover the costs of the bulk investments needed to replace nuclear capacity that has reached the end of its lifetime after LTO (60 years of operation).

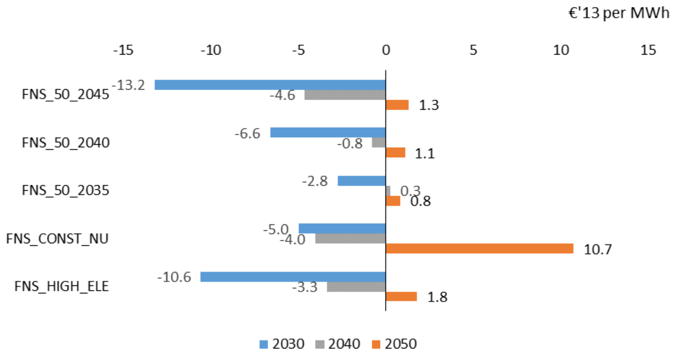
Prices in the ***FNS_HIGH_ELE*** scenario are relatively low, as the incremental demand is covered by new investments in power plants whose marginal costs do not increase with increased generation – constant returns of scale as in the case of variable RES - and the total sales are increasing, therefore investments for the development of power grid infrastructure are distributed among a larger pool of consumers. For the same reason, prices are declining in the very long term as shown in the results of the 2070 scenarios, despite the increased electricity demand.

Figure 15. Average electricity (pre-tax) prices in France



[12] Average price of electricity for each consumer sub-sector (industry subsectors, households, market services, non-market services etc) is weighted by the corresponding consumption levels. The pre-tax electricity prices in PRIMES are calculated in order to recuperate all costs, including capital and operating costs (including payments for carbon allowances), costs related to schemes supporting renewables, grid costs, and supply costs plus a mark-up factor representing a profit margin. End-user excise tax and VAT rates are added to calculate electricity prices after taxes. The latter are transmitted to PRIMES demand models.

Figure 16. Comparison of electricity prices compared to the low extensions scenario (FNS_50 _2030)

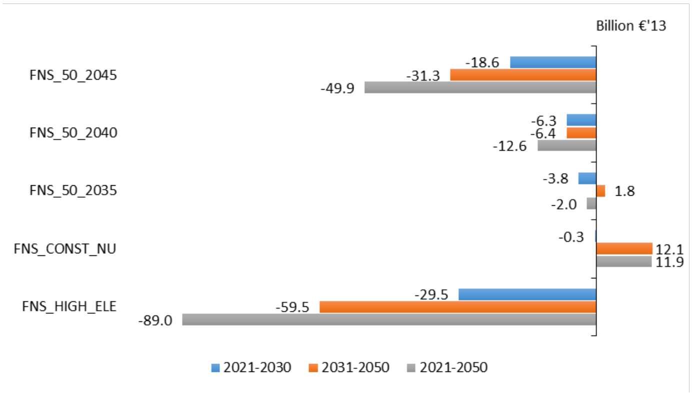


Energy system costs

Figure 17 shows the difference of the cumulative energy system costs for France between scenario FNS_50_2030 and the rest scenarios extending to 2050. Total Energy System Costs[13] are the lowest in the scenario with increased electricity demand (***FNS_HIGH_ELE***). The most expensive scenario is the high nuclear scenario (***FNS_CONST_NU***), indicating that maintaining nuclear capacity constant at today's levels will require significant investment in nuclear towards the end of the projection period. For **the main 2050 scenarios**, the cost decreases monotonously as the drop in the share of nuclear in the gross supply of electricity to 50% gets postponed, i.e. the ***FNS_50_2045*** scenario appears to be the least costly option and ***FNS_50_2030*** the most costly. The former shows a strong advantage in the medium-term (2021-2030), as the cumulative energy system costs in this decade are €19 billion lower than in the latter. Furthermore, it also presents an export advantage of 30 TWh/year in 2030 compared to ***FNS_50_2030***.

[13] Energy system costs that are computed by PRIMES come from the perspective of final energy consumers (industry, households, services, agriculture and transportation). The Total Energy System Costs can be seen as the overall payment to get the required energy services. Obviously the total energy system costs do not refer only to the purchasing of energy commodities but also to all kinds of expenditures incurring to consumers for energy purposes, since equipment purchasing costs and energy efficiency enabling expenditures are included (annuity payment for capital and energy efficiency investments, variable costs, fuel costs which reflect all costs incurring by energy suppliers, including taxes, payments for purchasing ETS allowances - auction payments - etc.). These are also influenced by developments in the supply side in the form of e.g. electricity prices. Auction (ETS) revenues may be excluded from total energy system cost when assuming that the recycling of public revenues in the economy is performed without transaction costs.

Figure 17. Cumulative energy system costs for France - difference from the FNS_50_2030 scenario

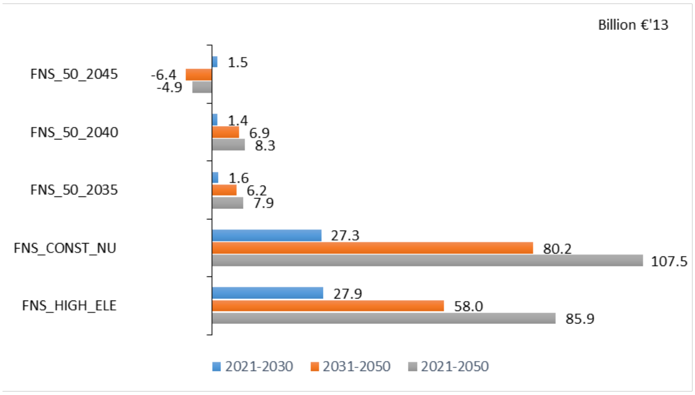


Note: Costs include auction payments for ETS allowances

Table 10. Total Cost of Electricity supply in France annually (billion Euro'13)

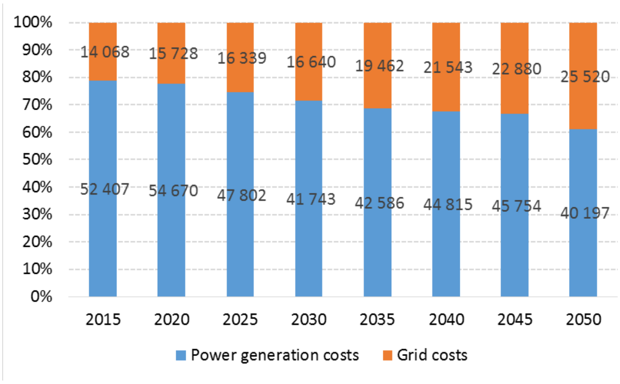
	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
FNS_50_2045	52.4	54.7	47.8	41.7	42.6	44.8	45.8	40.2				
FNS_50_2040	52.4	54.7	47.6	41.9	43.7	45.9	46.4	39.6				
FNS_50_2035	52.4	54.8	47.6	42.1	43.7	45.8	46.5	39.3				
FNS_50_2030	52.4	54.7	47.4	41.9	43.4	45.7	46.3	38.6				
FNS_CONST_NU	52.4	54.7	50.2	46.4	45.4	47.3	49.9	50.1				
FNS_HIGH_ELE	52.4	54.8	50.2	46.5	46.8	48.1	48.0	42.4				
FNS_EUCO_2070	52.4	54.3	47.9	41.8	45.4	51.6	52.9	48.3	52.2	57.0	57.6	52.3
FNS_SF_2070	52.4	54.3	47.9	41.7	45.2	49.9	57.5	55.4	60.6	68.0	66.9	57.9

Figure 18. Total cost of electricity supply in France relative to scenario FNS_50_2030



The total costs of electricity supply between all 2050 scenarios are compared with the FNS_50_2030 scenario and presented in Figure 18. As a general remark, the costs follow the trends observed in the total costs of the energy system, as it is mainly the evolution of the power system that differs across scenarios. It is also noteworthy that the wide penetration of renewables leads to increasing expenditures for the expansion of the grid infrastructure, therefore the share of the later in the costs of the power system increases significantly (Figure 19). In the scenarios extending to 2070, the cost of the power system increases substantially, as electricity demand expands due to the increased electrification in the demand sectors and the introduction of synthetic fuels.

Figure 19. Power generation costs and comparison with grid costs in the FNS_50_2045 scenario



Note: Absolute figures in the labels refer to billion €'13

Investment expenditures required by the power system are presented in Table 11. Scenario ***FNS_50_2045*** presents the lowest investment costs cumulatively in the period 2021-'50 across **the main 2050 scenarios** (and overall). Investment costs **in the additional 2050 scenarios** increase significantly; an increment of 10 billion Euros '13 cumulatively in the ***FNS_HIGH_ELE*** scenario and 74 billion Euros '13 in the ***FNS_CONST_NU*** compared to the respective cumulative expenditures in the ***FNS_50_2045*** case, despite the fact that these two scenarios include the highest numbers of reactors entering LTO. As expected, the need for investment in power plants and grid expansions increase significantly post-2050. It is noteworthy that the scenario including the wide penetration of synthetic fuels (***FNS_SF_2070***) requires cumulatively 80.4 more billion Euros of investment expenditure in the period 2021-2070, compared to the ***FNS_EUCO_2070*** scenario.

Table 11. Investment expenditure for the power system in France (in billion €'13 cumulatively)

	Power plants				Power grids				Total power system			
	'21-'30	'31-'50	'21-'50	'21-'70	'21-'30	'31-'50	'21-'50	'21-'70	'21-'30	'31-'50	'21-'50	'21-'70
FNS_50_2045	50.1	175.3	278.1	N/A	50.6	174.9	261.5	N/A	100.7	350.2	539.6	N/A
FNS_50_2040	76.3	166.4	289.1	N/A	57.2	174.1	267.0	N/A	133.5	340.5	556.1	N/A
FNS_50_2035	73.7	164.3	284.4	N/A	60.0	173.0	268.9	N/A	133.8	337.4	553.3	N/A

FNS_50_2030	80.2	155.0	281.5	N/A	63.3	173.6	272.6	N/A	143.5	328.6	554.1	N/A
FNS_CONST_NU	90.5	262.2	399.1	N/A	45.5	133.7	214.9	N/A	136.0	395.9	614.0	N/A
FNS_HIGH_ELE	85.9	178.6	310.8	N/A	71.4	146.4	253.5	N/A	157.2	325.0	564.4	N/A
FNS_EUCO_2070	41.8	230.3	331.0	459.3	45.9	207.9	289.9	477.7	87.7	438.2	620.8	937.0
FNS_SF_2070	41.8	270.3	371.0	514.5	46.0	231.5	313.5	502.9	87.8	501.9	684.5	1017.4

Impacts on the rest of Europe

EU-wide projections have been provided by the PRIMES model for the four main scenarios. In all main scenarios, the assumptions regarding the extension of the lifetime of nuclear reactors, as well as all other assumptions remain the same across all scenarios. The differences between the scenarios stem solely by the developments on the extensions of the lifetime for nuclear reactors operating in France.

The capacity expansion decisions in the PRIMES model, depend on the relative competitiveness of generation options among power sources, but also on national constraints, such as the requirements for ancillary services, replacement capacity, etc. as well as on national policies regarding renewables, nuclear, etc., including policies regarding the phase-out of nuclear energy in certain MS (Germany, Belgium). The existence of an established nuclear supply chain, from the construction of power plants to the production and transportation of nuclear fuel, affects the competitiveness of nuclear energy against its competitors. Such a value chain is much more developed in France than in most of the remaining EU Member States, and therefore nuclear investment in France is much more competitive (compared to other power generation options) than in most other European countries.

The projections show important amounts of nuclear investments taking place in the mid-term outside France, and new capacity coming online in 6 additional MS. In the period 2030-2050, 12 MS in total (including France) connect new nuclear capacity to their electricity networks (Table 12 and Figure 20). The average cost of power generation in France, remains lower than in the rest of Europe throughout the whole projection period, regardless of the scenario examined (Figure 21).

Table 12. Total nuclear capacity in France and rest of EU28 in the FNS_50_2045 scenario.

	2015	2020	2025	2030	2035	2040	2045	2050
France	63.2	61.3	59.5	59.5	56.3	49.1	45.7	37.2
Rest of EU28	57.6	52.9	45.6	50.4	56.2	68.7	71.0	71.9
Total EU28	120.8	114.2	105.1	109.9	112.6	117.8	116.7	109.2
Share of FR in EU28 nuclear capacity	52%	54%	57%	54%	50%	42%	39%	34%

Figure 20. Comparison of investments in new nuclear capacity between France and the rest of the EU in the FNS_50_2045 scenario

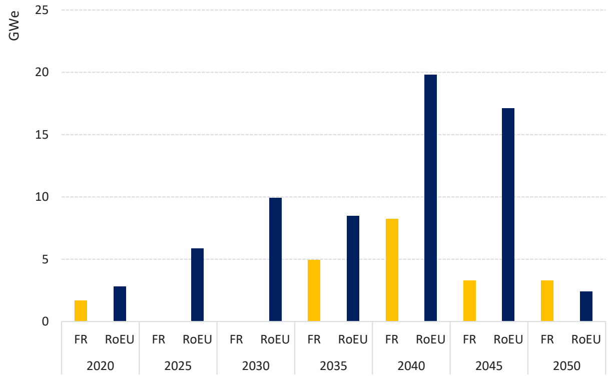


Figure 21. Average cost of electricity generation in France and the rest of the EU

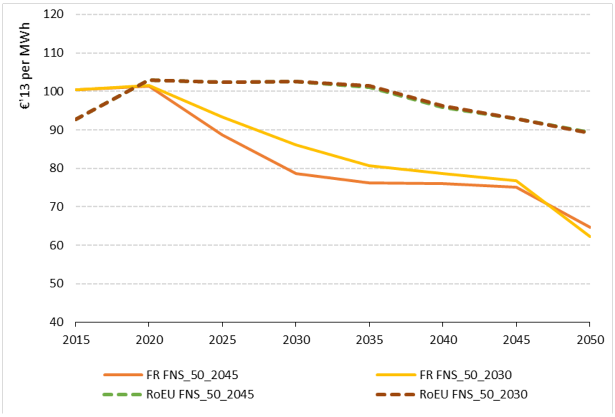
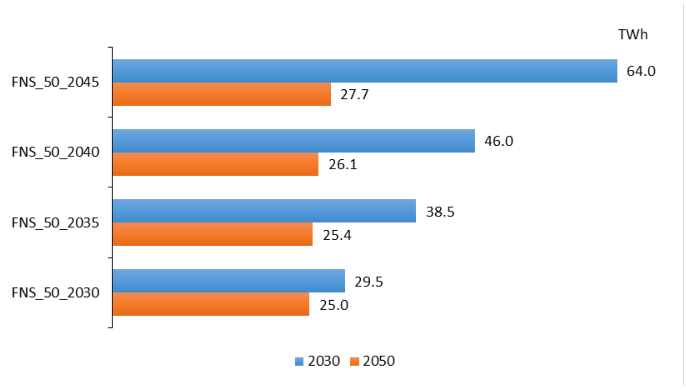


Figure 22. Net exports of electricity from France



The rest of the EU benefits from a significant amount of excess carbon-free generation that can be exported from France as the number of French nuclear reactors whose lifetime gets extended increases. Exports of electricity available from France stand at 64 TWh in 2030 in the FNS_50_2045, whereas they drop to less than 30 TWh in the FNS_50_2030 (Figure 22). The reduction in the availability of French exports translates into an increase in the average price of electricity of €1/MWh for the rest of the EU in 2030, between these two scenarios.

As changes in the trade of electricity, caused in turn by the nuclear developments in France, are the only driver leading to differences for the projections for the rest of the EU between scenarios, no significant deviation is observed between scenarios in terms of cumulative GHG emissions. In addition, the cumulative total energy system costs of the scenarios are quite close (Table 13), as the amount of cumulative exports lost represents less than 0.5% of the cumulative electricity generation, throughout the projection period, in the EU excluding France.

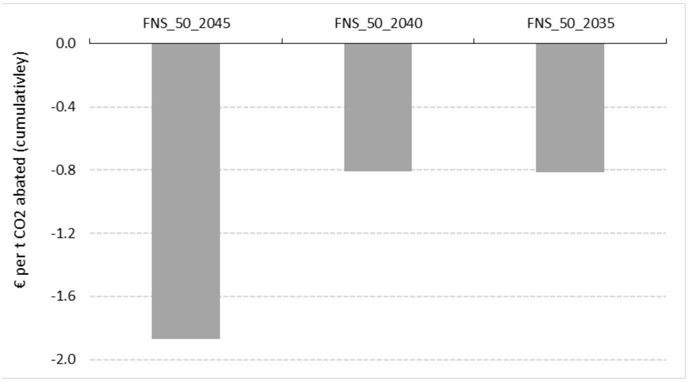
The importance of the French nuclear power for the EU is also apparent when looking at the average unit cost of CO_2 emission abatement for EU28 across scenarios. Having the FNS_50_2030 scenario as a basis, the study shows that the emission abatements of one ton of CO_2 would cost on average €1.9 less in the FNS_50_2045, for the period 2021-2050 (Figure 23).

The importance of the prolongation of the lifetime of French nuclear power plants, especially in the medium term, is also revealed by a previous exercise undertaken by E3Modelling, which is briefly presented in Box 1.

Table 13. Total energy system costs in the EU excluding France (billion Euro'13)

	2015	2020	2025	2030	2035	2040	2045	2050
FNS_50_2045	1289.4	1516.5	1643.2	1804.4	1867.5	2025.8	2233.2	2469.1
FNS_50_2040	1289.4	1516.5	1643.6	1803.7	1866.2	2024.5	2233.2	2470.8
FNS_50_2035	1289.4	1516.5	1643.3	1803.8	1866.5	2025.1	2231.3	2467.5
FNS_50_2030	1289.4	1516.5	1643.2	1803.7	1866.5	2024.9	2233.5	2471.4

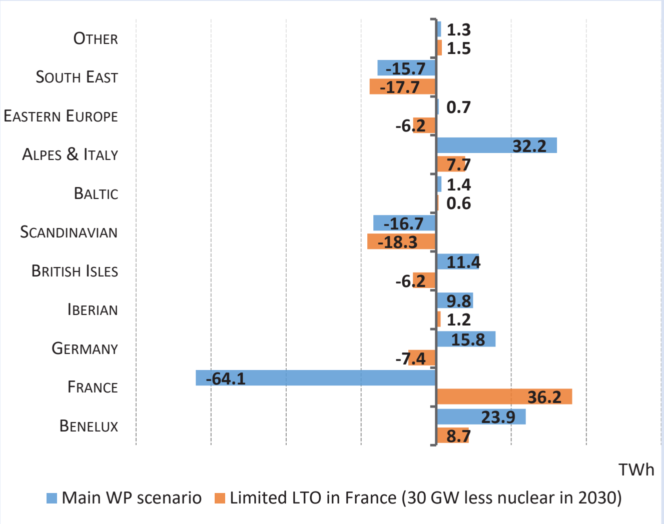
Figure 23. Average unit cost of emissions reduction in EU28 for 2021-2050, compared to the FNS_50_2030 scenario.



Box 1. **What if nuclear retrofitting in France is even lower than in the "low lifetime extensions" scenario?**

The current study has taken a cautious approach regarding the assumptions regarding the "low lifetime extensions" case for French nuclear reactors, as it is more likely that a significant part of the fleet will go in LTO once they reach their 40^{th} year of operation. In other words, even in the ***FNS_50_2030*** scenario, 22 GW of nuclear capacity gets lifetime extensions in the horizon up to 2030. In the "high lifetime extensions" scenario (***FNS_50_2045***) the respective figure is 42 GW. 22 GW of retrofitted nuclear capacity allows France to keep exporting almost half of the electricity it was exporting in 2015. An extreme case, where only a small part of French nuclear fleet goes into LTO has not been modelled, as it is considered unrealistic. However, a previous exercise, undertaken in early 2017 has revealed consequences of such low nuclear refurbishment rates in France in the medium term.

Figure 24. Impact on trade balance for EU regions in the case of very low retrofitting in France.



Note: WP - Winter Package

Assuming that only 12 GW of nuclear capacity goes into LTO in the period up to 2030 would lead to France becoming a net importer of electricity by 2030 (

Figure 24), as very low nuclear generation causes disturbances in the imports-exports balance. The gap left by scrapped nuclear capacity is partly filled by investments in CCGT in France, Germany, Belgium and the UK, thus increasing GHG emissions. It can be concluded then, that French nuclear plants are acting as the backbone of electricity exchanges in Central-West Europe in the medium term. Beyond the medium-term, the retirement of nuclear plants implies almost no dispatchable generation in the base load, as the power mix depends almost entirely in RES and gas-fuelled generation.

6. Discussion and concluding remarks

The current report presents the results of a quantitative modelling exercise on different pathways of the French power system in the wider European policy context that aims at the deep decarbonisation of the European economy in the long-term. Emphasis was given to the unique characteristics of the French power system - strong dependence on nuclear power - and the technical and economic challenges it is currently facing: whether the lifetime of a significant part of its nuclear fleet will/should be extended beyond 40 years of operation. The analysis has drawn conclusions from the elaboration of a total of eight scenarios that have been constructed using the PRIMES energy systems model, a powerful and analytical modelling tool that has been used extensively in the past three decades in policy analysis and impact assessments related to the EU energy sector.

The modelling exercise shows that the French energy system, as well as the EU energy sector to a lesser extent though, will benefit from the prolongation of the lifetime of the French nuclear reactors. Comparing the “high lifetime extensions” case, where the share of nuclear drops to 50% in 2045, with the “low lifetime extensions” one, where this takes place already in 2030, cumulative monetary savings of 50 billion Euros’13 are achieved in France in the period 2021-2050. The extension of lifetime of nuclear reactors in the “high lifetime extensions” case, implies a need for lower investments in the power system in the next decade (2021-’30) of around 43 billion Euros cumulatively compared to the “low” case, as the refurbished nuclear plants in LTO, cancel the need for investments in new power plants. This scenario also provides an export advantage of 30 TWh per year in 2030 compared to the case where the 50% share is reached already in 2030. In the remaining period up to mid-century (2031-’50), the “high lifetime extensions” scenario requires 22 billion Euros ’13 more than the investment expenditure of the “low lifetime extensions” case, in order to compensate for the ultimately retired nuclear capacity.

Besides the monetary benefit in investment expenditures, the “high lifetime extensions” case allows for an additional 400 TWh to be exported cumulatively (40% increase) compared to the case of limited lifetime extensions, therefore, the trade position of France is significantly improved in the former option. Moreover, it is found to be a beneficial policy option for final consumers, as the average pre-tax electricity price is kept at low levels in the mid-term (€116/MWh in 2030 in the “high lifetime extensions” scenario in contrast with €130/MWh in the “low” case) and increases only moderately afterwards (€125/MWh in 2050).

As far as GHG emissions are concerned, the “high lifetime extensions” scenario shows only a marginal improvement in cumulative GHG emissions between the two cases, as in the “low lifetime extensions” case, the nuclear capacity not entering LTO is replaced by low-carbon sources of electricity – variable RES – which become more and more competitive towards the medium term.

Apart from the main sensitivity scenarios modelled in this study, two additional scenarios with a horizon up to 2050 have been examined and have provided useful conclusions about the role of nuclear in contexts that deviate slightly from the pathway envisaged in the main 2050 scenarios. A scenario with constant nuclear capacity till 2050, exhibits larger cumulative GHG emissions reductions than the main scenarios, however, this comes at significantly higher costs. This is due to the very high investments in new nuclear power plants needed in the 2040s in order replace capacity that is ultimately retired after LTO. At this point in time, investments in RES are more cost-effective. The high-electricity scenario has identified the relatively high elasticity of nuclear power with respect to electricity demand in the short to medium term. In case the demand for electricity increases by 10% in 2030 compared to the main scenario, not only the extension of nuclear plants brings down the overall cost of the energy system, but new investments are found to be economic, with nuclear capacity exceeding the benchmark of 63 GW by 2030. The cost of the energy system in this case is found to be the lowest across all scenarios modelled, as nuclear generation and RES are power generation options with low or zero variable costs (constant returns of scale), and the fixed costs of the system are distributed among a larger pool due to the, by assumption, increase in electricity sales.

The exercise has also shown co-benefits for the EU energy system because of the prolongation of the lifetime of nuclear reactors, although quite small in scale. However, drawing on results from a previous modelling exercise with the PRIMES model, undertaken in early 2017, it can be concluded that an extreme case of very limited lifetime extensions (only 12 GW in LTO operation in 2030) leads to no exports of carbon-free electricity from France to its neighbours, which is compensated partially by investments in CCGT capacity, creating capacity lock-in effects for the next decades, and ultimately increasing EU GHG emissions. Consequently, the French nuclear fleet acts as an important backbone of carbon-free electricity in Europe in the medium term, via the power exchanges with its neighbouring countries.

Besides the role of the French nuclear fleet for the EU transition, nuclear power outside of France has an important role to play in the forthcoming transition of Europe towards a low carbon economy. Nuclear power plants have the merit to be a baseload dispatchable electricity source which is carbon free. The CCS technologies may compete but their penetration in the power mix depends on assumptions about the availability of underground storage of CO_2. The integration of large scale variable RES requires flexible resources which are provided, as confirmed by modelling results, by natural gas plants and storage technologies (batteries, pumping and power-to-H_2 in the long term).

The systematic patterns of export flows in the EU internal market are mainly driven by the location of nuclear capacities. The conventional coal or lignite capacities are phased out and cannot support exporting flows. Large-scale hydro is also a driver of trade, as in the case of Norway. In the long term, a driver of systematic export flows is wind offshore energy generated in the North Sea.

Apart from these systematic export flows, all other import-export flows are driven by the sharing of balancing resources. The model finds it optimal to build flexible capacities, such as storage and natural gas plants, close to consumption, rather than to export flexibility systematically to a certain direction. Therefore, the sharing of flexibility implies imports-exports in both directions.

A lack of nuclear in the long term implies lack of a driver of systematic export flows of electricity. The electricity trade is then driven by flexibility and the location of hydro and wind offshore resources. It is of course unlikely to see systematic export driven by solar PV because of the strongly imbalanced pattern of solar. Similarly, the high and rather homogeneous dispersion of wind onshore potential in the countries implies no interest to systematically exports based on wind onshore.

In the very long term, the analysis has shown that the full decarbonisation of the EU power system will require significant growth in electricity demand, due to the very high degree of electrification in the transport sector (electric vehicles) and in stationary applications (heat pumps) and potentially the introduction of synthetic fuels as a means to abate the remaining GHG emissions. Such significant demand growth reveals a new opportunity for nuclear power to regain momentum close to mid-century since the competitiveness of RES will drop as low-cost installation sites become saturated and new RES plants will need to be built at more remote and less favourable locations, in terms of natural resources and technical limitations.

However, this nuclear comeback cannot be realised in case a significant amount of reactors does not enter LTO and the nuclear industry is abandoned, as this would imply the beginning of a decline in human capacity with expertise in nuclear power, and the incurrence of stranded costs, as important parts of the nuclear supply chain (fuel fabrication, fuel and waste transportation routes) will perish. Reviving the nuclear industry towards the middle of the century, after a period of hibernation in the medium term is a task highly questionable regarding its successful outcome.

Annex A – Overnight investments costs (€'13/kW) for selected power generation technologies

		Overnight Investment Cost (EUR/kW)			
		2015	2020	2030	2050
Wind Offshore		3 175	2 778	2 048	1 891
Wind Onshore		1 200	1 066	915	848
Solar PV		1 100	814	663	554
Solar Thermal		5 500	4 237	3 437	3 075
Tidal-Waves		7 590	6 100	4 704	3 100
Geothermal		5 660	5 370	4 870	4 010
Biomass-Waste	Biogas	1 050	1 000	900	800
	Biomass Solid	2 710	2 650	1 950	1 800
Nuclear	3rd gen reactor in FR	5 100	4 500	4 500	4 500
CCGT	(high efficiency)	850	800	765	750

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At a time when France's Multi-Year Energy (PPE - *Plan Programmation Pluriannuelle de l'Énergie*) is being drawn up, eight scenarios provide an additional perspective to the RTE studies, by including three new factors: Europe, the long-term and the energy system as a whole.

Using the PRIMES model, a tool used by the European Commission to model the EUCO30 scenarios for the 'Clean Energy for All Europeans' package, Professor Pantélis Capros from the University of Athens / E_3 Modelling and his teams developed new versions of these scenarios. Some incorporate specific hypotheses for reducing the share of nuclear in the French electricity mix.

Based on these studies, the SFEN has two recommendations:

- **Reduction of nuclear power must be managed in line with the development of other low-carbon energies, and not preemptively.** France's Multi-Year Energy Plan (*PPE*) is designed to provide for the progressive taking into account of the numerous uncertainties, in 5 year periods, in terms of demand, the strategies of France's European neighbours, and expected technical and economic progress. Maintaining available nuclear power is less expensive and more consistent with the Multi-Year Energy Plan's adaptive approach; it will also make it possible for France to programme its decarbonisation more efficiently, in the face of these uncertainties.
- **A public discussion focused on the setting up of an industrial programme to bring about significant cost reductions for third generation nuclear power should be held.** The need for maintaining a core supply of nuclear power to 2050, and the potential rebound of this energy in France and Europe in the long-term, in order to achieve deep decarbonisation objectives, makes this discussion essential. Progress made during renewal of the French nuclear fleet, in terms of competitiveness, will be of benefit to the rest of Europe, where 70GW of new nuclear capacity is to be built between now and 2050.

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