Artelys | SOLUTIONS EN OPTIMISATION

Determination of a target electricity interconnection capacity between France and the United Kingdom

Report

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Summary

CONTEXT AND OBJECTIVES

At present, several interconnection projects between France and Great Britain are being considered in order to make better use of the synergies and complementarities between the British and continental European power systems. This study aims to provide quantitative elements enabling an informed decision-making process related to the interconnection capacity between France and Great Britain that should be targeted. The impact of a certain number of assumptions (in particular deployment of renewable energies, evolution of nuclear capacities, level of interconnection, etc.) is presented and discussed in order to identify the contexts in which an increase of the electricity interconnection capacity between France and Great Britain can be favourable.

A cost-benefit analysis of an increase of the electricity exchange capacity on the France-Great Britain border was carried out using the Artelys Crystal Super Grid software. In this report the benefits associated with a new interconnection are to be understood as the socio-economic welfare generated by the commissioning of this new interconnection.

SCENARIOS OF EVOLUTION OF THE EUROPEAN ELECTRICITY SYSTEM

In this analysis, a special attention was paid to taking into account the key uncertainties related to the evolution of the European electricity mix. Several scenarios have been established, with the aim of covering a set of coherent and contrasted European energy contexts. The objective is therefore to evaluate the value of interconnection projects considering their entire lifetime, taking into account the trajectory of the evolution of the European energy context, from their commissioning to the end of their operational life.

The following three main scenario trajectories have been modelled and simulated at national scale and hourly granularity, at the 2025, 2030 and 2040 horizons - each taking into account a set of ten climatic years. At each of these time horizons, FR-GB interconnection capacities ranging from 3 GW to 9 GW have been simulated and compared.

- **"Sustainable Transition[1]"**: From 2025, energy transition takes place at a relatively rapid pace and enables the 2030 European objectives to be achieved. Since the energy system does not undergo profound sectoral transformations until 2040 (mass electrification, highly developed energy efficiency, technological breakthroughs, etc.), the decarbonisation objectives for 2050 may nonetheless require an acceleration of the energy transition after 2040. In France, nuclear capacity decreases by 14 GW between 2025 and 2030, while the wind and solar power sectors

[1] The names of the scenarios have been chosen so as to reflect the names used in the CRE's Deliberation N° 2019-170. In particular, one should note that the Sustainable Transition used in this study is based on but not identical to the ENTSOs' Sustainable Transition scenario published in TYNDP 2018. More details can be found in Section 2.

grow by around 25 GW between 2025 and 2030, and then by an additional 25 GW between 2030 and 2040. Electricity demand decreases due to energy efficiency efforts.

- "**Conservative**": In a context of slower economic growth, the energy transition is assumed to be slower and delayed for the whole of Europe. With a lower level of renewable energy development, France maintains a high nuclear capacity until 2040, which is also in line with the most recent announcement of the French government. Demand in France and the United Kingdom is stable across the entire trajectory due to the slow progress of energy efficiency efforts.

- "**National Plans**": The energy transition generally follows the pace of the "Sustainable Transition" scenario in Europe. In France and the United Kingdom, the development of renewable energies is both faster and more ambitious. Both countries have a high nuclear capacity. The respective decarbonisation of their electricity mix is more advanced than in the other scenarios across the entire trajectory. Electricity demand grows due to the electrification of industry and transport.

Furthermore, a variant was considered using the European context described by the TYNDP 2018 "Distributed Generation" scenario associated with the assumptions made in the "National Plans" scenario for France.

It should be noted that the terms and conditions of the withdrawal of the United Kingdom from the European Union may have a significant impact on the analysis of the economic relevance of a new interconnection projects between Great Britain and France. In all the scenarios studied during this study, the United Kingdom is considered as being part of the European internal energy market. The operational use of interconnectors is therefore assumed to be optimal: flows dynamically adjust according to arbitrage opportunities. The "Value of interconnectors between France and Great Britain" [10] study conducted in 2017 by Artelys and Frontier Economics, which was based on TYNDP 2016 scenarios, had demonstrated that the value of interconnectors is deteriorated in scenarios where the United Kingdom is not part of the internal European energy market. Although this study does not consider the potential impacts of Brexit, it can reasonably be considered that the benefits mentioned in this document would be lower in the event of a "hard" exit of the United Kingdom from the European Union.

BENEFITS BROUGHT BY AN ADDITIONAL INTERCONNECTION PROJECT

Considered over its entire lifetime, a new interconnector does not appear economically relevant in any of the scenarios considered in this study.

The analysis reveals that the following two conditions are necessary for the profitability of 1GW of additional capacity to materialise: strong surplus of low-cost electricity generation in one of the two countries and high gas and coal production costs. These conditions are only met in the scenario "National Plans" at the 2030 horizon. In this context, maintaining a high nuclear power capacity in France (58 GW) coincides with an ambitious level of development of renewable energies (45 GW of wind power and 48 GW of solar power), in a context of stable demand. Consequently, France has considerable nuclear power surpluses that can generate value through exports to the United Kingdom, where 25% of the electricity generation in this scenario relies on natural gas. Given the assumption of a CO_2 price reaching more than € 80/t in 2030, the benefits brought by 1 GW of additional interconnection capacity exceed € 100 million/year, for a total annual cost estimated on average at € 75 million/year.

However, at the 2040 horizon, low levels of benefits are found to be associated with increases of the interconnection capacity beyond 4 GW, since the high production capacities in low-cost electricity generation technologies are envisaged in parallel with a further electrification of the national energy mixes, limiting the opportunities for imports/exports.

KEY DRIVERS FOR THE VALUE OF THE INTERCONNECTOR

The necessary conditions for a new interconnection between France and Great Britain to be economically relevant have been identified using a series of sensitivity analyses carried out on the basis of the "National Plans" scenario[2]. It appears that the creation of new markets for low-cost electricity, such as the development of hydrogen production via electrolysis, has a negative effect on the relevance of an interconnector since these alternative uses of electricity provide similar flexibility services as exports do, in particular by allowing for the system to adapt to intermittent renewable energy systems and the variability of demand. Furthermore, a CO_2 price that remains high from 2030 to 2040 has the effect of strengthening the level of generation savings via arbitrage operations between nuclear/renewable energy and fossil fuels, thereby increasing the value of the interconnector. Conversely, a CO_2 price lower than €30/t in 2030 has the effect of reducing this value by around 50%. The relevance of a new interconnector between France and Great Britain is also highly dependent on the development of other interconnectors. Finally, assuming an electricity mix that is already largely dominated by carbon-free technologies in Great Britain, the value of a new interconnector project lies mainly in the use of electricity surpluses in Great Britain, and is therefore subject to the availability of such surpluses. A very ambitious development of the wind energy sector in Great Britain by 2040 is likely to strengthen the value of a new interconnector.

[2] Considering that other scenarios provide unambiguous results, the sensitivity analyses have all been carried out on the basis of the "National Plans" scenario.

Table of contents

Table of figures

Authors

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Artelys is a company specialised in optimisation, forecasting and decision-support. With around one hundred studies and software projects in the energy field under its belt, Artelys is a leading player in the optimisation and techno-economic analysis of energy systems. In particular, Artelys has developed a software suite, Artelys Crystal, dedicated to the economic optimisation of energy system management and investments.

1 Introduction

1.1 Context

Overview of the France-England interconnector

At present, the level of interconnection between the British electricity system and its neighbours is relatively low. The only interconnector currently in operation between France and the United Kingdom is IFA2000 (2 GW). In addition to this interconnector, Great Britain is connected to the Netherlands (BritNed, 1 GW), Northern Ireland (Moyle, 500 MW) and the Republic of Ireland (East West Interconnector, 500 MW). This level of interconnection makes the United Kingdom one of the least well-interconnected countries, as noted by the group of experts on the target interconnection levels established by the European Commission[3].

In order to increase its interconnection levels with neighbouring countries, Great Britain introduced a *Cap & Floor* regulation in 2014, aimed at reducing the level of risk incurred by promoters of electricity interconnection projects between Great Britain and its neighbours.

As a consequence, many projects have emerged to bring out the synergies and complementarities between the British and continental electricity systems, including ElecLink (1 GW, FR, exempted), NEMO (1 GW, BE, in testing phase), NSN (1.4 GW, NO), FAB Link (1.4 GW, FR), IFA2 (1 GW, FR), Viking (1.4 GW, DK), GreenLink (500 MW, IE), Aquind (2 GW, FR) and GridLink (1.4 GW, FR).

Given the large number of candidate interconnectors, it is of critical importance to be able to understand the synergistic and competitive aspects of these various projects. This is because the target interconnection capacity between France and the United Kingdom depends not only on the complementarities between the production mixes (and the underlying energy/climate policies) and the structure of electricity demand, but also on the level of interconnection between Great Britain and its neighbours, and between France and its neighbours.

The purpose of this study is to provide quantitative elements enabling informed decision-making with respect to the target interconnection capacity between France and Great Britain. The impact of a certain number of assumptions, in particular concerning renewable energy deployment, changes in nuclear capacities, interconnection levels, etc., is presented and discussed, in order to identify the contexts in which an increase in electricity interconnection capacity may be particularly beneficial.

[3] https://ec.europa.eu/energy/sites/ener/files/documents/report_of_the_commission_expert_group_on_electricity_interconnection_targets.pdf

Issues to be covered in the study

In order to examine the various projects, their respective impacts in terms of socio-economic welfare must be analysed. Given the operational lifetime of electricity interconnection projects, the assessment of the impact on socio-economic welfare must take into account various possible evolutions of the European electricity systems. In particular, the definition of scenarios can reflect elements related to energy or climate policy (prioritisation of investments in renewable energy sectors, phase-out or reduction in the use of certain thermal technologies, etc.), economic conditions (which particularly influence the level of demand) and the diffusion of new uses and practices (electric vehicles, heat pumps, active demand management, etc.).

In order assess the impacts on the socio-economic welfare, we have carried out cost-benefit analyses based on detailed simulations of the operations of the European electricity systems for a large number of scenarios and variants.

1.2 Objectives

The purpose of this study is to determine a target interconnection capacity between France and the United Kingdom using a techno-economic perspective.

In this analysis, particular attention was paid to the consideration of uncertainties concerning changes in the European electricity mix. Several scenarios were established with the aim of covering a set of consistent and contrasted European energy contexts. Furthermore, the aim here is to assess the value of interconnector projects throughout their lifetime, taking into account the evolution of the energy context, from their commissioning to the end of their technical lifetime.

Lifetime analysis is of importance because an interconnector may be of proven economic interest over the short-term and yet only provide little value in the longer term, or vice versa. In this respect, the date of commissioning is also a key element, insofar as it also determines the context in which the infrastructure must be assessed (and its development).

1.3 Tool used: Artelys Crystal Super Grid

The analyses carried out in this study are based on quantitative indicators resulting from techno-economic simulations of the European electrical system. These simulations were carried out using the *Artelys Crystal Super Grid* software solution. Developed and distributed by Artelys, this tool is used, among other things, to carry out cost-benefit analyses of infrastructure projects and more specifically to assess the economic interest of interconnector projects. In the context of this study, the economic interest was assessed from the point of view of society as a whole and not just for the promoter.

The Artelys Crystal Super Grid tool includes a graphic interface used to create models and analyse results and a calculation engine that implements state-of-the-art optimisation algorithms enabling the optimisation and scheduling of production with an hourly time resolution across all European countries using multiple climatic conditions. The models take into account several techno-economic parameters, including the dynamic management of storage facilities, the costs of fuels and CO_2, a set of dynamic constraints relating to electricity production (ramping gradients, minimum production levels, etc.) and the unavailability of production assets due to maintenance.

Figure 1 illustrates the software's operating mode.

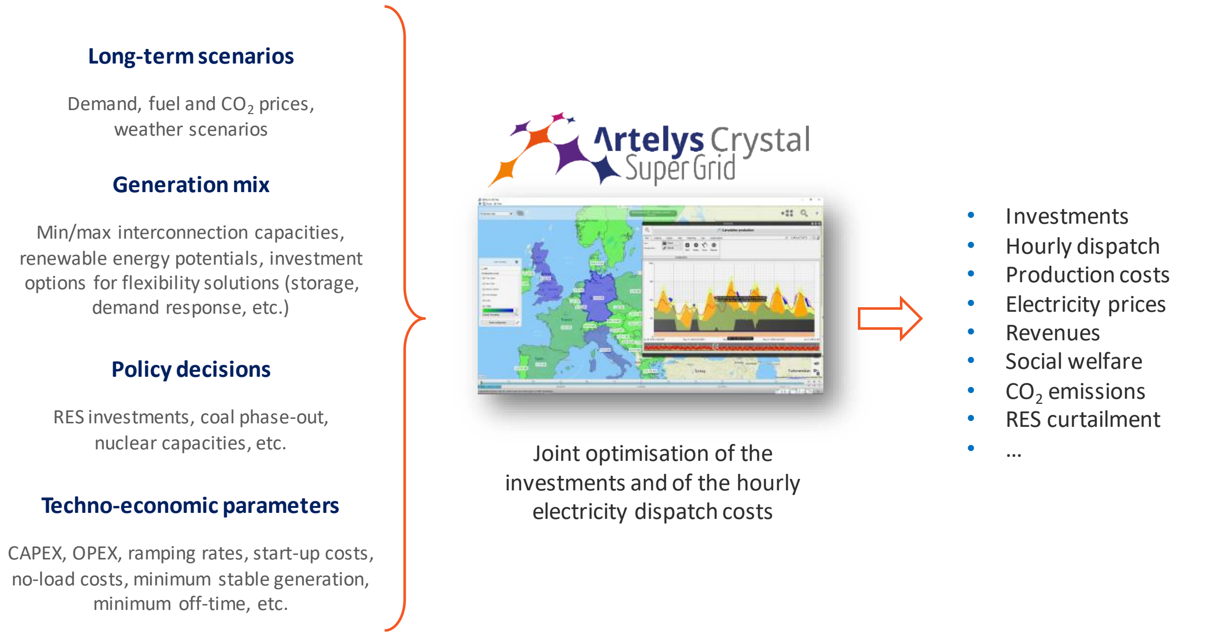


Figure 1 – Presentation of the Artelys Crystal Super Grid tool

1.4 Study approach

The gross benefits generated by an additional interconnector between France and the United Kingdom are assessed in a set of consistent and contrasted energy contexts. Following a review of publicly available scenario building exercises including France and the United Kingdom, three main scenarios and an additional variant were established for this study. The time horizons explicitly modelled and simulated are 2025, 2030 and 2040, each of which is applied on a set of ten climatic years. A series of sensitivity analyses was then carried out on the basis of the scenario taking into account French and British national plans[4], which is the only scenario for which the interconnector may be of economic interest. Figure 2 presents all the simulations carried out in this study.

[4] Since the other scenarios give unequivocal results, the sensitivity calculations were all carried out around the "National Plans" scenario.

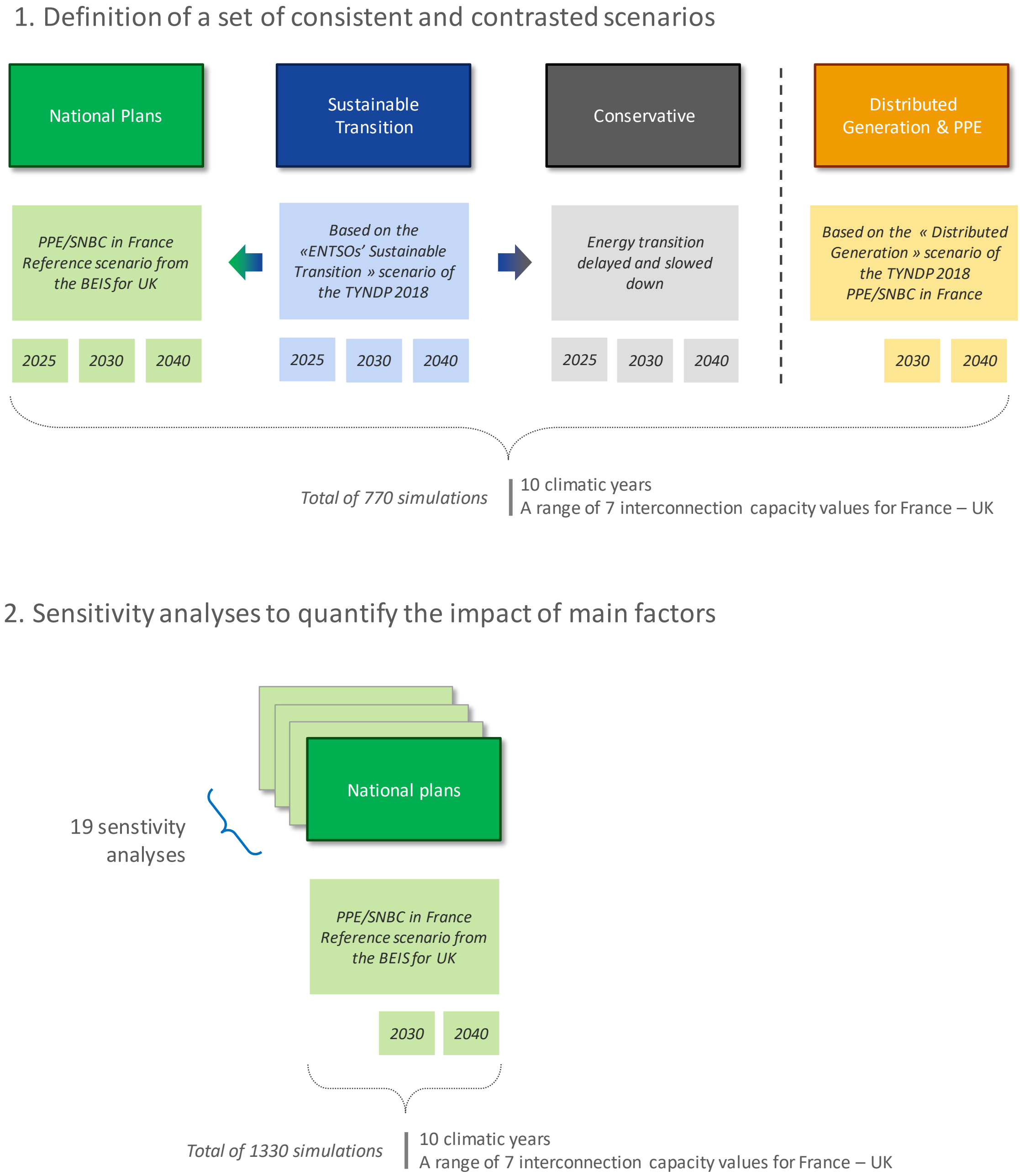


Figure 2 - Scope of the change scenarios covered by the study

For all the time horizons considered and for each of the selected scenarios, national production plans and cross-border trade[5] are jointly optimised with an hourly time-resolution across all European countries[6] using the *Artelys Crystal Super Grid* tool.

[5] Electricity trade flows between countries are explicitly simulated using a standard *NTC* (*Net Transfer Capacity*) approach, which represents maximum trading capacities between zones.
[6] More specifically, this concerns EU28, Switzerland, Norway and most Balkan countries; Iceland, Cyprus, Malta and Albania are not represented.

These simulations are carried out in parallel using various interconnection capacity assumptions between France and the United Kingdom. The interconnection capacities tested range from 3 GW to 9 GW with steps of 1 GW, in order to cover all the projects considered in the TYNDP 2018 between France and GB. The case of 4 GW of interconnection is considered to be the benchmark case, since this is the capacity that can assumed to be online by 2020 (IFA2000, ElecLink, IFA2). For each scenario, simulation results are analysed by comparing them with the relevant scenario's 4 GW benchmark. The difference in *socio-economic welfare*[7] between the 4 GW situation and the 5 GW situation corresponds to the gross benefit attributable to an initial (1 GW) interconnector project, and so on.

A cost-benefit analysis can be conducted by calculating the net present value of a project over its entire lifetime, based on:

- The gross benefits induced over each time horizon: the socio-economic welfare
- The total costs of the project, including investment costs, operational costs and an estimation of the economic value of the losses generated by the additional electricity flows.

[7] Economic indicator generally used to assess the benefits of a project for the entire society.

2 Scenarios concerning the European energy context

In order to take into account the uncertainty related to the evolution of the European energy systems, three trajectories were initially designed in collaboration with CRE, which has conducted a third-party consultation. Each of these trajectories reflects a different overall European context, the aim being to cover a contrasted spectrum of possible evolutions.

The key characteristics of the three main scenarios are as follows:

- **"Sustainable Transition"**: From 2025, energy transition takes place at a relatively rapid pace and enables the 2030 European objectives to be achieved. Since the energy system does not undergo profound sectoral transformation until 2040 (mass electrification, highly developed energy efficiency, technological breakthroughs, etc.), the decarbonisation objectives for 2050 may nonetheless require an acceleration of the energy transition after 2040. In France, nuclear capacity decreases by 14 GW between 2025 and 2030, while the wind and solar power sectors grow by around 25 GW between 2025 and 2030, and then by an additional 25 GW between 2030 and 2040. Electricity demand decreases due to energy efficiency efforts.

- **"Conservative"**: In a context of slower economic growth, the energy transition slows down and is delayed for the whole of Europe. With a lower level of renewable energy development, France maintains a high nuclear capacity until 2040, which is also in line with the most recent announcement of the French government. Demand in France and the United Kingdom is stable across the entire trajectory due to the slow progress of energy efficiency.

- **"National Plans"**: The energy transition generally follows the pace of the "Sustainable Transition" scenario in Europe. In France and the United Kingdom, the development of renewable energies is both faster and more ambitious. Both countries have a high nuclear capacity. The respective decarbonisation of their electricity mix is more advanced than in the other scenarios across the entire trajectory. Electricity demand grows due to the electrification of industry and transport.

Furthermore, a variant was considered using the European context described by the TYNDP 2018 "Distributed Generation" scenario associated with the hypotheses of the "National Plans" scenario for France. Figure 3 illustrates the differences between the scenarios in terms of baseload-like production capacity and annual demand level.

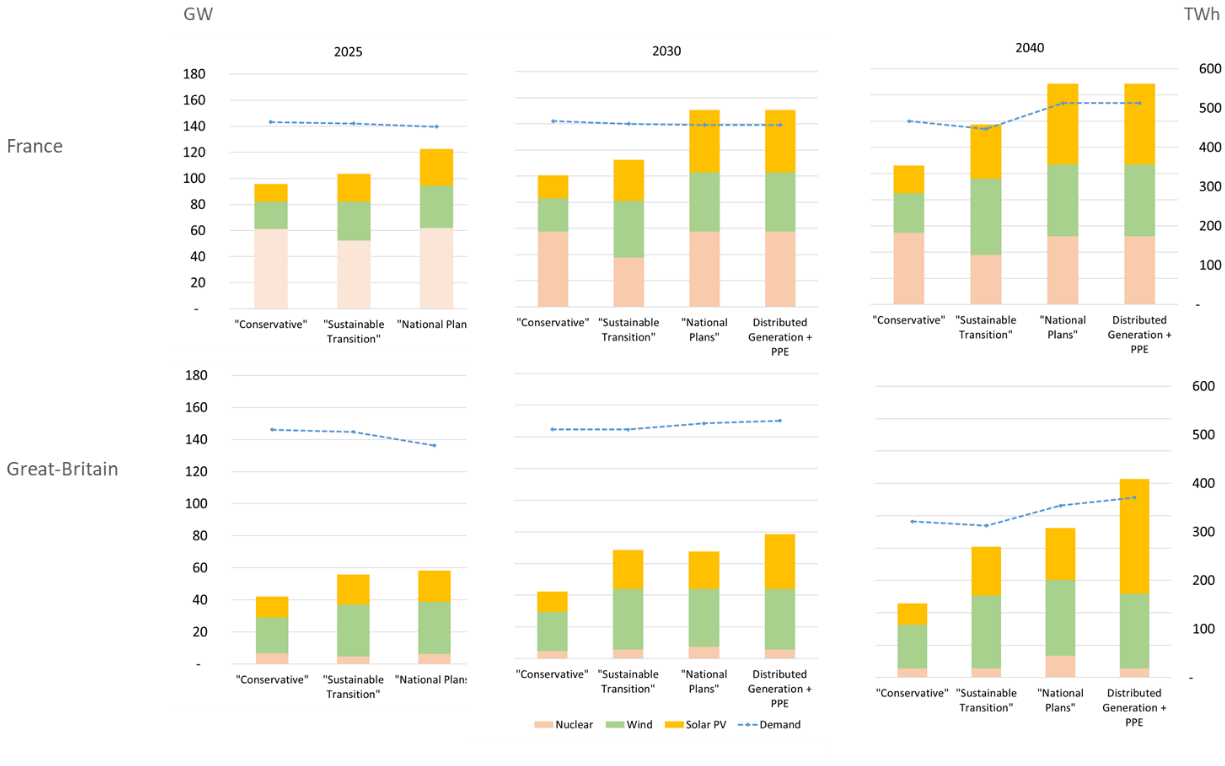


Figure 3: Main hypotheses of the three main scenarios and the "Distributed Generation + PPE" variant

For each scenario modelled, gas production capacities (CCGT, OCGT) were optimised, in order to limit loss of load to 4 hours/year on average over climatic years, subject to a minimum capacity taken from the assumptions of the source underlying the scenario.

2.1 Three main energy mix evolution trajectories

2.1.1 "Sustainable Transition" scenario

In order to be able to rely on a European benchmark scenario, one of the scenarios modelled in this study is based on the 2018 edition of the Ten-Year Network Development Plan (TYNDP) scenarios, which are jointly developed by ENTSOG and ENTSO-E. The TYNDP is drawn up every two years. In this context, scenarios that notably include the development of the European electricity network, production resources and demand levels over time scales of around fifteen years are produced. A "Best Estimate" scenario is proposed for short-term horizons (2020, 2025), while longer term horizons (2030, 2040) are explored via multiple scenarios, as illustrated in Figure 4.

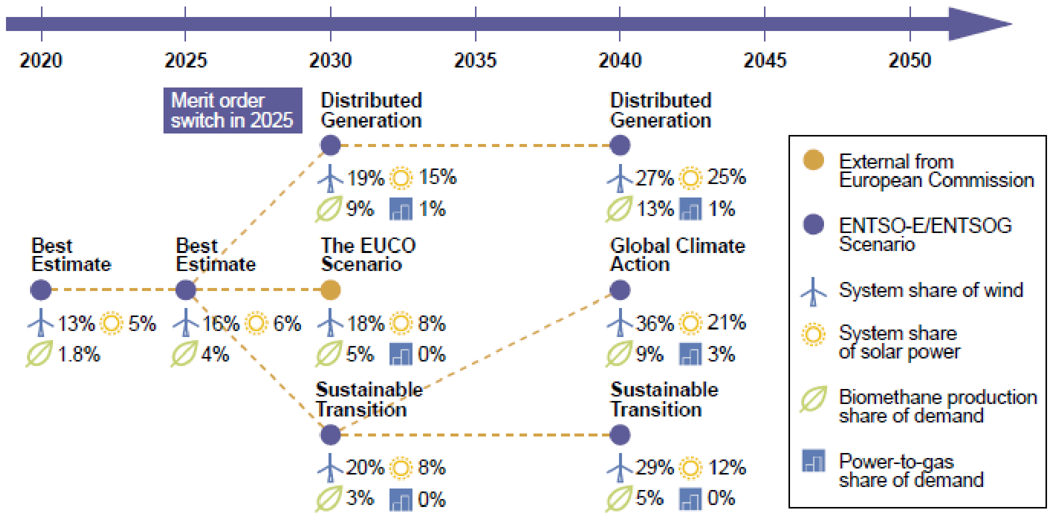


Figure 4: Structuring of TYNDP 2018 scenarios

The "ENTSOs' Sustainable Transition" scenario was used as a basis for the development of one of the trajectories explored in this study, called the **"Sustainable Transition"**. This scenario is mainly characterised by the development of the solar PV and wind power sectors, which cover more than 40% of European electricity production in 2040, and a decrease in nuclear production. Gas is then used as a pivotal energy carrier. This type of development is based on high carbon taxation from 2030 onwards, which encourages the use of gas compared to coal. The prices of fuels and CO_2 in this scenario, presented in Table 1, are based on the WEO 2016 "New Policies" scenario [6]. Some modifications were made by the ENTSOs, notably resulting in the modification of the merit order between gas and coal technologies in 2030 and 2040[8].

Table 1: Price of fuels and CO_2 – "Sustainable Transition" scenario (Source: TYNDP 2018)

	Unit	2025	2030	2040
CO_2 price	€/t	26	84	45
Oil price	€/MWh NCV	55	64	50

[8] Appendix II of the TYNDP 2018 report describes the modifications made as follows:
"*Scenario where WEO2016 scenarios are adapted to fit with the ENTSOs storylines:*

1) *2030 ENTSOs' Sustainable Transition*
    a. *Based on WEO 2016 New Policies*
    b. *Carbon price adjusted to set merit order Gas before Coal*
2) *2040 ENTSOs' Sustainable Transition*
    a. *A "Low Oil Price" scenario generated from WEO 2016 New Policies*
    b. *Setting the merit order to Gas Before Coal"* (source: [2])

Gas price	€/MWh NCV	30	35	22
Coal price	€/MWh NCV	9	10	9
Lignite price	€/MWh NCV	4	4	4

Overview of the TYNDP 2018 "ENTSOs' Sustainable Transition" scenario

The "ENTSOs' Sustainable Transition" scenario corresponds to a relatively ambitious energy transition in terms of reducing CO_2 emissions, subject to controlled transition costs. It is described by ENTSOG and ENTSO-E as complying with European electricity sector decarbonisation objectives for 2030 and as compatible with decarbonisation objectives for 2050 (80-95% reduction in CO_2 emissions), through increased developments between 2040 and 2050[9].

The focus is on the reduction of coal and lignite production, with gas remaining an important energy carrier until 2040. This transition from coal to gas is notably induced by the prices of CO_2 and fuels (please see Table 1), which lead to an inversion of the merit order from 2030 onwards: gas-based electricity production becomes cheaper[10] than coal-based electricity production.

The change in electricity demand in the "ENTSOs' Sustainable Transition" scenario reflects a context of moderate economic growth, which does not encourage investment in new technologies and infrastructures required for a structural change in the composition of energy demand. The electrification of end-uses (electric vehicles, heat pumps, etc.) and the energy efficiency gains are therefore also moderate. The gas demand for residential heat remains higher than in the "Distributed Generation" and "Global Climate Action" scenarios. As a result, demand increases slightly across the scope of the ENTSO-E[11]: 3,400 TWh in the "Best Estimate" scenario for 2025, and 3,500 TWh in 2030 and 3,600 TWh in 2040.

The scenario is also characterised by a clear progression of installed capacities in the wind and solar PV sectors across the entire scope of the ENTSO-E, going from 250 GW in 2025 to 400 GW in 2040 for wind power, and from 180 GW in 2025 to 350 GW in 2040 for solar PV. This change reflects public

[9] The scenario is described as follows in the TYNDP report [1]: *"Sustainable Transition (ST) seeks a quick and economically sustainable CO2 reduction by replacing coal and lignite by gas in the power sector. Gas also displaces some oil usage in heavy transport and shipping. The electrification of heat and transport develops at a slower pace than other scenarios. In this scenario, reaching the EU goal (80-95% CO2 reduction in 2050) requires rapid development during the 2040s to be achieved through increased technological adoption or evolution. ".*
[10] This comparison only takes into account variable production costs.
[11] I.e., the European Union, Switzerland, Norway and the Balkan states.

policies that support the development of these two technologies through grants and favourable regulation.

For all the countries modelled, **the installed capacities of thermal[12] and renewable energy production assets, as well as annual demand levels and the prices of fuel and CO_2, are taken directly from the TYNDP "ENTSOs' Sustainable Transition" scenario**.

To supplement the modelling of the **"Sustainable Transition"** scenario in Artelys Crystal Super Grid[13] software, a set of techno-economic assumptions (taken from previous work carried out by Artelys [4]) has been used, including, among others, the following:

- Technical parameters for thermal and hydro production assets by age category (yield, increase and decrease gradients, minimum production level, unavailability for maintenance, etc.)
- A breakdown of thermal asset installed capacities by age category
- Constraints concerning the management of hydro reservoirs, taking into account non-modelled uses (tourism, agriculture, etc.)[14]
- Wind and solar PV power production time-series, at the national level, with an hourly time resolution for ten different climatic years
- Hourly time-series of electricity consumption, at the national level, with an hourly time resolution for ten different climatic years [15]
- Furthermore, specific interconnection hypotheses were made in this study (see Section 2.1.4).

As shown in Figure 5, the variable renewable technologies deploy significantly in France, with 100 GW installed in 2040 (60 GW in wind power and 40 GW in solar PV power) compared with 50 GW in 2025 and 20 GW in 2017. Great Britain also sees an increase in its variable renewable capacity, but to a lesser extent, from 50 GW in 2025 to 80 GW in 2040, including 50 GW of wind power and 30 GW of solar PV. This scenario is also characterised by a low nuclear capacity in France: 52 GW in 2025 and 38 GW from 2030 (compared with 63 GW in 2017), equivalent to the closure of at least 25 reactors by 2030. Furthermore, Figure 6 shows that French and British demands are stable between 2025 and 2030 and will decrease slightly in 2040, in a context of a slow growth of European demand (see the box above).

[12] Excluding gas-fired power plants, which are subject to calibration.
[13] A description of the software is provided in section 1.3
[14] The datasets available on the ENTSO-E data platform [3] were used to help shape these assumptions
[15] Three time-series (corresponding to the climate conditions of 1982, 1984 and 2007) are provided by ENTSO-E for each country. These time-series were used to derive thermo-sensitivity hypotheses of demand by country, enabling ten different climate years to be reconstituted based on temperature records [4].

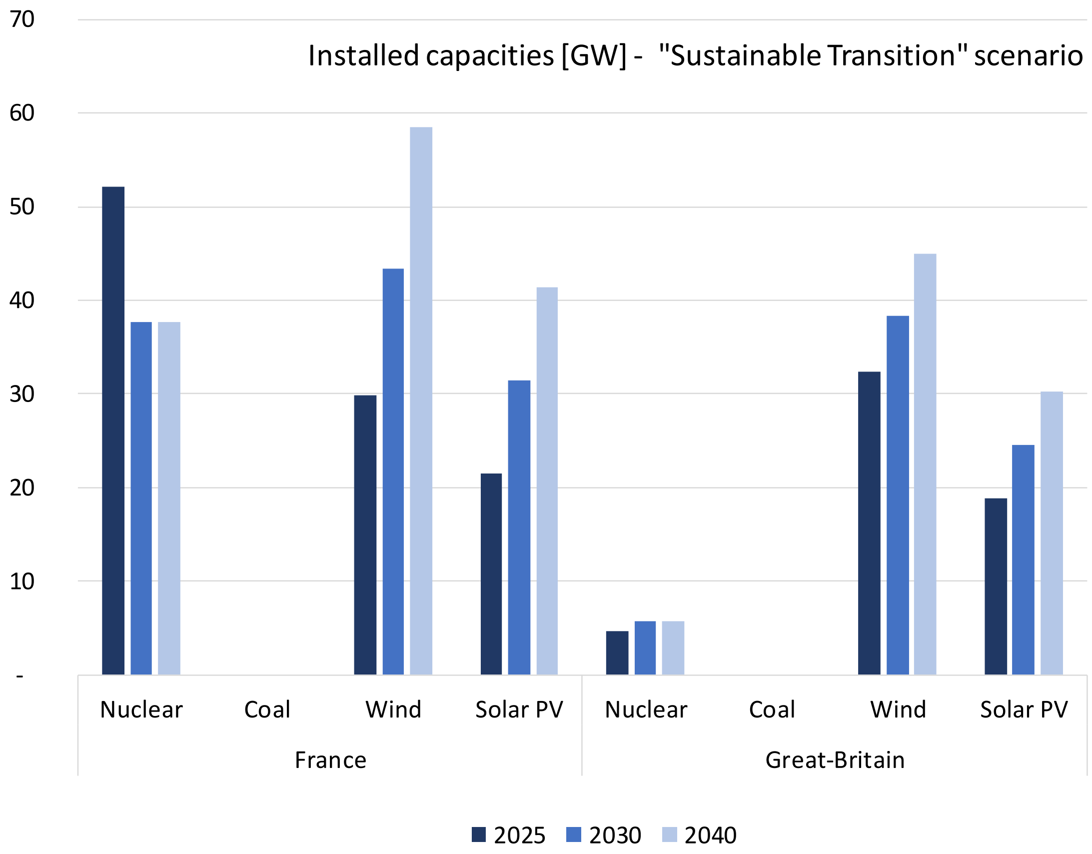


Figure 5: Installed capacity in France and Great Britain in the "Sustainable Transition" scenario

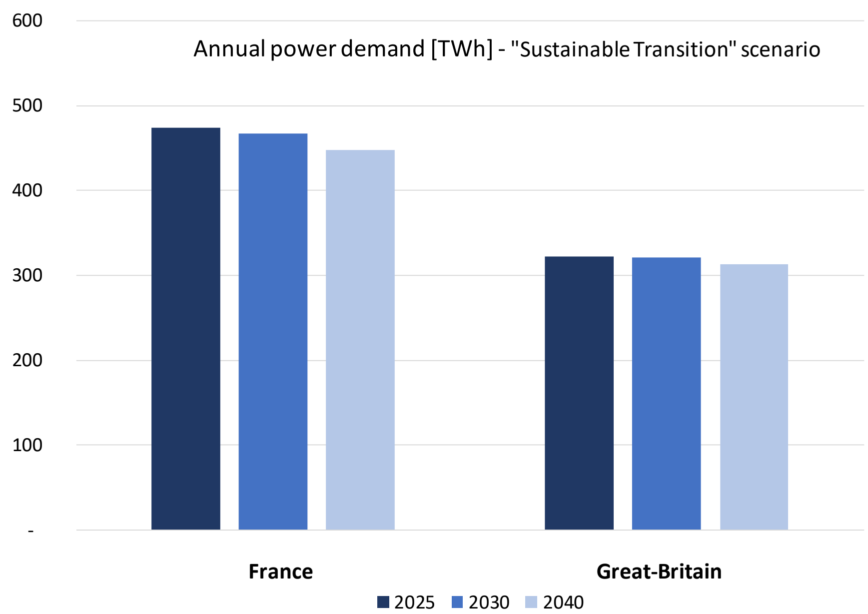


Figure 6: Annual electricity demand in France and Great Britain – "Sustainable Transition" scenario

In this scenario, France sees its low-carbon and low variable cost[16] electricity production capacity decrease between 2025 and 2030 (while demand remains stable), mainly due to the rapid closure of 14 GW of nuclear power. This results in a decrease in the annual net export level from 50 TWh to 30 TWh. Nevertheless, net exports rise to 60 TWh in 2040, in accordance with the development of renewable energy in a context of decreasing demand: from 470 TWh in 2030 to 450 TWh in 2040.

In Great Britain, the baseload-like production capacity continuously grows in this scenario, faced with a stagnant demand from 2025 to 2040. In addition, Great Britain has a large combined cycle gas capacity (30 GW in 2030, 20 GW in 2040), which as of 2030 becomes less expensive than the coal-fired and lignite-fired power plants still present in Eastern Europe, notably in Germany, Poland, the Czech Republic and the Netherlands. Consequently, Great Britain goes from being a net importer in 2025 (with 9 TWh of annual net imports) to a net exporter as of 2030 (with 35 TWh and 25 TWh of annual net exports in 2030 and 2040 respectively).

At the European level, the electricity mix goes towards a net decrease of nuclear capacity and an almost total phase-out from coal-fired and lignite-fired power plants in 2040, replaced mainly by gas in 2030 and then by the increase in renewable energy technologies in 2040. Figure 7 provides details on the generation mixes in this scenario in France, Great Britain and for the entire ENTSO-E scope, for each horizon modelled.

[16] I.e., here, nuclear, wind and solar power

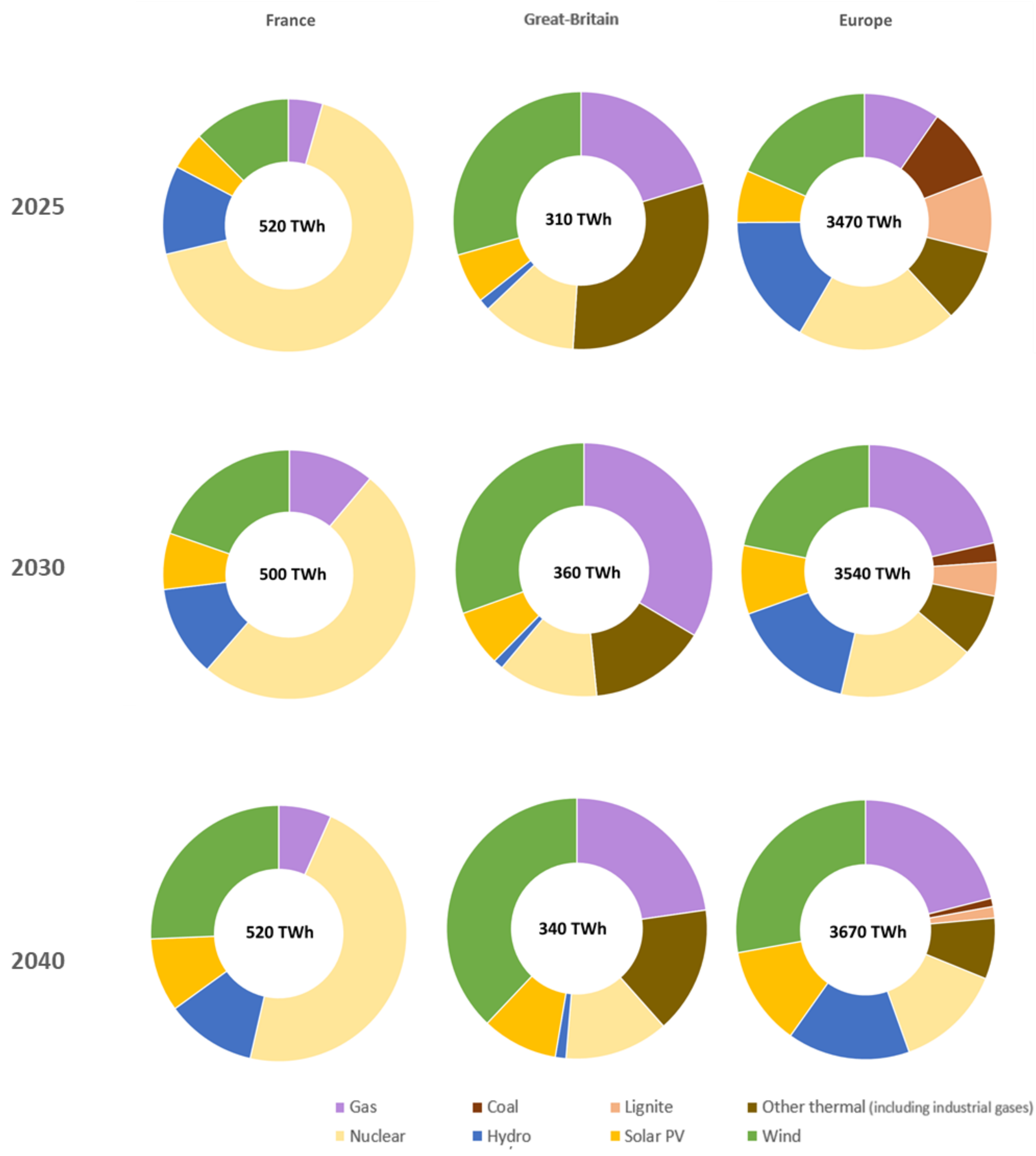


Figure 7: Electricity production mix – "Sustainable Transition" scenario

2.1.2 "Conservative" scenario

The second scenario considered explores the plausibility of a less ambitious change in the European energy context compared to the current situation. It involves taking into account the uncertainty surrounding the effective implementation of national and European energy transition plans. To do this, this scenario was developed on the assumption of a delay and slow down of the evolution undergone in the **"Sustainable Transition"** scenario (presented in section 2.1.1), based on the following principles:

- The 2025 horizon of the **"Conservative"** scenario corresponds to an intermediate state between the TYNDP "Best Estimate" scenario for the 2020 horizon and the **"Sustainable Transition"** scenario for the 2025 horizon.
- The 2030 horizon of the **"Conservative"** scenario includes most of the characteristics of the **"Sustainable Transition"** scenario for the 2025 horizon.
- The 2040 horizon of the **"Conservative"** scenario includes most of the characteristics of the **"Sustainable Transition"** scenario for the 2030 horizon.

The annual demands for the entire perimeter exactly follow this slowing-down, reflecting less progress in energy efficiency. They are presented for France and Great Britain in Figure 8.

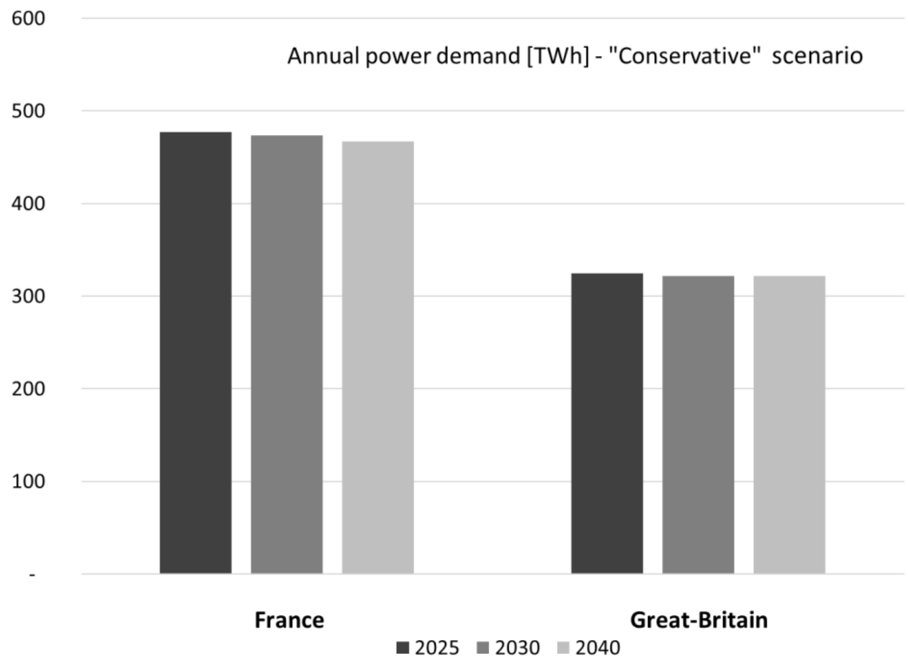


Figure 8: Annual electricity demand in France and in Great Britain – "Conservative" scenario

In the same way, all the production capacities (excluding renewable energy technologies in France and Great Britain) are taken from the **"Sustainable Transition"** scenario after applying the time delay. However, for France and Great Britain, the installed capacities of the wind and solar PV technologies are taken from the “low” trajectory provided by RTE’s 2017 Bilan Prévisionnel [5] (BP 2017), which corresponds to a lower level of development than that of the delayed **"Sustainable Transition"** scenario. In the **"Conservative"** scenario, the wind power installed capacity only reaches 30 GW in France in 2040 (compared to almost 45 GW in the 2030 "Sustainable Transition" scenario) and almost 30 GW in Great Britain (compared to almost 40 GW in the 2030 "Sustainable Transition" scenario). Similarly, the solar PV installed capacity is around 20 GW in France and 15 GW in Great Britain (compared with 30 and 25 GW considered in the "Sustainable Transition" scenario in 2030).

In addition, in a context of stable demand and slow development of renewable energy capacities in France, the nuclear capacity is assumed to be maintained at a high level until 2040, based on the assumption of the BP 2017 "Volt" scenario. Figure 9 illustrates the development of production capacities of the key impacted generation technologies in France and in Great Britain.

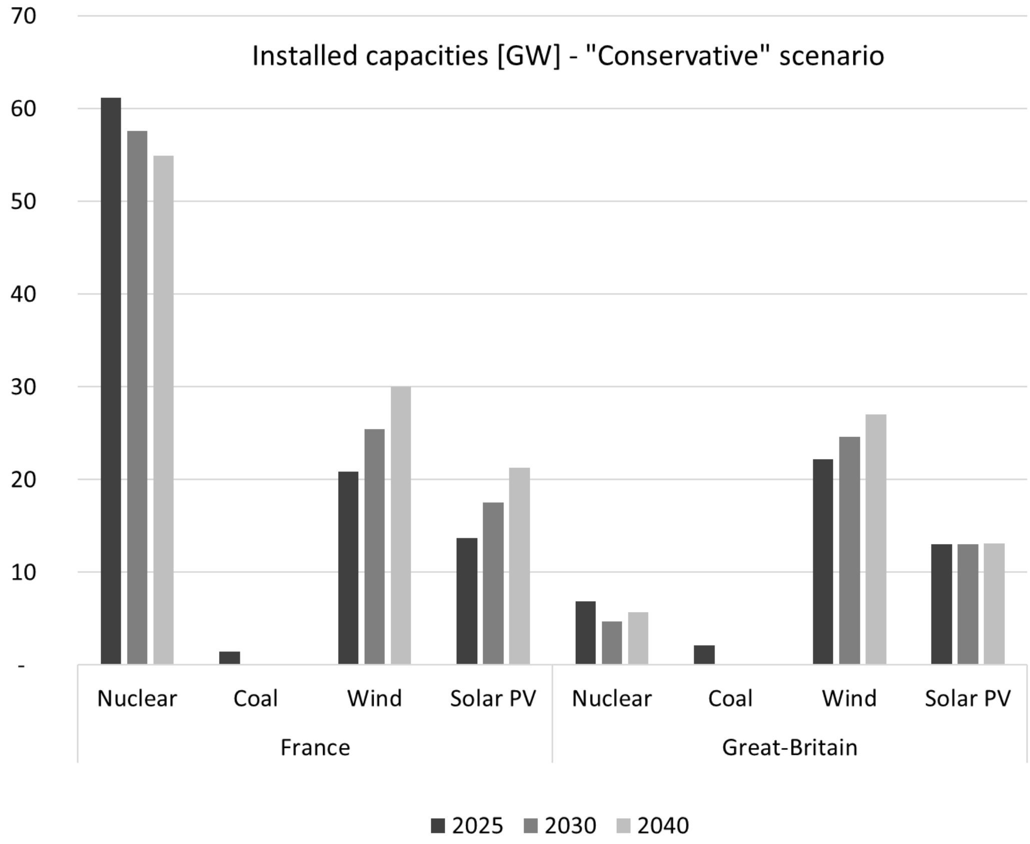


Figure 9: Installed capacities in France and Great Britain in the "Conservative" scenario

The hypotheses concerning changes in fuel and CO_2 prices in this scenario, presented in Table 2, are also more conservative. The "New Policies" scenario of the World Energy Outlook 2016[17] [6] (WEO 2016) was used after applying the time delay presented above.

Table 2: Price of fuel and CO_2 – "Conservative" scenario (Source: WEO 2016 – "New Policies")

	Unit	2025	2030	2040
CO_2 price	€/t	22	26	33
Oil price	€/MWh NCV	48	53	61
Gas price	€/MWh NCV	27	30	35
Coal price	€/MWh NCV	8	9	9
Lignite price	€/MWh NCV	4	4	4

Figure 10 presents the production mixes in France, in Great Britain and in the ENTSO-E scope in the **"Conservative"** scenario. In all three cases, the composition of the mix changes little between 2025 and 2040: nuclear power remains largely predominant in France, still covering 70% of production in 2040; Great Britain remains dependent (at a level of more than 50%) on fossil fuels, such as natural gas, or industrial fuels; at the European level, the wind and solar PV shares in total generation do not exceed 30% in 2040.

[17] These are the price hypotheses on which those of the TYNDP 2018 "ENTSOs' Sustainable Transition" scenario are based. Nevertheless, in the "ENTSOs' Sustainable Transition" scenario, corrections are made to the price of CO_2 in 2030 and to oil and gas prices in 2040, which imply a change in the order of economic precedence between gas and coal for electricity production. In the "New Policies" hypotheses of the WEO 2016, coal-fired power plants are therefore less expensive (in terms of variable costs) than gas-fired power plants.

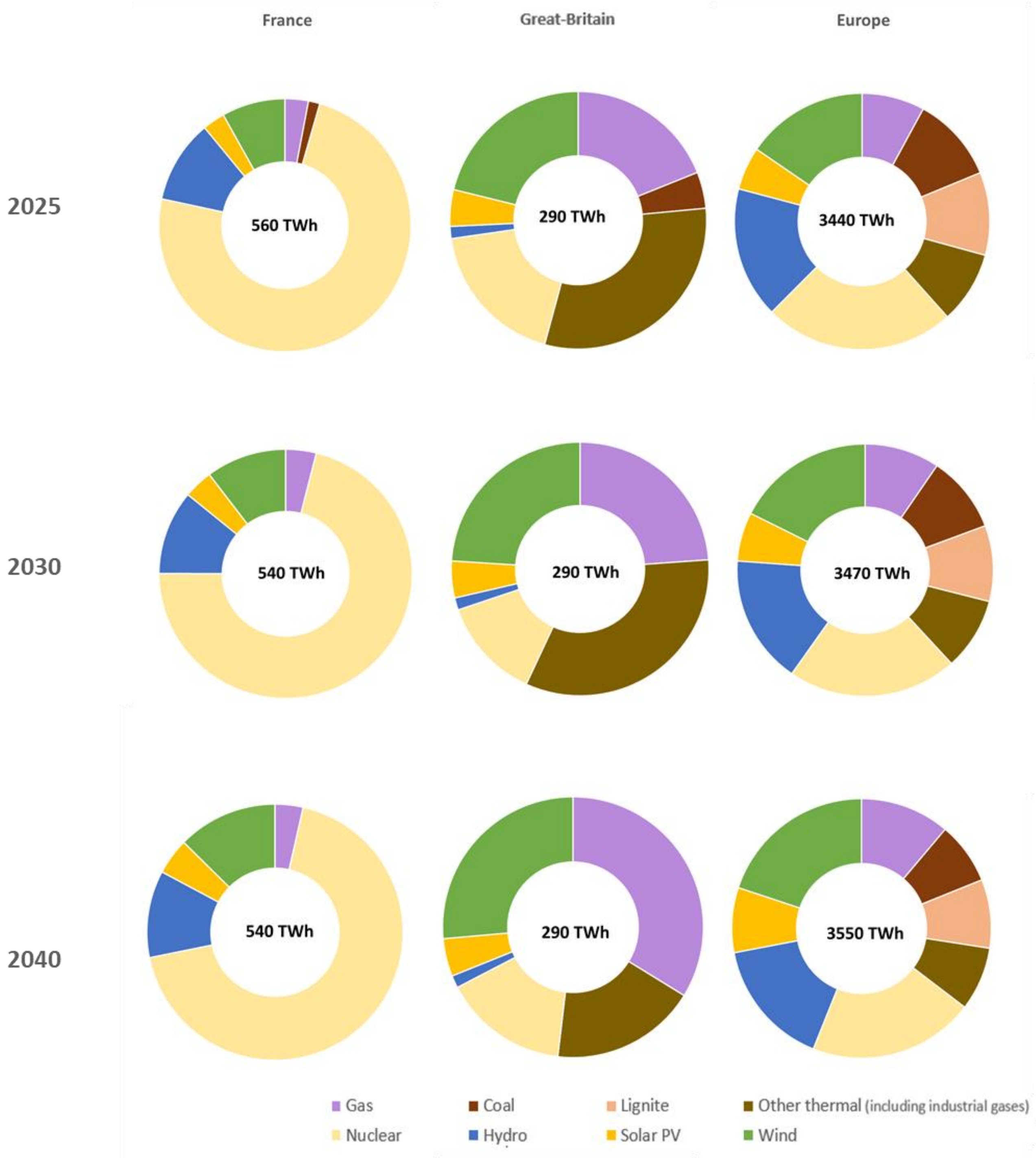


Figure 10: Electricity production mix – "Conservative" scenario

2.1.3 "National Plans" scenario

In contrast with the **"Conservative"** scenario, a **"National Plans"** scenario was created to explore the possibility of implementing energy transition objectives in accordance with the latest announcements by the French and British governments. This scenario presents the highest level of decarbonisation of the three main scenarios explored in this study[18].

This scenario is based on assumptions from the 2018 French strategy for energy and climate ("Programmation Pluriannelle de l'Energie" - PPE) [7] (PPE 2018) for France and from the central scenario of the *Department for Business, Energy and Industrial Strategy* (BEIS) published at the beginning of 2019 [8] for the United Kingdom. For all other countries, and for general assumptions, such as fuel and CO_2 prices, the **"National Plans"** scenario is identical to the **"Sustainable Transition"** scenario (see Section 2.1.1).

Figure 11 presents the production capacities as per the two national sources cited above. In France, the wind power sector undergoes a similar change to that of the **"Sustainable Transition"** scenario, reaching 55 GW in 2040. However, nuclear and solar power capacities are significantly higher, with 52 GW of nuclear power and more than 60 GW of solar PV capacity in 2040. In Great Britain, wind and solar power capacities are both comparable to the **"Sustainable Transition"** scenario, while the nuclear power capacity is significantly higher, doubling between 2030 and 2040 to reach 13 GW in 2040 (compared to 6 GW in the "Sustainable Transition" scenario).

[18] I.e., the "Sustainable Transition", "Conservative" and "National Plans" scenarios

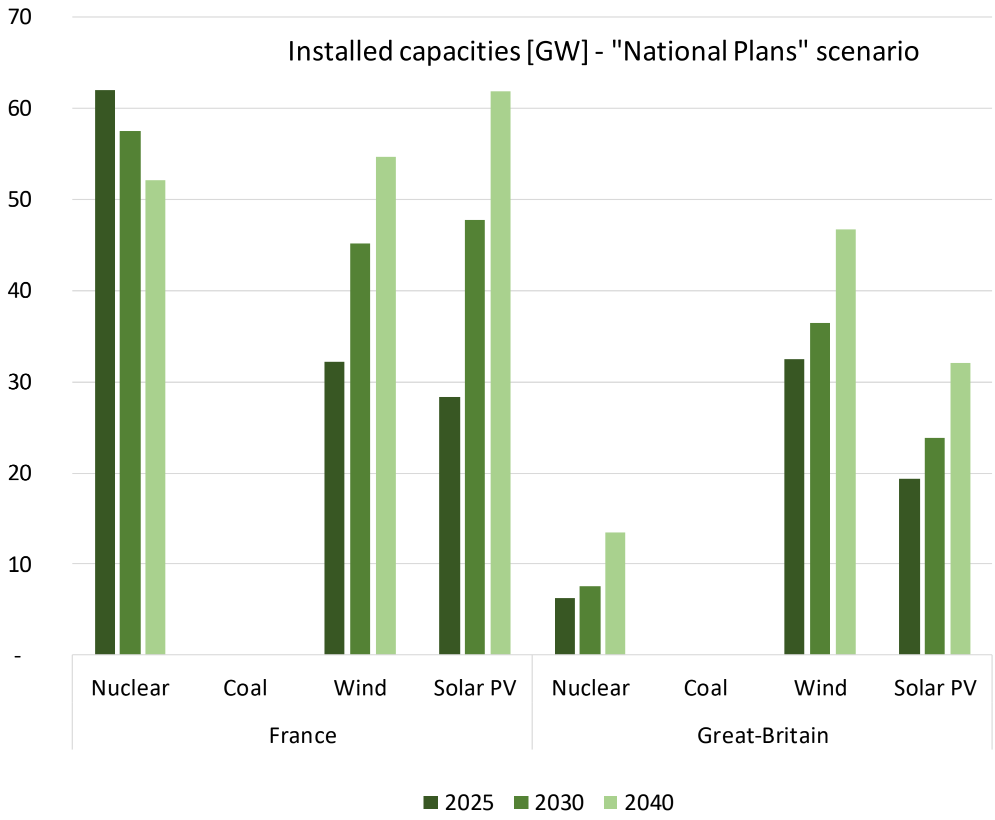


Figure 11: Installed capacities in France and Great Britain in the "National Plans" scenario

Electricity demands (excluding Power-to-Gas) in France and Great Britain, presented in Figure 12, are also higher than in the **"Sustainable Transition"** scenario, particularly in 2040. The increase, from 460 TWh to 510 TWh in France and from 330 TWh to 350 TWh in Great Britain between 2030 and 2040, is mainly explained by the electrification of transport (notably through the deployment of a large fleet of electric vehicles) and certain industrial uses.

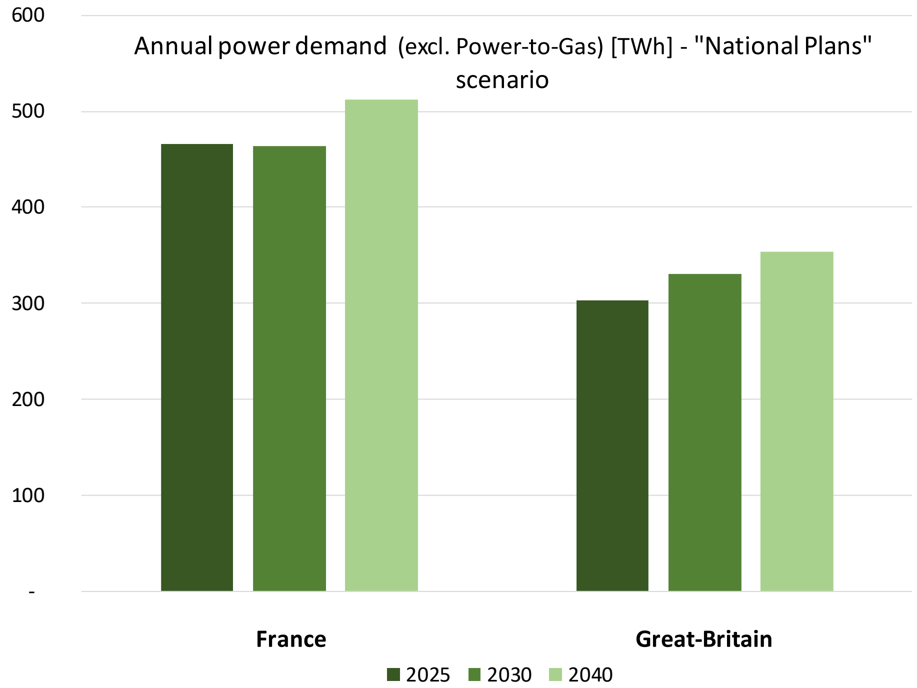


Figure 12: Annual electricity demand in France and Great Britain – "National Plans" scenario

In addition to this direct electrification of industry and transport, the PPE provides for the development in France of hydrogen production via water electrolysis, with targets of around 25 TWh in 2030 and 35 TWh in 2040. In order to properly assess the low-carbon production surplus available in France, which determines, in large part, the France-Great Britain interconnection value, this new usage was modelled in the **"National Plans"** scenario. The operations of electrolysers were considered as being flexible and responsive to the price signals from the electricity spot market, so that production is limited to the volumes that make economic sense, considering the other assumptions of the scenario[19]. Table 3 presents the hypotheses made concerning the selling price of hydrogen and the electrolyser installed capacities, as well as the final consumption level of Power-to-Gas[20].

[19] So-called "blue" hydrogen can also be produced through steam reforming with carbon recovery, from natural gas – which would have a better economic yield than production through electrolysis that consumes electricity from a power plant operating using fossil fuel.
[20] This level is determined endogenously by the Artelys Crystal Super Grid model (see the description in Section 1.3).

Table 3: Power-to-Gas hypotheses – "National Plans" scenario

	Unit	2030	2040
Hydrogen selling price[21]	€/MWh GCV	60	40
Electrolyser capacity[22]	GW	9	12
Electricity consumption for Power-to-Gas	TWh	12	15

As shown in Figure 13, carbon-free electricity production in the **"National Plans"** scenario reaches 70% at the European level as of 2030 and progresses again slightly in 2040, despite the electrification of a significant portion of the transport and industry sectors in France and the United Kingdom. The French electricity mix sees the share of nuclear power drop to 60% in 2040, replaced by wind and solar PV, whose production doubles between 2025 and 2040 to reach 260 TWh in 2040. The electricity mix in Great Britain is characterised by a simultaneous development of wind power, solar PV and nuclear power, which together cover more than 55% of electricity production in 2040. As a result of this change in the portfolio of low-carbon technologies (whose variable production costs are low), France and Great Britain are both net exporters: France has an export balance of 130 TWh in 2030 and 90 TWh in 2040; Great Britain has an export balance of around 25 TWh in 2030 and 2040.

[21] The selling price is assumed to be equal to the cost of producing hydrogen through natural gas steam reforming. The natural gas and CO_2 price hypotheses used are those of the **"National Plans"** scenario.
[22] These hypotheses correspond to the capacities required to produce the volumes of hydrogen stated in the PPE using electrolysers that operate on average 3,000 hours/year.

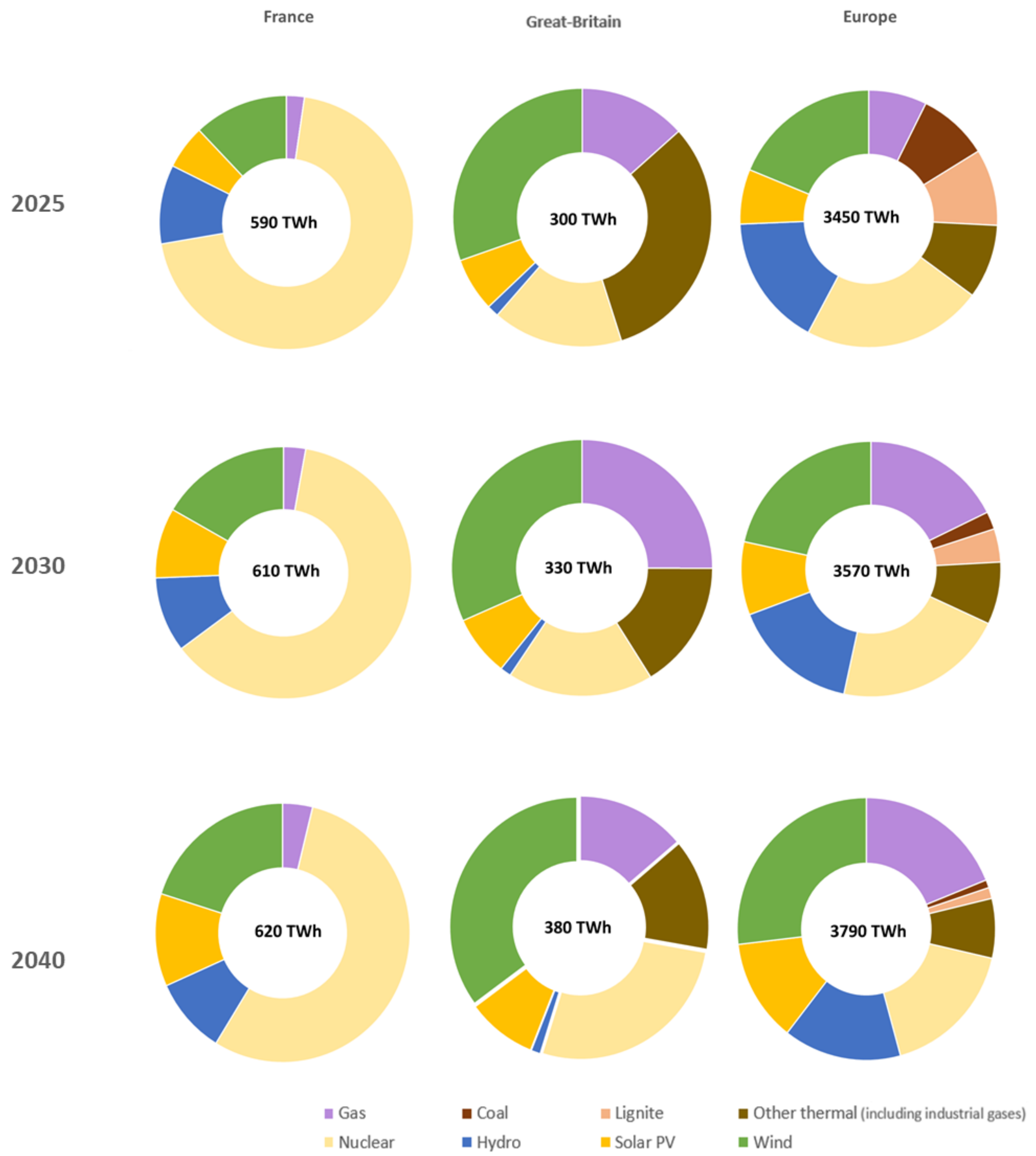


Figure 13: Electricity production mix – "National Plans" scenario

2.1.4 Level of interconnection capacity with neighbouring countries

The same set of assumptions concerning interconnectors other than France–United Kingdom was considered for the three main scenarios presented in sections 2.1.1, 2.1.2 and 2.1.3. The Reference

Grid network for 2027, defined in ENTSO-E's TYNDP 2018, was used as a basis for the establishment of these hypotheses.

For the 2025 and 2030 horizons, some projects that were not included (respectively included) in the 2027 Reference Grid were added (respectively removed), by considering the state of their progress and the estimated commissioning date mentioned in TYNDP 2018. For the 2040 horizon, the hypotheses of the "ENTSOs' Sustainable Transition" scenario were used as a starting point. However, modifications were made in order to take into account the assumptions made for 2025 and 2030, as well as the state of progress of each project considered. In particular, the GreenLink and Celtic projects connecting Ireland to Great Britain and France were respectively added from 2025 and 2030, due to their status. The interconnection capacity between Great Britain and Norway is also maintained at 2.8 GW in 2040, as in 2030 (since the TYNDP 2040 "ENTSOs' Sustainable Transition" scenario provides for this capacity to be 2.8 in 2030 and 1.4 GW in 2040). Moreover, given the high level of uncertainty at the time this report was written with respect to the realisation of the trans-Pyrenean interconnection projects between France and Spain, these projects were not included for the 2040 horizon.

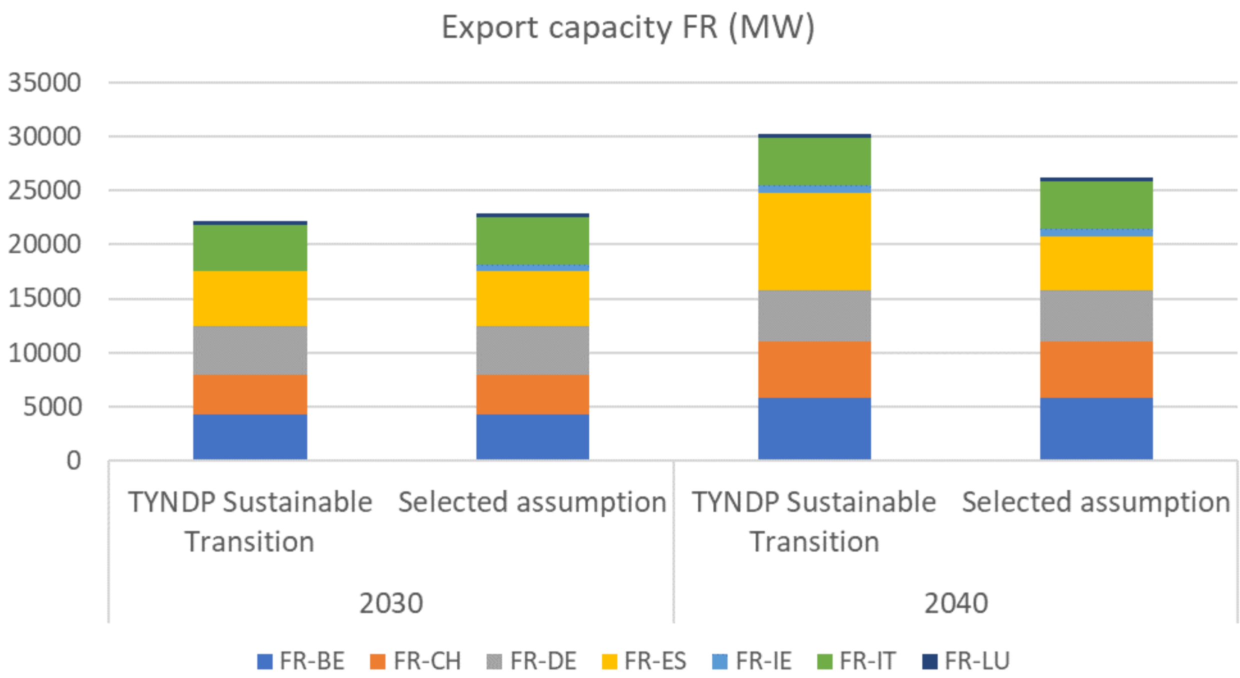
Table 4: Modifications made to the interconnection hypotheses of the "ENTSOs' Sustainable Transition" scenario (TYNDP 2018)

Border	Projects removed (-) or added (+) to the 2027 benchmark network to constitute the network in 2025	Projects removed (-) or added (+) to the 2027 benchmark network to constitute the network in 2030	Projects removed (-) or added (+) to the "ENTSOs' Sustainable Transition" scenario to constitute the network in 2040
France – Spain	Bay of Biscay[23] (- 2.2 GW)	-	Trans-Pyrenean (- 4 GW)
France – Germany	Vigy - Uchtelfangen[24] (- 1.5 GW)	-	-
France – Ireland	-	Celtic (+ 0.7 MW)	-
G.-B. – Ireland	GreenLink (+ 0.5 GW)	GreenLink (+ 0.5 GW)	-

[23] This project is considered from 2030 in this study, in accordance with the TYNDP hypotheses
[24] This project is considered from 2030 in this study, in accordance with the TYNDP hypotheses

G.-B. – Norway	-	-	NorthConnect (+ 1.4 GW)

As shown in Figure 14, the export capacities considered in our analysis, excluding France–Great Britain, exceed 20 GW in 2030 and 25 GW in 2040 for France, and exceed 8 GW in 2030 and 12 GW in 2040 for Great Britain.



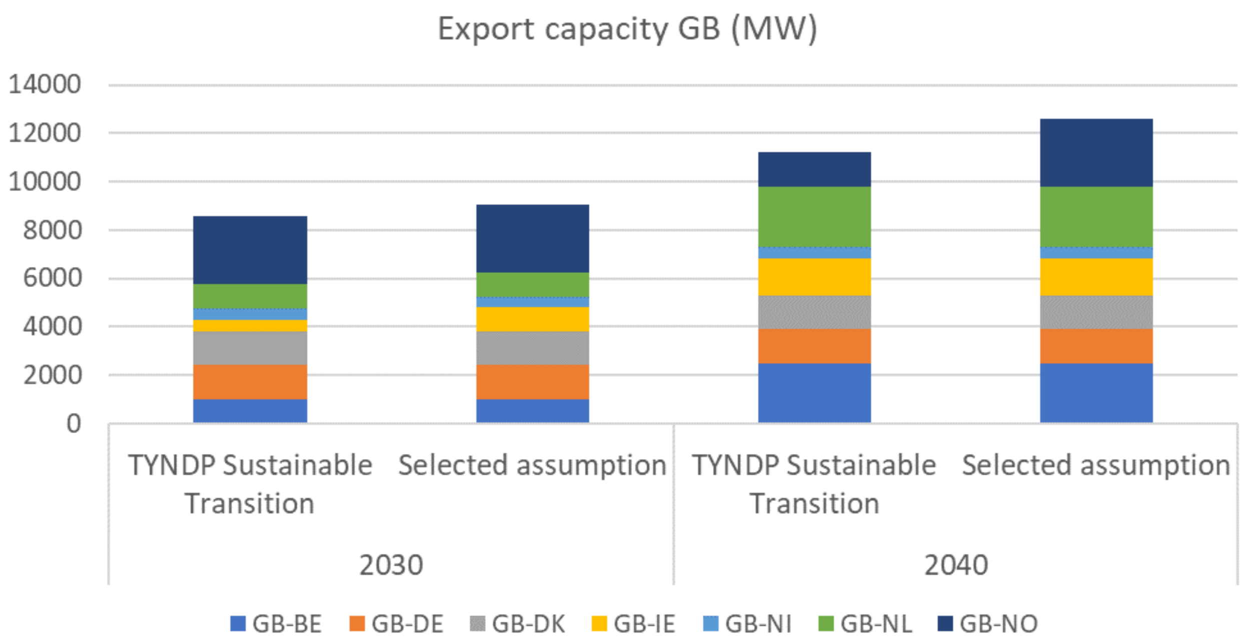


Figure 14: France and Great Britain export capacity

2.2 "Distributed Generation + PPE" variant

Finally, given the announcement made by the European Commission [9] to mainly use the TYNDP 2018 "Distributed Generation" scenario as a basis for the assessment and ranking of projects, which serves for the selection of Projects of Common Interest, an additional scenario was built for this study. However, since the announcement was made after the choice and modelling of the three main scenarios had been carried out, it was decided to consider "Distributed Generation" as a variant, exploring a different overall European context for the 2030 and 2040 horizons.

The selected variant, called **"Distributed Generation + PPE"**, is therefore built from a set of assumptions taken from the PPE 2018 for France (hypotheses identical to the **"National Plans"** scenario described in Section 2.1.3) and from the "Distributed Generation" scenario for the rest of Europe. As for the three main scenarios, a set of additional assumptions (many of which are taken from publicly available reports/datasets, see Section 2.1.1) were made in order to integrate the scenario in the Artelys Crystal Super Grid simulation tool.

This scenario differs from the three main scenarios with regards to:

- Fuel and CO_2 prices (see Table 5)
- Installed capacities, particularly solar PV, with a European capacity of 800 GW in 2040 compared to 350 GW in the **"Sustainable Transition"** scenario (see Figure 15)
- Annual demand levels: 4,000 TWh in 2040 compared to 3,700 TWh in the **"Sustainable Transition"** scenario
- Interconnectors in 2040 (see Figure 16), which are based on the assumptions of the TYNDP 2018 "Distributed Generation" scenario[25,26].

Table 5: Price of fuels and CO_2 - "Distributed Generation + PPE" scenario

	Unit	2030	2040
CO_2 price	€/t	50	80
Oil price	€/MWh NCV	64	72
Gas price	€/MWh NCV	35	39

[25] With the exception of the GreenLink Project, which was added in 2030 (and therefore maintained in the 2040 hypotheses), as for the three main scenarios, to take the project's state of progress into account.

[26] The interconnection capacity between France and Spain is the main difference, with 10 GW in "Distributed Generation + PPE", compared to 5 GW in "Sustainable Transition", notably due to the hypothesis of the realisation of the trans-Pyrenean interconnector projects. Given the very ambitious level of development of the PV solar power sector, particularly in the Iberian Peninsula, these projects were maintained in the hypotheses of the "Distributed Generation + PPE" scenario (in accordance with the "Distributed Generation" scenario).

Coal price	€/MWh NCV	10	10
Lignite price	€/MWh NCV	4	4

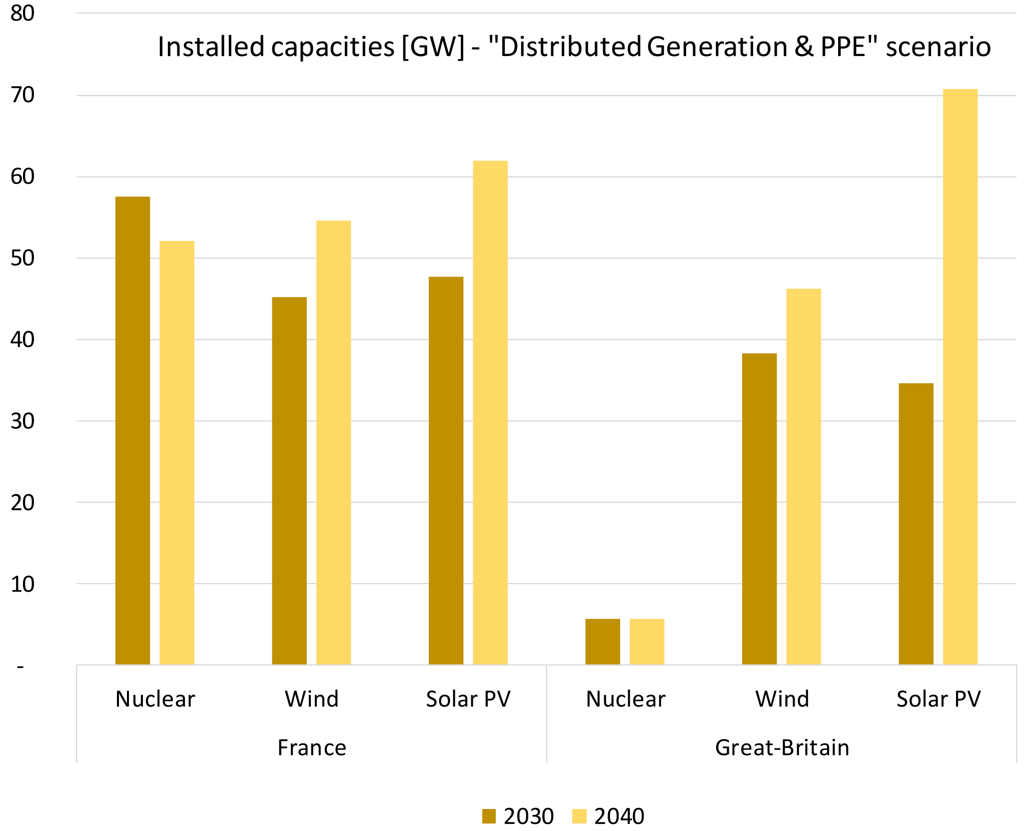
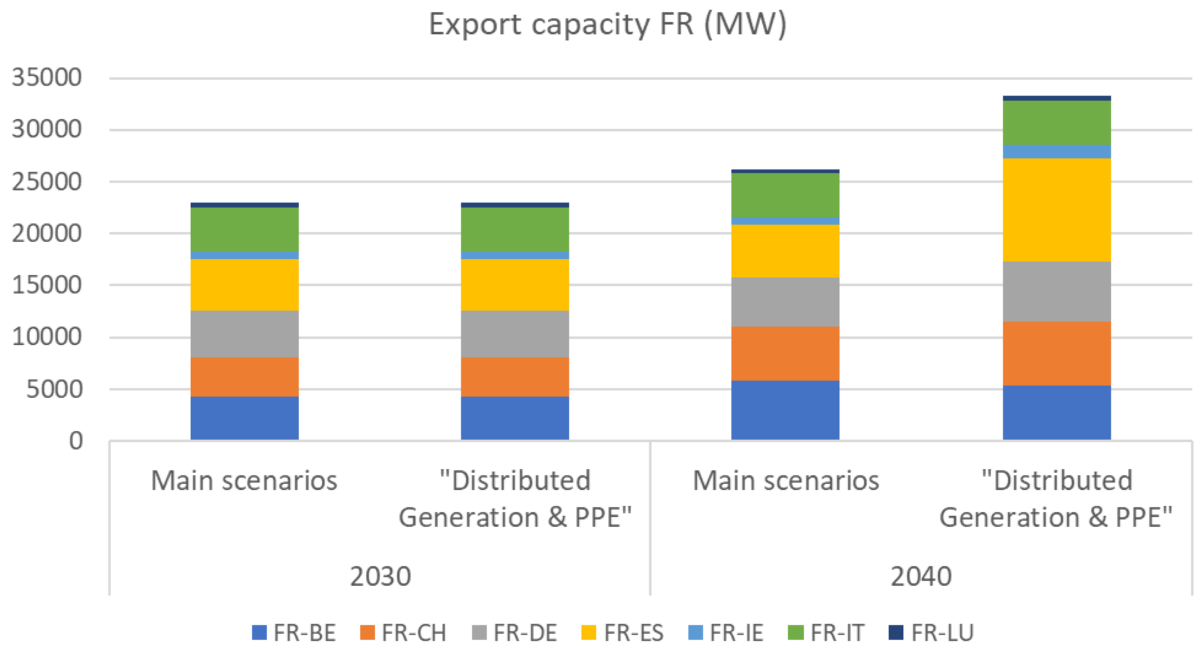


Figure 15: Installed capacities in France and Great Britain - "Distributed Generation + PPE" scenario



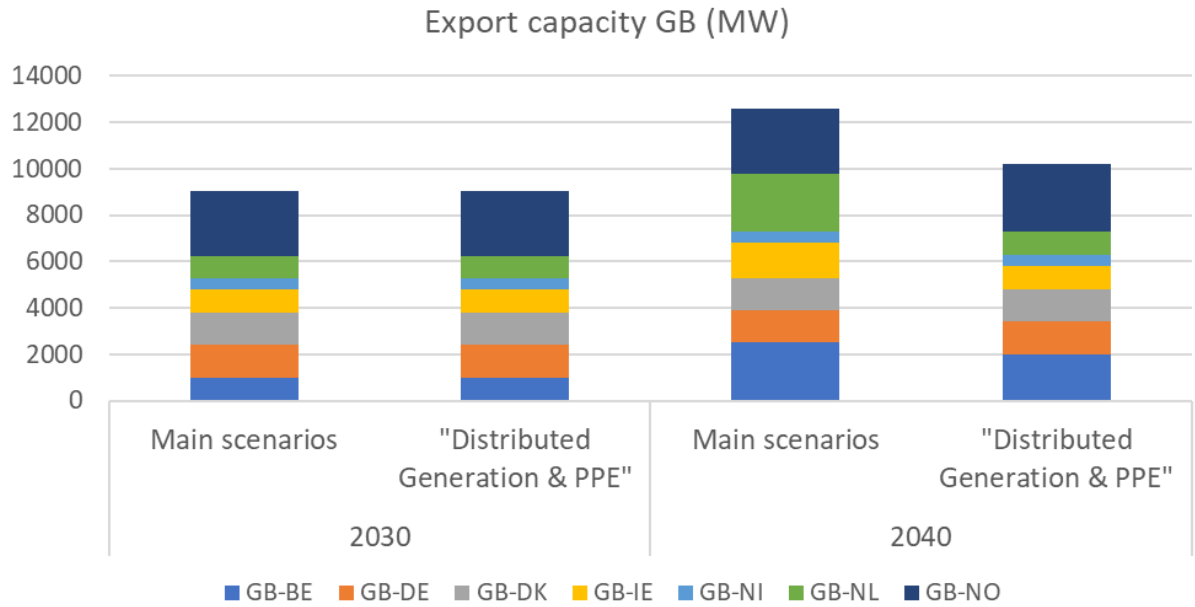


Figure 16: Export capacities for France and Great Britain in 2030 and 2040 – "Distributed Generation + PPE" scenario

2.3 Sensitivity analyses

In addition to the three main scenarios and the variant that uses the underlying assumptions of the TYNDP 2018 "Distributed Generation" scenario, a set of sensitivity analyses was carried out. These analyses were used to quantify the impact of the main elements that determine the value of an interconnector between France and Great Britain:

- Installed capacities of low-carbon electricity generation
- Demand levels

- Competition with other flexibility solutions
- The prices of fuels and CO_2
- The interconnection level

Since the results of the **"Sustainable Transition"** and **"Conservative"** scenarios are clear (the benefits in terms of socio-economic welfare generated by an increase in interconnection do not cover the investment costs for any of the horizons considered - see Section 3.2), all sensitivity analyses were carried out based on the **"National Plans"** scenario, with the exception of a sensitivity analysis concerning the France-Spain interconnection capacity on the **"Distributed Generation + PPE"** variant.

For each of the levers mentioned above, several configurations have been tested. Thus, alternative hypotheses were made concerning nuclear and wind power capacities in Great Britain and wind power capacity in Germany, in order to test the impact of a change in Great Britain's access to cheap electricity that could compete with imports from the French nuclear power sector. Similarly, various hypotheses concerning the demand for Power-to-Gas in France were tested, in order to consider several levels of French nuclear power availability for exports. Since the solar PV installed capacities in Europe and the coal-fired capacities in Germany and Eastern Europe were already contrasted between the main scenarios, they were not subject to additional sensitivity analyses.

Some of the services provided by a new interconnector between France and Great Britain could also be provided by other flexibility solutions, such as interconnectors with other neighbouring countries (for example, Belgium and the Netherlands for Great Britain, Switzerland and Spain for France) or storage assets, such as batteries. These different possibilities are treated via the sensitivity analyses carried out in this study.

Furthermore, as presented in Section 3, the benefits in terms of socio-economic welfare generated by a new interconnector are highly sensitive to commodity prices and especially to the CO_2 price, which has a highly significant impact on the difference in production costs between the nuclear and gas fleets (whose respective shares in the French and British mixes are significant). Several price trajectories taken from the WEO 2018 were tested, reflecting various macro-economic contexts in Europe.

Finally, it should be recalled that like all the scenarios, all the sensitivity analyses carried out in this study are based on the assumption of the United Kingdom remaining in the internal energy market of the European Union.

3 Assessment of the value of a new interconnector

3.1 Use of the reference interconnection capacity between France and the United Kingdom

The currently operational interconnectors and the ones being deployed will bring the electricity interconnection capacity between France and the United Kingdom to at least 4 GW between 2025 and 2040. This capacity was therefore used as a benchmark level in this study. The aim of this section is to illustrate the use of this capacity in the three main scenarios (**"National plans", "Conservative" and "Sustainable Transition"**) for the three simulated horizons (2025, 2030 and 2040). Figure 17 shows the annual trade flows between the two countries, in each context.

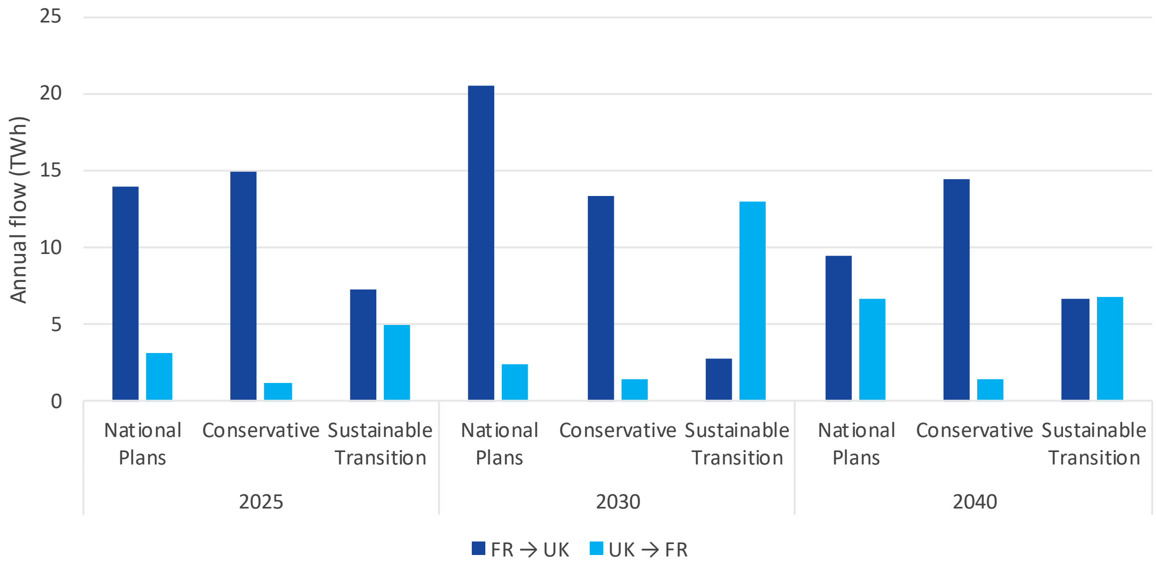


Figure 17 - Annual use of the France-United Kingdom interconnection in the three main scenarios

At 4 GW of interconnection, the flows range from 12 to 25 TWh/year. In the **"Conservative"** and **"National plans"** scenarios, the interconnector is mainly used in the France → United Kingdom direction. This is notably explained by the high nuclear power installed capacity in France, leading to regular and potentially prolonged periods of low marginal production costs in France. Figure 18 illustrates a period, in the **"Conservative"** scenario for the 2040 horizon, during which the interconnectors make it possible to export the French nuclear power surplus to the United Kingdom, thereby avoiding the operation of more costly CCGTs in the UK.

For the **"Sustainable Transition"** scenario, the same goes for the 2025 horizon (with a nuclear power capacity that is still high in France), but as of 2030, the nuclear power capacity falls to 38 GW. The interconnection is then much more heavily used in the United Kingdom → France direction.

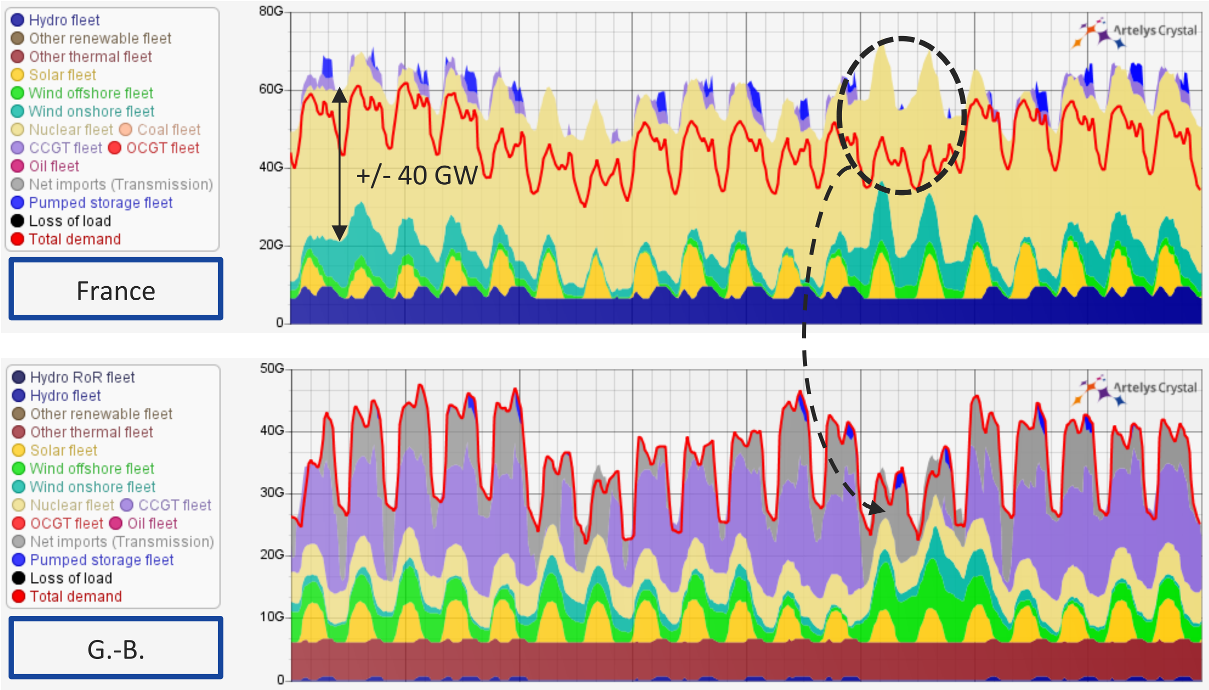


Figure 18 - Example of cumulative production (GW) in France and Great-Britain – 2040 "Conservative" scenario

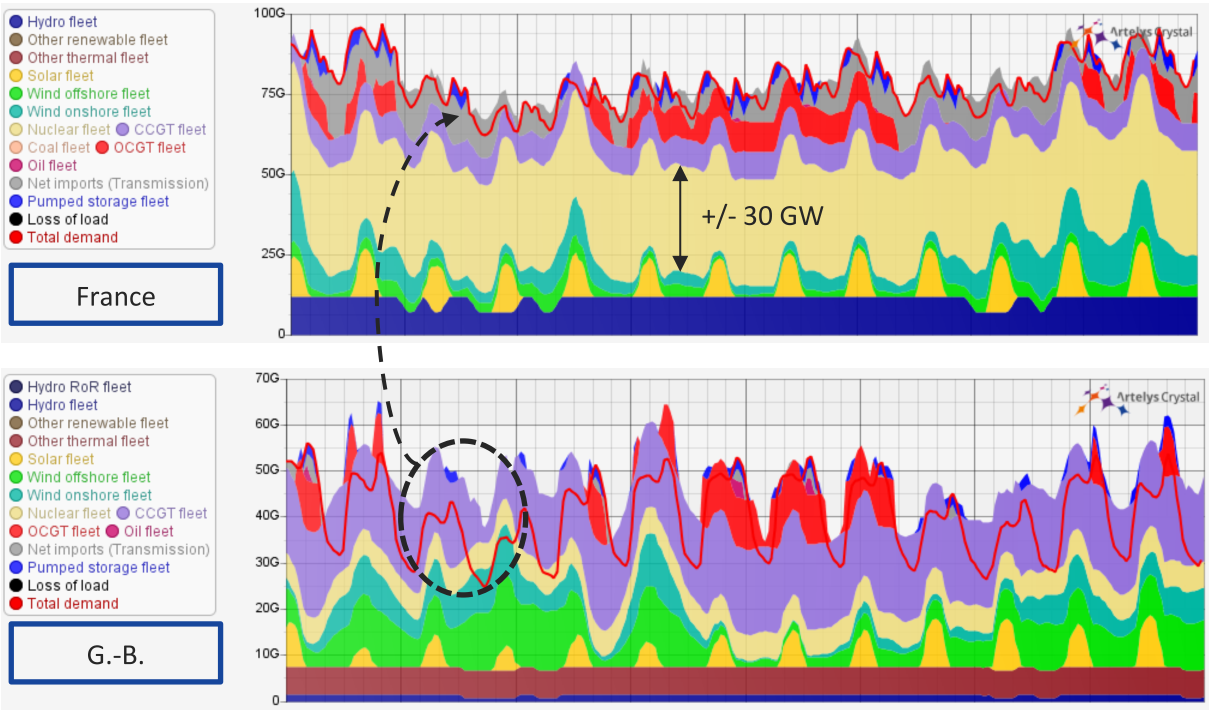


Figure 19 - Example of cumulative production (GW) in France and Great-Britain – 2040 "Sustainable Transition" scenario

Figure 19 presents the production results of the **"Sustainable Transition"** scenario in 2040. During this period, the interconnection is used to export British production (since the CCGT technology is setting the price) during periods when no more baseload and semi-baseload generation technologies are available in France.

3.2 Gains generated by an increase in capacity of the FR-GB interconnector

In this study, the value of a new interconnector is measured through the impact on the socio-economic welfare[27] it generates. In other words, we evaluate the operational benefits brought by the capacity increment, all other things being equal. The socio-economic welfare of the entire area modelled is directly determined by the total production costs over the simulated period, as well as by the level of loss of load. In this study, the capacity value of a new interconnector is low, and the increased socio-economic welfare is predominantly generated by arbitrage operations. The values associated with a new France–United Kingdom interconnector presented in this section should therefore be interpreted as reductions of production costs generated across the entire geographical perimeter by the addition of the interconnector.

In general, two factors impact the amount of production cost savings:

- Economic arbitrage operations between various production sectors made possible by the new interconnector, by removing congestion on the network, and
- The difference in production costs between the sectors concerned by these arbitrage operations.

A new interconnector generates production savings in all cases, since it enables the use of the least expensive production technologies to be increased. In this case, this mainly concerns the nuclear, wind and solar PV technologies, which are used below their available capacities during more or less prolonged periods, depending on the scenarios considered. An interconnector generates an even greater value if the difference in production costs between these three low-cost technologies and their thermal alternatives (gas, coal, lignite mainly) is high, which is determined by the prices of fuels and of CO_2. **The analysis reveals that a new interconnector between France and the United Kingdom would only be economically justified in a context where the following two conditions are simultaneously fulfilled[28]:** high available production surplus in one of the two countries, and high gas and coal

[27] Different interconnector projects may have a different impact, due, in particular, to their location – determining the possible services provided to the network. In this study, only the trade capacity between the two countries was considered, since the projects are considered interchangeable in this regard.

[28] The scenarios studied are calibrated to reach at most 3-4 hours of failure on average over the ten climate years simulated with 4 GW of interconnection. Under these conditions, and in view of the correlation between residual renewable energy peak demands in France and Great Britain, the interconnector does not enable any failures beyond 4 GW to be prevented (please see Appendix 1 – Calibration of peak generation capacities). The valuations presented in this section do not therefore contain any capacity values.

production costs. This corresponds to the situation described in the **"National Plans"** scenario for the 2030 horizon.

3.2.1 "Sustainable Transition" scenario

Figure 20 shows that a new interconnector between France and the United Kingdom could generate, in the **"Sustainable Transition"** scenario, around €10 million to €20 million/GW/year of variable production cost gains, for the initial GWs of additional interconnection capacity. These gains would arise from a greater use of low variable cost units. In 2025 and 2030, given the stable demand levels and the moderate development of renewable energies, the price-setting technologies in France and Great Britain are mostly the gas and coal fleets. As a result, an additional interconnector (beyond 4 GW) would only allow the maximisation of the use of the most economical technology, i.e., coal in 2025 (mainly in Germany) and gas in 2030 (therefore the CCGTs in Great Britain enable coal-based production to be reduced in Eastern Europe). However, the difference in production costs between these two sets of technologies is limited, meaning that the economic gains attributable to the interconnection increment are also limited. In 2040, the development of the wind and solar power sectors, as well as the drop in demand levels, leads to a higher nuclear and renewable energy surpluses. In this context, a new interconnector would result in higher surplus gains, insofar as it would enable arbitrage operations between cheap sectors (nuclear, renewable energies) and fossil fuel-fired thermal power plants. Figure 21 illustrates the arbitrage operations at the European level that are enabled by each interconnection increment.

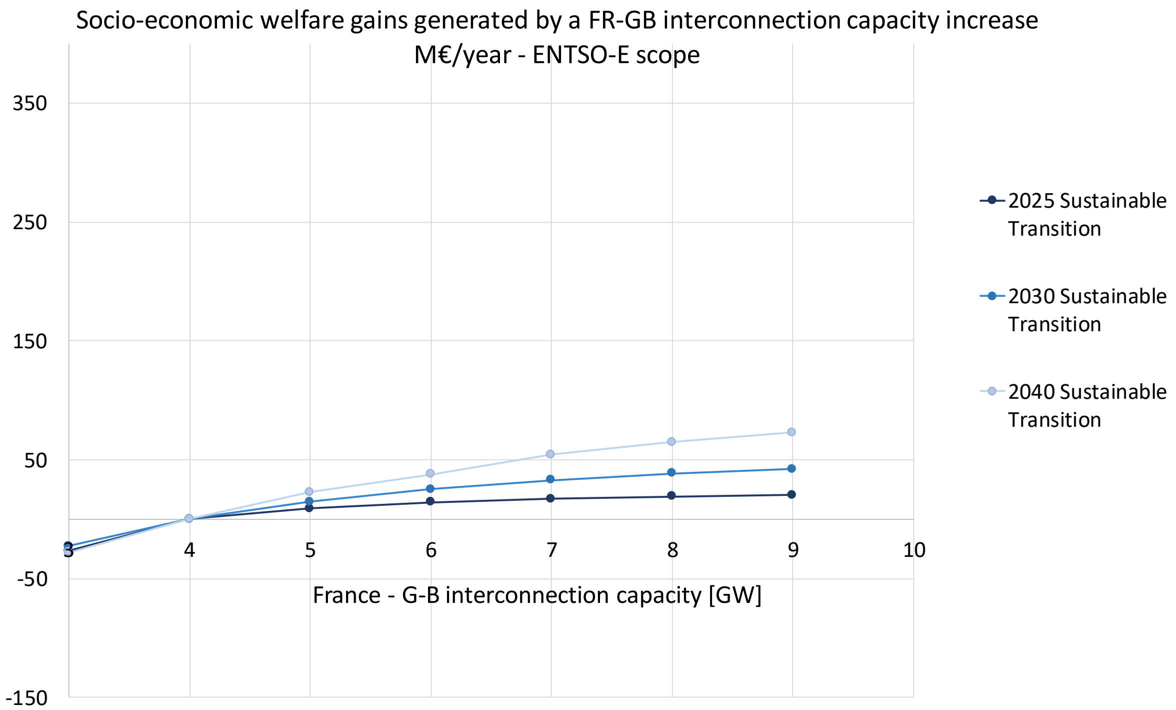


Figure 20: Socio-economic welfare gains generated by a France – Great-Britain interconnection capacity increase "Sustainable Transition" scenario

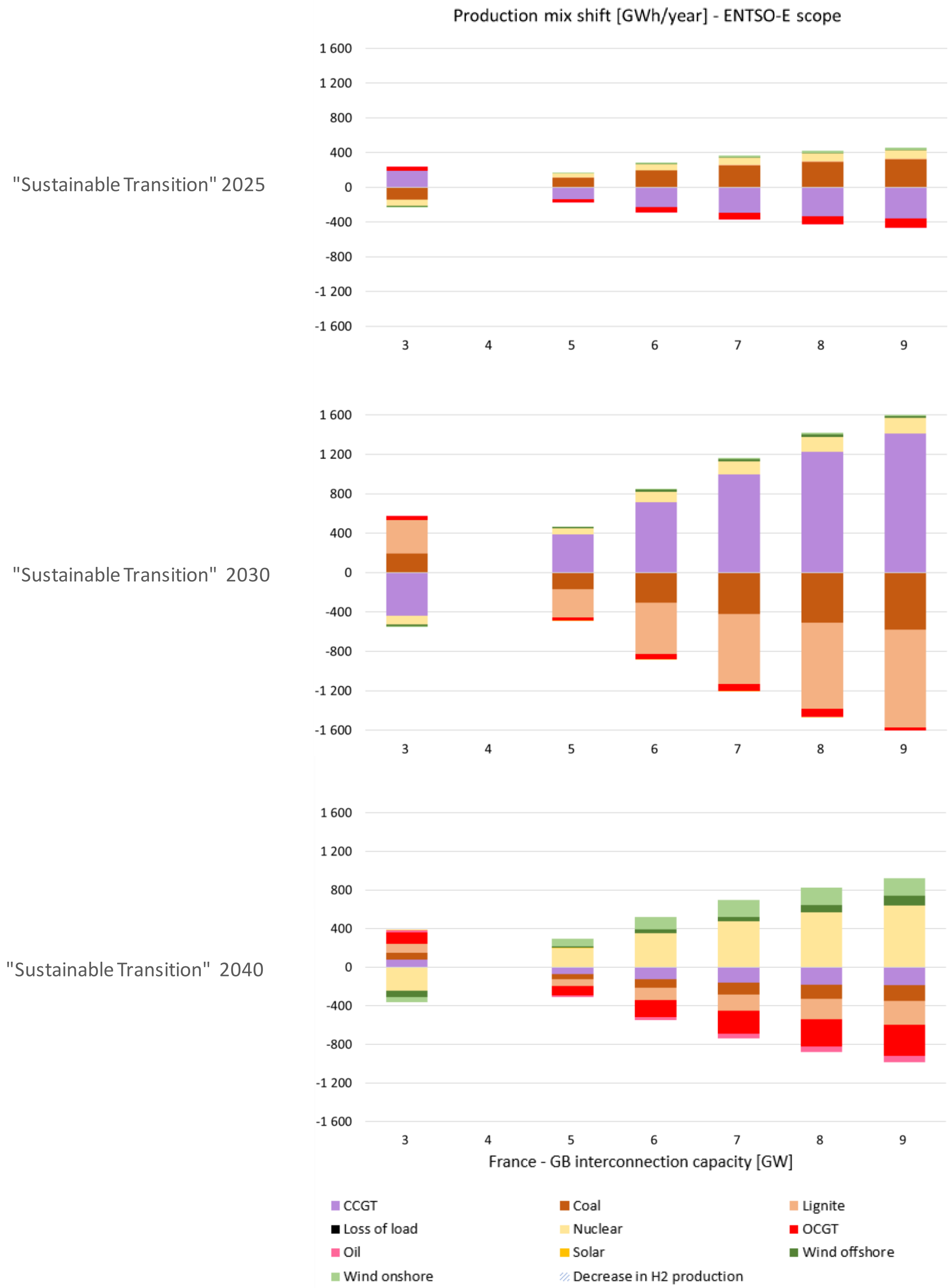


Figure 21: Impact of an interconnector on annual production by sector – "Sustainable Transition" scenario

3.2.2 "Conservative" scenario

The **"Conservative"** scenario corresponds to a situation where limited changes appear in the European electricity system compared to 2025. The economic value of a France–United Kingdom interconnection increment is therefore stable in this scenario between 2025 and 2040. The arbitrage operations induced by the interconnector are the same as those presented in Figure 21 for the "Sustainable Transition" scenario for the 2025 horizon: use of continental coal (mainly in Eastern Europe) instead of British gas. These arbitrage operations are both limited in terms of volume and low in value, since gas-based and coal-based production costs are relatively similar. Consequently, as shown in Figure 22, the economic valuation of a new France–United Kingdom interconnector is very low in this scenario for the three horizons considered.

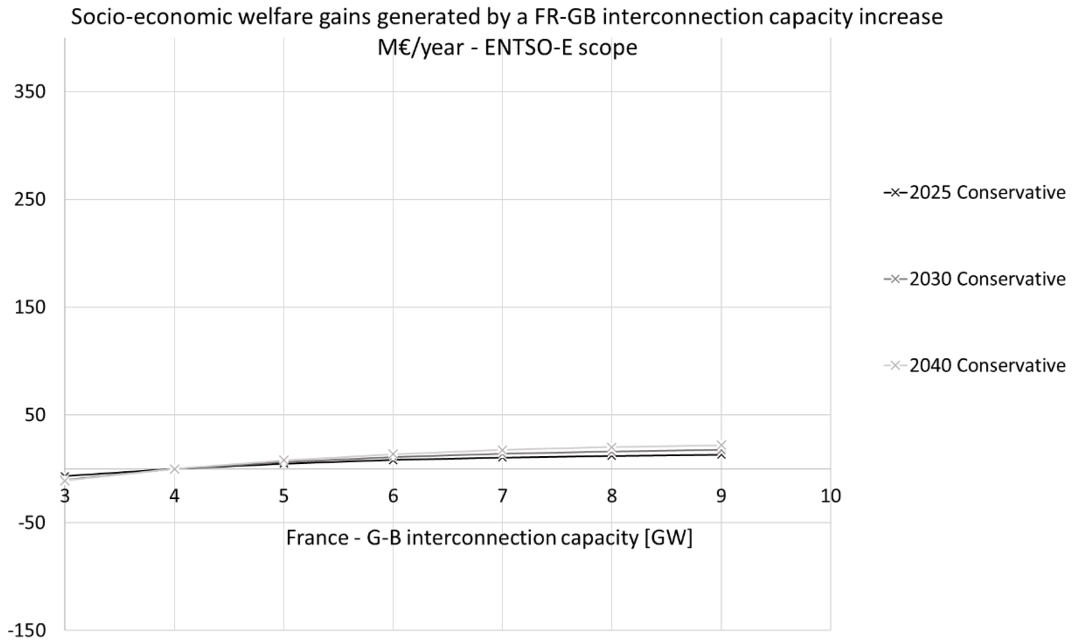


Figure 22: Socio-economic welfare gains generated by a France – Great-Britain interconnection capacity increase - "Conservative" scenario

3.2.3 "National Plans" scenario

The **"National Plans"** scenario is the one in which a new interconnector has the greatest economic value, which could reach more than €100 million/year for an additional GW of capacity in 2030, as shown in Figure 23.

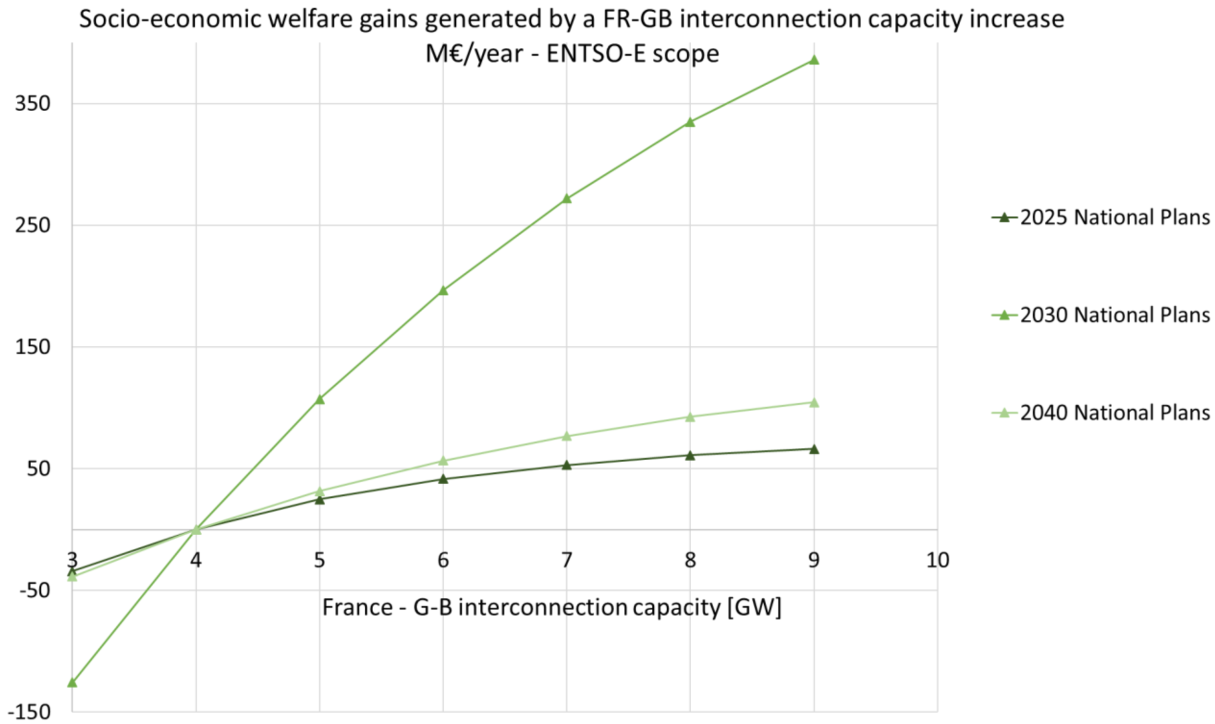


Figure 23: Socio-economic welfare gains generated by a France – Great-Britain interconnection capacity increase – "National Plans" scenario

In this scenario, the installed capacities in the low cost generation technologies (nuclear, wind and solar power) are the highest (from 2025 to 2040), resulting in greater surpluses of low variable production cost electricity than in the other scenarios.

By 2025, for an additional 1 GW of interconnection, the arbitrage operations between the French nuclear and British gas sectors are similar to those of the 2040 **"Sustainable Transition"** scenario, both in terms of volumes and variable production costs avoided, resulting in a comparable economic valuation: around €20-25 million/year. From 2030, the **"National Plans"** scenario also has two characteristics that distinguish it from the other two main scenarios.

On the one hand, the nuclear and renewable energy available in France for export to Great Britain is considerably higher, particularly in 2030. As a result, the arbitrage volume made possible by an additional 1 GW of interconnection reaches around 2 TWh/year by 2030, across the entire scope simulated (see Figure 24). In 2040, due to the hypotheses concerning the electrification of a growing number of uses in France, national demand (excluding Power-to-Gas) increases to 510 TWh, limiting the power available for export, despite the development of renewable energies. Nevertheless, in parallel, Great Britain sees its nuclear and renewable energy capacities increase by 6 GW and 20 GW respectively between 2030 and 2040. Thus, the growth of demand in Great Britain is offset by a higher increase in production capacity in renewables. The drop in exports from France to Great Britain is then accompanied by an increase in imports, maintaining a certain level of trade made possible by a new interconnector. Figure 17 illustrates the rebalancing of flows between the two directions in this scenario at the 2040 horizon. The production costs avoided by these arbitrage operations are considerable in 2030 (in particular, due to a high CO_2 price): around €110 million/year. In 2040, under the hypothesis of a CO_2 price that is significantly lower than in 2030, the value of the arbitrage operations enabled by an additional interconnector is much lower: €30 million/year.

Furthermore, in this scenario, the production of hydrogen via electrolysis develops in France as of 2030, creating a new market for cheap electricity. Consequently, during periods of congestion on the interconnector, nuclear capacity in France is still used to produce hydrogen (within the limit of the electrolysis installed capacities). In this context, arbitrage operations no longer occur only between low-cost resources (nuclear, wind, solar power) and production by gas-fired power plants, but also between the use of low-cost resources to produce hydrogen (valued at the market price of the hydrogen) and substitution of these low-cost resources by gas-fired and coal-fired power plants in neighbouring countries. **The arbitrage enabled by a new interconnector therefore has a value that is limited by the presence of electrolysers**. Figure 24 illustrates the annual breakdown of these arbitrage operations.

Figure 24: Impact of an interconnector on annual production by sector - "National Plans" scenario

3.2.4 "Distributed Generation + PPE" variant

As shown in Figure 25, the surpluses generated by the interconnector are lower in the **"Distributed Generation + PPE"** scenario than in the **"National Plans"** scenario in 2030 and similar in 2040.

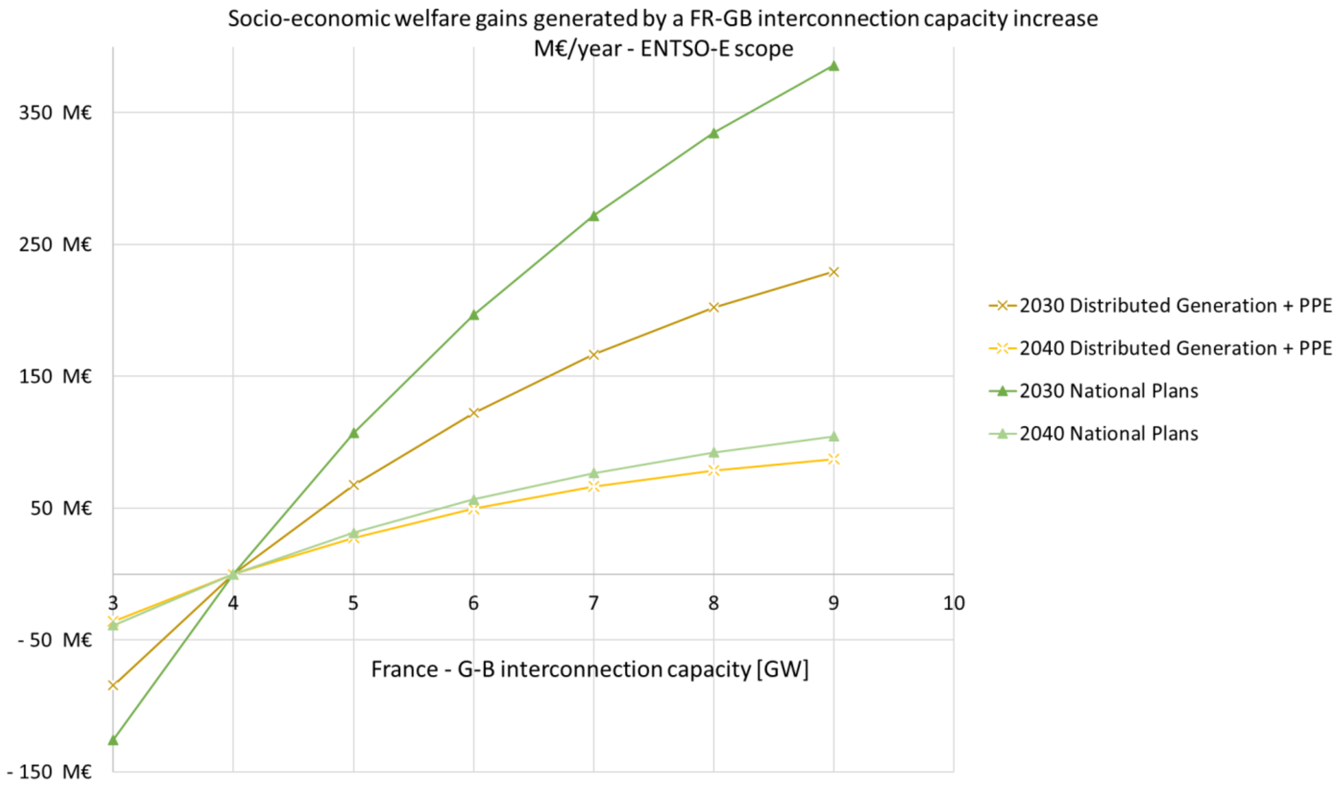


Figure 25: Socio-economic welfare gains generated by a France – Great-Britain interconnection capacity increase - "Distributed Generation + PPE" scenario

In this scenario, by 2030, the interconnector enables arbitrage operations between French nuclear power and British gas in similar proportions to those of the 2030 **"National Plans"** scenario – linked to the use of PPE scenarios for France, where a high nuclear capacity is maintained, while the electrification of transport and industry is still limited at this time horizon. The difference in economic value is explained by a lower CO_2 price (of around €35/t), which limits the difference in production costs (respectively selling price) between nuclear power (respectively production of hydrogen through water electrolysis) and CCGTs.

Conversely, by 2040, the volume of arbitrage (see Figure 26) enabled by the interconnector is much lower than in the **"National Plans"** scenario. This is explained by the lower nuclear capacity in Great Britain (6 GW compared to 13 GW in the 2040 **"National Plans"** scenario), limiting the latter's exports. Nevertheless, with a CO_2 price of €80/t in 2040 (compared to €45/t in the 2040 **"National Plans"** scenario), the economic value of trade is similar to that of the **"National Plans"** scenario.

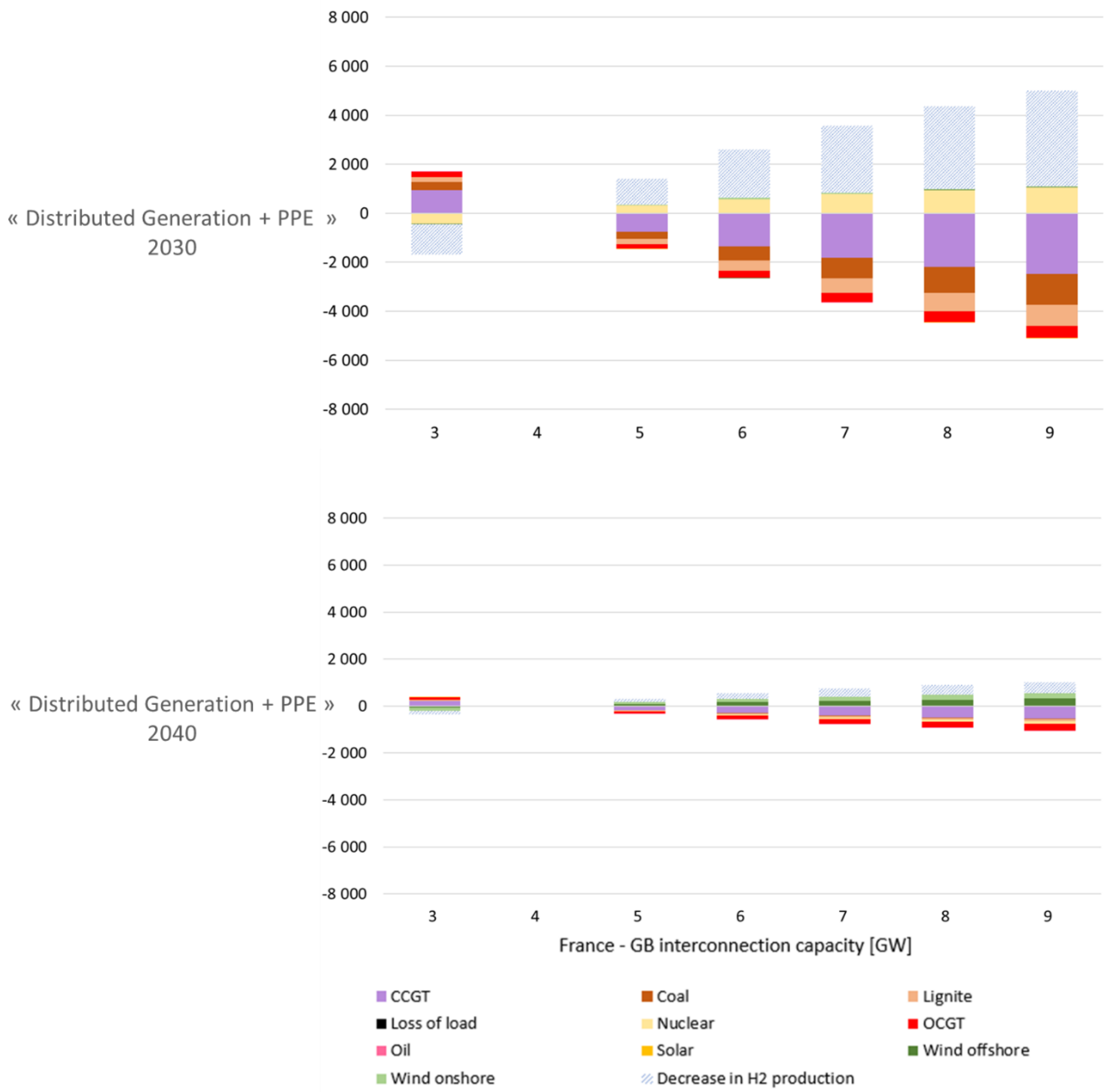


Figure 26: Impact of an interconnector on annual production by sector "Distributed Generation + PPE" scenario

3.3 Distribution of the collective surplus generated by an interconnection increment

As shown in Figure 27, the benefits generated by a new interconnector is not allocated equally amongst countries[29]. Variations in national benefits are mainly the effect of the convergence of prices induced by an increase in interconnection capacity: producers in net exporter countries generally benefit from a rise in prices, while consumers in net importer countries generally see their surplus increase, given that the price tend to decrease. Moreover, it is important to recall that the United Kingdom is considered a member of the European internal energy market until 2040 (and beyond). The distribution of the benefits of a new interconnector may be different depending on the terms of the United Kingdom's exit from the European Union (please see the box below).

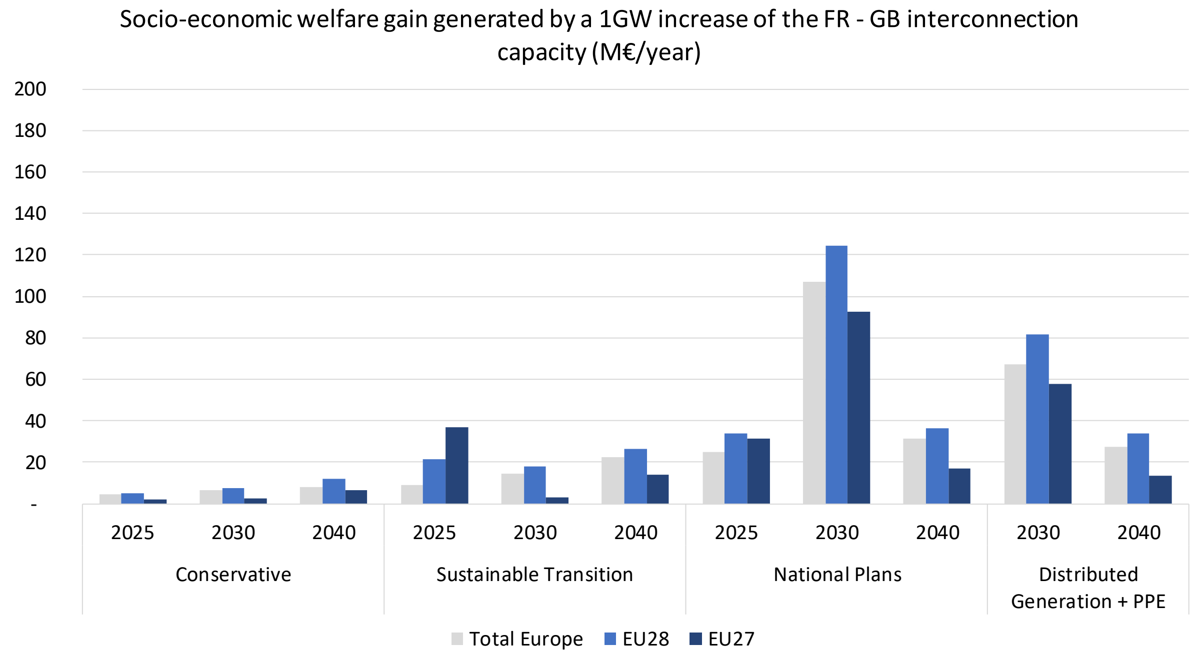


Figure 27: Distribution of the annual surplus generated by a 1 GW interconnection increment

Generally, countries other than France and the United Kingdom see negative impacts on their economic surpluses due to additional interconnector. Considering the United Kingdom outside the European Union therefore has a significant impact on the EU's surplus, as illustrated in Figure 27.

[29] It is nevertheless important to note that the breakdown of the surplus by country requires that a hypothesis be made concerning the distribution of congestion rents between bordering countries. In this study, all congestion rents are distributed according to a uniformity criterion: 50% in each of the countries concerned. This hypothesis explains that the United Kingdom sees its surplus decrease in the "Sustainable Transition" scenario in 2025, while it takes advantage of the interconnector to reduce the production costs of the electricity to which it has access. A new interconnector with France would have a negative impact on the United Kingdom's other interconnectors, thus reducing its congestion rents.

Furthermore, the terms of the United Kingdom's exit from the European Union, in particular the commercial rules concerning electricity trading, would have an impact that was not taken into account in this study, but which was the subject of a dedicated study [10], whose main results are presented in the following box.

Potential impacts of Brexit on the value of a France-GB electricity interconnector

The United Kingdom's exit from the European Union (Brexit) could have a significant impact on the value of electricity interconnection projects between France and Great Britain. Various types of consequences have been discussed in recent years:

- Impact on the **British economy** and in particular the electricity demand growth rate
- Impact on the **renewable energy support policy in the United Kingdom**, in particular from the point of view of European coordination in this area
- Impact on the **sizing of the British electricity system** (how neighbours are considered when assessing *system adequacy*)
- Impact on the **operational management of electricity interconnections** (particularly in the absence of market coupling)

During the study undertaken in 2017 on behalf of the CRE, which was based on the ENTSO-E TYNDP 2016 scenarios, several Brexit conditions have been simulated:

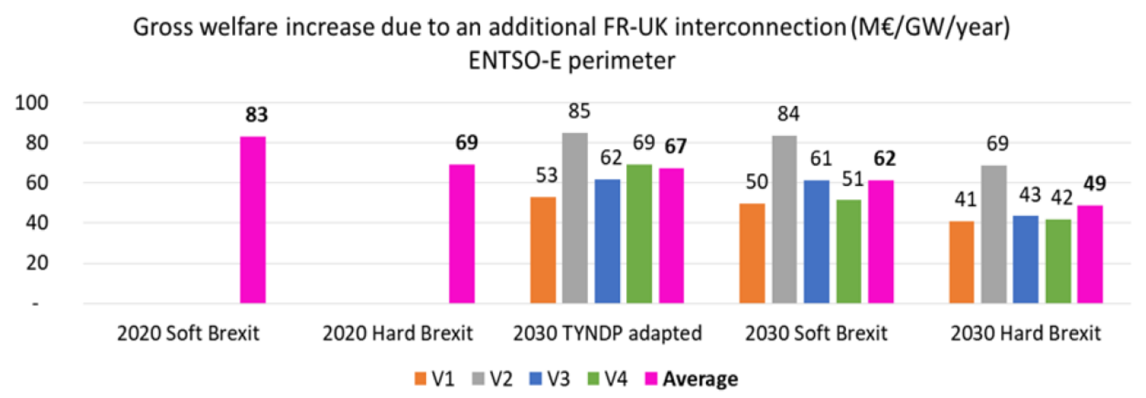
So-called "**Soft**" Brexit:

- European coordination in terms of renewable energy deployment is assumed not to apply to the United Kingdom
- Economic growth in the UK is assumed to be revised downwards

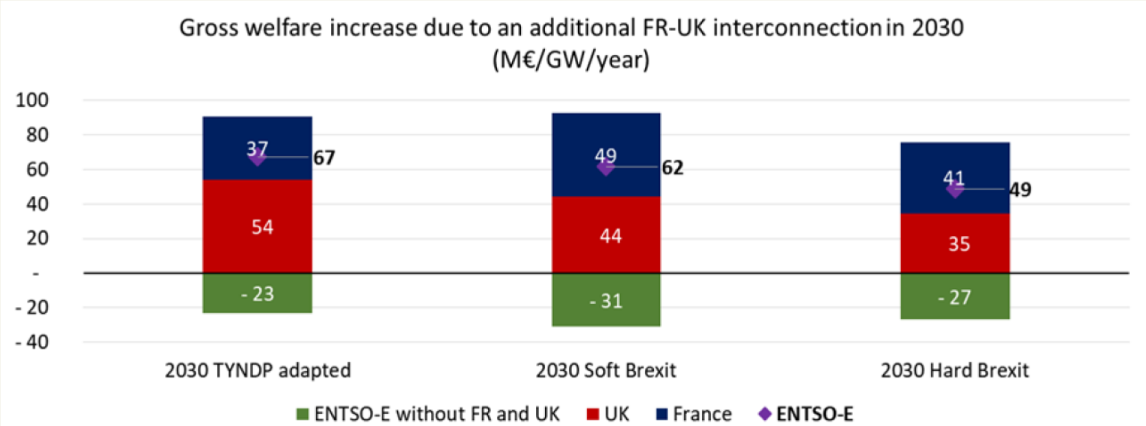
So-called "**Hard**" Brexit:

- European coordination in terms of renewable energy deployment is assumed not to apply to the United Kingdom
- Economic growth in the UK is assumed to be more significantly revised downwards
- The British electricity markets are assumed to be decoupled from those of its neighbours
- Additional investments in the United Kingdom to be able to independently guarantee security of supply

On the basis of these scenarios, the main results of this study showed that the benefits associated with an increase in trading capacity between France and Great Britain could be sufficient to compensate for investment costs in the event of a Soft Brexit (based on the hypotheses made in the TYNDP 2016), but that a Hard Brexit would not be favourable to new projects.



In addition, the United Kingdom captured most of the value of an additional interconnector in all the scenarios (the NPV of the United Kingdom was positive even in the event of a "Hard" Brexit).



The main result of this earlier study (the deterioration of the value of an interconnector project in the event of Brexit, particularly if it is "Hard") also appears to be applicable in this study. However, it is difficult to assess whether the impacts of Brexit would be of the same order of magnitude without carrying out dedicated simulations.

In addition, since in most cases the interconnector causes electricity prices to drop in the United Kingdom and to increase in France, the economic surplus gain would be mainly passed on to French producers and British consumers.

3.4 Analysis on the lifetime of the 1st additional GW

Figure 28 presents the benefits generated by the 1st additional GW of interconnection capacity and compares them to the costs of such projects. The net present value in 2025 of an additional GW has been calculated (see the box below for more details). In order for the project to be considered economically relevant, the value of the benefits discounted on the date of commissioning must be greater than the total costs (dotted lines in the figure). In the main scenarios[30], the addition of 1 GW of interconnection in 2025 does not generate enough value over its lifetime to cover the average total costs considered here (see the box below). In the **"National Plans"** scenario, the surplus gain is nonetheless comparable to the typical investment costs associated with this type of interconnector project.

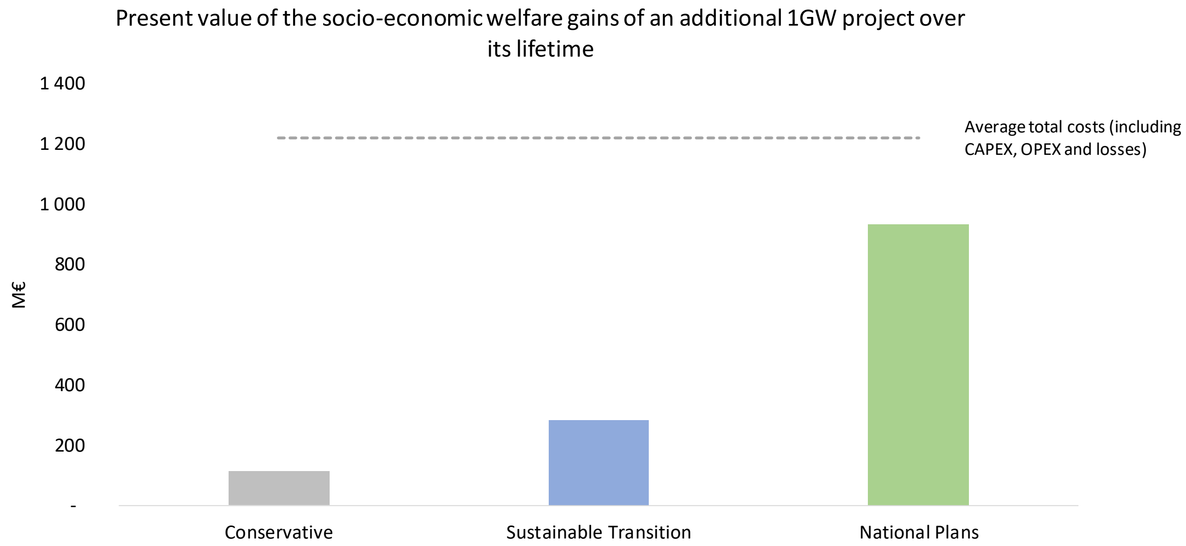


Figure 28 – Total gains and costs generated by an additional 1 GW and discounted in 2025 – for the three main scenarios

The key indicator studied to analyse the interconnector project is **its net present value**. It is based on the discounting of the benefits in terms of socio-economic welfare (SEW) generated by the project. This indicator is calculated using a discount rate of **4%**[31] and a lifetime of **25 years**[32], according to the following formula**:**

$$PV = \sum_{horizon=2025}^{2049} \frac{1}{(1+4\%)^{horizon-2025}} \Delta SEW_{horizon}$$

A linear interpolation of the SEW benefits has been carried to evaluate values for the years between the simulated time horizons (2025, 2030, 2040). The benefits are assumed to be constant from 2040 onwards.

[30] The "Distributed Generation & PPE" variant was only considered and simulated for the 2030 and 2040 horizons. For comparison, the value of a new interconnector discounted in 2025 (commissioned in 2025) was calculated using the "Sustainable Transition" scenario for the 2025 horizon, which would generate €630 million in collective surplus gains. Nevertheless, the hypotheses used for France in the 2025 "Sustainable Transition" scenario are not in line with the PPE, so this calculation is outside the framework of the "Distributed Generation & PPE" scenario. The values discounted in 2030 and beyond (corresponding to commissioning within these same horizons) for this scenario are provided in Figure 29.
[31] According to the ACER recommendation [12]
[32] Hypotheses provided by the CRE

The net present value can be directly compared with the average costs of the interconnector projects included in the TYNDP:

- Average investment costs of €650 million/GW (varying between €600 million and €700 million/GW depending on the projects)
- Average operational costs (OPEX and losses) of €35 million/GW/year (varying between €20 million and €45 million/GW/year depending on the projects)

Furthermore, since a new interconnector generates a different impact on the socio-economic welfare depending on the time horizon, the value of a project depends on the year of its commissioning. Figure 29 shows the discounted value of the addition of 1 GW of interconnection depending on the year of commissioning. For the **"National Plans"** scenario, the year that maximises the economic value generated by the project is around 2027-2028.

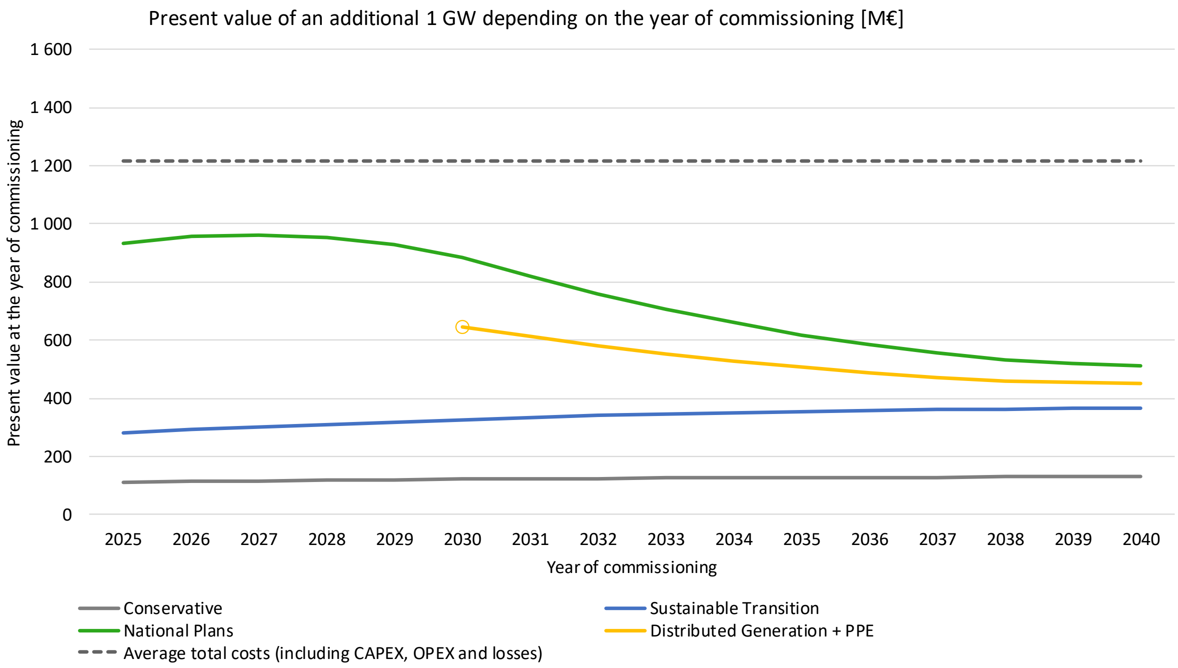


Figure 29 – Present value of an additional 1 GW of interconnection depending on the year of commissioning

4 Analysis of the main determining factors

The objective of this section is to identify the main factors that influence the economic value of a new interconnector and to quantify the impact of a variation of these factors. In view of the results presented in section 3, the sensitivity analyses were carried out based on the **"National Plans"** and **"Distributed Generation + PPE"** scenarios only, since the results are fairly clear for the other scenarios. In total, 18 sensitivity analyses were carried out on the **"National Plans"** scenario, and an additional analysis was carried out on the **"Distributed Generation + PPE"** scenario.

As presented in section 3, the economic value of a new interconnector is mainly driven by the arbitrage operations between low-cost production technologies (renewable energy or nuclear) and more costly generation technologies (thermal generation). These arbitrage operations are possible during periods when one of the two countries has access to cheap renewable energy or nuclear production, and when thermal production sets the price in the other country. The elements considered in this study as having a highly significant impact are the level of demand, installed capacities (renewables, nuclear), interconnectors with other neighbouring countries and the price of fuels and CO_2.

It appears that **the creation of new markets for low-cost electricity,** such as the development of a hydrogen value chain, **has a negative effect on the relevance of an interconnector** –since these alternative uses of electricity provide the same flexibility as exports to adapt to intermittent renewable energy systems and the variability of demand. **Furthermore, a CO_2 price that remains high from 2030 to 2040 has the effect of strengthening the level of generation savings** via arbitrage operations between nuclear/renewable energy and fossil fuels, thereby increasing the value of the interconnector. Conversely, a CO_2 price lower than €30/t in 2030 has the effect of halving this value. Finally, **the relevance of a new interconnector between France and Great Britain is highly dependent on the development of other interconnectors**.

4.1 Demand and alternative uses of cheap electricity

In the scenarios studied, and particularly in the "National Plans" scenario, a new interconnector finds most of its value by allowing the use of nuclear and renewable energy to replace gas, and to a lesser extent coal. Since the direction of such exchanges is mainly in the France to Great Britain direction, one of the major factors impacting the value of the interconnector is the demand level in France, which determines the volume of nuclear power being available for exports. The electrification of new uses is thus competing with exports to access output of the French nuclear fleet, especially if the demand is flexible. In this context, several levels of Power-to-Gas development have been tested as sensitivity analyses on the **"National Plans"** scenario.

Figure 30 shows that by 2030, the collective surplus gain generated by an additional 1 GW of interconnection could range from €70 million/year (in the case of hydrogen production through electrolysis of 27 TWh/year[33]) to €160 million/year (if Power-to-Gas does not develop at all). Since the average annual costs are €75 million/year (see the hypotheses in Section 3.4), the economic relevance of a new interconnector is therefore highly dependent on the level of electrification of new uses in France. This variability is explained by the importance of having access to French nuclear power for a new interconnector to develop value in 2030, as presented in section 3.2. In the event of high national electricity consumption, the French power production technologies would not be as available for exports, and trading with Great Britain would be more limited. The same phenomenon occurs for the 2040 horizon, to a lesser extent however, since the value of the interconnector is also driven by exports from Great Britain to France, notably made possible through the simultaneous growth of the nuclear, wind and solar PV technologies (see Section 2.1.3).

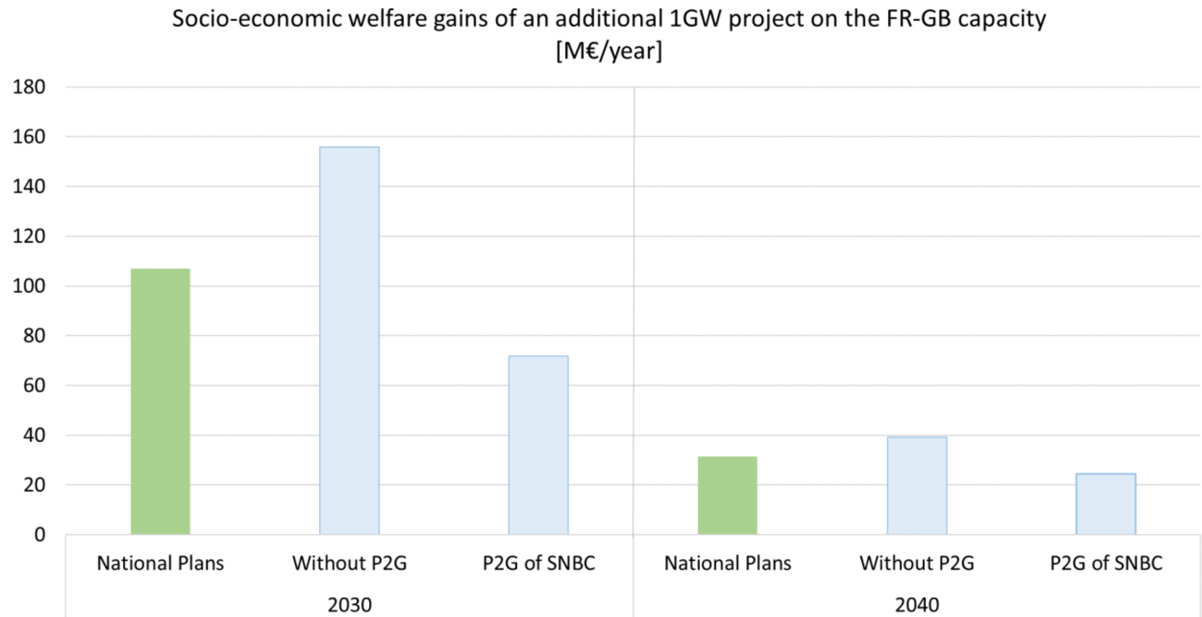


Figure 30: Sensitivity of the surplus gain generated by a new interconnector to the development of the Power-to-Gas sector in France – "National Plans" scenario

4.2 Interconnectors with neighbouring countries

The value of a new interconnection infrastructure is also dependent on the development of other infrastructures capable of providing similar services. In this study, two types of potentially competing flexibility solutions have been considered. On the one hand, the impact of alternative assumptions relating to the level of interconnection that each of the two countries has with its other neighbours was measured. On the other hand, an analysis of sensitivity to the presence of hourly flexibility

[33] In the **"National Plans"** scenario, consumption for Power-to-Gas is determined endogenously by economic valuation. The annual volumes produced are intermediate between these two sensitivity analyses (please see section 2.1.3)

solutions was carried out by adding 3 GW of batteries (discharge time of 2 hours) in France and Great Britain.

By 2030, the value of a France-Great Britain interconnector could be reduced by almost €20 million/year through the construction as of 2030 of three interconnectors planned only from 2040 in the **"National Plans"** main scenario (see Table 6), but whose commissioning dates announced by the promoters in the context of the TYNDP 2018 are mostly before 2030. Conversely, removing a set of projects (see Table 6) from the European network used at the 2040 horizon would also increase the value of a France–Great Britain interconnector by almost €20 million/year.

Table 6: Analysis of sensitivity to the level of interconnection with other neighbouring countries – "National Plans" scenario

	Capacity added for sensitivity on the 2030 horizon	Capacity removed for sensitivity on the 2040 horizon
France – Switzerland	1.5 GW	1.5 GW
France – Belgium	-	1.5 GW
GB – Netherlands	1.5 GW	1.5 GW
GB – Belgium	1.5 GW	1.5 GW

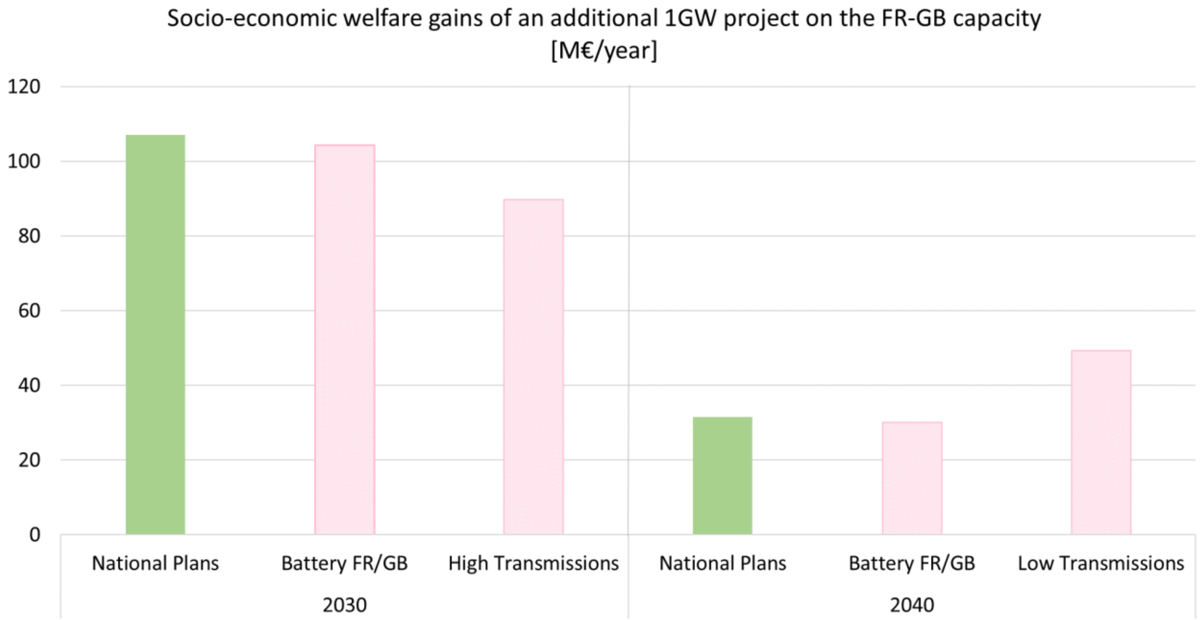


Figure 31: Sensitivity of the surplus gain generated by a new interconnector to competing flexibility solutions – "National Plans" scenario

Furthermore, the interconnector value is less dependent than could be expected on the deployment of 3 GW of batteries in France and Great Britain. This is because batteries provide flexibility for a few hours, which does not compete with the use of the France – Great Britain interconnection for arbitrage operations between nuclear and gas production.

An analysis of sensitivity to the France-Spain interconnection was also carried out on the "Distributed Generation + PPE" scenario for the 2040 horizon. In this scenario, the interconnection capacity between France and Spain reaches 10 GW, i.e., 1 GW more than the capacity corresponding to the addition of the "Bay of Biscay" and trans-Pyrenean projects. This capacity is justified by the extremely high level of development of the solar power sector throughout Europe, and in particular in the Iberian Peninsula – with more than 80 GW of installed capacity in 2040. As shown in Figure 32, in this context, the value of a new France–Great Britain interconnector is linked to the use of the solar power surpluses accessible in Continental Europe. This value decreases by €7 million/year by 2040, i.e. a loss of almost 25%, when the France-Spain interconnection is assumed to only reach 5 GW (instead of 10 GW), limiting the possibility of using solar power production from the Iberian Peninsula.

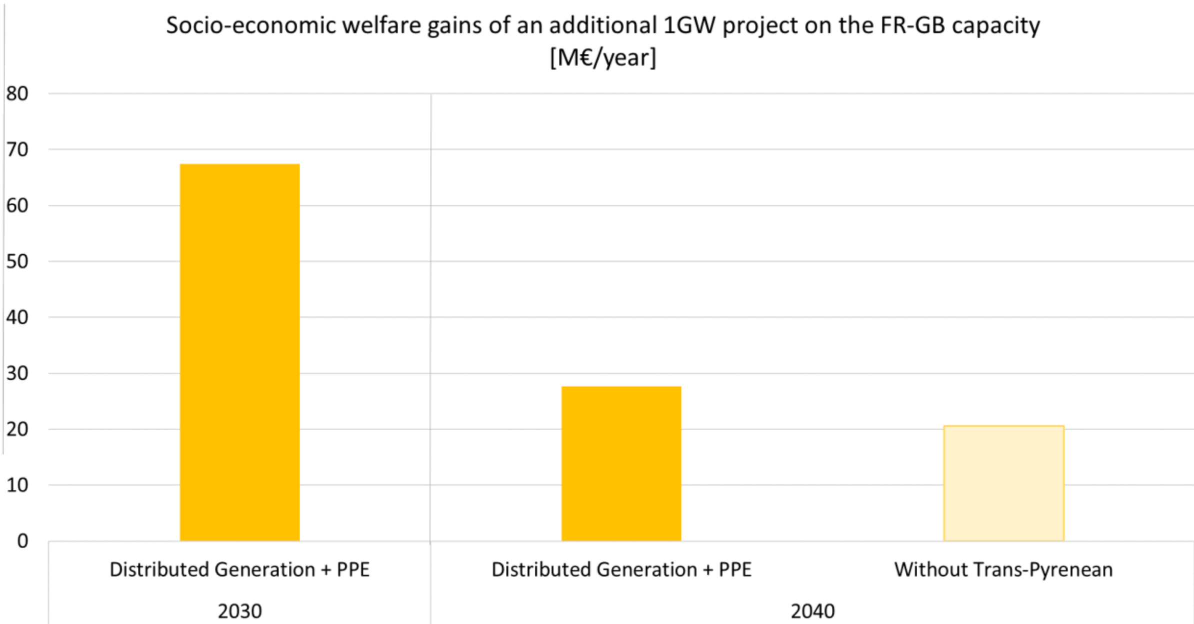


Figure 32: Sensitivity of the surplus gain generated by a new interconnector to the capacity on the France-Spain border – "Distributed Generation + PPE" scenario

4.3 Nuclear and wind power installed capacity

The wind and nuclear power[34] installed capacities in France, the United Kingdom and their neighbouring countries contribute to a large extent to the determination of the frequencies and durations of periods of high divergence of electricity prices. This section presents the results of six sensitivity analyses conducted on these parameters, based on the **"National Plans"** scenario:

- Use of low nuclear installed capacity hypotheses for Great Britain in 2030 and 2040:
  - 3 GW in 2030 compared to 6 GW in the "National Plans" scenario
  - 6 GW in 2040 compared to 13 GW in the "National Plans" scenario
- Addition of 10 GW of wind power capacity in Great Britain in 2030 and 2040
- Use of high wind power capacity hypotheses for Germany in 2030 and 2040, according to the scenarios developed by network operators [11]:
  - Addition of 25 GW of wind power in 2030
  - Addition of 40 GW of wind power in 2040

In the **"National Plans"** scenario, Great Britain switches from being a net importer in 2030 to being a net exporter in 2040. In particular, the interconnector with France is mainly used to export from France to the United Kingdom in 2030, while it is operated in a more balanced manner in 2040[35].

[34] The impact of the PV solar power installed capacity is quantified using the "Distributed Generation & PPE" scenario, whose results are presented in section 3.2
[35] Please see section 3.1

Consequently, a variation in low marginal cost capacities does not have the same impact in each of these two contexts on the value of an interconnection capacity increment – as shown in Figure 33.

In 2030, increasing the wind power production capacity in Great Britain has the effect of reducing production costs over certain periods of import from France, thereby limiting the arbitrage opportunities provided by a new interconnector. Conversely, in the hypothesis of a lower nuclear power capacity in Great Britain, the CCGT sector would be marginal over more prolonged periods, thereby increasing opportunities for arbitrage operations with nuclear production in France. By 2030, an additional 1 GW of interconnection could then generate more than €120 million/year of collective surplus gains.

In 2040, lowering the nuclear power capacity would have a two-fold impact on the value of an additional interconnector. On the one hand, this would limit exports from Great Britain to France, while on the other hand, increasing exports from France to Great Britain. Since the interconnector is used relatively symmetrically in this context[36], the impact on the value of a 1 GW increment remains limited. Faster growth of the wind power sector in Great Britain would, however, have a positive impact on the economic relevance of a new interconnector with France: this would accentuate production surplus periods in Great Britain, which is already a net exporter in the **"National Plans"** scenario for the 2040 horizon (as opposed to the 2030 horizon, in which Great Britain is a net importer).

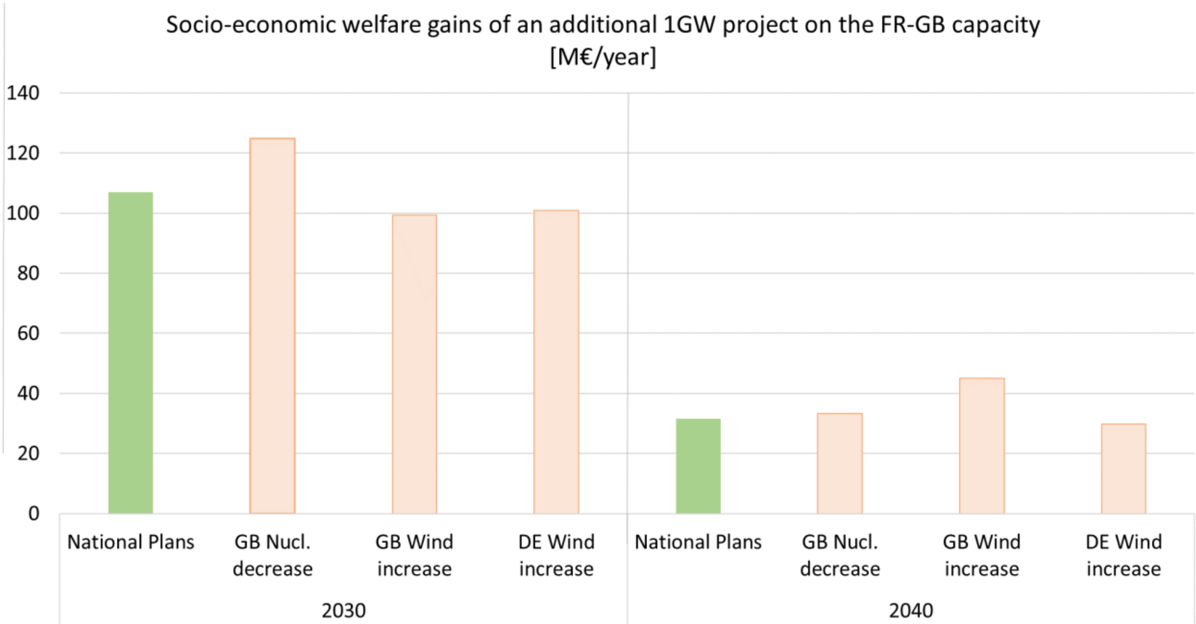


Figure 33: Sensitivity of the surplus gain generated by a new interconnector to baseload production capacities - "National Plans" scenario

[36] Please see Figure 17

Furthermore, a more significant development of wind power in a country neighbouring France, such as Germany, would provide additional import opportunities, particularly for Great Britain in 2030. Nevertheless, the negative impact on the value of the interconnector between France and Great Britain is limited by the parallel interconnection capacity between Great Britain and Germany (1.4 GW in the scenarios studied). In addition, the correlation between wind power systems in France, Germany and the United Kingdom limits the possibilities of enhancing the value of the interconnector between France and Great Britain to use wind power surpluses in Germany.

4.4 Fuel prices

Finally, fuel and CO_2 prices are also an extremely important factor in the determination of the value of a new interconnector. This is because the interconnector finds its value in the arbitrage operations that it enables between the two countries it connects: the greater the price differences, the greater the utility of the interconnector. Several sensitivity analyses were therefore carried out on these economic parameters, using two price trajectories taken from the WEO 2018 and shown in Table 7.

Table 7: Fuel and CO_2 price scenarios

		New Policies (WEO 2018)[37]		Sustainable Development (WEO 2018)		"National Plans[38]"	
	Unit	**2030**	**2040**	**2030**	**2040**	**2030**	**2040**
CO_2 price	€/t	28	39	80	130	84	45
Oil price	€/MWh NCV	53	62	40	36	64	50
Gas price	€/MWh NCV	28	31	26	26	35	22
Coal price	€/MWh NCV	10	11	9	8	10	9
Lignite price	€/MWh NCV	4	4	4	4	9	9

These various price scenarios only have a small impact on the arbitrage operations enabled by a 1 GW interconnection increment between France and Great Britain. As detailed in section 3.2, arbitrage operations are carried out between additional nuclear production and a drop in Power-to-Gas consumption on the one hand, and fossil-based thermal production (mainly based on gas) on the other. In this context, the price scenarios mentioned above mainly have an impact on the economic value of arbitrage operations, but only marginally affect the production mix variation generated by a new interconnector. Figure 34 shows that the value of the interconnector is therefore directly linked to the price of CO_2:

- Considering a price scenario where the CO_2 price is less than €30/t in 2030, the value of a new interconnector varies by almost €50 million/year, i.e., 45% of the value in the main scenario (with a CO_2 price of more than €80/t) – falling to €60 million/year.

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[37] This fuel and CO_2 price change scenario is the one on which the hypotheses of the TYNDP 2018 "ENTSOs' Sustainable Transition" scenario are built. Some prices, particularly CO_2 prices in 2030 and gas prices in 2040, were nevertheless modified in the "ENTSOs' Sustainable Transition" scenario (please see document 7, p17), leading to an inversion of the order of economic precedence between gas and coal within these two horizons. This sensitivity analysis uses the original WEO 2018 benchmark scenario to test the direct application of the economic elements underlying this scenario.

[38] Based on the TYNDP "ENTSOs' Sustainable Transition" scenario

- Conversely, with a CO_2 price of around €130/t[39] in 2040, an additional 1 GW of interconnection would increase its value by 80% compared to the main scenario (with a CO_2 price of €45/t), reaching €60 million/year (i.e., the same value as in 2030 with arbitrage operations that are much larger in volume (please see 3.2) but a CO_2 price lower than €30/t).

The economic value of the arbitrage operations[40] enabled by an additional 1 GW of interconnection is also linked to the price of gas. A lower gas price in 2030 in the "Sustainable Development" scenario (for a similar CO_2 price) results in a deterioration of their value of €15 million/year. Nevertheless, the price of CO_2 is a more significant determining factor, since it impacts the production cost of both the gas and coal sectors, both affected by the arbitrage operations made possible by the interconnector between France and the United Kingdom.

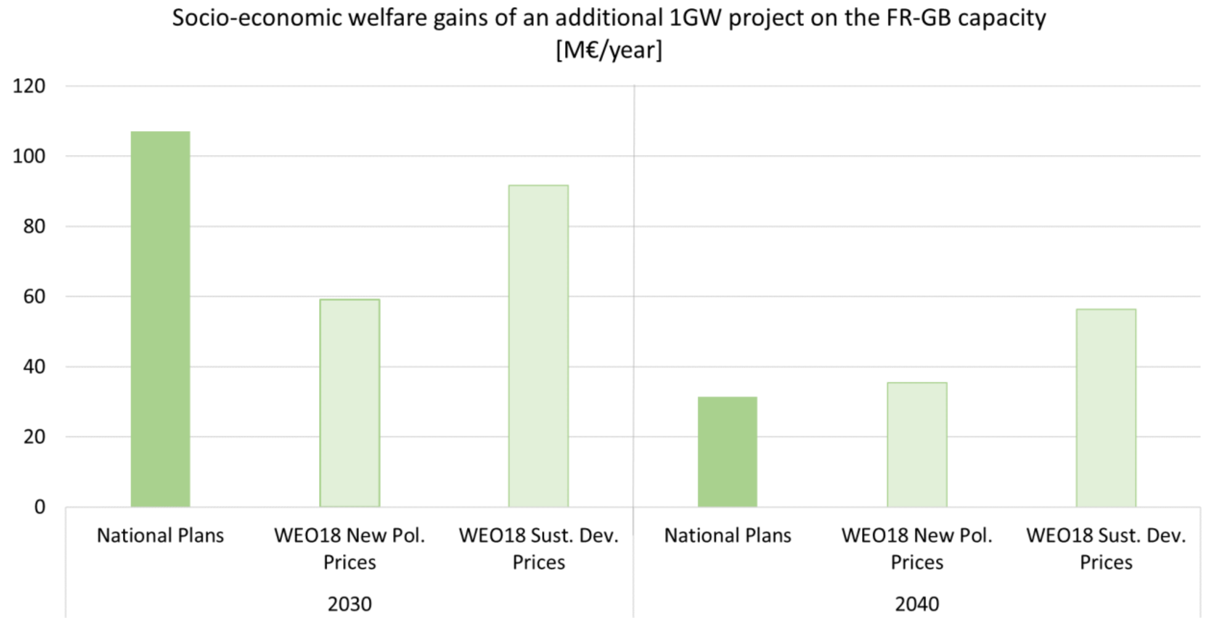

Figure 34: Sensitivity of the surplus gain generated by a new interconnector to fuel and CO_2 prices – "National Plans" scenario

[39] It should be noted that this price is a particularly ambitious hypothesis with regard to the other public benchmark scenarios.

[40] Between nuclear valuation for Power-to-Hydrogen, on the one hand, and to limit the production of gas-fired and coal-fired power stations, on the other hand, please see Figure 24.

4.5 Analyses of sensitivity to the benefits generated over complete lifetime

All the sensitivity analyses carried out based on the "National Plans" scenario were used to assess the impact of the main determining factors on the entire lifetime of a new interconnector between France and the United Kingdom[41]. Figure 35 shows that the development of the *Power-to-Gas* sector in France, and more generally the level of electricity demand, has a particularly significant impact. Without the development of this sector in France, an interconnector commissioned in 2025 would be economically relevant – over its entire lifetime – based on the increase socio-economic welfare it would generate, mainly at the 2030 horizon (taking into account the hypotheses of this scenario: high nuclear and renewable energy capacities in France and no significant electrification within this horizon). Nevertheless, in all the other scenarios, the low gains generated by a new interconnector for the 2040 horizon would limit its total economic relevance – even under the assumption of a lower level of development of interconnectors with other neighbouring countries or a lower level of nuclear development in the United Kingdom (see sections 4.1 4.2, 4.3 and 4.4).

[41] Discounted in 2025, the total collective surplus gains (i.e., over lifetime) generated by an additional 1 GW of interconnection would be €630 million in the "Distribution Generation + PPE" scenario, with the removal of the trans-Pyrenean interconnector projects (please see the sensitivity analysis in 4.2) in 2040 and supplemented by the "Sustainable Transition" scenario for the 2025 horizon (please see document 29, p53).

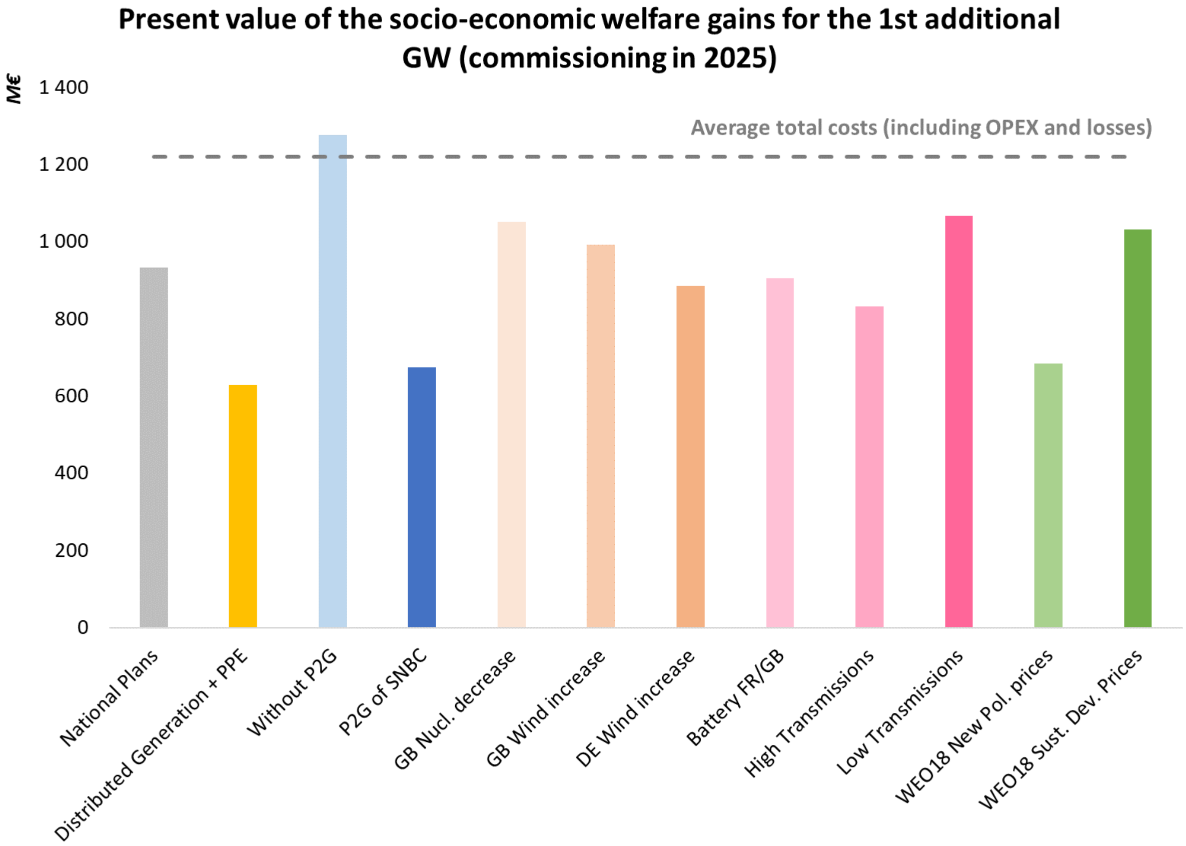

Figure 35: Discounted value of collective surplus gains for the first additional GW of interconnection according to the different sensitivity calculations of the "National Plans" scenario

Conclusion

The analysis carried out on the three main scenarios ("Sustainable Transition", "Conservative" and "National Plans") and the "Distributed Generation + PPE" variant reveals that, **considered over its entire lifetime, a new interconnector would not be economically relevant in any of the scenarios considered in this study.**

Two conditions seem necessary for a new interconnector between France and the United Kingdom to generate benefits that outweigh its costs:

- **High nuclear and/or renewable energy production surpluses in one of the two countries**
- **High gas-fired and coal-fired power plant production costs.**

These two conditions are only simultaneously met in one of the configurations tested within the framework of this study: the "National Plans" scenario for the 2030 horizon. In this context, maintaining a high nuclear power capacity in France (58 GW) coincides with an ambitious level of development of renewable energies (45 GW of wind power and 50 GW of solar power), in a context of stable demand. Consequently, France has considerable nuclear power surpluses that can produce value through exports to the United Kingdom, whose electricity mix in this scenario contains 25% natural gas. Moreover, in this scenario, production cost gains are high since the price of CO_2 is greater than €80/t - unlike the "Distributed Generation + PPE" variant, in which the same arbitrage operations take place, but the production cost gains are limited by a lower CO_2 price of €50/t. The benefits generated by an additional 1 GW of interconnection therefore exceed €100 million/year in the "National Plans" scenario for the 2030 horizon, for a total annual cost estimated on average at €75 million/year.

All the scenarios give a low value to increases of the interconnection capacity beyond 4 GW in 2040, since high production capacities in low-cost generation technologies are only envisaged for this horizon in parallel with hypotheses for the increasing electrification of the national energy mixes concerned, limiting the opportunities for imports/exports.

The sensitivity analyses carried out also highlighted the predominant factors that could have an impact on the value of a new interconnector:

- **Creating new electricity markets for cheap electricity,** such as the development of a hydrogen value chain, **reduces the relevance of an interconnector.** A new interconnector between France and the United Kingdom could notably prove to be economically relevant under the hypothesis of high renewable energy and nuclear capacities in France (as provided by the PPE) but with limited electrification of new uses.
  - This phenomenon is due to the competition between these alternative uses to provide similar flexibility services as exports could.
- **A new interconnector can only find economic value in a context of a high price signals on CO_2, maintained at a high level between 2030 and 2040.**

    - This would strengthen production cost decreases through arbitrage between nuclear power/renewable energy and fossil fuels, increasing the value of the interconnector.

- **The relevance of a new interconnector between France and Great Britain is also highly dependent on the development of other interconnectors**, which can provide similar services.

- Finally, a **very ambitious development of the wind or nuclear power sectors in Great Britain** by 2040 appears to strengthen the value of a new interconnector, particularly in the context of extensive electrification in France.

Finally, it should be recalled that in all the scenarios studied during this study, **the United Kingdom is considered part of the European internal energy market**. The operational use of interconnectors is therefore assumed to be optimal: flows are dynamically adjusted according to arbitrage opportunities. The "*Value of interconnectors between France and Great Britain*" [10] study conducted in 2017 by Artelys and Frontier Economics, which was based on TYNDP 2016 scenarios, had demonstrated that the value of interconnectors is deteriorated in scenarios where the United Kingdom is not part of the internal European energy market. Although this study does not consider the potential impacts of Brexit, it can reasonably be considered that the benefits mentioned in this document would be lower in the event of a "hard" exit of the United Kingdom from the European Union.

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Appendix 1 – Calibration of peak generation capacities

For all the scenarios studied in this report, peak generation capacities (gas combustion turbine) were calibrated to reach around 3-4 hours of scarcity prices on average over the ten climate years considered herein with 4 GW of interconnection between France and GB. Based on these adapted capacities, the gains generated by an increase in interconnection capacity between France and the United Kingdom are calculated as production cost savings resulting from the arbitrage operations enabled by this additional interconnection capacity.

The simulation results show that interconnection increments (beyond 4 GW) do not enable the residual loss of load situations to be reduced, thus limiting the contribution of these new interconnectors to security of supply (little or no reduction of the energy not served). This can be partially explained by the correlation between the hourly electricity demand profiles and the wind power production between the two countries, in particular during periods of peak demand for intermittent renewable energies. Figure 36 shows the distribution of flows during the 100 hours of highest residual demand in France and in the United Kingdom, for each climate year studied in the "Sustainable Transition" scenario in 2030. The interconnector is only saturated for a limited number of these periods of higher net demand.

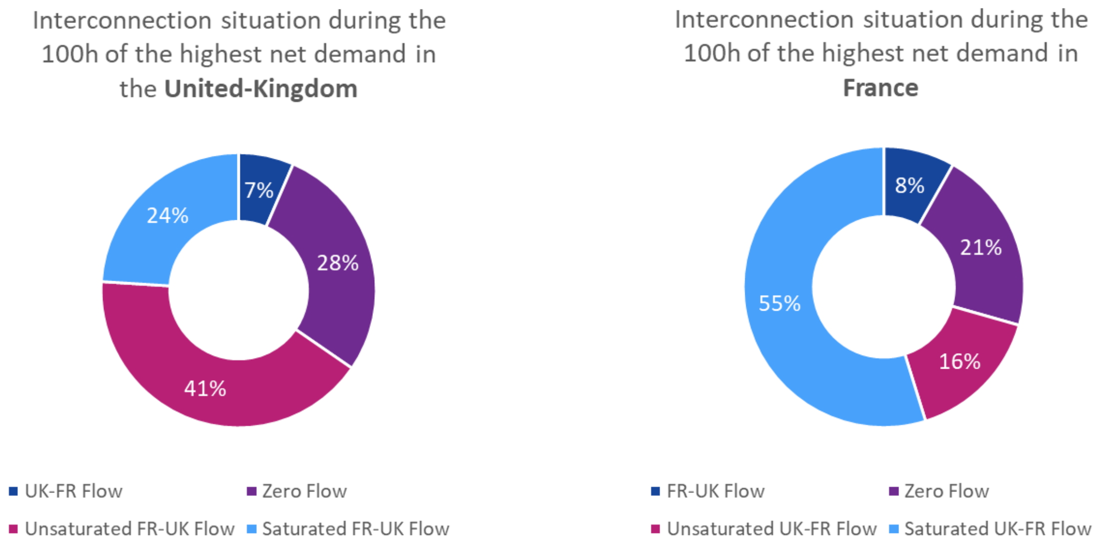

Figure 36 - Time distribution of interconnection situations during the 100 hours of the highest net demand in France and in the United Kingdom during the year 2030 of the "Sustainable Transition" scenario

The few hours of residual loss of load are found to be simultaneous between France and the United Kingdom. As a result, increasing the interconnection capacity does not enable one of the countries to cover a larger portion of its demand through increased imports, since the second country also lacks capacity at the same time.