OPTIMIZATION SOLUTIONS

Benefit analysis of electricity interconnections between France and the United Kingdom

Report

Artelys FRANCE
81 rue Saint-Lazare
75009 Paris FRANCE
+33 1 44 77 89 00

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R23100

SAS au capital 125 182 €
RCS Paris B 428 895 676
TVA FR 82428895676
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Executive Summary

CONTEXT AND OBJECTIVES

The aim of this study is to provide a quantitative and qualitative analysis informing decision-making on the development of new electricity interconnections between France and Great Britain.

The economic benefits associated with a new interconnection project are estimated via the increase in social welfare brought about by the commissioning of this new interconnection. The expected gains in terms of security of supply are also assessed. These benefits are evaluated for the years 2030, 2040 and 2050.

The future evolution of the power generation and capacity mix, energy demand and infrastructure cannot be known with certainty. Several scenarios and variants are therefore studied (including different assumptions about renewable energy deployment, nuclear capacity, interconnection levels, etc.) in order to identify the opportunities and risks associated with an increase in electricity interconnection capacity between France and Great Britain.

STUDIED SCENARIOS

Three scenarios are constructed based on reference scenarios developed in 2022 by RTE for France, National Grid for Great Britain, and ENTSO-E for the rest of Europe. These scenarios define different energy system pathways that are credible considering the energy policy decisions announced in France and Great Britain. The three scenarios are as follows:

- **Scenario 1**: In the first scenario, France and Great Britain achieve carbon neutrality by 2050, thanks to a strong increase in electricity consumption and the massive deployment of renewable power generation capacity.
- **Scenario 2**: In the second scenario, France and Great Britain also achieve carbon neutrality by 2050, thanks to the strong uptake of renewable energy. However, electricity consumption increases less strongly than in scenario 1, and the energy system relies more heavily on centralized solutions, such as nuclear power in France. Therefore, the growth in renewable energy capacity is lower than in the first scenario.
- **Scenario 3**: The third scenario represents a delay in the implementation of clean energy transition policies and plans, and the failure to achieve carbon neutrality by 2050. In France and Great Britain, this translates into a delay in the deployment of renewable capacity, the continued use of fossil-fired thermal capacities, the incomplete electrification of end-uses and reduced ambitions for the deployment of electrolyzers.

Sensitivity analyses are also carried out on the second scenario to analyze the impact of various techno-economic parameters on the benefits associated with new France-GB interconnections, including the price of gas, the development of additional interconnections linking Great Britain and France to other European countries, the availability of the French and British nuclear power fleets, the amount of offshore wind capacity deployed in Great Britain, hydrogen demand levels and the capacity of electrolyzers installed in France and Great Britain.

ASSESSING THE VALUE OF A NEW INTERCONNECTION

The analysis conducted shows that increasing the interconnection capacity allows for **a better integration of renewable energy,** which replaces more costly power generation technologies, such as fossil-fired power stations. Increasing the interconnection capacity **reduces the curtailment of British wind power generation**, which is significant in some scenarios due to the strong development of wind power in Great Britain. In addition to reducing the operating costs of the power system, these production shifts help to **reduce carbon dioxide emissions (CO_2).**

The analysis also shows that the present value of the benefits expected from the first additional interconnection project (with a capacity of 1.4 GW) varies **between 1.5 and 2.4 billion euros per GW of interconnection capacity**, depending on the scenario (the present value is estimated in 2025, assuming a commissioning date of 2030, a 25-year lifetime and a discount rate of 4.5%). The present value of the benefits associated with the second interconnection project varies **between 1.3 and 2.1 billion euros per GW of interconnection capacity**. The increase in social welfare stemming from the increase in interconnection capacity in 2050 is highly uncertain, but this has a limited impact on the estimate of the present value of the benefits expected over the full lifetime of the project (see Figure 1).

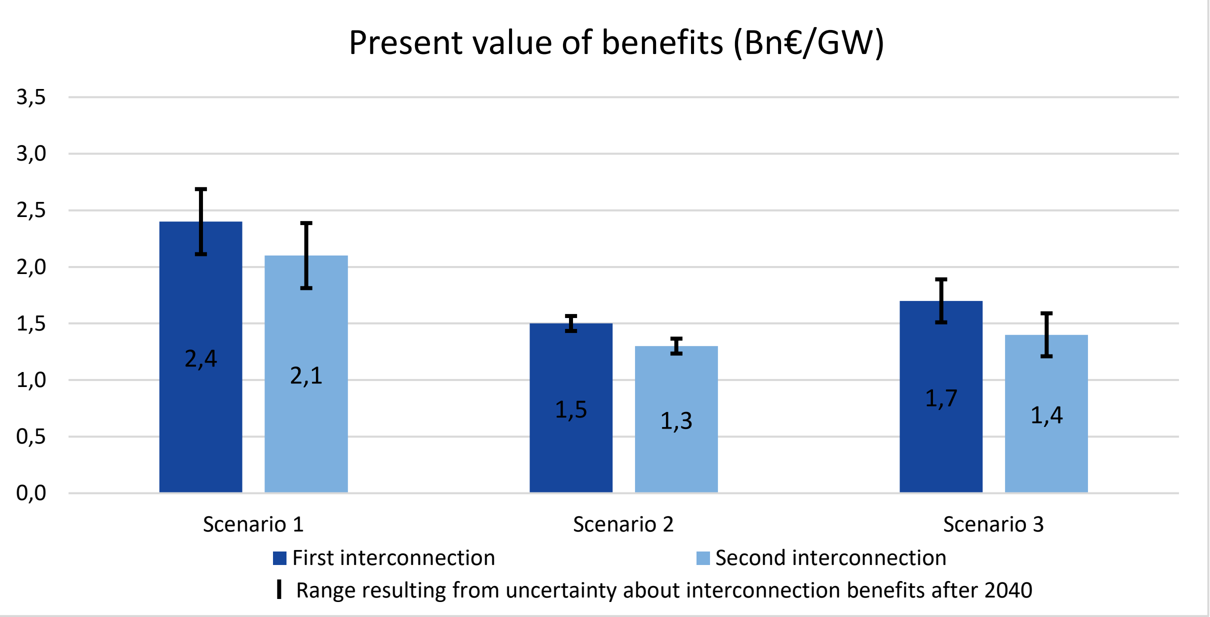

Figure 1 –Present value of benefits from interconnection projects between France and Great Britain

Sensitivity analyses indicate that several factors have a negative impact on the estimated economic benefits generated by new interconnection projects:

- Lower **wind power capacity in Great Britain** than planned,
- **Gas prices** below the level considered in the central scenario (scenario 2 - 40€/MWh $_{gas}$),

- Greater development of interconnections between Great Britain and the rest of Europe, competing with France-UK interconnectors

Among these three factors, the amount of UK wind power capacity is the most decisive one. Indeed, in the sensitivity analysis focusing on this parameter, the present value of the benefits falls to 786 million euros per GW for the first interconnector project (1.4 GW) and 659 million euros per GW for the second interconnection (1.2 GW) (see Figure 2). This is due to the fact that a significant proportion of the value associated with the interconnection comes from the export of low-cost UK wind power to continental Europe.

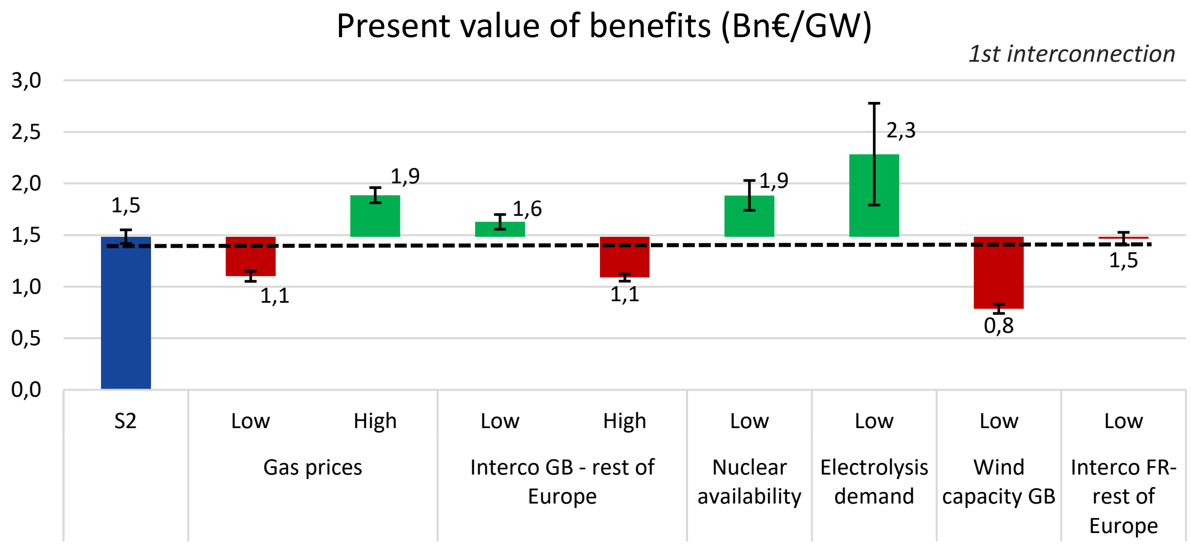

Figure 2 - Present value of benefits in sensitivity analysis

Results show that most of the economic gains generated by new interconnection projects are captured by Great Britain, although France also benefits from the development of additional interconnection capacity (see Figure 3). Furthermore, increasing the interconnection capacity increases congestion rents over the geographical scope considered in most cases, including for interconnections linking France and Great Britain.

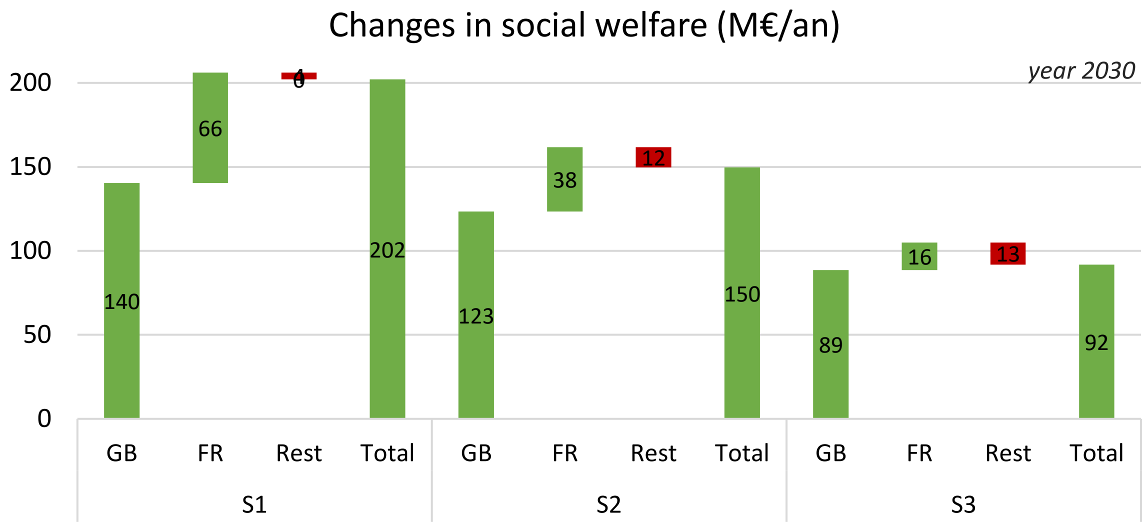

Figure 3 – Geographical breakdown of changes in social welfare in 2030

Finally, increasing the interconnection capacity improves France's security of supply in all three scenarios studied, as early as 2030, with over 50% of the additional interconnection capacity in use on average in times of high residual demand in France (see Figure 4). In the case of Great Britain, interconnections contribute only marginally to its security of supply in 2030, and in scenario 3 in 2040. In contrast, the contribution of additional interconnections to security of supply in Great Britain is substantial in 2040 in scenarios with high renewable penetration levels (scenarios 1 and 2).

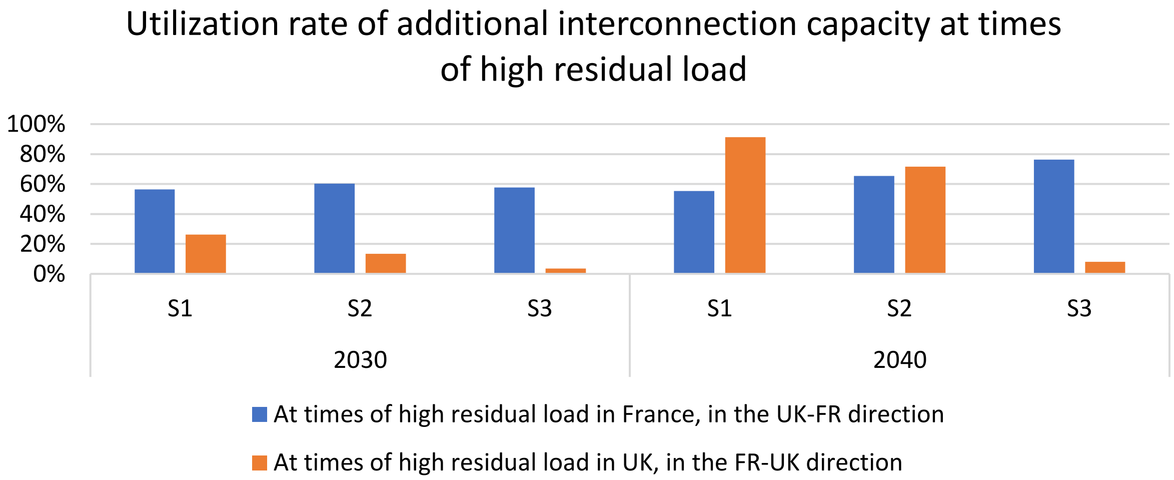

Figure 4 - Average utilization rate of additional interconnection capacity during the 250 hours of highest residual load in France and Great Britain

In summary, the simulations conducted show that increasing the interconnection capacity generates economic benefits and enhances the security of supply in most cases. France and Great Britain unevenly capture these benefits.

Nevertheless, the decision to invest in an interconnection project should not be solely based on the projected benefits but should also consider the risks that the expected benefits will not fully materialize. Therefore, an inventory of the main risks associated with these interconnection projects is made. Among these risks, the level and speed of wind power development in Great Britain, as well as the ability of the UK grid to transport renewable electricity produced in the north to the south of country, warrant special attention: a significant delay in either the development of the wind portfolio or that of the transmission grid would considerably reduce the interest of new interconnection projects. Supplementary analyses of the impact of congestion in the UK transmission system on the benefits of the interconnection are provided in appendix.

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Artelys is a company specializing in optimization, forecasting and decision support. With several hundred studies and software projects in the energy sector to its name, Artelys is a leader in the optimization and techno-economic analysis of energy systems. Artelys has developed a software suite, Artelys Crystal, dedicated to the economic optimization of energy system planning and investment.

Introduction

a. Context

The integration of renewable energy requires an in-depth transformation of the way in which electricity systems operate. The need for flexibility within these systems is increasing sharply, specially to compensate the intermittency of wind and solar power and the fact that they are non-dispatchable. Electricity interconnections are one way of meeting the growing need for flexibility in electricity systems. Against this backdrop, electricity interconnections are expanding rapidly in Europe, and this trend is set to continue in the years ahead.

For a long time, Great Britain had relatively few electricity interconnections with continental Europe, but it has recently seen a significant increase in its interconnection capacity. Between 2018 and 2022, Great Britain doubled its electricity interconnection capacity. As of early 2023, it has 8.4 GW of capacity across eight interconnectors. Three of these are connected to France: IFA 2000 (1,000 MW, commissioned in 1986), IFA2 (1,000 MW, commissioned in 2021) and ElecLink (1,000 MW, commissioned in 2022). The UK government wants the development of interconnections to continue and gains to reach at least 18 GW of installed capacity by 2030 (UK Government, 2023). Several additional interconnection projects are already under development.

Historically, France has been better interconnected with its neighbors than Great Britain. France's interconnections have also expanded in recent years, and several projects are currently under development (e.g., the Savoie-Piémont interconnection between Italy and France, the Avelin-Avelgem interconnection between Belgium and France and the Celtic Interconnector linking Ireland and France).

Since the commissioning of the IFA 2 (2021) and ElecLink (2022) projects, the interconnection capacity between France and the United Kingdom stands at 4 GW. Additional projects linking the two countries are under consideration, which could increase interconnection capacity between France and the UK to 8.8 GW, i.e., a doubling of existing capacity.

b. Objectives

The purpose of this study is to provide a quantitative and qualitative analysis informing decision-making on the development of new electricity interconnections between France and Great Britain.

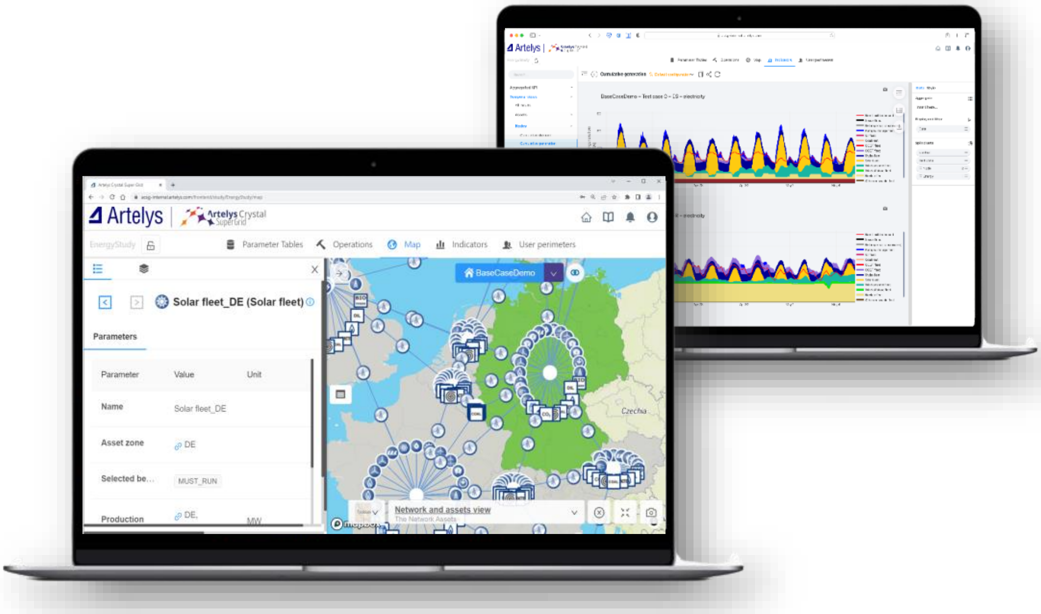
The benefits that could result from the development of additional interconnection capacity are estimated using techno-economic simulations of the European power system at hourly time steps, making it possible to quantify the economic gains that could be reaped (measured in terms of social welfare) and the contribution of new interconnections to security of supply for France and Great Britain. Great care was taken to properly account for the uncertainties associated with the changing nature of the European energy system. Several scenarios were designed to describe a set of credible and contrasting European energy futures.

Different risks that could impact the development, construction and operation of interconnection projects, as well as how they would affect the expected benefits of additional interconnection capacity, are also analyzed.

c. Artelys Crystal Super Grid

The quantitative analyses in this study are based on techno-economic simulations of the European electricity system. These simulations were carried out using the *Artelys Crystal Super Grid* software. Developed and distributed by Artelys, this piece of software is notably used to conduct cost-benefit analyses for power systems, and more specifically to assess the benefits associated with the development of interconnection projects. In this study, the interest of completing a project is assessed from the point of view of society as a whole, rather than from the perspective of the project owner.

The *Artelys Crystal Super Grid* tool includes a graphical interface used to create models and analyze results, and the tool implements advanced algorithms for the optimization and scheduling of electricity production on an hourly basis across all European countries simultaneously under multiple climate scenarios. Models take into account a wide range of techno-economic parameters, including fuel and CO2 costs, and can represent a variety of operational scenarios including the dynamic management of storage facilities and the unavailability of production assets due to maintenance.



Solar fleet_DE (Solar fleet)

Parameters

Parameter	Value	Unit
Name	Solar fleet_DE	
Asset zone	DE	
Selected be...	MUST_RUN	
Production	DE,	MW

Figure 5 – Overview of the Artelys Crystal Super Grid software user interface

d. Methodology

The benefits generated by an increase in interconnection capacity between France and the UK are assessed via a set of credible and contrasting energy scenarios. Following a review of publicly available future energy scenarios in France and the UK, three main scenarios were selected. The years simulated are 2030, 2040 and 2050. A set of sensitivity analyses is also performed, in order to assess the robustness of the results to variations in certain techno-economic parameters.

For all periods considered, and for each of the scenarios selected, national production plans and cross-border commercial exchanges (dispatch) are mutually optimized for all European countries, at hourly time steps, in the Artelys Crystal Super Grid software. These simulations are performed for three levels of interconnection capacity between France and Great Britain: 4 GW, 5.4 GW and 6.6 GW. The first level, with 4 GW of interconnection capacity, is the reference case since it corresponds to the current interconnection capacity (as of 2023) between France and Great Britain.

Figure 6 shows the simulations run in this study.

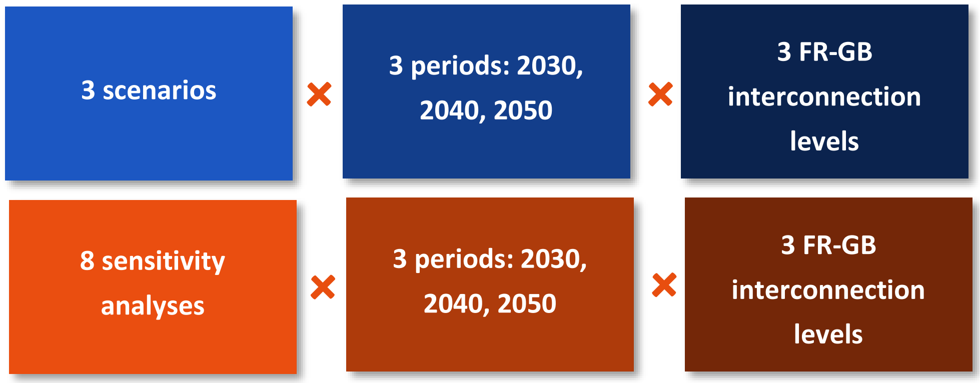


Figure 6 – Schematic representation of simulations carried out in the study

The results of the simulations performed for the different interconnection levels are then compared to determine the impact of increasing the interconnection capacity.

One of the main indicators assessed in this study is **the change in social welfare[1] brought about by an increase in interconnection capacity.** The impact of the first additional interconnection project between France and Great Britain is estimated via the difference in social welfare between the 5.4 GW configuration and the 4 GW configuration. For the second interconnection project, the impact is calculated as the difference in social welfare between the 6.6 GW and the 5.4 GW configurations. The present value of the expected benefits is then computed by discounting the annual changes in social welfare.

In addition, the impact of increasing the interconnection capacity on **the generation levels of different technologies**, overall **greenhouse gas emissions** and **security of supply** for both countries are also assessed, by comparing the results of simulations performed for different levels of interconnection capacity between France and Great Britain.

Finally, the risks and uncertainties that could have an impact on the benefits of additional electricity interconnection capacity are identified and discussed.

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[1] Economic indicator typically used to evaluate the benefits of a project for society as a whole.

1 Scenarios

1.1 Background and scenario building

1.1.1 Three scenarios based on three data sources

The scenarios analyzed in this study were based on three studies with prospective reference scenarios for the European Union, France, and Great Britain:

- The **"Ten-Year Network Development Plan"** (TYNDP) exercise carried out in 2022 by ENTSO-E and ENTSOG
- The "**Futurs Energétiques 2050**" covering France, published by RTE in 2022.
- The "**Future Energy Scenarios 2022**" covering Great Britain, published by National Grid in 2022.

Ten-Year Network Development Plan (TYNDP) 2022 (ENTSO-E)

The TYNDP scenarios focus mainly on the European Union (Europe of Twenty-Seven), over a modelling scope which represent electricity exchanges with neighboring countries. This study shows three main scenarios:

- « **Distributed Energy** »: This scenario supports a massive deployment of renewable energy on a local and decentralized basis, as well as a significant electrification, while targeting a 55% reduction in emissions by 2030 and carbon neutrality by 2050.
- « **Global Ambition** »: This scenario analyzes a future in which the development of renewable energy sources is centralized, and global low-carbon energy markets develop, with a more important role for low-carbon liquid and gas energy carriers. This scenario also targets a 55% reduction in emissions by 2030 and carbon neutrality by 2050.
- « **National Trends** »: This scenario has been developed based on decarbonization strategies and energy policies defined at national levels by European countries, to reflect the specific features and policy choices announced by each country.

The first two scenarios cover the 2030, 2040 and 2050 periods, while the third covers the 2025, 2030 and 2040 periods.

Futurs Energétiques 2050 (RTE)

RTE's "Futurs Energétiques 2050" scenarios are aligned with carbon neutrality in 2050 and are structured along two main axes that define the way electricity is produced and consumed in France. Two sets of power generation scenarios are proposed, the first (called "M") assessing the effect of decommissioning and replacing France's nuclear fleet with large-scale renewable energy sources, the second (called "N") analyzing the effect of launching a program to build new nuclear reactors to complement the development of renewable energy sources. Three variants are proposed in each scenario, leading to a total of six generation scenarios. In addition, three main consumption scenarios are considered. The reference scenario represents a consumption pathway based on the gradual electrification of the French energy system, a strong focus on energy efficiency, and moderate economic and demographic growth. The other two consumption scenarios represent contrasting social and economic development paths based on moderate use and consumption, and a gradual reindustrialization of France over the coming decades. Combining the different production and consumption scenarios results in a total of eighteen scenarios for the 2030, 2040, 2050 and 2060 periods.

Future Energy Scenarios 2022 (National Grid)

In its forecast "Future Energy Scenarios 2022" exercise, National Grid offers four contrasting scenarios for Great Britain:

- « **Consumer Transformation** »: This scenario aims to achieve carbon neutrality by 2050 and relies on a massive electrification of uses (especially heating, which currently relies mainly on natural gas), major changes in consumption patterns and individual behavior (offering, for instance, greater flexibility of demand), and a strong focus on energy efficiency.
- « **System Transformation** »: This scenario also aims for carbon neutrality in 2050 but is based on the use of low-carbon hydrogen produced from methane steam reforming with carbon capture and electrolysis for a variety of sectors and uses (including heating). However, unlike "Consumer Transformation", this scenario does not consider major changes in consumer behavior or extensive implementation of energy efficiency measures, focusing mainly on the development of centralized energy production and transportation infrastructures.
- « **Leading the Way** »: This scenario makes it possible to achieve carbon neutrality by 2047. It groups together the most ambitious assumptions for both energy consumption and production in order to achieve this objective.
- « **Falling Short** »: This scenario does not make it possible to achieve carbon neutrality by 2050. Indeed, this scenario assumes a slower pace of energy infrastructure deployment and adoption of low-carbon technologies than previous scenarios, resulting in limited electrification of uses and high residual natural gas consumption, with low mobilization of carbon capture devices.

It's important to notice that all four scenarios are based on a massive deployment of renewable energy for power generation, and especially offshore wind resource. The scenarios cover each year of the period between 2019 and 2050.

1.1.2 Philosophy of the three scenarios

In this study, three scenarios were constructed for 2030, 2040 and 2050 based on the reference scenarios described above. To ensure the credibility of the scenarios thus constructed we have maintained a coherent narrative and considered the latest political announcements concerning the respective energy strategies of France and the UK. For France, this translates into a set of assumptions pertaining to the power generation mix reflecting the implementation of a national program aiming to develop new nuclear reactors.

- **Scenario 1**: This scenario represents a future where electricity consumption strongly increases in France and Great Britain and assumes that very ambitious development plans for renewable energy are in place. For France, a scenario assuming the implementation of a new nuclear program aiming to build a pair of EPRs every 5 years, and a policy of reindustrialization was selected (RTE's "N1 - reindustrialization" scenario), while in Great Britain, this translates into a change in consumption patterns and the deep electrification of heating systems (National Grid's "Consumer Transformation" scenario).
- **Scenario 2**: Like Scenario 1, this scenario represents strong growth in renewable energy. Nevertheless, **electricity consumption increases less strongly** than in scenario 1. Moreover, the energy system relies more heavily on **centralized solutions** than in scenario 1, such as nuclear power in France or hydrogen production by steam methane reforming with carbon capture in Great Britain. As a result, the **growth in renewable energy capacity is less ambitious than in scenario 1**. In France, a consumption pathway incorporating moderate demographic and economic growth is considered, in addition to the more ambitious development of new nuclear power (RTE’s “N2 – reference” scenario). In Great Britain, hydrogen created by steam reforming with carbon capture and water electrolysis plays an important role in mobility and heating, while heating remains poorly electrified (National Grid's "System Transformation" scenario).
- **Scenario 3**: Unlike scenarios 1 and 2, which achieve carbon neutrality by 2050, this scenario represents a future in which the deployment of energy infrastructures and low-carbon technologies is slower than expected, and **carbon neutrality targets are not reached by 2050**. For France, the generating fleet is based on a scenario with moderate development of new nuclear power (RTE’s “N1 - sobriety” scenario). However, the development rates forecast in the “N1 - sobriety” scenario have been modified to reflect a delay in the development of new wind, solar and nuclear power capacity, as well as continued use of residual fossil-fired power capacity. The consumption pathway has also been adapted to reflect a delay in the electrification of energy uses and a less ambitious deployment of electrolyzers. In Great Britain, the "Falling Short" scenario is naturally used.

Assumptions for the other countries modelled are similar for all three scenarios and are based on the TYNDP 2022 "National Trends" scenario for the 2030 and 2040 years, and the "Global Ambition" scenario for 2050 (the "National Trends" scenario does not exist for 2050).

Sensitivity analyses were also performed around the second scenario, to assess the impact of various techno-economic parameters on the benefits brought about by the increase in electricity interconnection capacity between France and Great Britain, and the robustness of the results. More specifically, to study different levels of capacity for the France-Great Britain interconnection, the sensitivities evaluated the effect of the price of gas, the development of interconnections between Great Britain and the rest of Europe, a slowdown in the development of interconnections between France and the rest of Europe, the availability of French and British nuclear power fleets, offshore wind power capacity in Great Britain, hydrogen demand and the capacity of electrolyzers installed in France and Great Britain.

1.2 Scenario description

1.2.1 Assumptions common to all scenarios

Each scenario is characterized by a set of assumptions that define the techno-economic parameters used to represent the power system over the geographical scope considered, i.e., the EU-27 countries, the UK, Norway, Switzerland and the Balkan countries. Some of these assumptions are shared by all scenarios. More specifically, in this study, the configuration of the power system modeled outside France and Great Britain remains the same for all three scenarios. This means that the assumptions pertaining to capacity mix, electricity consumption (final and for electrolysis) and the electrolyzer fleet in EU-27 countries (excluding France), Norway, Switzerland and the Balkans are the same for all three scenarios. These factors are taken from the "National Trends" scenario for 2030 and 2040, and from the "Global Ambition" scenario for 2050. These are shown in Figure 7, Figure 8, Figure 9 and Figure 10. Between now and 2050, renewable energy is expected to grow very strongly, with an inflection point in 2040. The pathway of the dispatchable generation fleet represents a gradual replacement of fossil-fired capacity (especially coal and gas) by low-carbon thermal capacity (based on hydrogen or biomass). The number of electrolyzer fleet is also rising sharply until 2050. This development of electrolysis capacity goes with a significant growth in electricity consumption, most of which is attributed to the production of hydrogen by electrolysis.

Method for modeling hydrogen production by electrolysis

The development of hydrogen production from electricity (also known as Power-to-Gas) is a key element in the design of future power systems, as electrolyzers can provide an important source of flexibility.

In the present study, hydrogen production by electrolysis has been explicitly modeled. In each country, the capacity of electrolyzers installed and their annual production were determined, based on data from the reference scenarios used (RTE's Future Energy Scenarios 2050 in France, National Grid's Future Energy Scenarios 2022 in Great Britain and ENTSO-E and ENTSOG's TYNDP 2022 for the rest of Europe).

If the quantity of hydrogen produced over the year is fixed, the hourly operation of the electrolyzers is optimized to produce hydrogen when electricity prices are lowest, and thus minimize the cost of hydrogen production. The flexibility that electrolyzers bring to the power system is thus well represented.

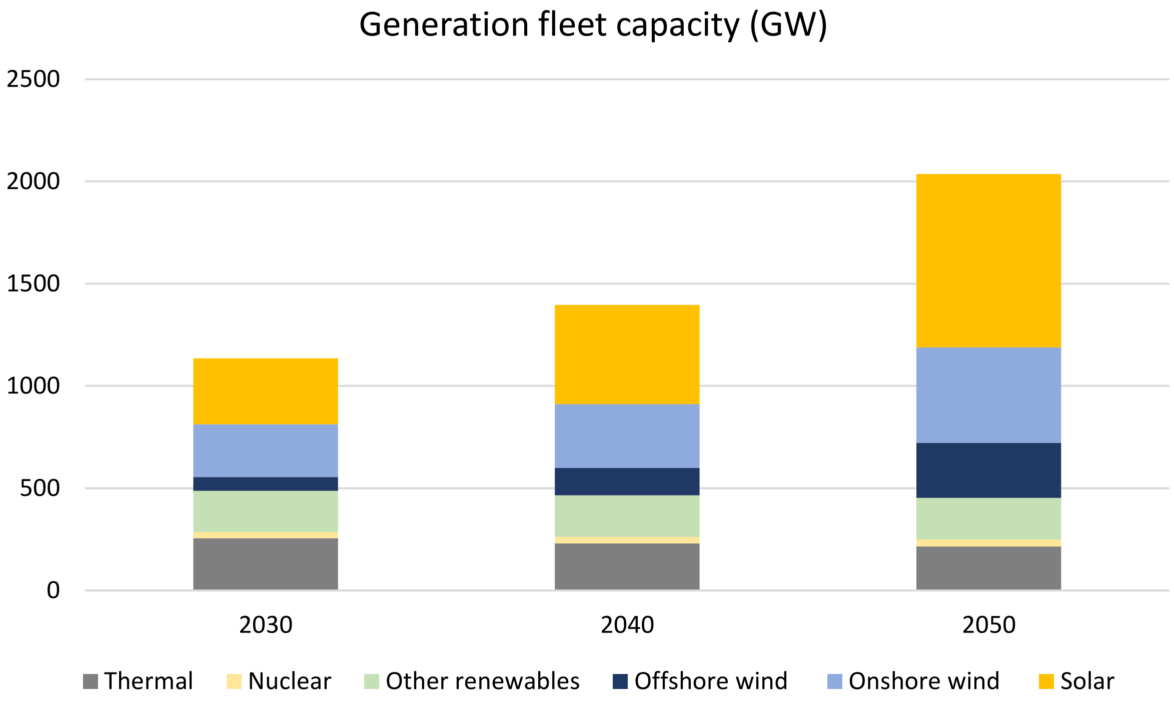


Figure 7 – Aggregate capacity mix of countries modeled (excluding France and Great Britain) in 2030, 2040 and 2050

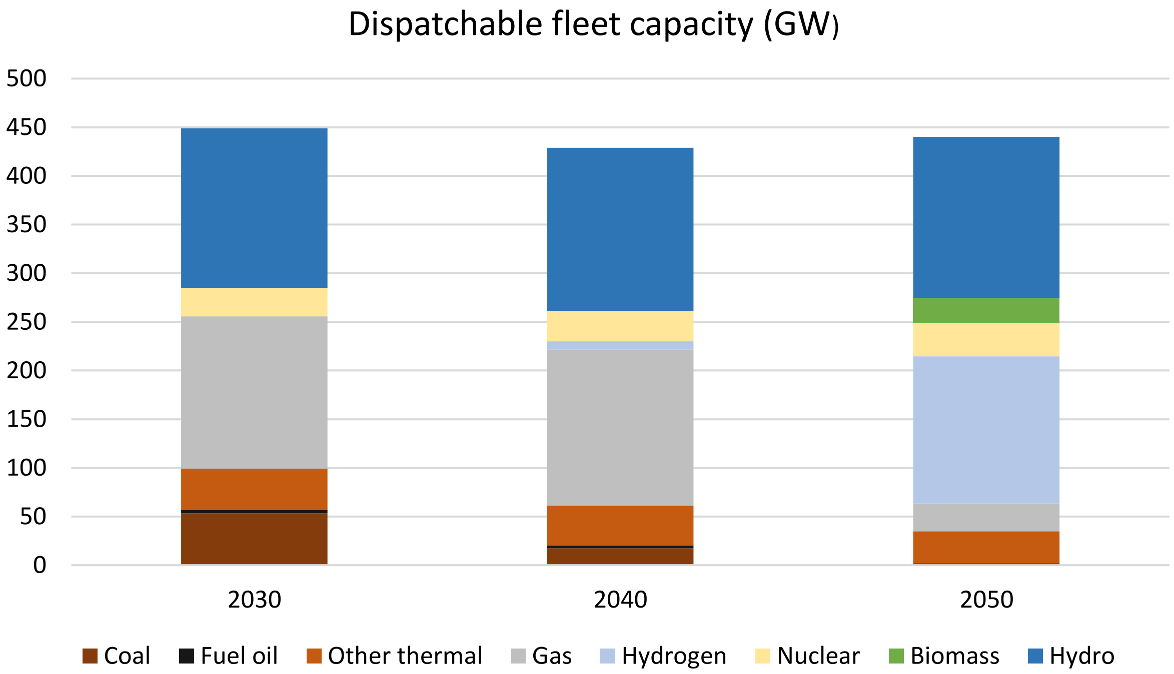


Figure 8 –Breakdown of the dispatchable fleet by technology in the countries modelled (excluding France and Great Britain) in 2030, 2040 and 2050

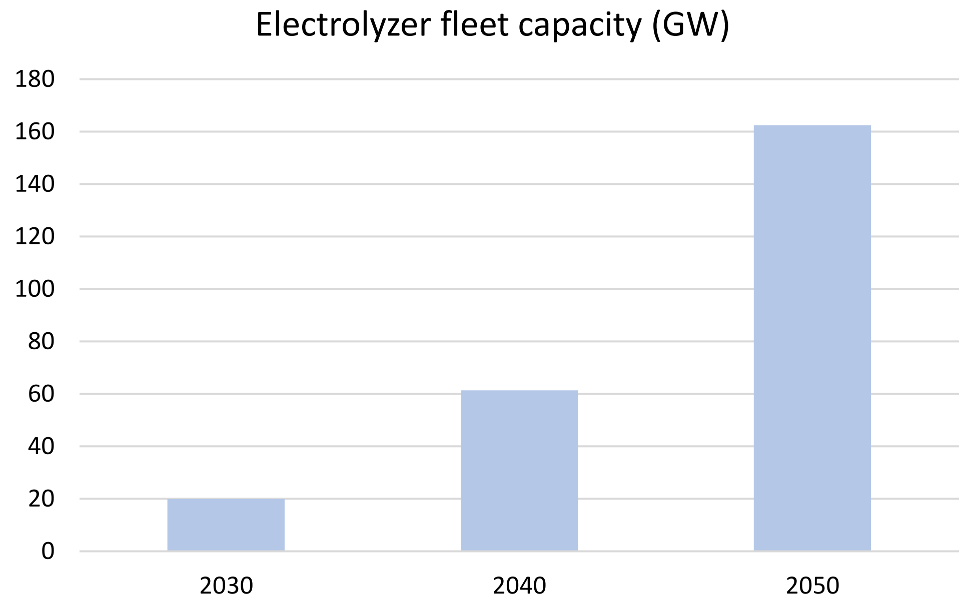


Figure 9 – Installed electrolyzer capacities in the modelled areas (excluding France and Great Britain) in 2030, 2040 and 2050

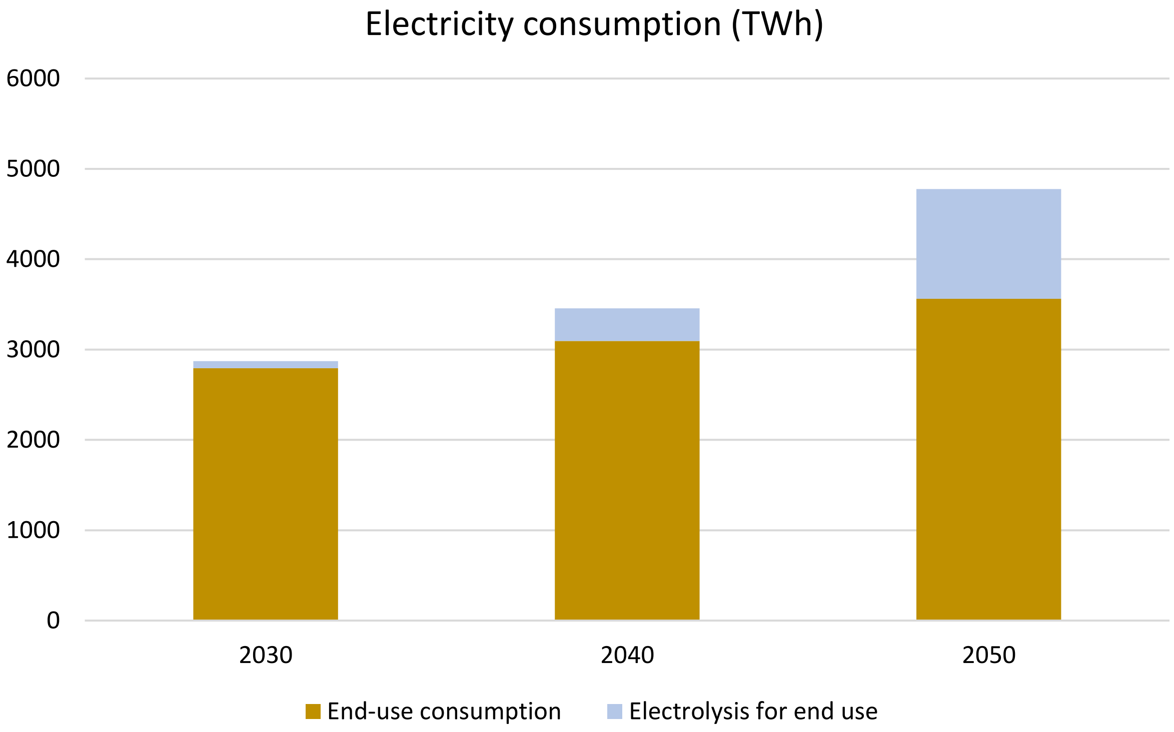


Figure 10 – Electricity consumption in the modelled area (excluding France and Great Britain) in 2030, 2040 and 2050

The NTC (Net Transfer Capacity) exchange capacities between the countries over the scope modelled, which represent the maximum active power flow that can transit between two countries, are derived from the same TYNDP scenarios as the generation and electrolyzer fleets and electricity consumption. Among these assumptions, the NTC capacities linking France and Great Britain to their neighbors deserve attention. Figure 11 shows the development of NTC capacity linking Great Britain and its neighbors (excluding France) over the years, while Figure 12 shows the evolution of NTC capacity between France and its neighbors (excluding Great Britain). Significant development of interconnection capacity between Great Britain and France is envisioned by 2040, with a marked slowdown in the rate of construction of such infrastructure between 2040 and 2050.

Gas prices and carbon prices are two important factors that are common to all three scenarios. The gas price is set at 40€/MWh for each scenario over all the periods studied, while carbon price rises between 2030 and 2050. Table 1 summarizes the values used for these parameters in the three main scenarios.

Table 1 – Gas and carbon prices used in the three main scenarios in 2030, 2040 and 2050.

	2030	2040	2050
Gas price (€/MWh)	40	40	40
Carbon price (€/t)	70	90	168

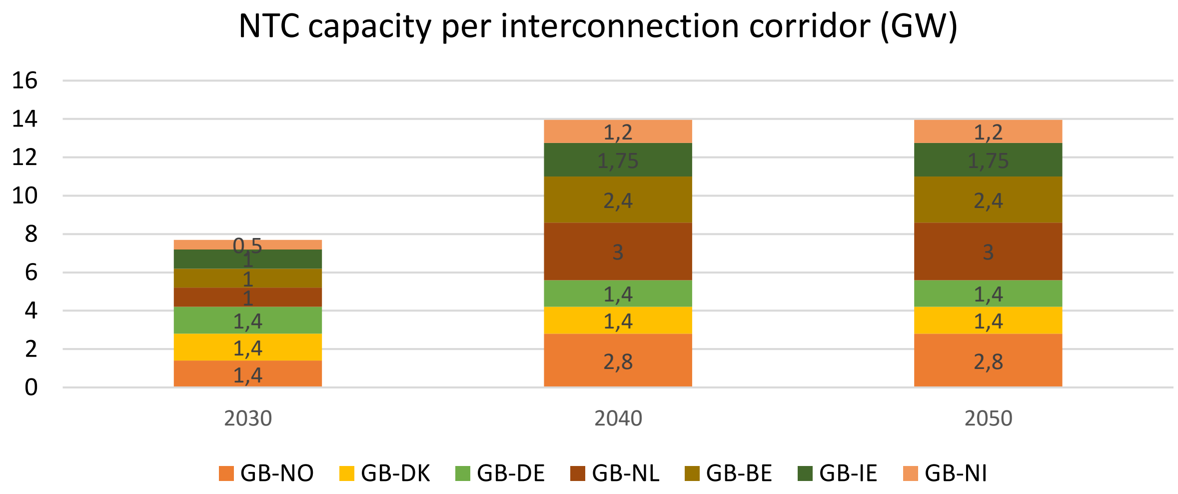


Figure 11 – NTC interconnection capacity between Great Britain and neighboring countries (excluding France) in the baseline scenarios in 2030, 2040 and 2050

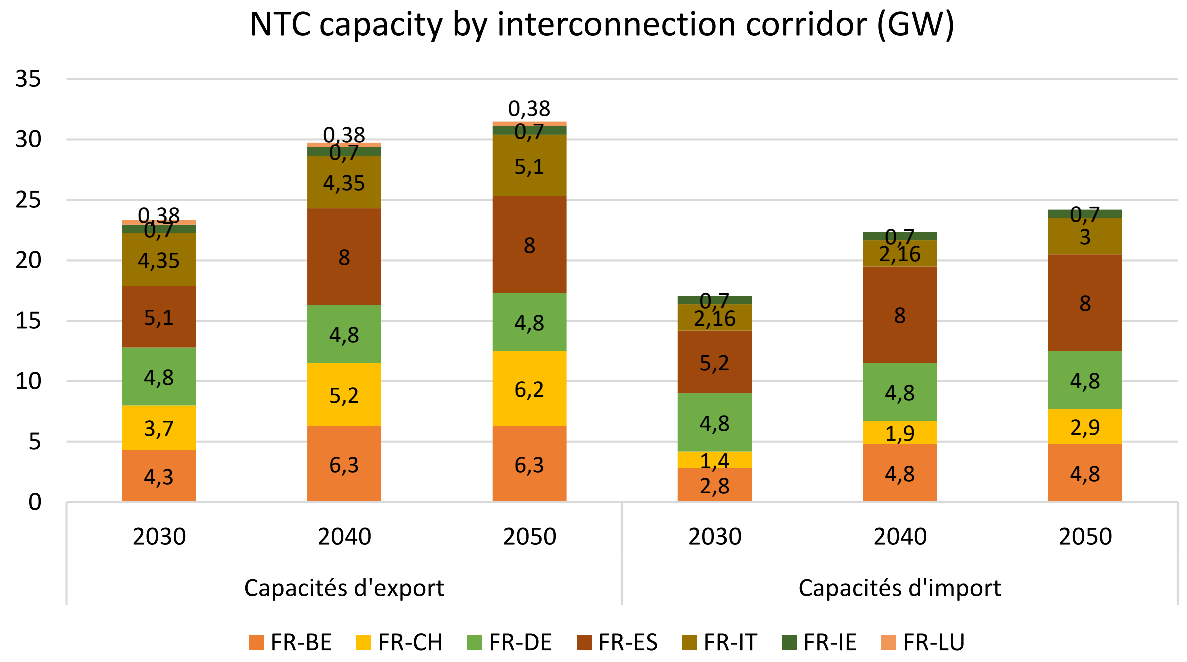


Figure 12 – French export and import capacities (excluding the France-UK corridor) in the baseline scenarios in 2030, 2040 and 2050

1.2.2 Scenario 1

This scenario represents a future characterized by high growth in electricity consumption in France and Great Britain, with generation fleets relying heavily on renewable energy, while being compliant with carbon neutrality in 2050.

The first point that distinguishes the French and British electricity systems is the proportion of renewable energy in each country's capacity mix, as Figure 13 shows. In France, renewable energy represents a little bit more than half of the mix in 2030, while in Great Britain, renewable energy covers around two-thirds of the capacity mix as early as 2030.In both countries, the share of the mix covered by renewable energy rises sharply between 2030 and 2050, with more significant growth in France due to the reduction in the share of nuclear power. The development of offshore wind capacity clearly dominates other renewable energy sources in the UK, while solar power plays a more prominent role in France. A second element concerns the pathway and nature of the mix of dispatchable capacities present in each country. In France, the capacity of the dispatchable fleet decreases between 2030 and 2050. The dispatchable fleet relies on hydraulic resources and nuclear reactors, although the latter will be partially replaced by hydrogen turbines in 2050. In contrast to France, the capacity of the dispatchable power fleet in Great Britain increases between 2030 and 2050. The dispatchable capacity available in 2030 relies mainly on gas-fired power fleet, which are gradually replaced by a varied mix including hydrogen turbines, biomass power plants and new nuclear reactors, as shown in Figure 14.

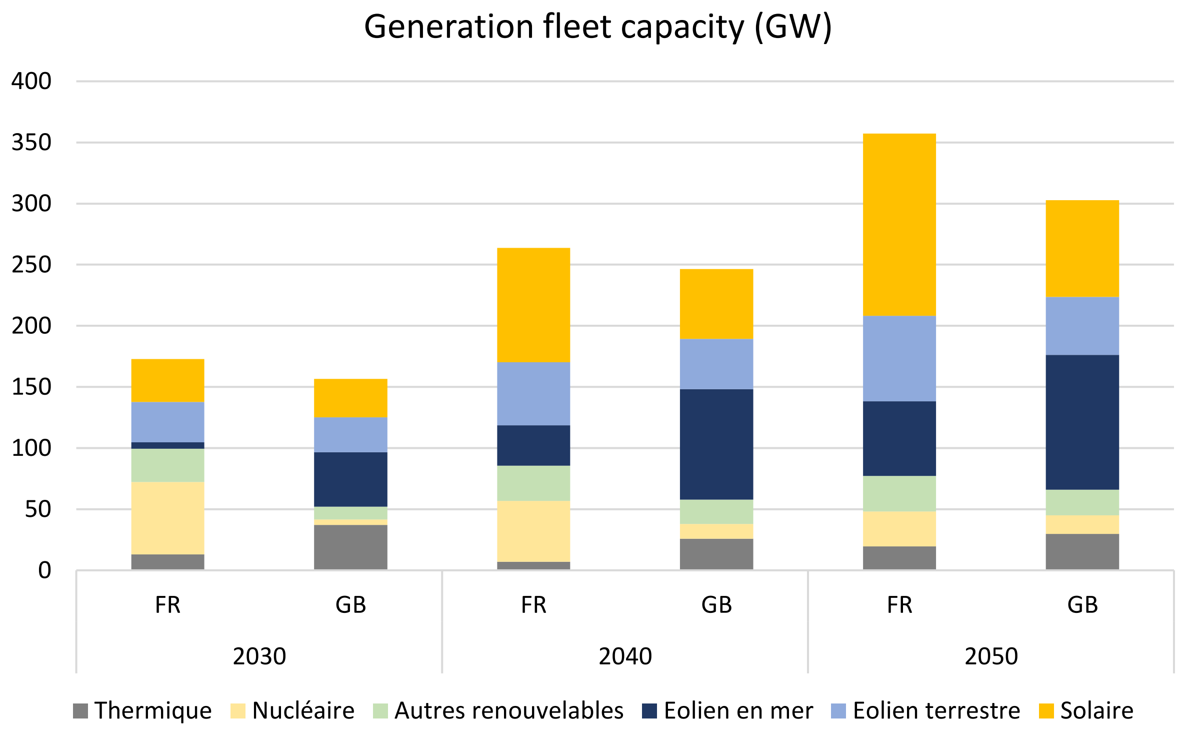


Figure 13 – Capacity mix in France and Great Britain in scenario 1 in 2030, 2040 and 2050

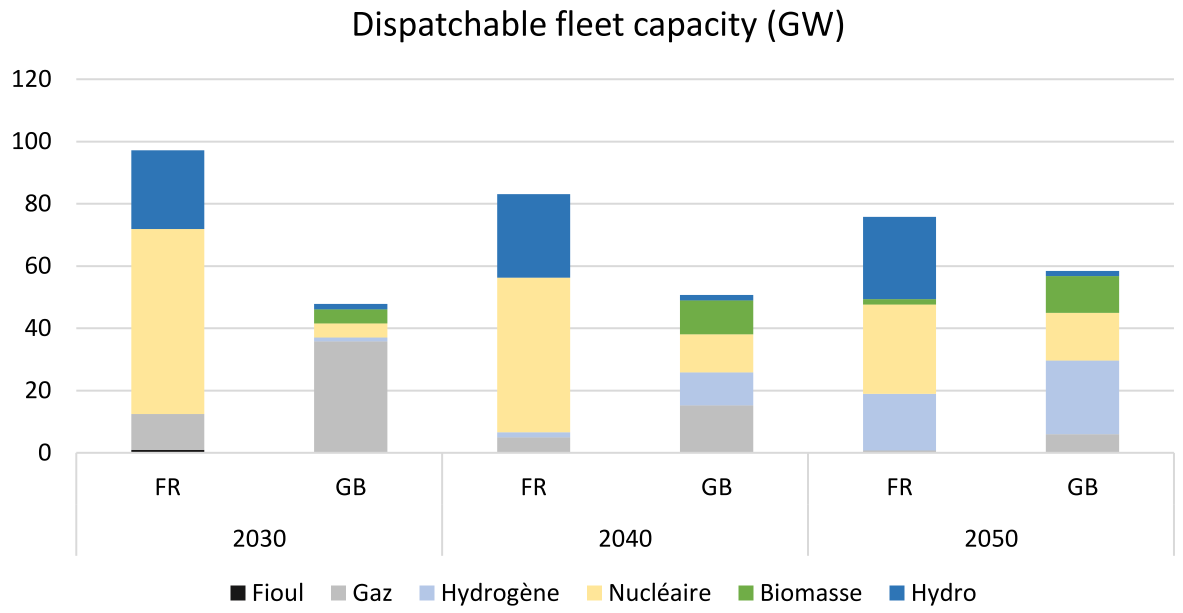


Figure 14 – Breakdown of dispatchable electricity generation capacity in France and Great Britain in scenario 1 in 2030, 2040 and 2050

In this scenario, electricity consumption rises sharply in France and Great Britain between 2030 and 2050, as shown in Figure 15. In France, this growth is due mainly to the implementation of a deep reindustrialization policy, with the share of manufacturing industry in gross domestic product rising from today to 2050 (without returning to the levels of the 1990s). In Great Britain, the increase in electricity consumption reflects the deep electrification of the residential (heating) and transport sectors, as well as a less important role for hydrogen, mainly used in the aviation and maritime transport sectors in 2050.

Electricity consumption associated with hydrogen production is set to rise sharply between 2030 and 2050, in both France and the UK. This growth is naturally associated with significant deployment of electrolyzer capacity, as shown in Figure 16. However, installation rates differ between France and the UK, with linear capacity growth between 2030 and 2050 in France, and exponential growth in the UK. Capacity is therefore significantly higher in France than in Great Britain in 2030, but the opposite is observed in 2050.

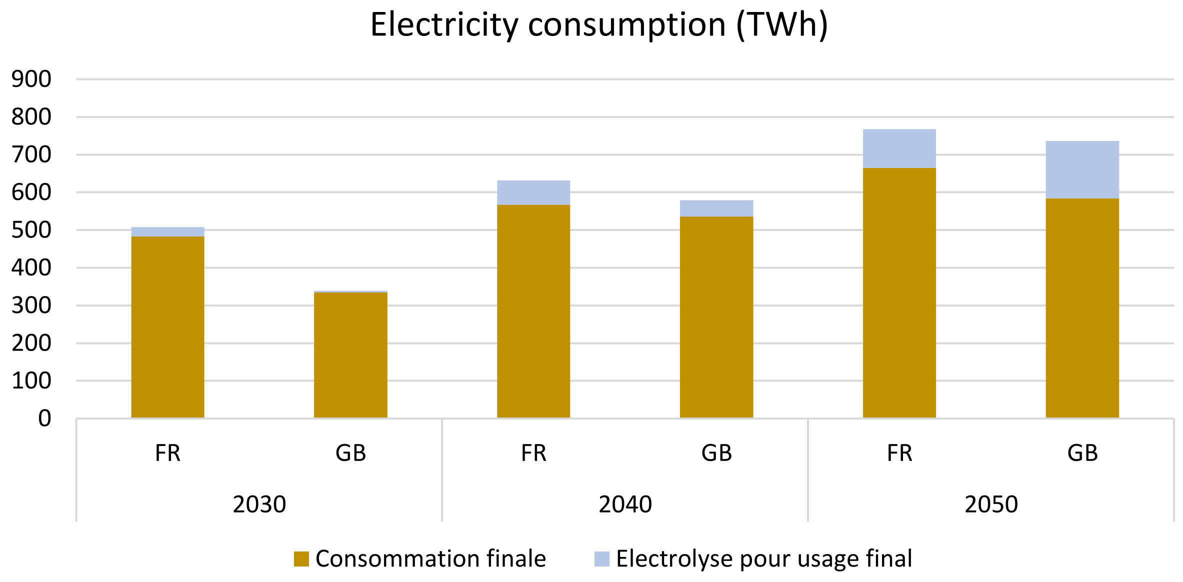


Figure 15 – Electricity consumption in France and Great Britain in scenario 1 in 2030, 2040 and 2050

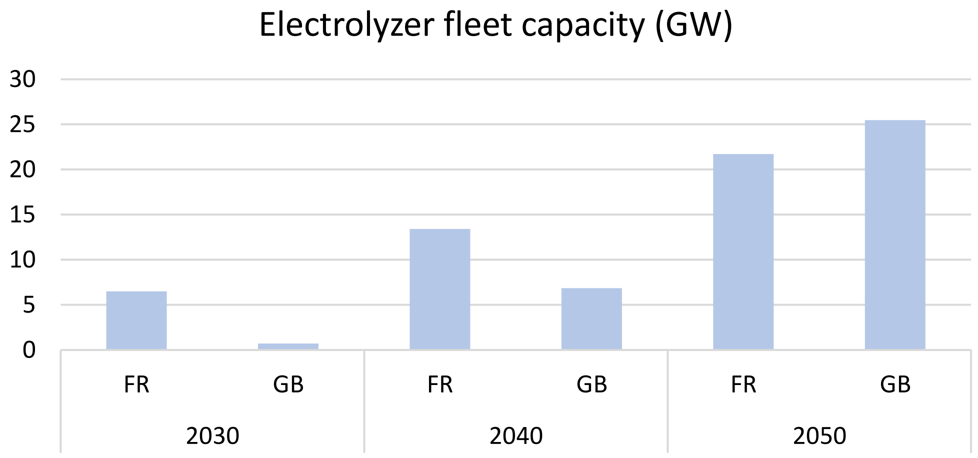


Figure 16 – Installed electrolyzer capacities in France and Great Britain in scenario 1 in 2030, 2040 and 2050

Simulation results, using the techno-economic parameters described above, allow a brief analysis of the production mixes in France and Great Britain, which are displayed on the Figure 17 and Figure 18.

The trajectory followed by the French generation mix between 2030 and 2050 reflects the growing role of renewable energy, and a sharp reduction in nuclear generation, from over two-thirds in 2030 to just over 20% in 2050. In 2050, hydrogen-powered turbines generate small amounts of electricity (around 3%), mainly during peak periods of low renewable production.

Unlike the French mix, the UK generation mix is largely dominated by renewable energy from 2030 (over 75%). More specifically, offshore wind generation alone accounts for almost half of total generation in 2030, and this trend is set to continue in 2040 and 2050. In addition, nuclear generation in Great Britain, which remains marginal in 2030 (around 5%), increases almost fourfold between 2030 and 2050 (representing around 10%), mainly due to the shift away from natural gas-fired power plants.

A small proportion of electricity production is generated by hydrogen turbines. Biomass power plants are not used to produce significant volumes in this scenario.

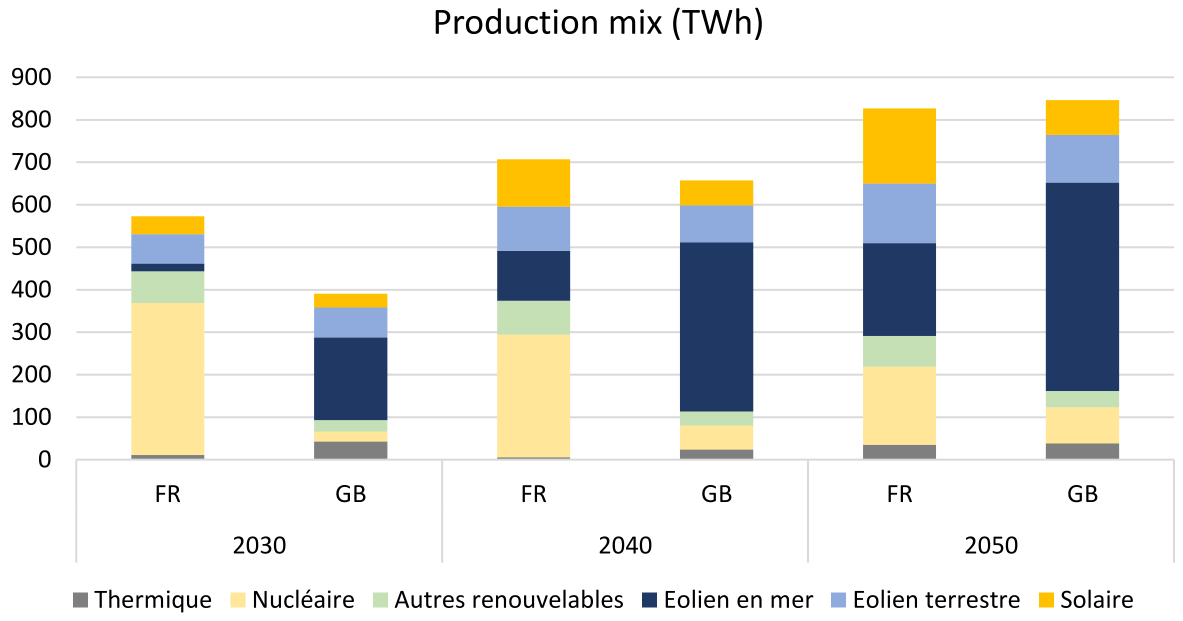


Figure 17 – Generation mix in France and Great Britain in scenario 1 in 2030, 2040 and 2050

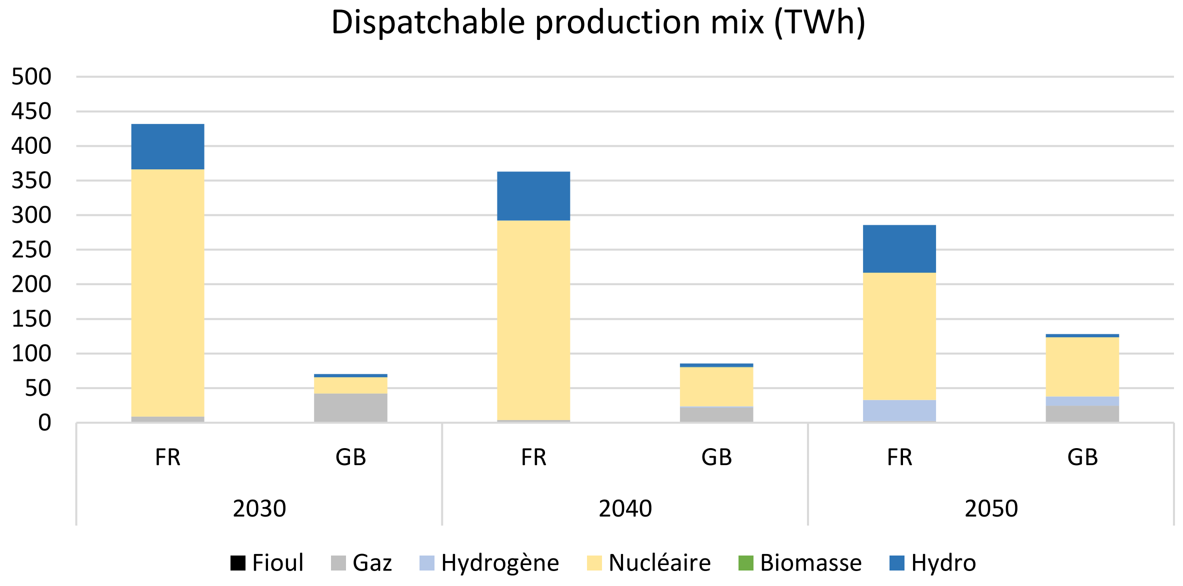


Figure 18 – Breakdown of the dispatchable generation mix in France and Great Britain in scenario 1 in 2030, 2040 and 2050

1.2.3 Scenario 2

As in scenario 1, this scenario represents strong growth in renewable energy. Nevertheless, **electricity consumption increases less strongly** than in scenario 1. Furthermore, the energy system relies more heavily on **centralized solutions** than in scenario 1, such as nuclear power in France or hydrogen production by steam methane reforming with carbon capture in Great Britain. As a result, **growth in renewable energy capacity is less ambitious than in scenario 1.**

In France, the capacity mix in 2030 is identical to scenario 1, with the RTE scenarios diverging only from 2040. As shown in Figure 19, renewable energy expands between 2030 and 2050, but nuclear power retains an important place in the French power system. In fact, the development of new nuclear reactors compensates partly for the decommissioning of the historic nuclear power fleet. The residual capacity of gas-fired power plants is gradually replaced by hydrogen turbines between 2030 and 2050. Compared to scenario 1, the total capacity of the generating fleet is significantly lower, by around 20% in 2040 and 30% in 2050.

In Great Britain, renewable energy already account for more than half of the generating fleet in 2030, with offshore wind alone accounting for more than a quarter of total capacity. This trend is set to continue in 2040 and 2050. Furthermore, as Figure 20 shows, nuclear capacity increases sharply between 2030 and 2040 (threefold) but remains stable between 2040 and 2050. Natural gas-fired dispatchable capacity is partially replaced by hydrogen. Significant residual capacity remains until 2050 (between 20 and 25% of total dispatchable capacity). Although total generation capacity remains lower in scenario 2, the proportion of dispatchable capacity is higher than in scenario 1 (around 25% in scenario 2 versus 20% in scenario 1).

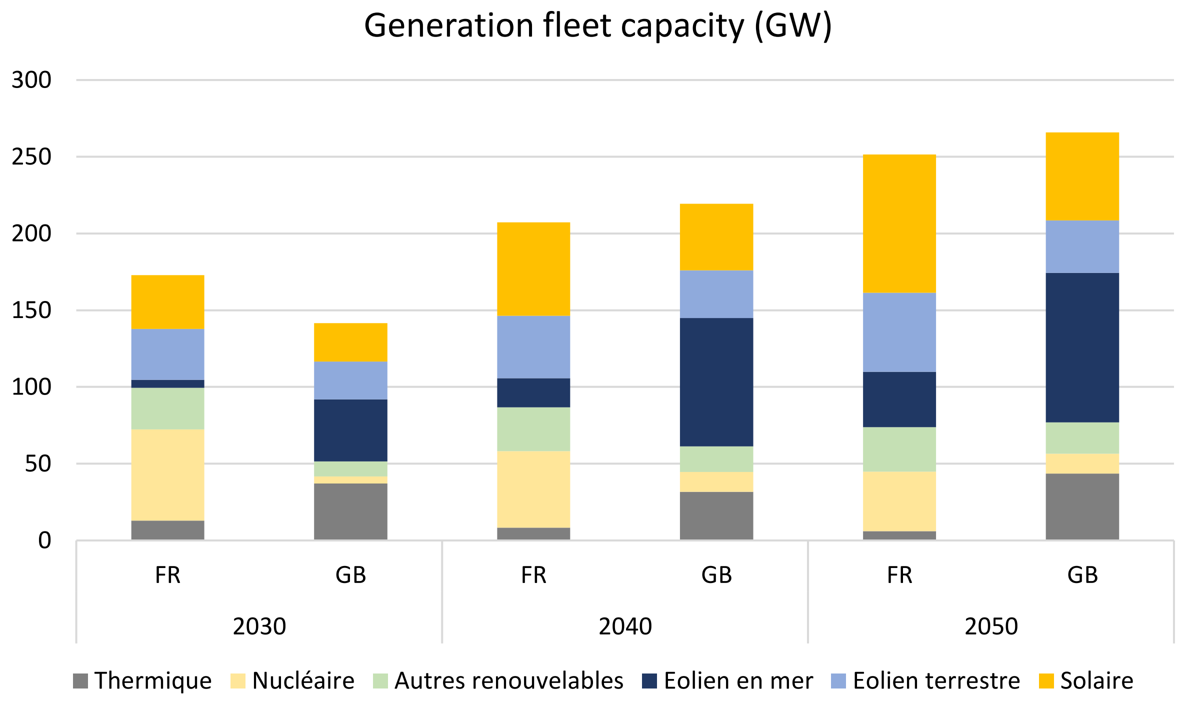


Figure 19 – Capacity mix in France and Great Britain in scenario 2 in 2030, 2040 and 2050

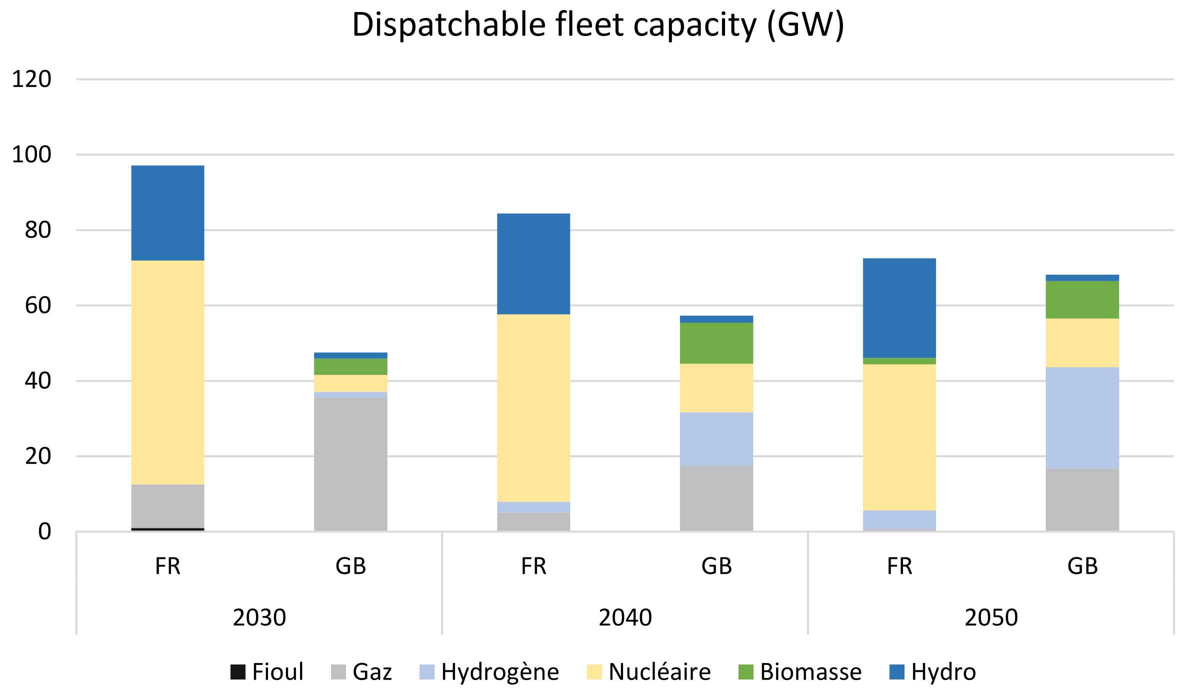


Figure 20 – Breakdown of dispatchable electricity generation in France and Great Britain in scenario 2 in 2030, 2040 and 2050

Final electricity consumption in France increases moderately between 2030 and 2050 in this scenario, as shown in Figure 21, reflecting moderate demographic and economic growth. Electricity consumption for electrolysis approximately doubles between 2030 and 2050. However, it remains below 10% of total electricity consumption over all periods. Growth in electrolysis capacity is sustained but remains moderate, with an increase of around two-thirds between 2030 and 2050. Compared to scenario 1, this is roughly half as fast.

In Great Britain, we assume a partial electrification of uses (transport mainly), while hydrogen is placed at the center of the energy system. Final electricity consumption thus rises steadily between 2030 and 2050 (by around 50%), and electricity consumption for electrolysis increases drastically (by a factor of 15), accounting for over a third of total consumption in 2050. This growth in electricity consumption for hydrogen production is accompanied by a significant deployment of electrolyzer capacity (almost 20-fold between 2030 and 2050), which is also a major source of flexibility for the UK electricity system. Compared with Scenario 1, electrolysis capacity will be approximately doubled in 2050.

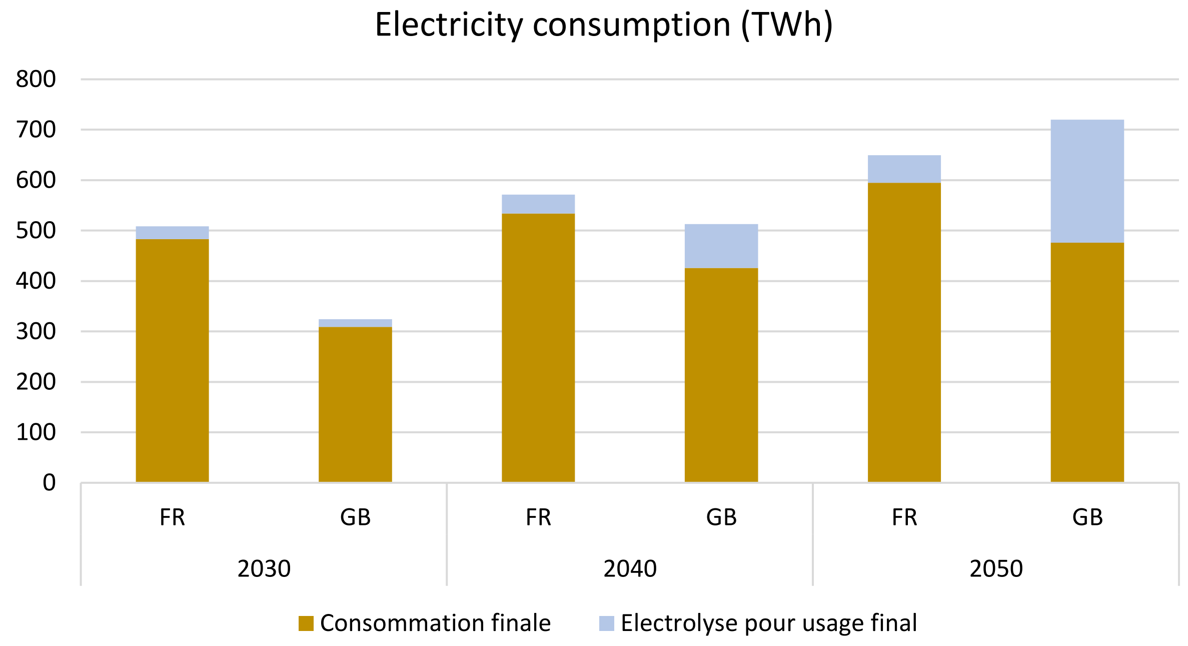


Figure 21 – Electricity consumption in France and Great Britain in scenario 2 in 2030, 2040 and 2050

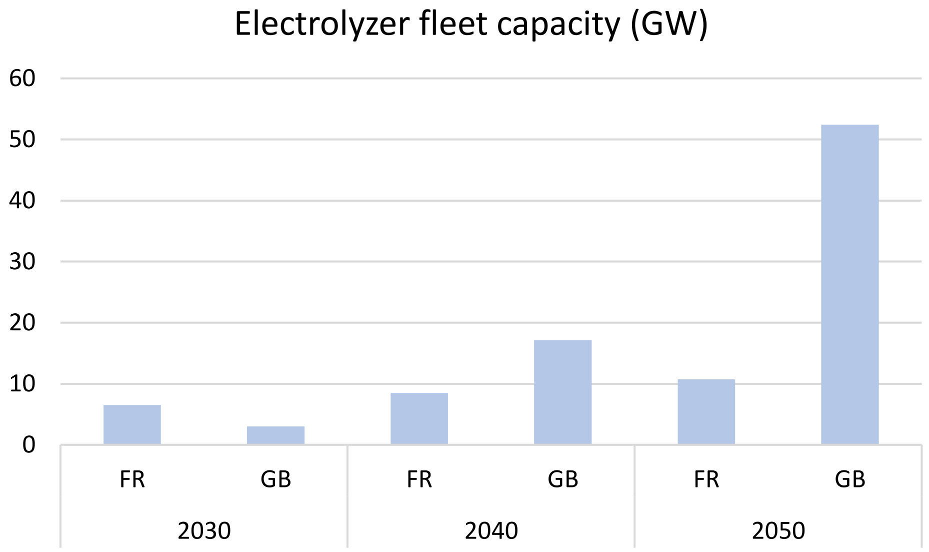


Figure 22 - Installed electrolyzer capacities in France and Great Britain in scenario 2 in 2030, 2040 and 2050

Pathway of France generation mix between 2030 and 2050 reflects the growing role of renewable energy, and a slight decline in nuclear generation, from over two-thirds in 2030 to just under 40% in 2050. In 2050, hydrogen-powered turbines generate very small amounts of electricity (between 1% and 2% of total production), mainly at peak times during periods of low renewable production.

The UK generation mix is largely dominated by renewable energy by 2030 (over 75%). Especially, offshore wind generation alone accounts for just under half of total generation in 2030, and this trend continues in 2040 and 2050. In addition, nuclear generation in Great Britain, which remains low in 2030 (around 5%), increases almost fourfold between 2030 and 2050 (representing over 10% of the total).

Residual gas capacity is also used over the three-time periods considered, representing a share of total generation fluctuating between 4% and 8%. Hydrogen turbines and biomass are not mobilized to produce significant volumes in this scenario.

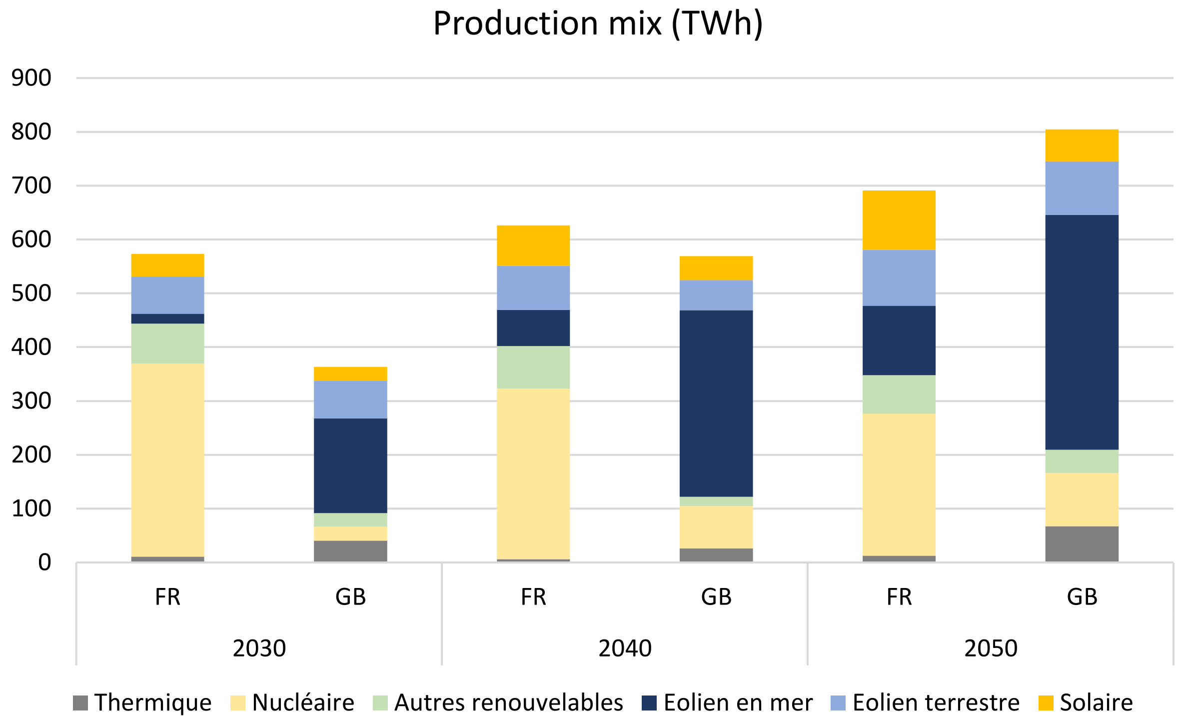


Figure 23 – Dispatchable generation mix in France and Great Britain in scenario 2 in 2030, 2040 and 2050

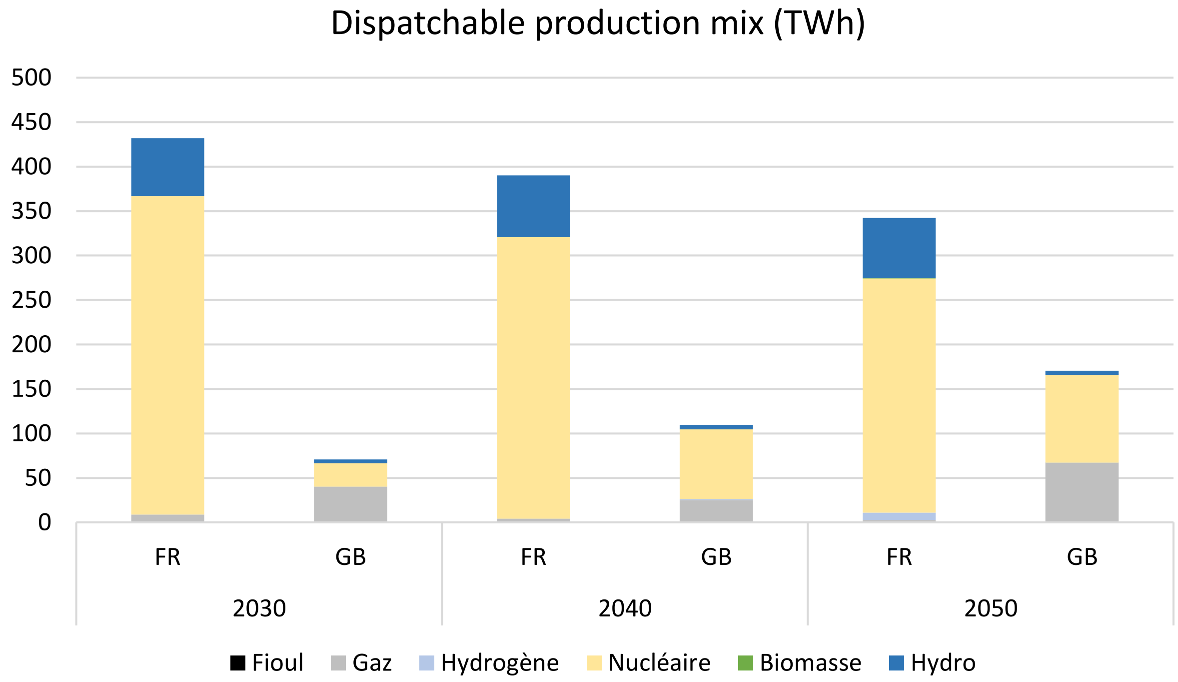


Figure 24 – Breakdown of the dispatchable generation mix in France and Great Britain in scenario 2 in 2030, 2040 and 2050

1.2.4 Scenario 3

The third scenario represents a future where the deployment of energy infrastructures and low-carbon technologies is slower than expected, and carbon neutrality targets are not reached by 2050.

In France, a delay in development of renewable energy and new nuclear power is assumed. Despite the delay, the share of renewable energy increases sharply between 2030 and 2050. The share of nuclear power declines sharply from around a third in 2030 to just over 10% in 2050, due to the decommissioning of old nuclear reactors and the absence of new build. In addition, the gas turbine fleet is extended, and its capacity decreases only slightly between 2030 and 2050.

In the case of Great Britain, this scenario is characterized by a generation fleet based on renewable energy and a natural gas-fired power plants, as shown in Figure 25. Offshore wind still accounts for more than half of the renewable energy fleet, and this trend increases over time. Fossil fuel capacity increases especially between 2030 and 2050. In addition, new nuclear reactors are also being built between 2030 and 2050 (see Figure 26).

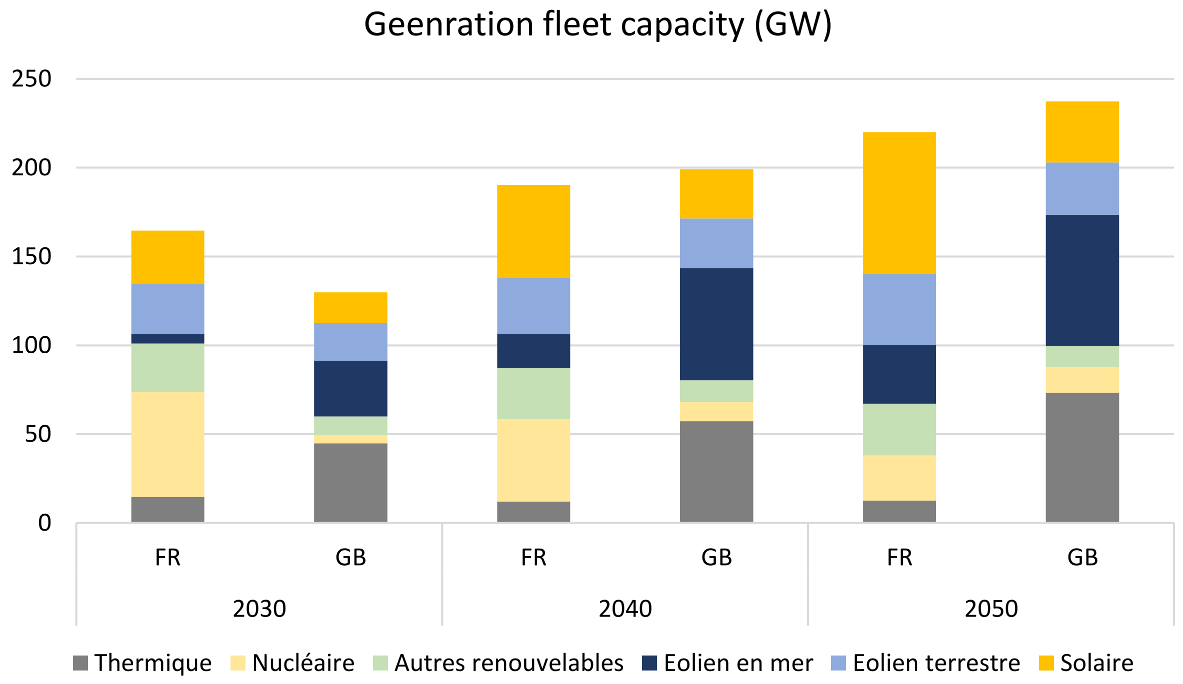


Figure 25 – Capacity mix in France and Great Britain in scenario 3 in 2030, 2040 and 2050

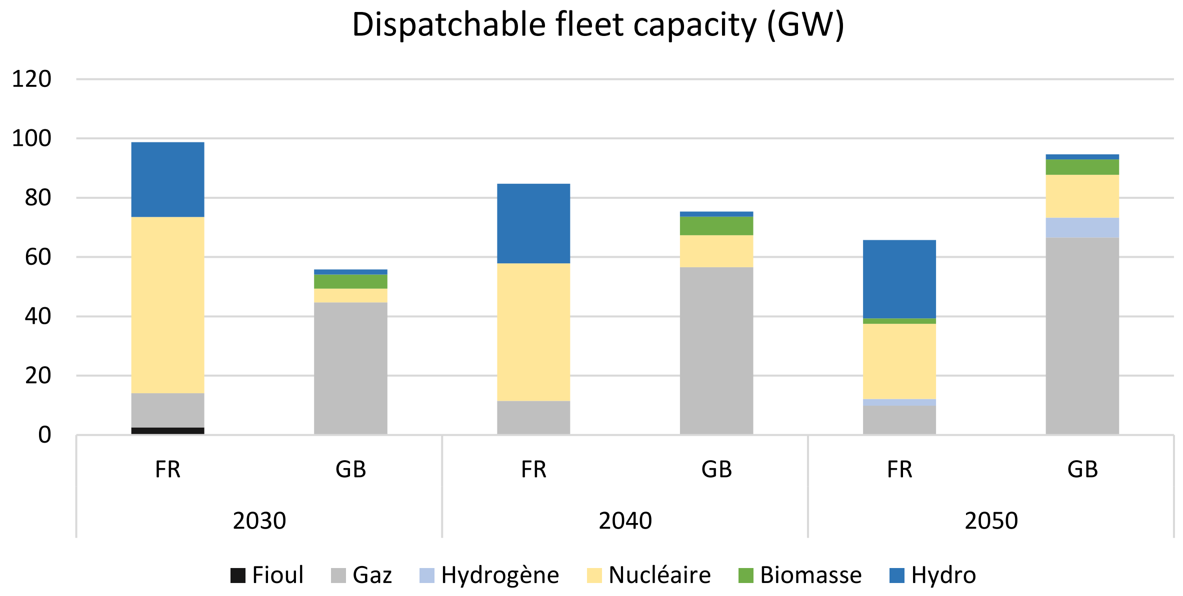


Figure 26 – Breakdown of dispatchable electricity generation in France and Great Britain in scenario 3 in 2030, 2040 and 2050

Growth in electricity consumption in France is low for the whole path (around 20%), and the share of consumption attributed to electrolysis remains low over all the periods studied (below 5% in 2050). Electrolysis capacity changes very little between 2030 and 2050.

Electrification in Great Britain is incomplete, which leads to a significant increase in electricity demand. On the other hand, natural gas will continue to be widely used in the industrial and residential sectors, while hydrogen will hardly develop at all. The development of electrolysis capacity is therefore very limited.

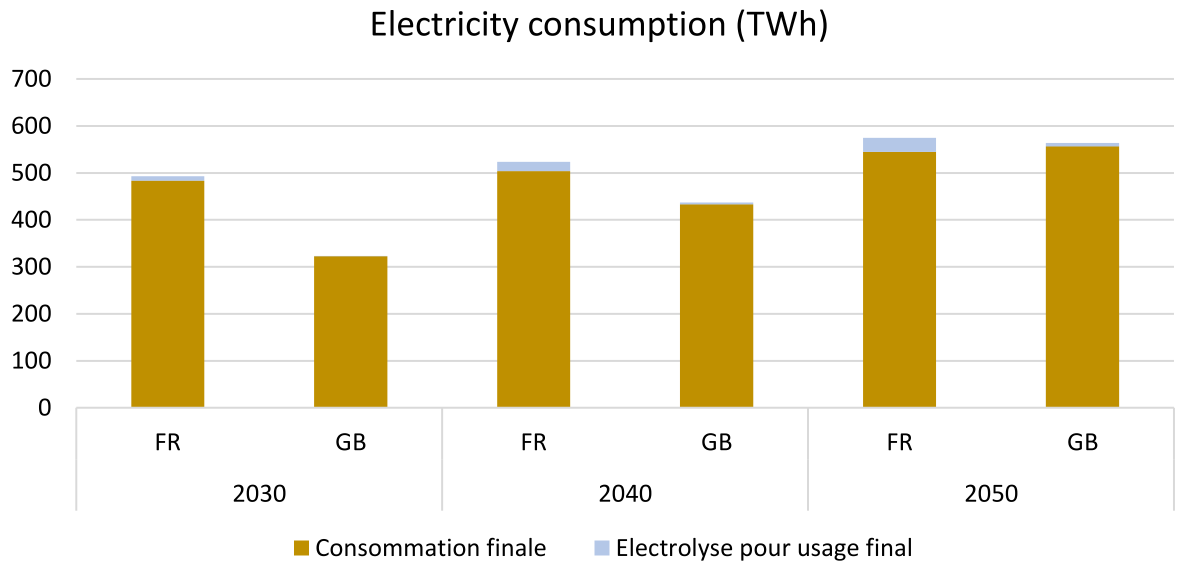


Figure 27 – Electricity consumption in France and Great Britain in scenario 3 in 2030, 2040 and 2050

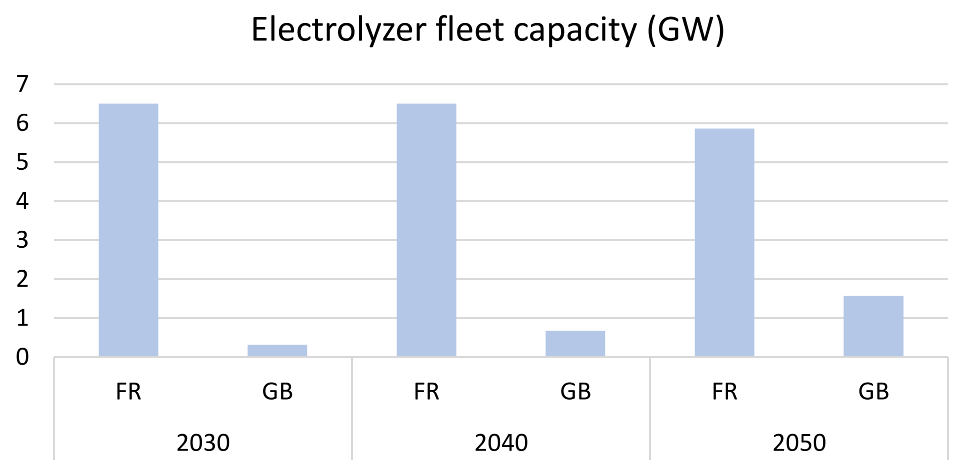


Figure 28 – Installed electrolyzer capacities in France and Great Britain in scenario 3 in 2030, 2040 and 2050

The delay in the development of renewable energy capacity is having a major impact on the French generation mix, such that renewable energy will not account for more than 50% of the generation mix before 2050. The decline in nuclear power capacity between 2040 and 2050 will result in a significant increase of power generation from gas-fired (around 10% of total output).

In the UK, renewable energy will account for most of electricity production by 2030 (around 75%), with offshore wind alone producing more than half of total output by 2040. Gas-fired power plants continue to play a substantial role (over 10%) over all the timeframes studied. Finally, the share of nuclear power in the generation mix increases slightly between 2030 and 2050 (from 9% to 13%).

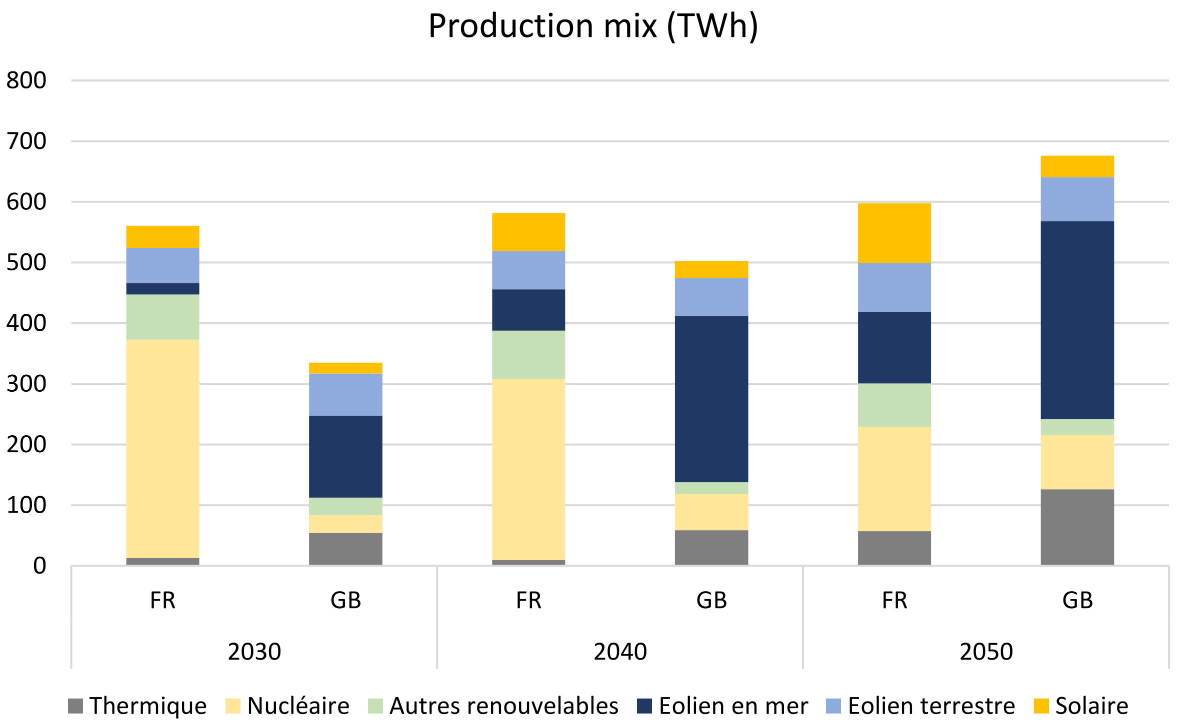


Figure 29 – Generation mix in France and Great Britain in scenario 3 in 2030, 2040 and 2050

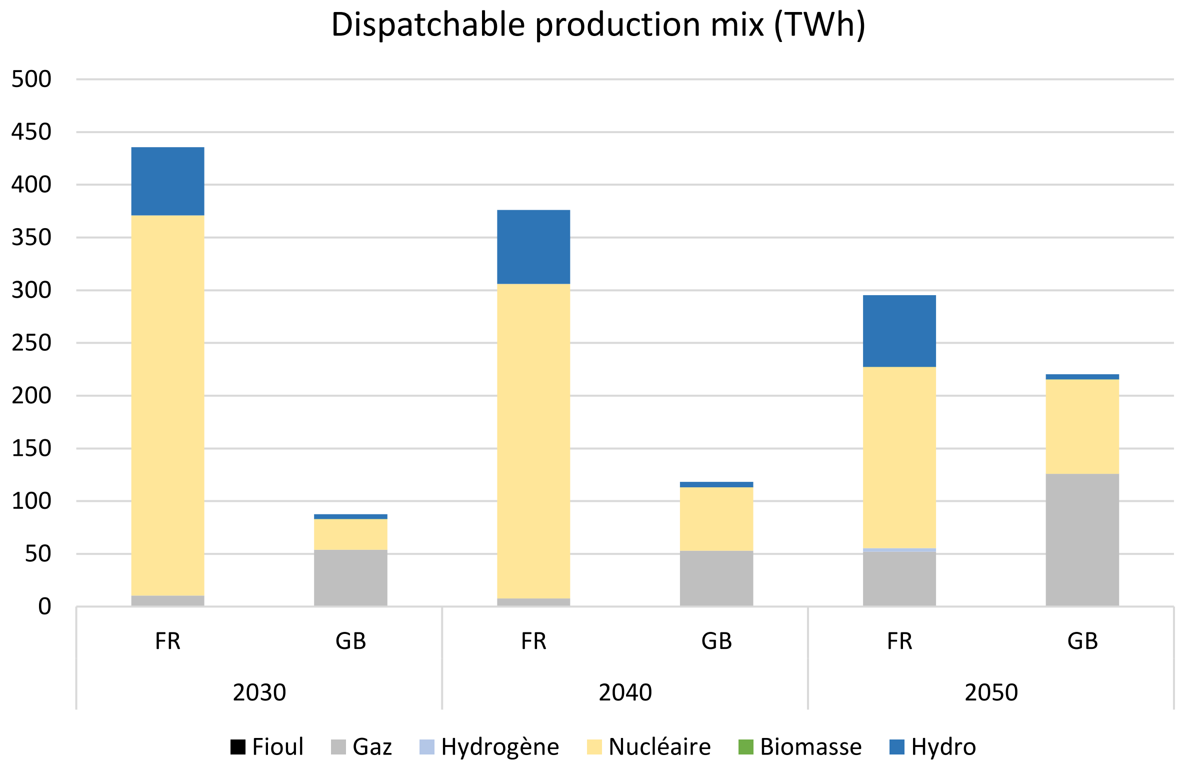


Figure 30 – Breakdown of the dispatchable generation mix in France and Great Britain in scenario 3 in 2030, 2040 and 2050

1.3 Description of sensitivity analyses

Sensitivity analyses conducted for the second scenario are designed to assess the impact of gas prices, the development of interconnections between Great Britain and the rest of Europe, the availability of French and British nuclear power fleet, hydrogen demand and the capacity of electrolyzes installed in France and Great Britain, offshore wind capacity in Great Britain, and a slowdown in the development of interconnections between France and the rest of Europe.

1.3.1 Gas prices

In all three baseline scenarios, gas price is set at €40/MWh over the three time periods considered. The first sensitivity analysis assesses the effect of gas price on the interconnection value, which falls into two levels, set at around €20/MWh and €60/MWh. These prices are assumed to remain constant in 2030, 2040 and 2050.

1.3.2 Interconnections between Great Britain and the rest of Europe

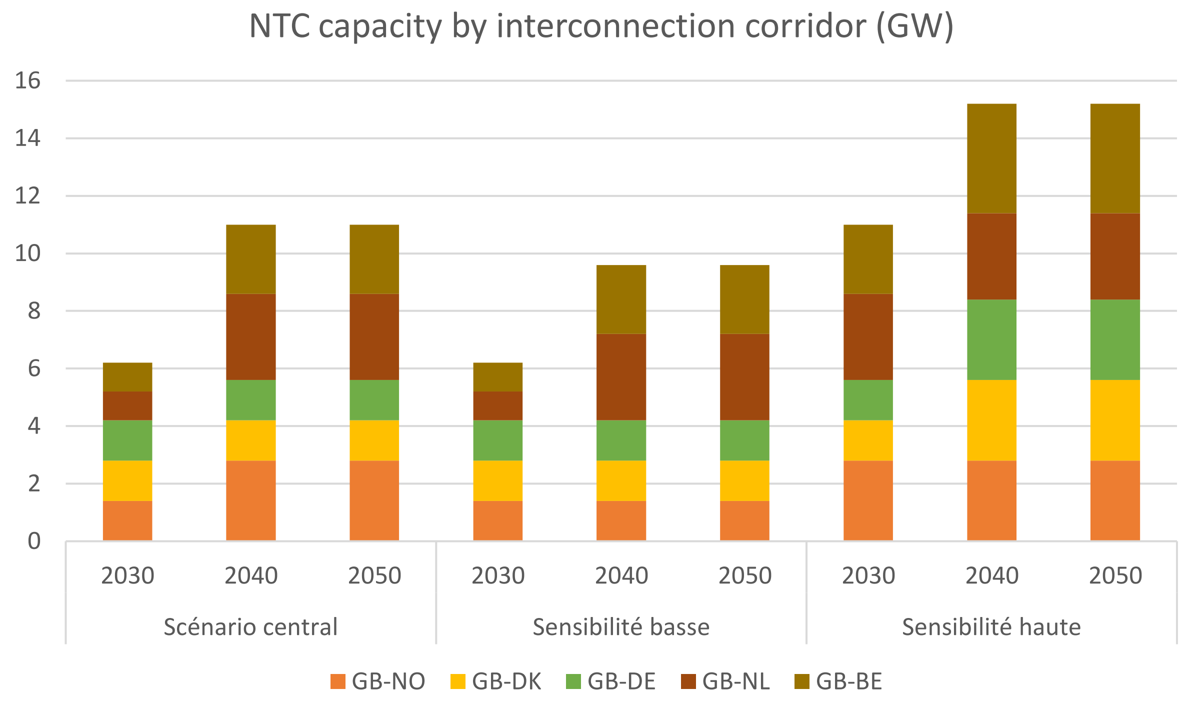


Figure 31 – NTC capacity between Great Britain and the rest of Europe in the main scenario and sensitivity assessing the impact of other interconnection projects in 2030, 2040 and 2050

Several interconnection projects between Great Britain and the rest of Europe are currently under study, including NorthConnect (linking Great Britain to Norway), Viking and Aminth (linking Great Britain to Denmark), NeuConnect and Tarchon (linking Great Britain to Germany), LionLink (linking Great Britain to the Netherlands) and Nautilus and Cronos (linking Great Britain to Belgium). The development of these projects is likely to influence the value of an interconnection project linking France to Great Britain. The second sensitivity evaluates the impact of the development of various interconnection projects linking Great Britain to the rest of Europe, by modifying the NTC exchange capacities linking Great Britain to different European countries. Table 2 and Figure 31 summarize the configurations studied in this sensitivity analysis.

Table 2 - Details of interconnection projects considered in the sensitivity analysis assessing the impact of interconnection projects linking Great Britain to the rest of Europe

	Years	UK-NO	UK-DK	UK-DE	UK-NL	UK-BE
Current level	2023	North Sea Link (1,4 GW)	-	-	BritNed (1 GW)	Nemo (1 GW)
Main Scenario	2030		Viking (1,4 GW)	NeuConnect (1,4 GW)		
	2040	NorthConnect (1,4 GW)	Viking	NeuConnect	LionLink (2 GW)	Nautilus (1,4 GW)
	2050	NorthConnect	Viking	NeuConnect	LionLink	Nautilus
Low sensitivity	2030		Viking	NeuConnect		
	2040		Viking	NeuConnect		Nautilus
	2050		Viking	NeuConnect		Nautilus
High sensitivity	2030	NorthConnect	Viking	NeuConnect	LionLink	Nautilus
	2040	NorthConnect	Viking + Aminth (1,4 GW)	NeuConnect + Tarchon (1,4 GW)	LionLink	Nautilus + Cronos (1,4 GW)
	2050	NorthConnect	Viking + Aminth	NeuConnect + Tarchon	LionLink	Nautilus + Cronos

1.3.3 Nuclear power fleet availability

The third sensitivity analysis concerns the availability of the French and British nuclear power fleet. The aim of this sensitivity analysis is to represent a situation comparable to that of 2022, when almost half of France's thermonuclear fleet had to be placed under extended maintenance following the identification of a generic fault in the cooling system of certain reactors. The reduction in nuclear availability has been calculated to achieve an electricity production level of around 280 TWh in 2030. This availability is applied uniformly in France and Great Britain over all the timeframes modelled.

1.3.4 Hydrogen demand and electrolysis capacity

An additional sensitivity evaluates the effect of a delay in the deployment of electrolyzer capacity and a reduced demand for hydrogen. More precisely, in this sensitivity, electricity consumption from electrolysis is reduced by half in France and Great Britain, and electrolyzer capacity is also halved.

1.3.5 British offshore wind deployment

All the scenarios used for Great Britain are based largely on the development of offshore wind power. Extremely ambitious political targets have been announced for the development of this sector, targeting a capacity level of 50 GW by 2030 (compared with 13.1 GW in 2021). These initiatives put offshore wind resources at the heart of the UK electricity system, and the associated assumptions are therefore likely to have a non-negligible effect on the value of the interconnection. In order to assess their impact on the value of the interconnection, a sensitivity analysis has been conducted, setting the level of offshore wind capacity at the level of the "Falling Short" scenario (a lower level seems unlikely, considering the projects under study and the policy measures announced).

1.3.6 Interconnections between France and neighboring countries

Finally, the last sensitivity analysis concerns the development of interconnection projects between France and the rest of Europe. This sensitivity evaluates the effect of a delay in the development of such projects, and applies exclusively to the 2040 period, for which the capacities available in 2030 are used (see Figure 12 in the description of assumptions applied to all scenarios).

2 Assessing the value of a new interconnection project

This study analyzes two types of benefits that may arise from increasing the interconnection capacity between France and the UK:

- **Generation cost savings and spatial arbitrage opportunities:** increasing the interconnection capacity makes it possible to replace costly means of production by less costly ones (especially by integrating more renewable energy), thus reducing the total production costs of the power system and increasing the overall social welfare. These shifts in production substitutions can also reduce greenhouse gas emissions.
- **Capacity value of interconnection and security of supply**: increasing the interconnection capacity can contribute to security of supply, by transporting more electricity during hours of high net demand in the power systems it connects.

In this study, the benefits in terms of generation cost savings and spatial arbitrage opportunities as well and security of supply have been evaluated separately. Section2.1 assesses the benefits of interconnection from the point of view of arbitrage value. In this section, it has been assumed that the interconnection is never remunerated on the fault value (i.e., that the fault cost is equivalent to the cost of peak generation capacity on either side of the interconnection). The benefits of interconnection in terms of security of supply are assessed in section2.2.

2.1 Benefits of interconnection from generation cost savings and arbitrage opportunities

Calculation method for interconnection impacts

This study evaluates the impact of increasing the interconnection capacity using several metrics: impact on electricity generation from different technologies, impact on greenhouse gas emissions, and impacts on overall social welfare.

All indicators are calculated for the addition of one and two interconnection projects compared with the current level. For this purpose, three levels of interconnection capacity between France and Great Britain were simulated:

- The current level (4 GW)
- A level with one additional project, with an assumed capacity of 1.4 GW (i.e., a total FR-GB interconnection capacity of 5.4 GW)
- A level with two additional projects, with capacities of 1.4 and 1.2 GW respectively (i.e., a total FR-GB interconnection capacity of 6.6 GW)

For all indicators, the differences in outcomes between simulations were then calculated and scaled linearly to be representative of a 1 GW difference in interconnection capacity, as follows:

- Impact $_{\text{first interconnection}}$ = (Result$_{5,4\text{ GW}}$ – Result$_{4\text{ GW}}$) / 1,4 GW
- Impact $_{\text{second interconnection}}$ = (Result$_{6,6\text{ GW}}$ – Result$_{5,4\text{ GW}}$) / 1,2 GW

Hence, in the remainder of this document, the impact of interconnection projects is systematically presented in the form of results scaled in such fashion.

In addition, unless otherwise stated, indicators are computed over the entire geographical scope modelled (the European Union, the United Kingdom, Norway, Switzerland and five Balkan countries).

2.1.1 Better integration of renewable energy and reduction in thermal generation

Figure 32 illustrates the variations in production by technology resulting from the increase in interconnection capacity between France and the UK. Across the whole geographical scope considered, increasing the interconnection capacity leads to a better integration of renewable generation (i.e., less curtailment). The additional renewable electricity available displaces generation from thermal power plants, effectively reducing the need for thermal generation.

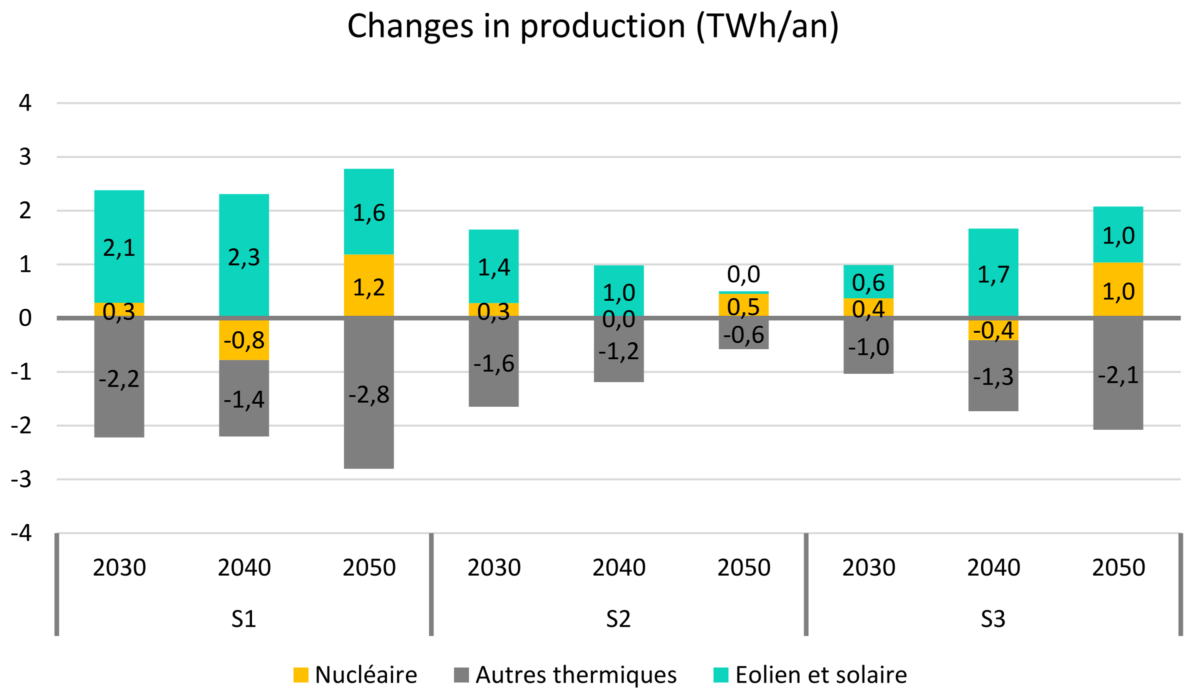


Figure 32 - Variations in generation by scenario over the full geographical scope for the first interconnection project

In the second scenario, the new interconnection capacity does not allow for an increase in renewable generation levels in 2050, which is otherwise the case in all other scenarios. This is due to the fact that, in this scenario, curtailment levels in the UK are already very low without any increase in interconnection capacity, thanks to the high penetration of electrolysis plants (and therefore a very flexible electrical load, which allows wind power generation to be very well integrated). Thus, increasing the interconnection capacity does not reduce renewable curtailment any further.

In contrast to

Figure 32, which shows differences in production over the full scope of the model (the European Union, the United Kingdom, Norway, Switzerland and five Balkan countries), Figure 33 shows variations in production in three different zones (the UK, France and the rest of Europe).

Specifically, it can be seen from the figure that:

- Most of the additional **renewable generation** is in Great Britain (mainly wind power)
- Most of the displaced **thermal generation** is in the rest of Europe
- The increase in interconnection capacity pushes up **nuclear generation** in Great Britain and drives it down in France.

As regards the impact on the operation of the French nuclear power fleet of increasing the level of interconnection capacity between France and Great Britain, two opposing effects are at play:

- On one hand, when gas power plants set the price of electricity in Great Britain (these plants' marginal cost of production is higher than the marginal cost of nuclear power plants), and the French nuclear power fleet is not running at full capacity, **increasing the interconnection capacity allows for an increase in the amount of French nuclear production exported** to Great Britain, such that the interconnection leads to an increase in French nuclear production.
- On the other hand, when the marginal generation units in Great Britain are wind power plants (i.e., when not all British wind power generation available can be injected into the power system and part of it has to be curtailed)**, increasing the interconnection capacity increases exports of British wind power generation to France**, which can lead to a drop in French nuclear generation.

Although building new electricity interconnections historically tended to increase electricity exports from France to Great Britain, and thus French nuclear generation (the first case described above), simulations conducted in this study show that this trend could be reversed by 2030. Indeed, Figure 33 shows that increasing the interconnection capacity between France and Great Britain reduces French nuclear generation overall over the year, meaning that the second case described above occurs more often than the first. Over the year, French nuclear generation is more often displaced by British wind power generation surpluses than it is exported to Great Britain as a substitute for fossil-fired generation.

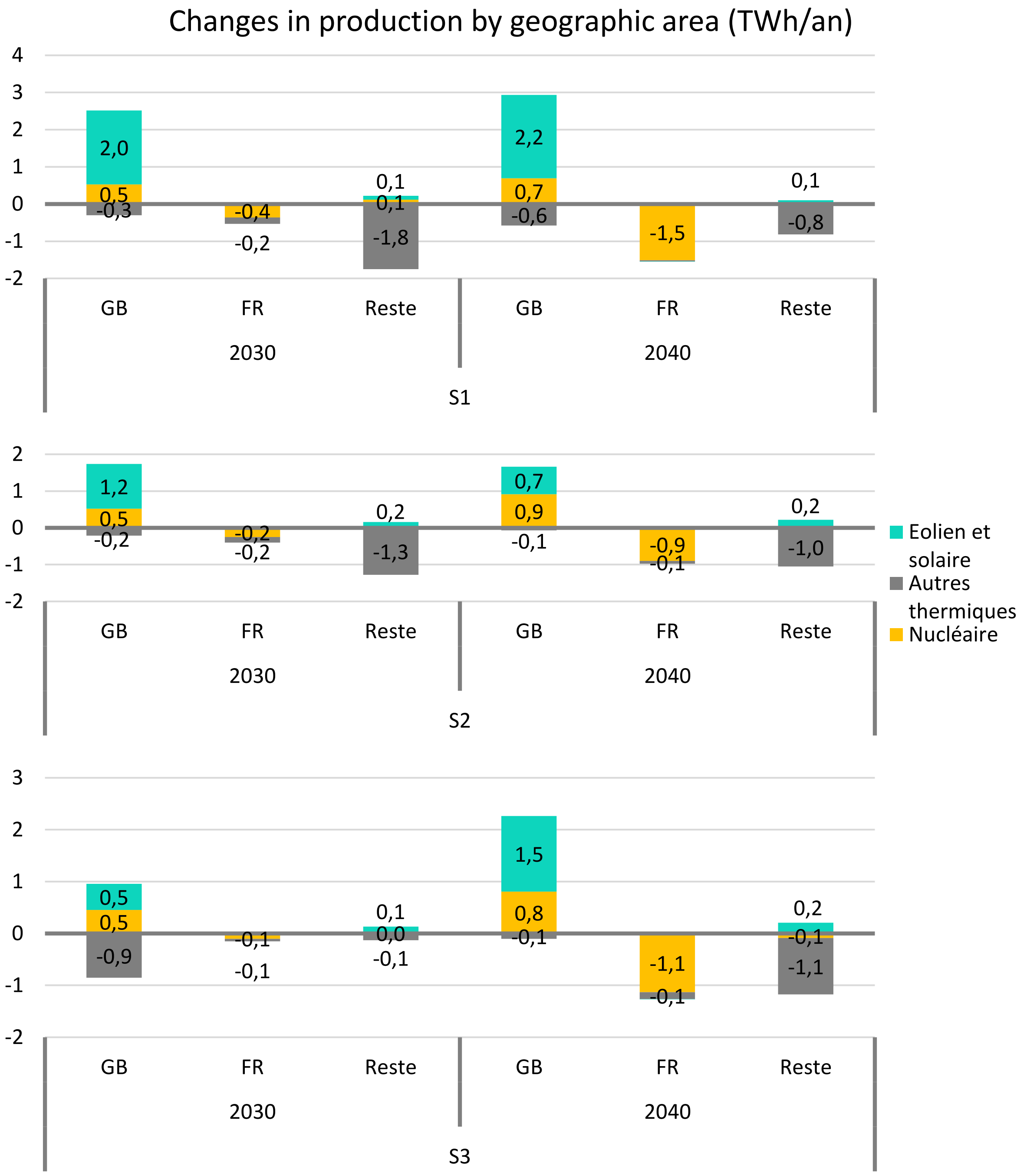


Figure 33 - Changes in production by sector and geographical area for the first interconnection project

Figure 34 illustrates the difference between the impacts of the first additional interconnection project and the second additional interconnection project. The effects of the second interconnection project in terms of displaced production are similar to the effects of the first additional interconnection project, though slightly attenuated. The observed reduction in displaced production volumes between the first and second interconnection projects is between 8% and 13% for most scenarios and years, and 21% for scenario 3 in 2030.

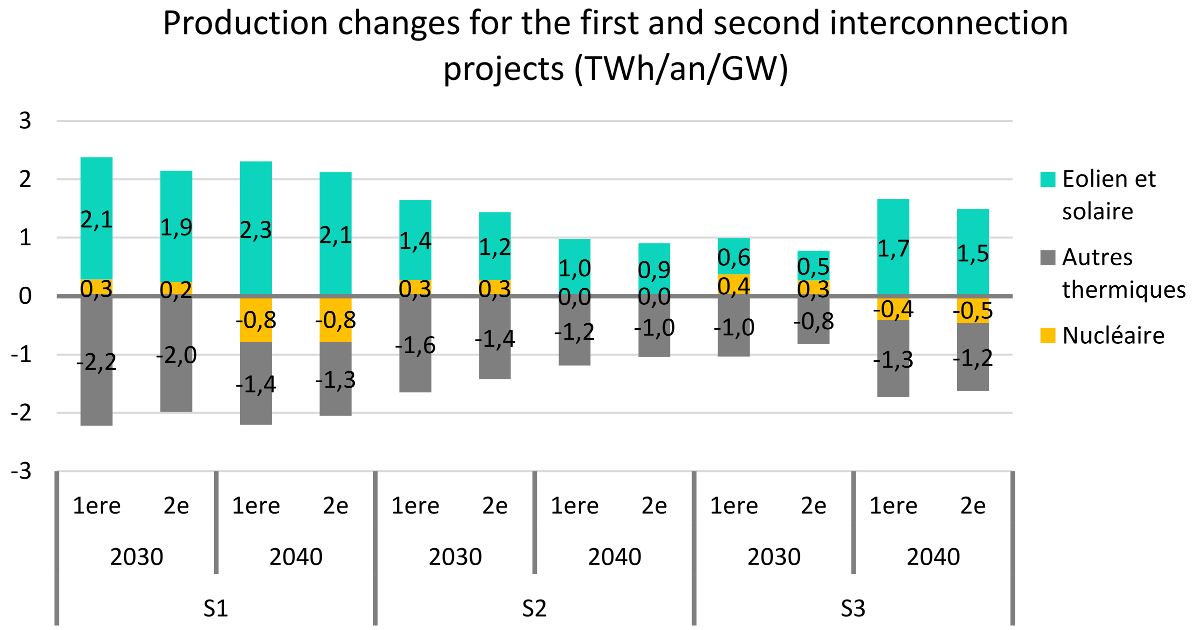


Figure 34 - Changes in production by sector across the geographical scope for the addition of the first and second interconnection projects

2.1.2 Reduction in greenhouse gas emissions

Besides reducing the operating costs of the power system, the reduction in thermal power generation resulting from the improved integration of renewable energy also **reduces carbon dioxide emissions**, as illustrated in Figure 35.

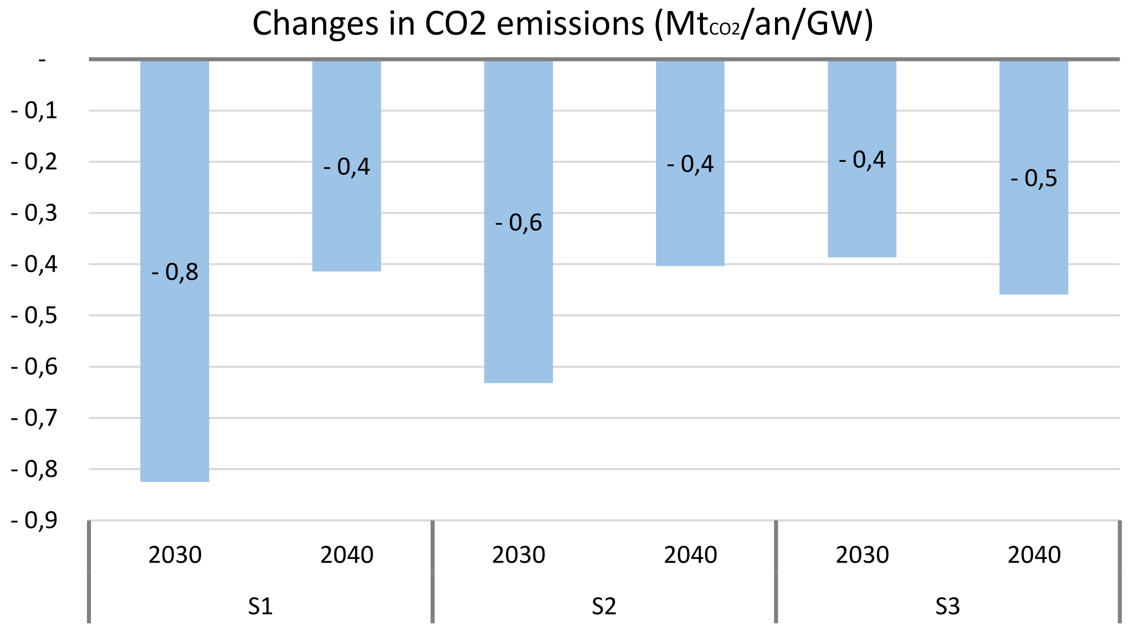


Figure 35 - Changes in CO2 emissions observed for the first interconnection project

2.1.3 Increase in overall social welfare

Over the full geographical scope modelled, the increase in interconnection capacity between France and Great Britain allows for the replacement of electricity generation from assets with high marginal costs (i.e., thermal generation) by generation from technologies with lower marginal costs (especially through the better integration of solar and wind power). These production shifts enable a reduction in total power production costs, and an increase in social welfare. The economic gains generated by the addition of the first interconnection project are illustrated in Figure 36.

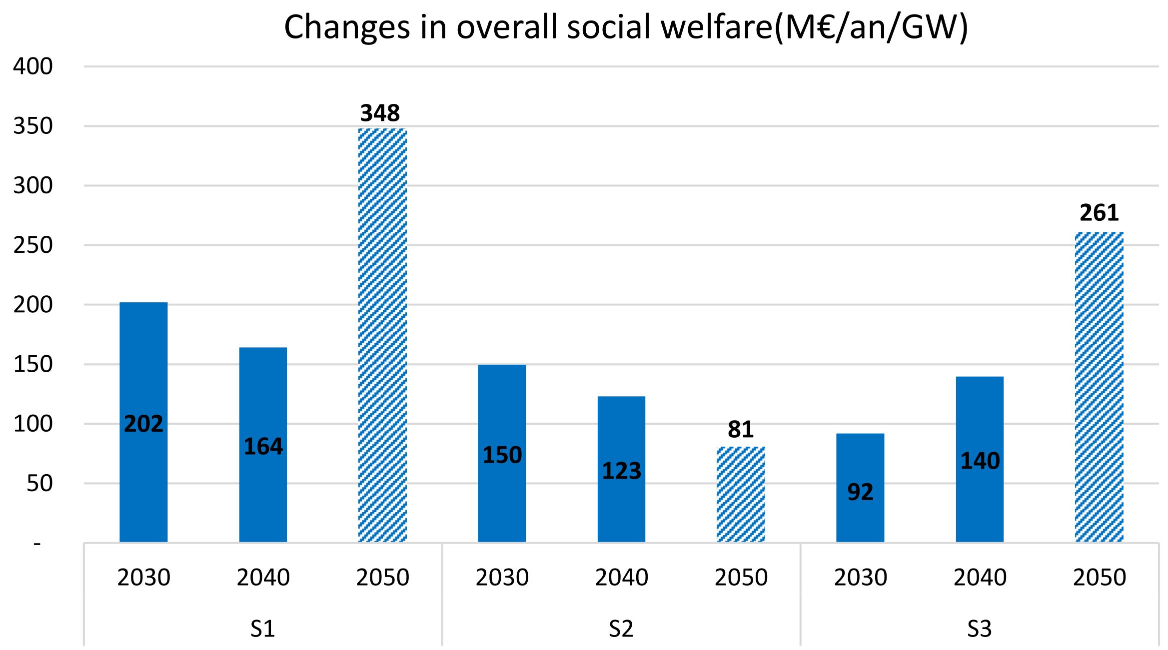


Figure 36 - Changes in overall social welfare over the scope modelled resulting from the addition of the first interconnection project

Figure 37 compares the changes in overall social welfare resulting from the addition of the first interconnector with that of the second interconnector. As with displaced production (Figure 34), the effects of the second interconnection project on social welfare are similar to the effects of the first additional interconnection project, but slightly attenuated. The reduction observed in social welfare gains between the first and second interconnection projects is between 10% and 15% for most scenarios and years, and around 7% for scenario 1 in 2050 and 20% for scenario 3 in 2030.

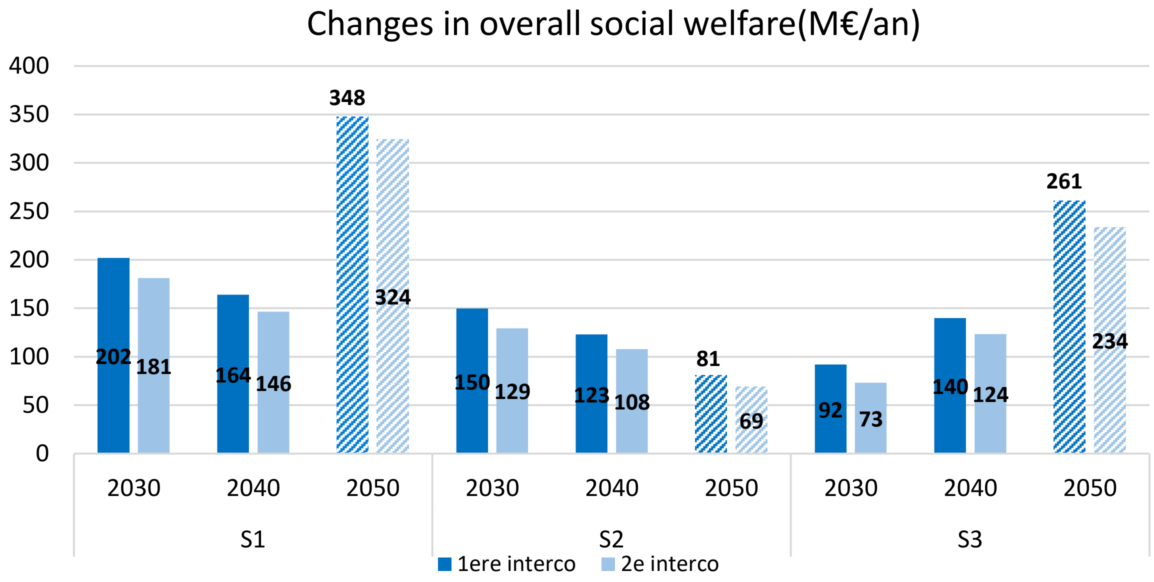


Figure 37 - Changes in overall social welfare for interconnection projects between France and Great Britain

For 2030 and 2040, the economic benefits of adding an interconnection project range from €92 to €202 million/year/GW, with an average of €145 million/year/GW.

By 2050, the overall economic gains made possible by adding an interconnection project widely differ between scenarios. In scenarios 1 and 3, they increase sharply in 2050 compared with 2040. This is due to two factors:

- A reduction in non-nuclear thermal generation thanks to better integration of renewables and nuclear: 2.7 TWh of non-nuclear thermal generation avoided in scenario 1 and 2 TWh in scenario 3 in 2050 (see Figure 32 - Variations in generation by scenario over the full geographical scope for the first interconnection project).
  By contrast, in 2040, the non-nuclear thermal generation avoided by the addition of the first interconnection project was only 1.4 TWh in scenario 1 and 1.3 TWh in scenario 3.
- The rise in the variable costs of electricity generation from the non-nuclear thermal power fleet: around €125/MWh$_{el}$ in 2050, compared with €100/MWh$_{el}$ in 2040 for combined-cycle gas power plants. Consequently, avoiding 1 TWh of non-nuclear thermal generation in 2050 saves more than avoiding 1 TWh of non-nuclear thermal generation in 2040.

In contrast, in scenario 2, the overall social welfare generated by the first interconnection project is lower in 2050 than it is in 2040. This is because, unlike all other scenarios, in scenario 2, increasing the interconnection capacity does **not allow for the integration of more renewable energy in 2050**, as the curtailment of renewable energy in the UK is already very low at current interconnection levels. (See

Figure 32 - Variations in generation by scenario over the full geographical scope for the first interconnection project). The good integration of renewable energy in the UK is explained by the high penetration of electrolysis, and therefore a very flexible electricity demand, which enables wind power generation to be well integrated.

2.1.4 The present value of the benefits of interconnection projects is significant

Method for calculating the present value of interconnection project benefits

The key indicator studied to assess the value of an interconnection project is the present value of the benefits expected from the project, calculated over its entire lifetime.

This indicator is calculated in three steps:

1. **Calculating annual project values for 2030, 2040 et 2050**
   The annual value of the project is calculated as the increase in overall social welfare generated by the interconnection project (see Figure 36).

2. **Accounting for average interconnection availability**
   As interconnections do not always operate at full capacity, the calculation of the overall social welfare must consider the average availability of interconnection projects. Based on the availability observed for the IFA2 interconnector between 2021 and 2023 and for the ElecLink interconnector between 2022 and 2023, we assume an average interconnection availability of 95%.

3. **Obtaining annual values for non-simulated years**
   Considering the significant uncertainties surrounding the results for 2050, two methods are used to assess the present value of the benefits of the interconnection over its lifetime:
   - Interpolation of annual benefits using the result of the 2050 simulation.
   - Extrapolation of annual benefits obtained for the 2040 simulation to subsequent years.

   The two methods of are illustrated in Figure 38.

4. **Discounting annual values and calculating the present value of benefits**
   The discounting was done assuming 2025 to be the reference year, assuming a **discount rate of 4.5%**, **an amortization period of 25 years** and **commissioning date of 2030**, using the following formula:

$$VAB = \sum_{year=2030}^{2054} \frac{1}{(1+rate)^{year-2025}} * Gains\ Social\ Welfare_{year}$$

5. Calculating the average present value of interconnection project benefits
For each additional interconnector, the present value of the benefits retained by scenario is the average, for a given scenario, between the benefits of the two methods discounted over 25 years.

Figure 39 illustrates the calculation for the first additional interconnection. A similar approach is applied for the second additional interconnection.

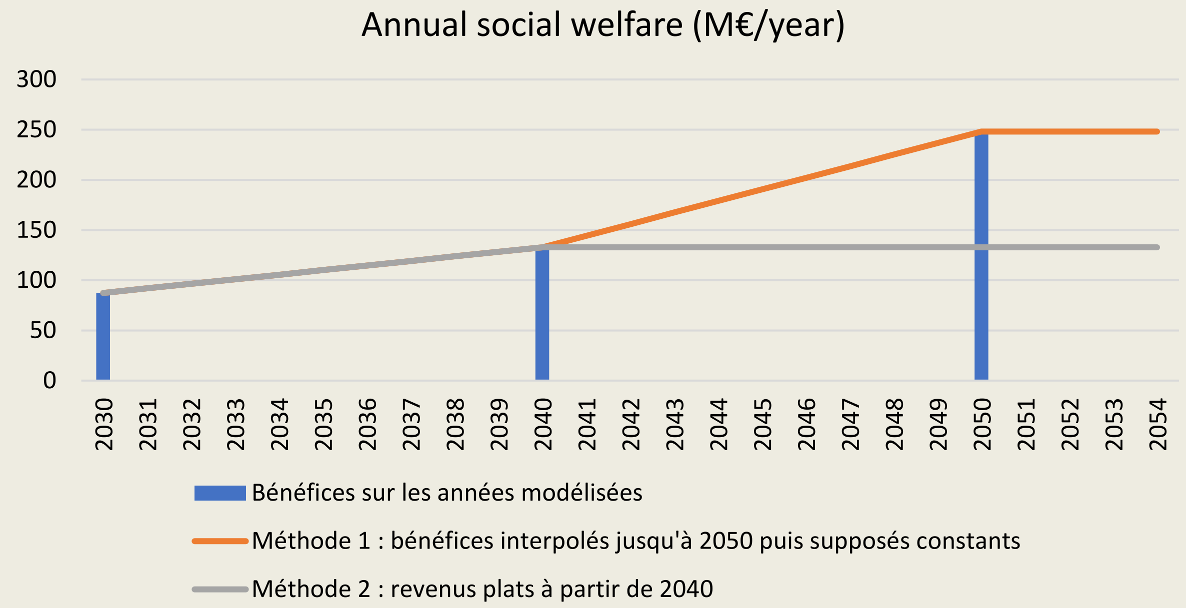


Figure 38 - Method used to compute annual benefits considering an average availability of 95% (illustrated in the case of scenario 3)

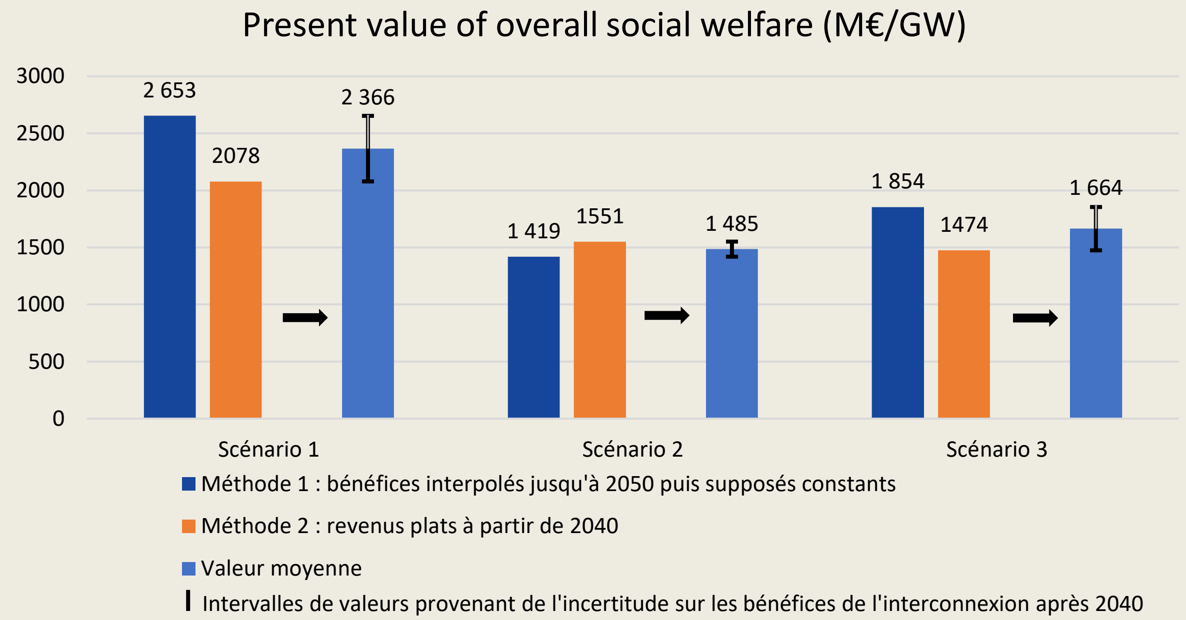


Figure 39 - Present value of the benefits of an additional interconnection project between France and Great Britain, considering an average availability of 95%

Depending on the scenario and the discounting method used, the present value of the benefits of the first interconnection project over its entire lifetime **varies between €1.5 and €2.4 billion/GW.**

Figure 40 compares the average present value of the first and second interconnection projects. The value of the second interconnection project is lower than that of the first. The observed reduction in present value generated by the second interconnection project compared with the first varies between 10% and 13%.

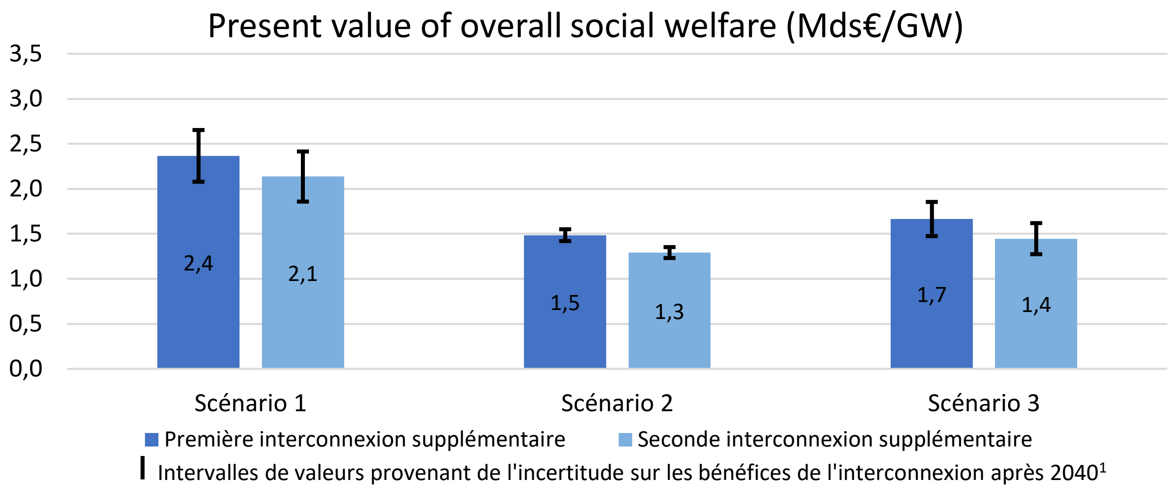


Figure 40 - Present value of expected benefits from interconnection projects between France and Great Britain, considering an average availability of 95%

Sensitivity analyses

In order to assess the robustness of these results to multiple sources of uncertainty, eight sensitivity analyses were modeled. All sensitivity analyses were built on scenario 2. The assumptions of the eight sensitivity analyses are explained in section 1.3.

Figure 41 **Figure 41Figure 41**illustrates the variations in overall social welfare generated by the first interconnection project in 2030 and 2040. Of the eight sensitivity analyses, three lead to a significant decrease in the overall economic benefits generated by the interconnection project:

- **Low gas prices:** the interconnector derives a significant part of its value from the fact that it enables the displacement of gas-fired electricity generation on one side of the interconnector by renewable energy or nuclear generation on the other side of the interconnector**.** Reducing gas prices implies reducing the cost of electricity generation from gas, and therefore reducing the savings made by resorting to nuclear or renewable energy.
- **A strong development of interconnection capacities between the UK and the rest of continental Europe:** the UK-France interconnection would then find itself in greater competition with other interconnections. Other interconnections already allow part of British wind power surpluses to be sold on the European continent, thus reducing the British surplus that can be exported by the UK-France interconnector, and therefore the benefits that come with it.
- **Wind power capacity in the UK below expected levels:** the interconnector generates a significant proportion of its value from the fact that it enables excess UK wind generation,

which would otherwise be curtailed, to be valorized on the European continent. If British wind power capacity does not reach the expected levels, for example due to a drop in the rate of wind power plant construction (BBC, 2023) or delays in connecting wind power plant to the British grid (Financial Times, 2023), the wind power surplus excess that can be transported by the interconnector will be lower so the benefits of the interconnector will decrease accordingly.

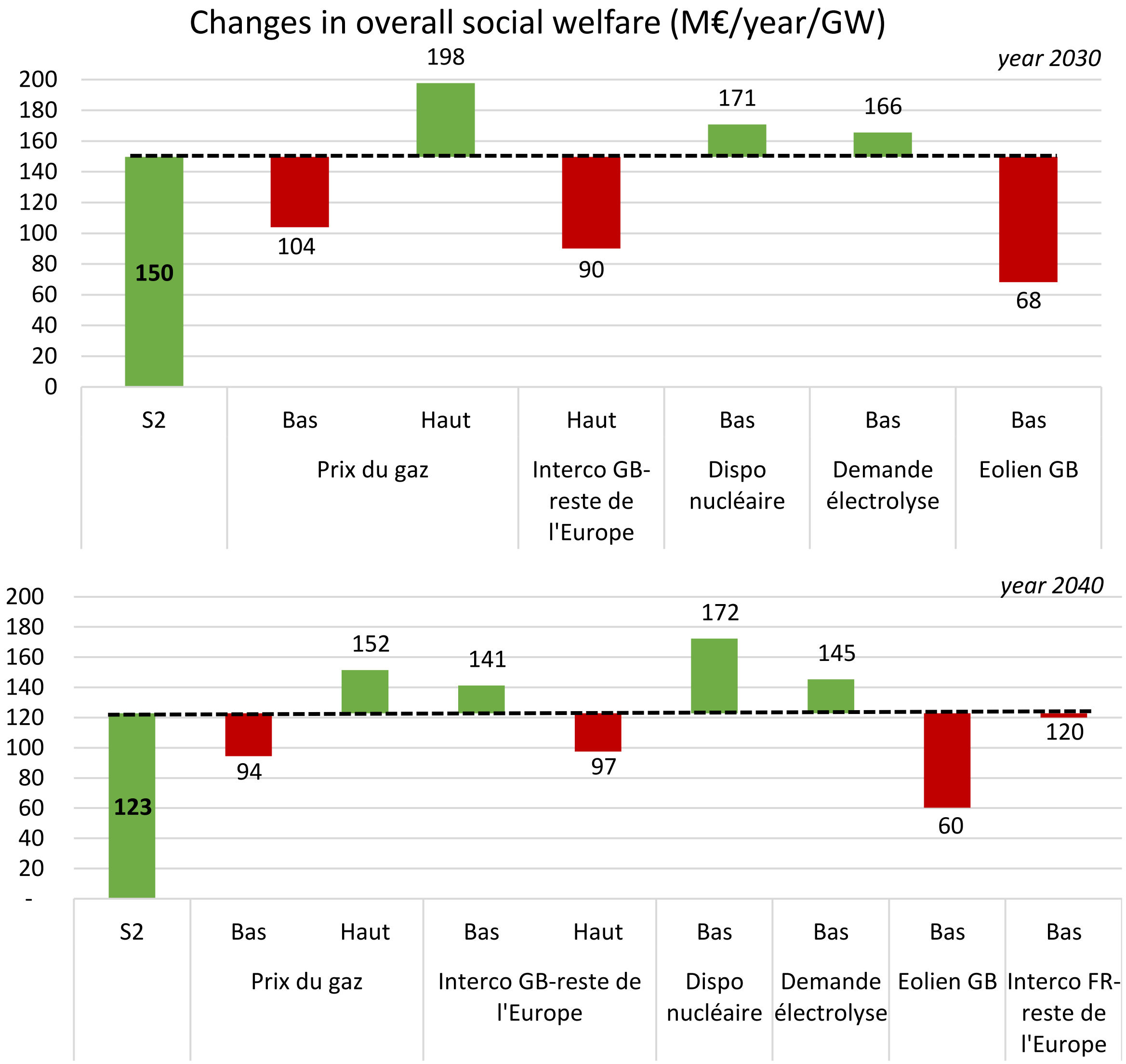


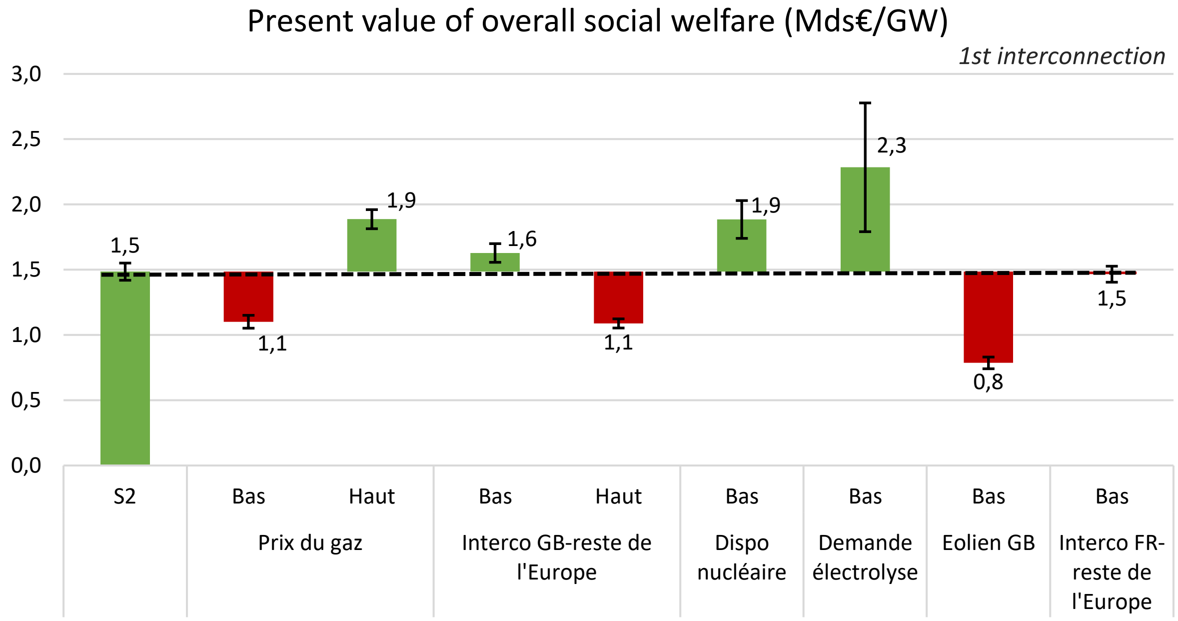
Figure 41 - Variations in overall social welfare in sensitivity analyses for the first interconnection project

By 2050, the main factor determining the added value of an interconnector is the existence or not of curtailed wind power generation in the UK, which a new interconnector would valorize. This factor varies between scenarios 1 and 3: it is high in scenarios 1 and 3, but low in scenario 2, which explains why the interconnector has a lower value than in the other two scenarios.

Sensitivities are performed on scenario 2. Consequently, the sensitivity pertaining to low levels of wind power development in the UK has no impact on wind curtailment, as it is already zero. This sensitivity has little impact on changes in overall social welfare allowed by the addition of interconnection projects in 2050.

On the other hand, the sensitivity pertaining to electrolyzer deployment has a strong impact on the results. Indeed, assuming a more limited for electrolysis effectively reduces the electricity demand and its flexibility, freeing up wind power generation surpluses, which can then be exported by the interconnector.

Figure 42 illustrates the present value of expected benefits over the full lifetime of the first and second interconnection projects, for scenario 2 and all sensitivity analyses. The sensitivity analysis with the greatest impact on the present value of the interconnector's benefits is the one relating to wind power development in the UK. In this scenario, the value of the interconnector is 786 M€/GW for the first project and 659 M€/GW for the second project. These values are under twice lower than the value observed in scenario 2.



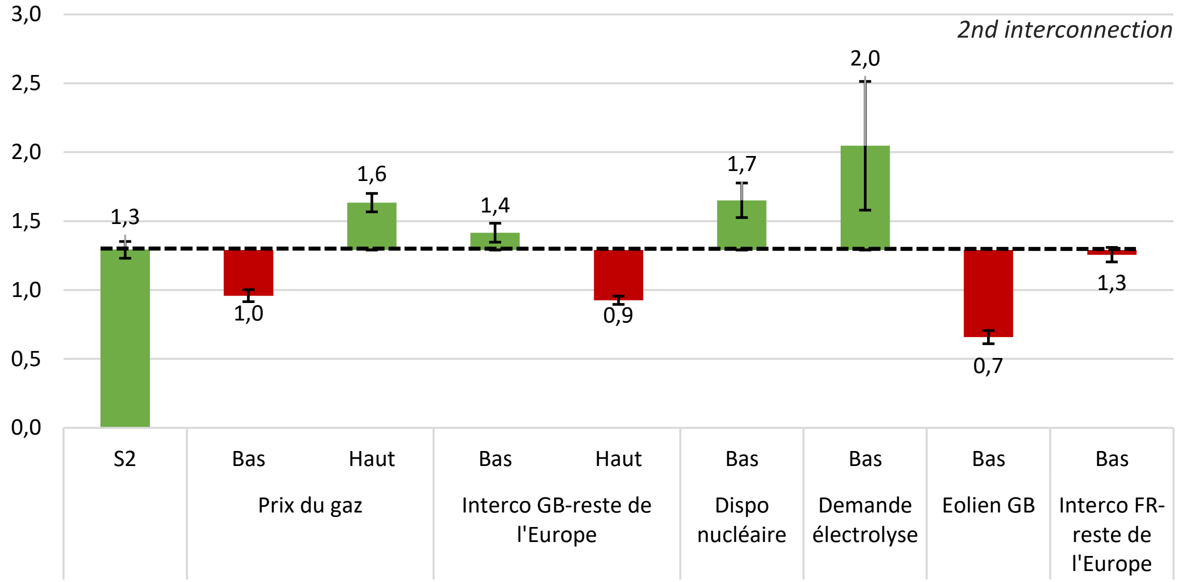
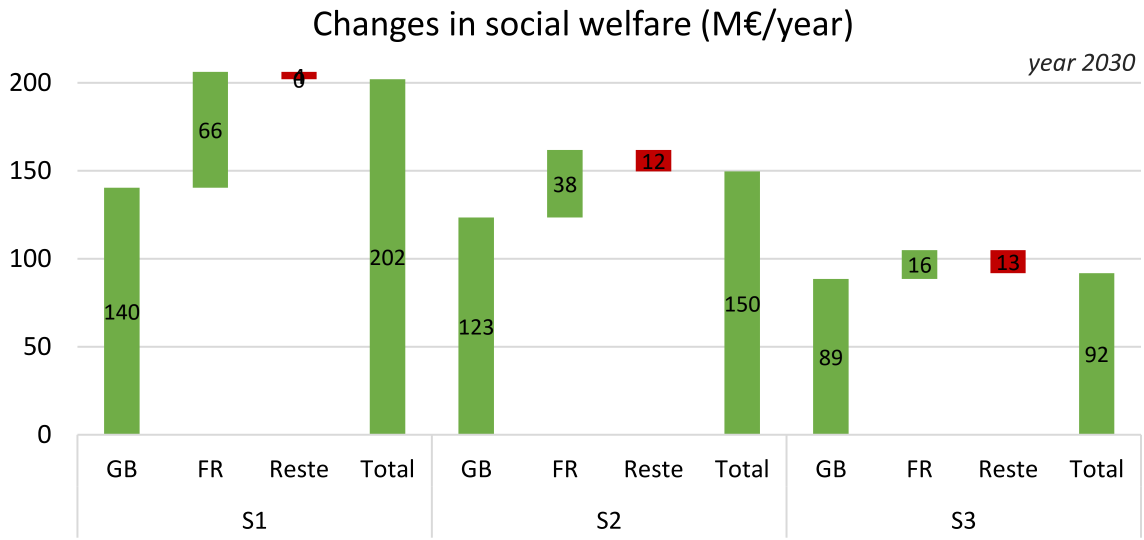


Figure 42 - Present value of benefits from the first and second interconnection projects over their full lifetime in sensitivity analyses, considering an average availability of 95%

2.1.5 The benefits of interconnection projects are unevenly split between countries

Figure 43 illustrates the distribution of economic benefits across the different geographical areas ("Rest" representing the aggregation of the 34 areas in the model other than France and Great Britain). For each interconnector, congestion rents are split equally between the two interconnected countries.

In most scenarios, the interconnection project benefits the UK thanks to the export of surplus UK wind power generation. The benefits for France remain positive in most simulations, except in scenario 3 in 2040. The drop in social welfare in France in scenario 3 in 2040 is explained by the significant fall in electricity prices in continental Europe, which reduces the value of exports from France to the rest of continental Europe.



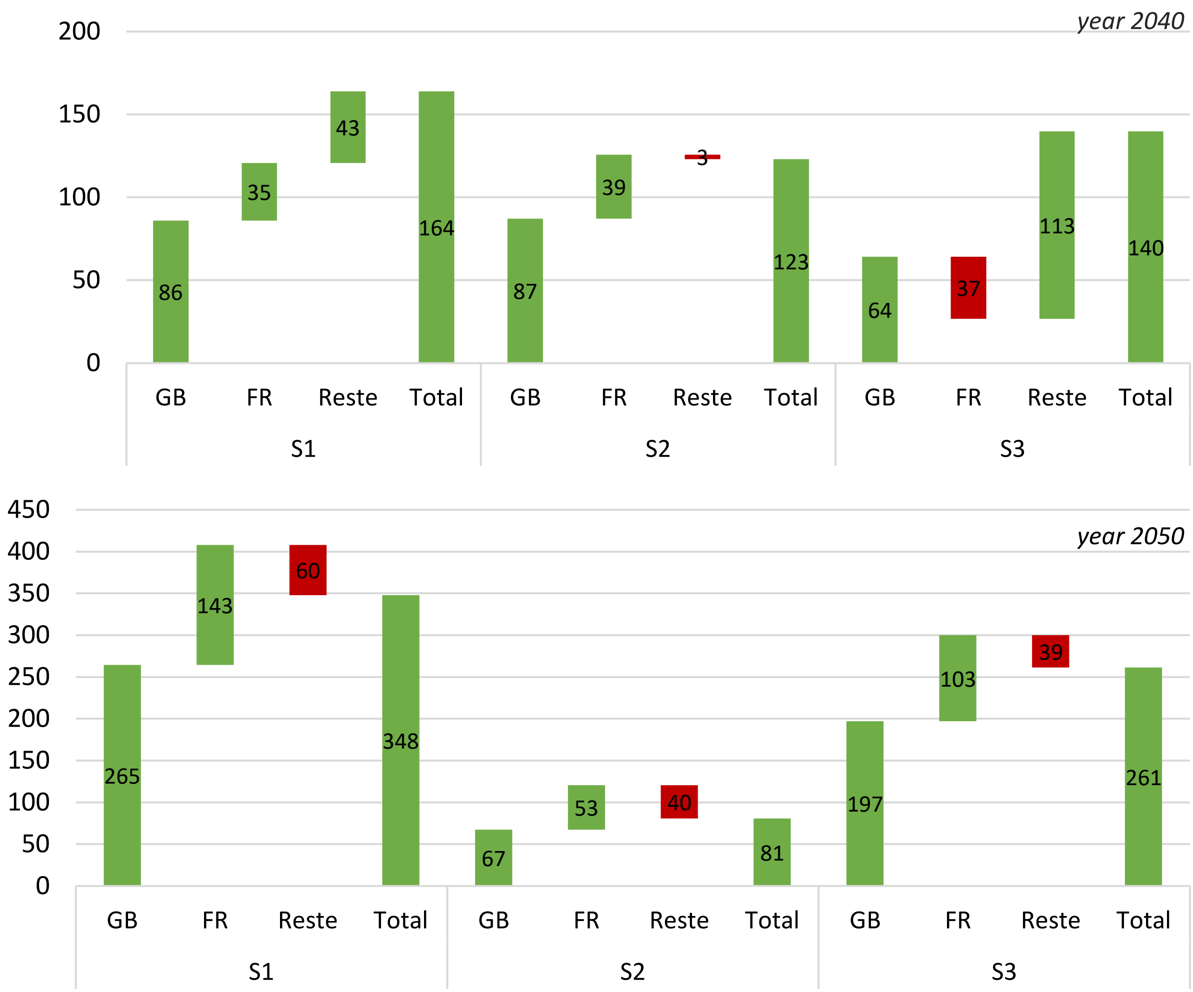


Figure 43 - Changes in overall social welfare by geographical area, for the first interconnection project

If the second interconnector is completed, the trend remains the same, with most of the benefits being captured by the UK, except in scenario 2 in 2050. Impacts for France remain positive overall, except in scenario 1 in 2040.

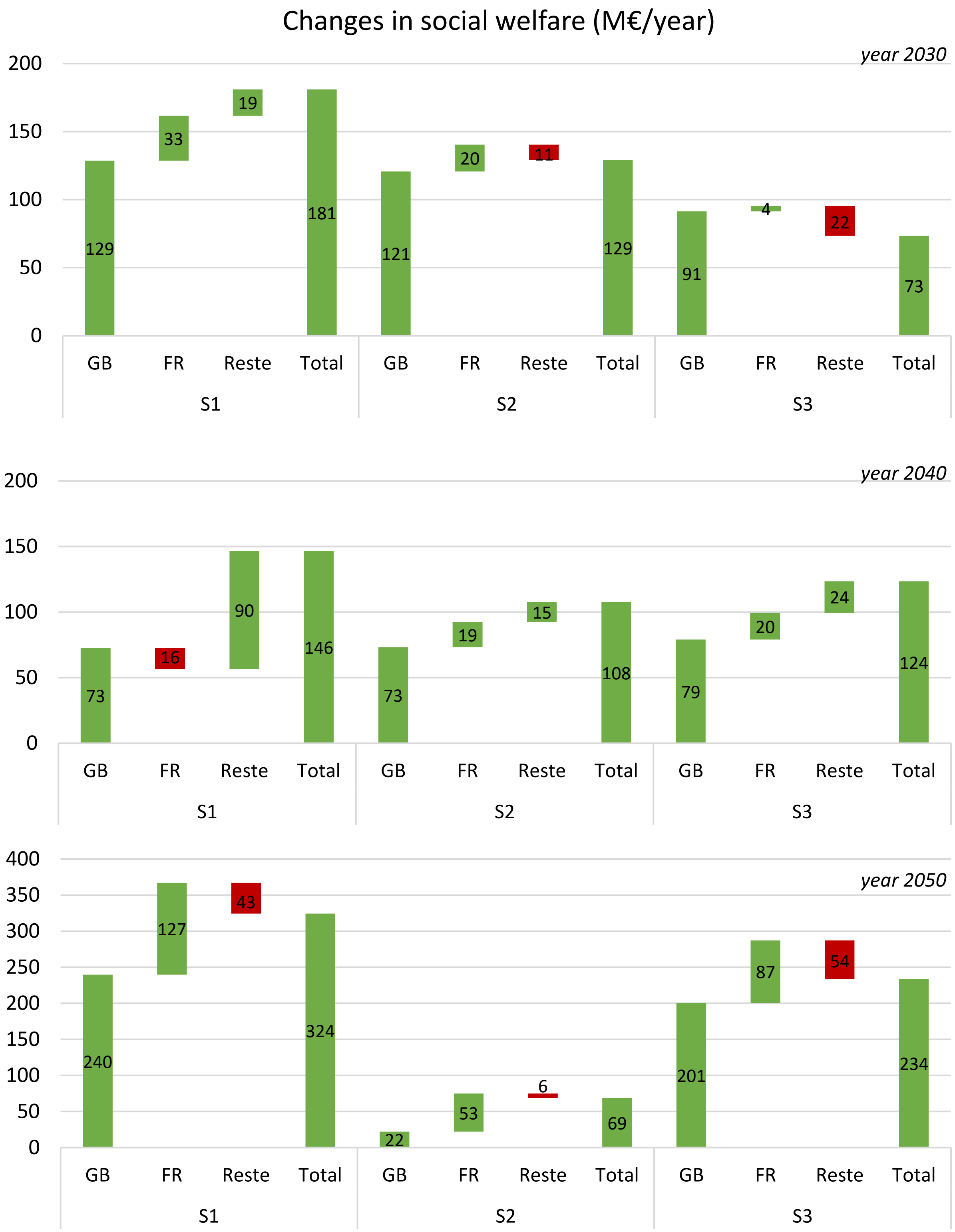


Figure 44 – Changes in overall social welfare by geographical area, for the addition of the second interconnection project

In the sensitivity analysis focusing on the impact of low nuclear availability in France and Great Britain, the addition of the first interconnection project benefits Great Britain, and reduces the overall social welfare of the rest of Europe (excluding France). In the sensitivity analysis based on low electrolysis development, the gains in social welfare provided by the addition of the first additional interconnection project are still mostly captured by Great Britain. However, in this scenario, the increased interconnection capacity no longer serves the rest of Europe, unlike in scenario 2. By 2040, in this sensitivity analysis, increasing the interconnection capacity increases the overall social welfare for the rest of Europe by €55 million/year (see Figure 45).

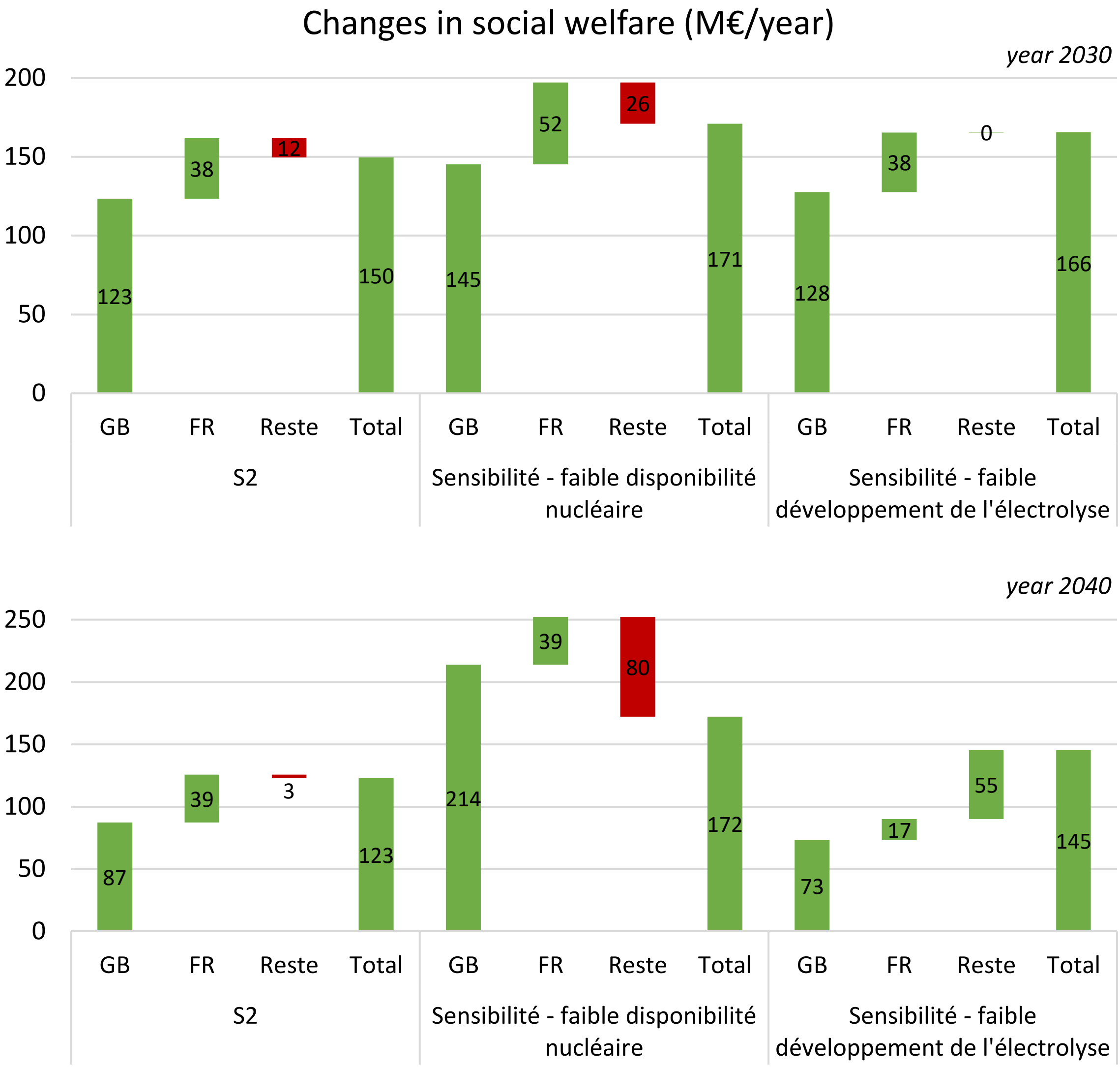


Figure 45 - Changes in overall social welfare by geographical area, for the addition of the first interconnection project, in sensitivity analyses analysing low nuclear availability and low electrolysis development

2.2 Contribution to security of supply

In addition to the benefits in terms of spatial arbitrage opportunities assessed above, interconnections can also contribute to the security of supply of interconnected countries. Indeed, during the most critical hours for their respective power systems, interconnections can sometimes provide electricity and contribute to covering (residual) demand peak.

Nevertheless, interconnections do not necessarily contribute to peak electricity demand at full power. In fact, full utilization of an interconnector during peak demand in one country requires that generating capacity be available in sufficient quantities in the second interconnected country, and that this capacity be cheaper than the marginal generating capacity in the first country. In this study, the effective contribution of the UK-France interconnector to peak electricity demand was therefore calculated for import flows transiting to France and the UK, in order to measure the interconnector's contribution to security of supply in each country.

Method for calculating the contribution of the interconnection to security of supply.

A key indicator studied to analyze the contribution to security of supply of the interconnection for a given country is the rate of utilization of the interconnection to import electricity in that country during the most critical hours for its power system.

The most critical hours for a country's power system are determined as **the hours of highest residual load**. Residual load refers to **the difference between electricity demand and nondispatchable** (i.e., mainly wind, solar and run-of-river hydro) **electricity generation.** In this study, the number of hours of high residual load to be considered in the calculation was set at 250 hours per year, based on the rules of the French capacity mechanism. [2].

Furthermore, to consider only **the marginal contribution to security of supply of the interconnection capacity increment** (and not the average capacity value of all UK-French interconnections), the utilization rate has only been calculated on the last chunk of interconnection capacity.

For the first interconnection project (with an assumed capacity of 1.4 GW), the utilization rate at times of high residual load in is therefore calculated as follows, based on the outcomes of the simulation with an interconnection level between France and Great Britain of 5.4 GW:

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[2] The rules of the French capacity mechanism define periods of the year (known as PP1 and PP2 days) over which capacity obligations are calculated. These periods can be up to 25 days a year. On these days, capacity obligations are calculated over the periods [7am; 3pm[and [6pm; 8pm[, i.e. 10 hours a day. Over the year as a whole, capacity obligations are therefore calculated over periods of up to 250 hours per year.

$$Utilization\ rate_{FR,\ 1st\ interco} = \frac{\sum_{\substack{250\,h\ of\ highest\ residual\\ load\ in\ FR}} \max\left(flow_{GB\rightarrow FR}(t) - 4\ GW, 0\right)}{1{,}4\ GW * 250\ hours}$$

For the second interconnection project (with an assumed capacity of 1.2 GW), the utilization rate at times of high residual load in France is therefore calculated as follows, based on the simulation with an interconnection level between France and Great Britain of 6.6 GW:

$$Utilization\ rate_{FR,\ 2nd\ interco} = \frac{\sum_{\substack{250\,h\ of\ highest\ residual\\ load\ in\ FR}} \max\left(flow_{GB\rightarrow FR}(t) - 5{,}4\ GW, 0\right)}{1{,}2\ GW * 250\ hours}$$

Utilization rates are also calculated for Great Britain. The two main differences are that the hours considered for the calculation are the 250 hours of highest residual load in Great Britain (which are not necessarily the same hours as in France), and that the interconnection flow considered is the flow from France to Great Britain.

Figure 46 illustrates the contribution to security of supply of the interconnector from the French point of view. On average over the three scenarios, the first additional interconnector with Great Britain contributes 58% of its maximum capacity in 2030 (and 51% for the second interconnector project) to meeting peak electricity demand. In 2040, the contribution of the first additional interconnector with Great Britain varies between 55% and 76% of its maximal capacity.

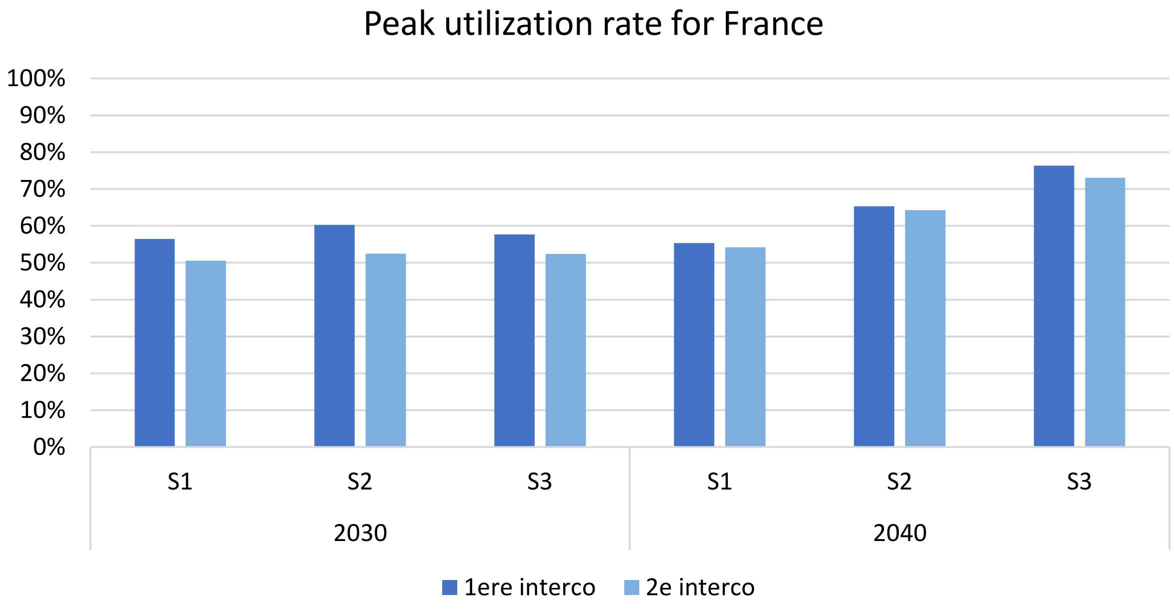


Figure 46 - Average utilization rate of the additional interconnection in the Great Britain to France direction, during the 250 hours of highest residual load in France

Figure 47 illustrates the contribution to security of supply of the interconnector from the British point of view. In 2030, the contribution to security of supply of the additional interconnectors from the UK viewpoint is lower than the contribution to security of supply from the French viewpoint. On average, the first additional interconnector with France contributes only 14% of its full capacity to meeting peak UK residual load. This is due to the oversized nature of the British generation mix.

In 2040, the contribution to security of supply of the interconnector from the UK's viewpoint varies greatly between the scenarios. It is high in scenarios 1 and 2, but low in scenario 3 (scenario of delayed development of renewable capacity and continued use of fossil-fired generation capacity).

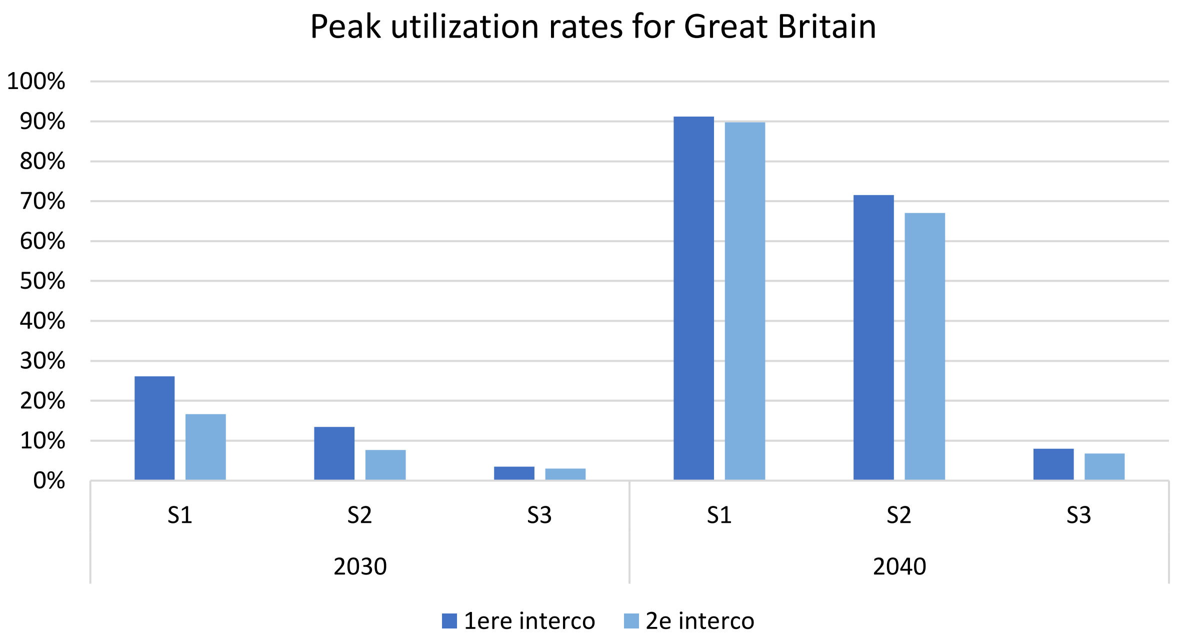


Figure 47 - Average utilization rate of the additional interconnection in France to Great Britain direction, during the 250 hours of highest residual load in Great Britain

3 Risks for interconnections linking France and Great Britain

The decision to increase interconnection capacity between France and the UK can only be based on the techno-economic analyses described above. Special attention must also be paid to the risks inherent in the planning, construction, and operation phases of interconnections. In this section, different points of analysis relating to technical and financial uncertainties of interconnection projects are dealt with to better understand the circumstances likely to degrade the value of such interconnection projects for the community.

The aim of the analysis presented in this section is to characterize levels of risk associated with each of these issues, and to determine if considering these risks can have an impact on the analysis of the relevance of developing additional interconnection projects between France and Great Britain.

Risks considered and analyzed in this section are:

- **Technological risks,** linked to the maturity of the interconnection technologies envisaged.
- **Supply risks,** concerning the components needed to build interconnections.
- **Risks relating to the social and political** suitability of interconnection projects, which could lead to their delay or even cancellation.
- **Risks associated with sub-optimal operation of interconnections,** especially since the unbundling of electricity markets that occurred following the Brexit.
- **Risks of unavailability of interconnections.**
- **Risks associated with internal network congestion.**

Analysis of these risks was based on a literature review and interviews with Artelys experts who are regularly involved in these topics. Documents published on the three interconnection projects between France and Great Britain currently under study were analyzed. These projects are :

- **GridLink interconnection project** with a capacity of 1.4 GW (ENTSO-E, 2023).
- **AQUIND interconnection project** with a capacity of 2*1 GW (ENTSO-E, 2023).
- **France-Alderney-Britain (FAB) interconnection project** with a capacity of 1,25 GW (ENTSO-E, 2023).

3.1 Upstream risks in the development of interconnections

3.1.1 Low technological risks

Technological risks cover all issues related to the industrial maturity of the interconnection technologies envisaged. They cover both **issues of technological maturity of components** (cables, converters, etc.) **and construction work** (cable laying, converter station construction, etc.). Risks are considered low for interconnection projects between France and the UK. This type of infrastructure is widely deployed in the English Channel, and all the technologies involved, from the manufacture of individual components to the construction of the line, have been mastered.

Technological maturity

All the projects mentioned above are based on technologies already widely used in existing power interconnections between France and Great Britain. They all involve two converter stations, high-voltage direct current (HVDC) land cables and high-voltage direct current (HVDC) sea cables. Their length is shorter than that of the IFA2 interconnector (see Table 3), commissioned in January 2021 (NationalGrid, 2021). The converters are Voltage Source Converters (VSC), relatively recent technology (less than 20 years old) but well mastered (GridLink Interconnector Limited, 2020). Finally, GridLink is offering to use marine cables operating at 525 kV. Although this technology is more recent than 320 kV cables, it has already been used for the North Sea Link interconnector (OFGEM, 2016) commissioned in 2021, and planned for NeuConnect (Prysmian Group, 2022), a project currently in the approval process. **The risk associated with technological maturity is therefore assessed as low.**

	Existing interconnection			Interconnection project		
	IFA2000	IFA2	ElecLink	GridLink	AQUIND	FAB Link
Commissioning date	1986	2021	2022	2025	2026	2030
Power (en MW)	2 * 1 000	1 000	1 000	1 400	2 * 1 000	1 250
HVDC submarine cable lenght (in km)	45	200	0	140	182	170
Length of HVDC land cable (in km)	25	25	69 *(including 51 km in the Channel Tunnel)*	13,5	56	40
Voltage (en kV)	270	320	320	525	320	320
Converter type (VSC = Voltage Source Converter LCC = Line Commutated Converter)	LCC	VSC	VSC	VSC	VSC	VSC

Table 3 - Technical characteristics of existing or planned France-UK power interconnections

Sources : IFA2000 ((RTE, s.d.) ***and*** (GridLink Interconnector Limited, 2020)***), IFA2 (*** (Prysmian Group, 2023) ***and*** (RTE, 2023)***),ElecLink*** (GetLink Group, 2019)***, GridLink (*** (ENTSO-E, 2023) ***and*** (GridLink Interconnector, 2021)***), AQUIND*** (ENTSO-E, 2023)***, FAB Link (*** (ENTSO-E, 2023) ***and*** (FAB Link, 2018) ***et*** (FAB Link Ltd, 2016)***)***

Focus on hybrid interconnections

Against a backdrop of strong growth in offshore wind generation capacity and electricity interconnections, a new type of interconnection is emerging: hybrid interconnections, linking several countries and offshore wind power plants simultaneously. Interconnections have a dual purpose: to bring wind power to the coast, and to enable the flow of electricity between market areas.

Several projects of this type between Great Britain and continental Europe are currently under study, including:

- ***Nautilus*** linking Great Britain and Belgium, scheduled for 2029 (ENTSO-E, 2023). Initially conceived as a classic electrical interconnection, ***Nautilus*** is now being designed as a hybrid interconnection (ACER, 2021).
- ***LionLink*** linking Great Britain and the Netherlands, scheduled for 2030 (ENTSO-E, 2023).
- ***TritonLink*** linking Denmark and the Netherlands, scheduled for 2031 (ENTSO-E, 2023).

While no hybrid interconnection project is currently envisaged between France and Great Britain, this technology was mentioned in 2015 for the FAB Link project, before being rejected in 2017 for technical reasons. (RTE).

The first European hybrid interconnector (**Kriegers Flak project - Combined Grid Solution** project) was inaugurated in October 2020 in the Baltic Sea. It links Germany and Denmark. The implementation of this project required the development of innovative technologies, including a Master Controller for Interconnector Operation (MOI), a digital control unit, harmonizing offshore power generation and market requirements. In addition, as the East German and German transmission grids are not synchronized, a converter station consisting of two converters (AC-DC-AC) was installed in the Bentwisch substation, ensuring the transfer of energy between the two zones (Russel, 2020).

If hybrid interconnection projects between France and the UK were to be developed, the current risk analysis would have to be reviewed, and take into account the risks associated with the structure of offshore market areas (due to the UK's exit from the European single market).

Cable construction

Risks associated with the construction of interconnections between France and the UK are also considered low, due to the shallow depth and nature of the seabed.

Maritime routes may require cable protection methods and preliminary soil treatment. These techniques are generally mastered, although not always sufficient: a drifting boat, for example, ripped out the IFA 2000 cable during a severe storm in November 2016 (RTE, 2020).

Cable protection depends mainly on the nature of the seabed. When the ground allows it (in soft soil), silting is preferred. In rocky or stony areas, to avoid hooking, cables are protected by riprap (GridLink

(GridLink Interconnector Ltd, 2021)) or encase (FAB Link (RTE, 2016)). If the cable crosses other cables, it must be protected with concrete mats.

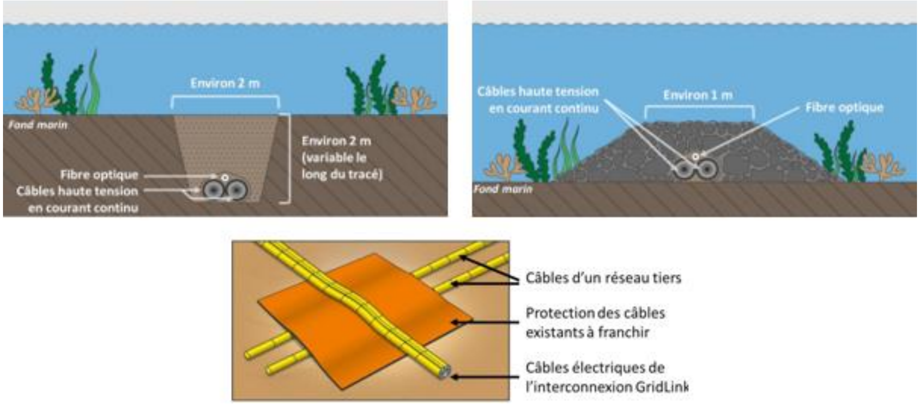


Figure 48 - Protection techniques envisaged for the GridLink interconnection (top left: silting, right: riprap, bottom: concrete mattress).
Source of illustration: (GridLink Interconnector Ltd, 2021)

Projects for the interconnection between France and Great Britain also mention technical constraints during ground preparation. Soil pre-treatment involves removing the main obstacles along the route. A pre-sandblasting step is also necessary to embed the cable in a portion of non-mobile sediment, reducing the risk of the cable being uncovered during a sand movement ((GridLink Interconnector Ltd, 2021), (AQUIND Ltd)).

3.1.2 Supply risks: short-term shortages unlikely, but sharply rising costs

With the rapid development of renewable energy and electrical interconnections, the supply of some components is becoming a major challenge. **The risk of shortages of the main components needed for interconnections is considered low by 2030, but the impact of growing demand is already being felt in terms of project costs.**

Shortage risks

Shortage risk, assessed as low in the short term, concern the whole supply chain: raw materials, processed materials, and manufactured products.

Reserves at constant consumption are substantial: 40 years for copper and 80 years for the bauxite from which aluminum is extracted (Commissariat général au développement durable, 2020). However, consumption of these materials is expected to rise sharply in the medium term, to ensure the development of electricity transmission infrastructures (both onshore and offshore) and guarantee the connection of renewable energy production fleets (BloombergNEF, 2023). n addition, magnesium and silicon are among the critical materials identified by the European Union (Commission européenne, 2020) mainly due to Europe's dependence on imports: 100% of magnesium and 63% of silicon are imported (Commission européenne, 2020), and the strong growth in demand forecast for these materials, as a result of the energy transition. For example, according to the IEA's "Announced Commitments Scenario", demand for silicon is set to double by 2030 (IEA, 2022).

As regards processed materials, there is a risk that European production of high-permeability grain-oriented electrical steel, used in transformers, will not be able to meet demand in the short term. The main European manufacturers are ThyssenKrupp Electrical Steel (DE), Orb Electrical Steels (UK), ArcelorMittal Frydek Mistek (CZ) and Stalprodukt (PL) (Trinomics, 2021).

Finally, there is a supply risk for manufactured products, resulting in saturation of production units. Converters are mainly produced in Denmark, China and the United States. Since Europe has some major producers, such as Siemens and ABB, no industrial saturation has been identified in 2018. However, China is a leader in the development of converters for the hybrid interconnections mentioned above. (Trinomics, 2021).

As for HVDC cables, the main manufacturers are Prysmian (IT), General Cable (USA) and Nexans (FR). The production capacity of European manufacturers should be sufficient for the projects considered by TYNDP 2018. (Trinomics, 2021). However, the cable industry is already stretched and has slowed down some projects. For example, for the NeuConnect project, only three companies responded to the four lots of the invitation to tender for cable manufacturing (including one bid that was deemed inadmissible because it could not meet the deadline). Thus, NeuConnect, which had expected to have its cables manufactured simultaneously in four factories, found itself forced to have them manufactured by just two companies, causing delays (OFGEM, 2022).

Special case of the interconnection between the UK and Morocco

An ambitious interconnection project between the United Kingdom and Morocco is currently under study. The plan is to link the two countries via two 3,800 km undersea cables, for a total exchange capacity of 3.6 GW. As cable production capacity is insufficient to meet this demand, the Xlinks group in charge of the project has set up a subsidiary to manufacture the cables. Production is scheduled to start in 2025. (XLCC, 2022).

If many projects of this kind continue to develop, the cable supply chain is likely to become even tighter.

Interconnection costs rising sharply

While risks of supply disruptions (shortages) are considered low, the costs of interconnector components are rising sharply. For example, the budget for the Celtic interconnector between France and Ireland has risen by 530.7 million euros following the results of the tender for its supply. It now stands at 1,482 million euros (CRE, 2022). The cost of the Bay of Biscay interconnection project between France and Spain has also risen, from 1,750 to 2,850 million euros (CRE, 2023). **The sharp rise in costs represents a risk for the development of interconnection projects.**

The increase in interconnection project costs is due to the rise in raw material prices, and the high demand on production units. Between January 2021 and March 2022, the price of copper increased by 34%, compared with an average increase of 2% in the 2010s. Over the same period, aluminum prices increased by 76%, compared with 1% in the 2010s. This rise can be explained by growing demand, limited supply, and the disruption of supply chains by the geopolitical context (AIE, 2022) In addition, the progressive saturation of manufacturing capacity is driving up component production costs.

3.1.3 Social and political acceptability: a significant risk

Obtaining permits is a critical stage for interconnection projects. This step can lead to route modifications, resulting in delays or even project cancellations. **This risk is significant and has already occurred on several interconnection projects.**

Difficulties in obtaining authorizations

Complex studies and the stakes involved in the projects can sometimes cause delays in getting permits. The average time required to obtain authorizations for PCI transmission projects is 3.5 years in 2022 (ACER, 2023), against 3 years in 2019 (ACER, 2020) Furthermore, obtaining authorizations depends on the way public institutions operate. A change in the decision-making authorities may therefore lead to delays.

Local opposition

Projects can also be suspended due to local opposition. For example, the British Secretary of State Kwasi Kwarteng refused to approve the AQUIND project on the English side due to local community pressure(Department for Business, Energy & Industrial Strategy, 2022). The reasons for this decision included:

- Damage caused to protected monuments.
- Negative impact on tourism.
- Lack of consideration for other alternatives.
- Delay incurred by work to protect an area exposed to rising water levels.

The North-South Interconnector project between Ireland and the UK has also been the subject of several lawsuits, resulting in significant delays (EirGrid, 2023). For instance, the North East Pylon Pressure Campaign Ltd has appealed the decision to issue planning permission for the project on the Irish side (Cour Suprême irlandaise, 2019).

Change of route

Socio-political restrictions can also lead to changes in project routes. New feasibility and environmental impact studies are then required, **causing delays.**

The Celtic interconnection between France and Ireland, for instance, was delayed following the relocation of the Irish converter station (ACER, 2021). Initially planned at Kilquane (Eir Grid Group, 2020), it was finally placed at Ballyadam in November 2020, on the basis of the results of feasibility studies and the expression of local preferences (EirGrid, 2023).

International relations

Finally, as electricity exchanges are international issues, political differences between countries can affect interconnections, both during the development phase and the operational phase. This represents a high risk for interconnections.

The United Kingdom's exit from the European Union, and thus from the Single Day Ahead Market, has led to a decoupling of electricity markets between France and the UK. The decoupling and resulting reduction in traded volumes may result in a reduction in the social welfare, which is quantified in Section 3.2.1.

Recently, two interconnection projects between Norway and the UK (one already commissioned) have been restricted by Norwegian energy policy: the capacity of the North Sea Link interconnector (commissioned in 2021) has been reduced from 1,400 MW to 1,100 MW (Stattnet, 2023) and the North Connect project (initially scheduled for commissioninzg by 2027 (ENTSO-E, 2022)) has been refused the permits required on the Norwegian side.

These decisions are part of a process to control hydraulic reservoirs, with the objective of securing the country's electricity supply. These new regulations extend the power of the Norwegian state, which until now has only been authorized to dispatch reservoirs in the event of rationing (Ministère Norvégien du Pétrole et de l'Energie, 2023). The Norwegian government would like to see these measures implemented before the winter of 2023/2024.

3.2 Downstream risks in the operation of interconnections

The operation of interconnections also presents risks that can affect the expected returns of projects. These are represented on three levels: risks linked to the sub-optimal operation of interconnections, risks stemming from the unavailability of interconnections, and risks associated with congestion of domestic grids**.**

3.2.1 Risks associated with the sub-optimal operation of interconnections are limited

Suboptimal electricity trade between France and the UK

Before Brexit, both France and the UK were part of the European electricity market, and especially the Single Day Ahead Coupling (SDAC). Under this system, all market players submit their purchase or sale bids on different platforms, which then collect all the bids in order to optimize the operating efficiency of the different generation, storage and transmission assets. The market matching algorithm establishes an equilibrium price that maximizes the social welfare of the bidding zones, considering interconnection capacities. Exchange capacities are allocated according to a method known as implicit matching.

Due to Brexit, the UK has left the SDAC. The level of flow optimization between Great Britain and the European countries has been degraded**. Electricity exchanges are conducted through explicit auctions**: participants buy interconnection capacity to exchange electricity the following day. These purchases are made daily before the SDAC and are therefore based on price prediction.

This could lead a player to make a wrong prediction concerning the direction in which prices will differ. He may want to import electricity from the country where electricity is most expensive to the country where electricity is cheapest. **If the risk of error is too high**, players may decide not to buy interconnection capacity. **Some interconnection capacity may not find a buyer**. In this case, the interconnector is under-utilized, leading to a shortfall in the overall social welfare.

This is illustrated in the following graphs. In the graph on the left, before market separation, trade flows are always in the direction of price differentials. In the graph on the right, the spread points represent these transverse flows and sub-optimal exploitation of the interconnection. Differences reflect errors in price prediction.

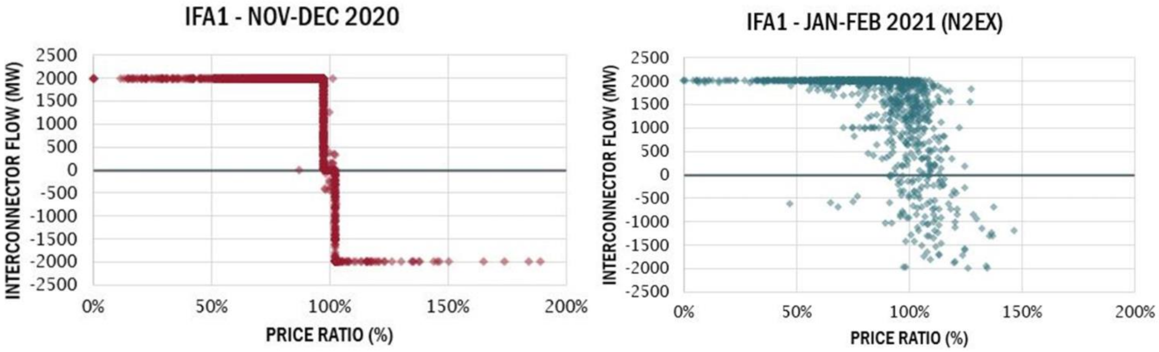


Figure 49 - Exchange capacity flows based on price differentials

Images source: (Frontier Economics, 2021)

Since then, the European Union and the UK have been working on a system to minimize the impact of market decoupling: Multi-Region Loose Volume Coupling (MRLVC).

Economic consequences of suboptimal exchanges

The Artelys Crystal Super Grid model built to assess the economic benefits of new interconnection projects does not consider the sub-optimal exchange of electricity between Great Britain and its neighbors.

Nevertheless, other studies have estimated the economic consequences of suboptimal exchanges the estimates of the resulting economic losses produced by these studies do not put the profitability of the projects into question.

According to an analysis by Frontier Economics, decoupling of the Day Ahead Market implied an estimated £45 million lost value in trade for all UK interconnections in 2021 (Frontier Economics, 2021), i.e**., £7.5 million per GW of interconnection**. This result is an estimate based on observations of induced losses on the IFA 2000 interconnector in the first two months of 2021.

Another study, by Bowei GUO and David NEWBERY, estimates the social cost of decoupling the European and British electricity markets on the IFA 2000 interconnector at €15.6 million per year (Guo & Newbery, 2021) or €7.7 million/GW. This result is based on forecasting methods for the electricity price differential between the two countries. An ex-post comparison of these predictions with actual trading in the second quarter of 2021 showed that the model's estimate was pessimistic compared with the actual economic losses observed: in the second quarter of 2021, the economic losses observed were 2.17 M€, compared with the 7.98 M€ expected in the model. The 7.7 M€/GW is a high estimate of losses due to market decoupling.

Moreover, the economic losses induced by market decoupling are tending to be **reduced with the introduction of Multi-Region Loose Volume Coupling (MRLVC).**

La Figure 50 illustrates the impact of unoptimized exchanges on the present value of the benefits expected from the first interconnection project over the whole discounting period, **using an estimate of decoupling losses of 5 M€/GW/year.** Based on these assumptions, the present value of interconnection project benefits over its entire discounting period is reduced by only 2% to 3%, according to scenarios in comparison with the result of the model assuming perfect market coupling. **The impact of decoupling on interconnection profitability is minimal.**

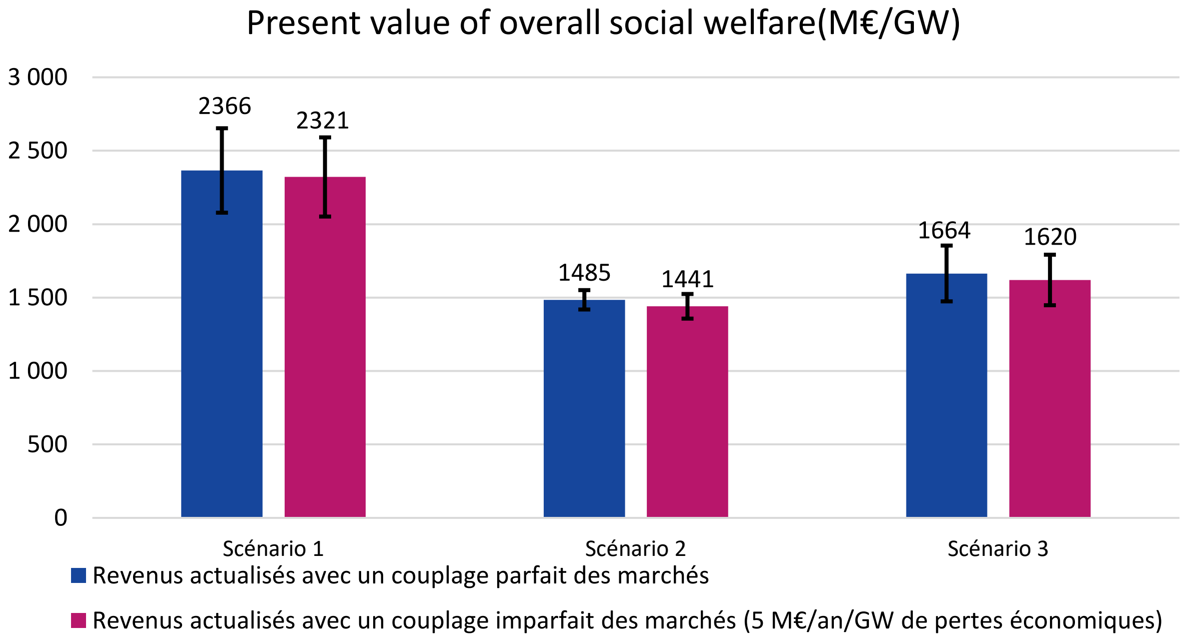


Figure 50 - Sub-optimized impact of exchanges on the present value of the first interconnection project benefits on the overall duration, including an average availability of 95%

Focus on Multi-Region Loose Volume Coupling (MRLVC)

Multi-Region Loose Volume Coupling is an implicit mechanism for allocating capacity. This coupling takes as input the volumes entered in the order book of the SDAC and the Great Britain Day Ahead Market. It deduces a cross-border flow that will be used as an input to SDAC.

There are two options for setting up the MRLVC: the common order book and the preliminary order book.

Using a common order book means that the MRLVC waits for the SDAC auctions to close. This means that all order book volumes are available to the MRLVC. However, this configuration requires the SDAC to wait for the MRLVC to finish before launching its optimization calculation, which would involve a change in SDAC deadlines and/or procedures.

Using a preliminary order book would limit the impact of the MRLVC on the SDAC. It would take as input the volumes entered a few minutes before the closing of the SDAC, which would correspond to the closing of the British Day Ahead Market. This would ensure that MRLVC data is available before SDAC is calculated.

Finally, a shared order book results in a higher overall social welfare but has a significant impact on the SDAC. In contrast, the preliminary order book is less restrictive, but also less attractive economically. The preliminary order book is also prone to auction manipulation, where a player could intentionally change its bids once the MRLVC calculation has been launched.

Figure 51 illustrates that the MRLVC could reduce economic losses due to market decoupling by 80 to 95%.

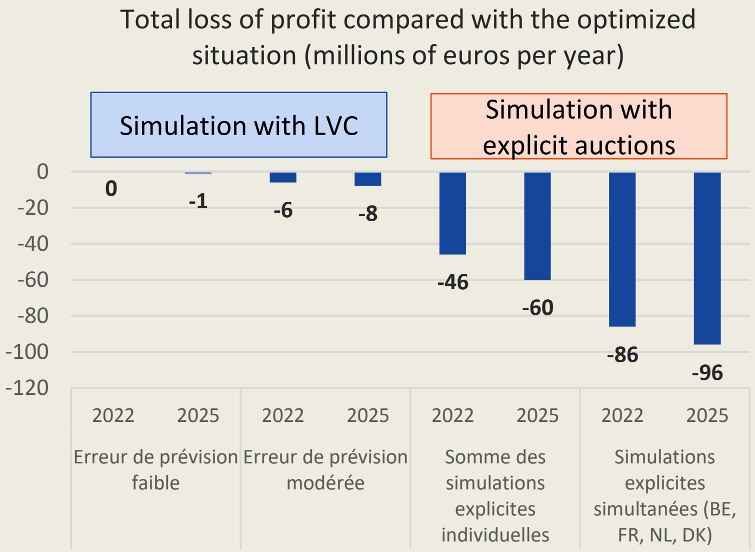


Figure 51 - Estimation of total profit losses in Loose Volume Coupling and explicit auction simulations

Source: Figures taken from (CEPA LLP, 2021)

3.2.2 Risks associated with low interconnector availability are moderate

An interconnector can become unavailable as a result of:

- A unilateral reduction in interconnection capacity by its operator, as described above between Norway and the UK.
- Planned, unplanned maintenance or failure.

<u>**Unavailability risk due to breakdown or maintenance**</u>

Unavailability of an interconnection may be due to a breakdown, maintenance or even unavailability of the internal electrical grid. **This phenomenon can reduce the overall social welfare gains resulting from increased interconnection capacity**. Figure 52 shows the availability of existing interconnections between France and Great Britain from 2021 to 2023.

Except for major damage, the average availability of interconnections is 95%. However, extended unavailability can occur in case of a serious accident. For example, the IFA 2000 interconnector was reduced to 1 GW (out of 2 GW installed) in September 2021 due to a fire in the UK converter station (National Grid, 2021) It took more than a year for the interconnector to return to full power.

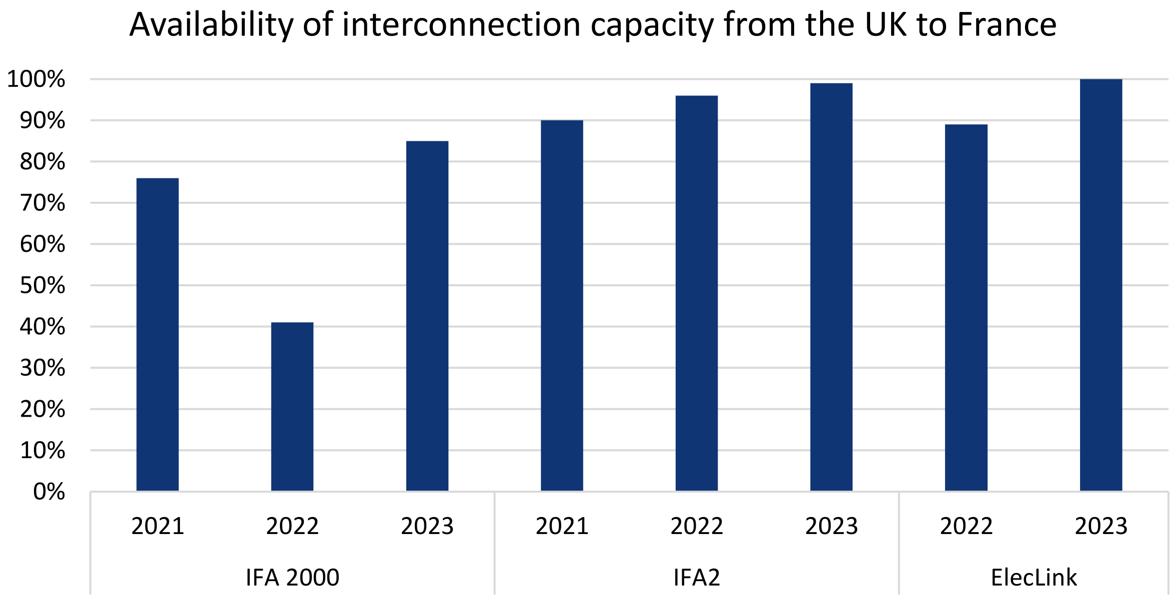


Figure 52 - Availability rate of interconnection capacity from the UK to France for the three interconnections in operation
Source: (ENTSO-E, 2023)

To assess the impact of major damage on the present value of interconnection project benefits, it has been assumed in all three scenarios that the interconnection is subject to major unavailability (represented by a total absence of benefits in one year), with still an average availability of 95% in the other years. These assumptions are shown in Figure 53.

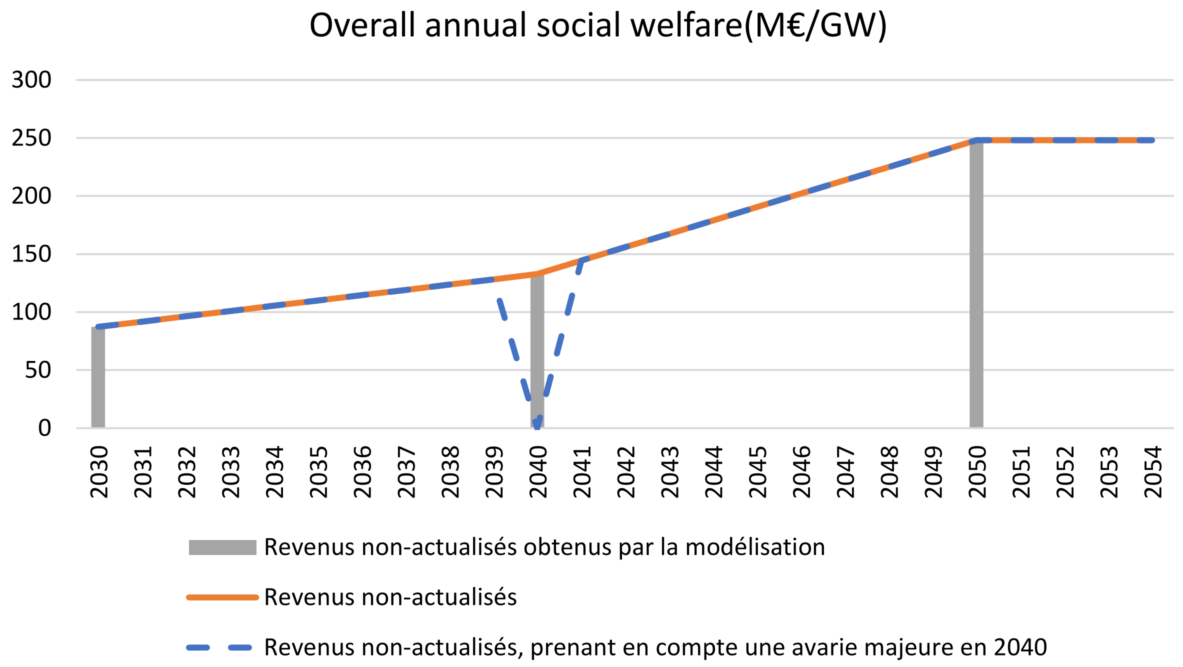


Figure 53 - Interpolation of theoretical and expected annual benefits, assuming low interconnection availability (scenario 3)

Figure 54 compares the theoretical present value of expected benefits with the present value expected in the case of major damage to the interconnection. The present value of benefits is then reduced by 3% to 4%, depending on the scenario.

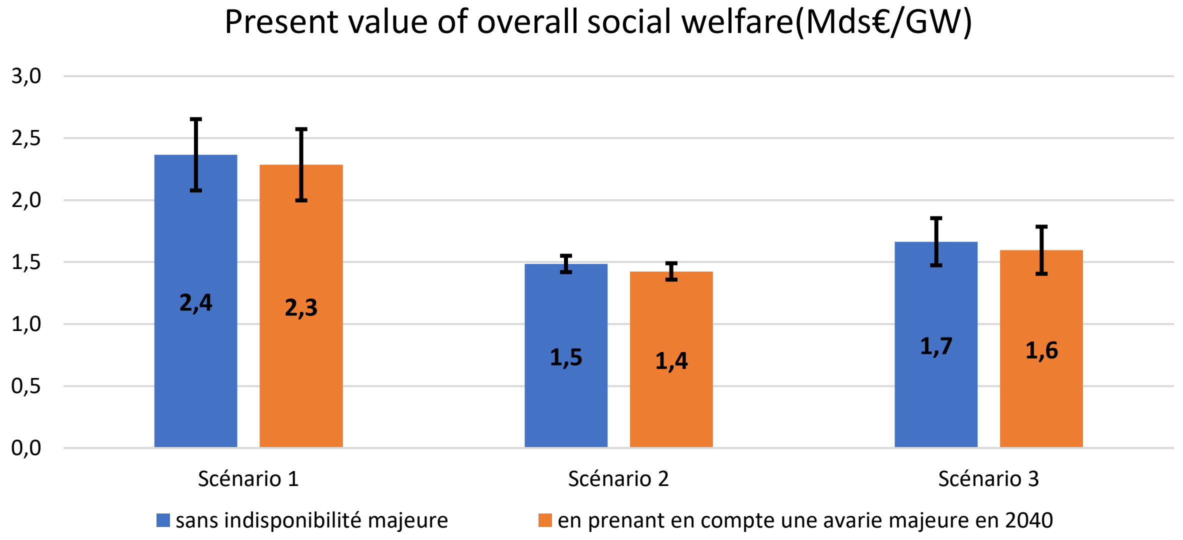


Figure 54 - Theoretical present value of expected benefits and expected present value assuming 95% availability of interconnection and one year without benefits, for the first additional interconnection

3.2.3 Risks associated with congestion of domestic networks are significant

Risks associated with internal grid constraints can be seen at two levels. On one hand, developing interconnections may require reinforcement of internal grids on either side of the border. These reinforcement costs must be considered when the decision is made to develop interconnections. On the other hand, significant congestion on either side of the border may limit flows over the interconnection, and thus reduce the economic benefits of interconnections relative to the estimated values in this study.

Risk of internal congestion in the UK grid

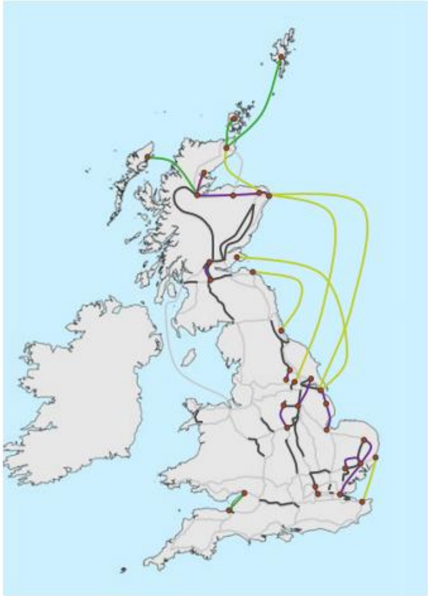
In the UK, areas of grid congestion are mainly located on the UK-Scottish border. This situation is likely to increase with the development of wind power in the North Sea, if the planned reinforcements are not implemented. While electricity demand is mainly located in the south of the country, wind power generation capacity is developing mainly in the north of the country, **generating increasing the flows from the north to the south of the UK.**

Internal congestion in the UK grid, leading to an incapacity to transport electricity from wind power generation sites to the interconnection points with France, located in the south of Great Britain, would reduce the benefits that could be generated by interconnections between France and Great Britain. Indeed, the quantitative analyses presented in section2.1.1 show that a significant part of the value of new interconnection projects comes from the ability of the new lines to bring British wind power generation to continental Europe.

The south-east grids in the North London region also require closer attention. New interconnections and growing London demand could lead to grid saturation in certain scenarios. (National Grid ESO, 2022).

To handle the increase in flows and limit congestion in its grid, National Grid is planning major grid developments, including offshore power links (see Figure 55).

In a scenario of greater development of interconnections between the UK and its neighbors, the Network Options Assessment 2021/2022 forecasts an additional need for grid exchange capacity at the UK-Scottish border of 20 GW by 2030 and 30 GW by 2035. (National Grid ESO, 2022).



Legend	
Existing grid	⬜
Upgrading the existing grid	⬛
New infrastructure for onshore grid	🟪
New offshore grid reinforcements	🟨
Other projects	🟩
Onshore substation to connect new projects	🔴

Figure 55 - Guidelines for the development of the British electricity transmission grid
Image source: (National Grid ESO, 2022)

Besides grid upgrades, other solutions are also possible to limit the cost of internal grid congestion, especially the switch from a single electricity price in Great Britain to a zonal or nodal pricing system. Switching to a zonal or nodal pricing system would reduce revenues and thus the profitability of interconnections between France and Great Britain.

While it is difficult to estimate the internal grid reinforcement costs induced by various interconnection projects unitarily, the additional grid upgrade costs for FAB Link and IFA2 have been estimated at **£42 million and £97 million respectively** (OFGEM, 2015). However, these projects could reduce congestion management costs locally (OFGEM, 2015).

Internal congestion risk on the French grid

In France, the GridLink and AQUIND interconnections plan to connect to areas already electrically loaded and identified as sensitive for RTE's internal grid. For example, GridLink's connection point is close to the connection points of the IFA 2000 and ElecLink interconnections, the border with Belgium and the Gravelines nuclear power fleet (CRE, 2021). These areas are expected to become even busier with the commissioning of new EPRs and the deployment of offshore wind power.

According to a study by RTE, the additional grid development costs would be **80€ million for GridLink and 120€ million for AQUIND,** in the PPE 2035 scenario of the Schéma Décennal de Développement du Réseau 2019 based on the TYNDP 2020 and updated over 25 years (CRE, 2021).

Appendix 1 – Assumptions and data tables

Interconnection capacities

		2030	2040	2050
British Isles import/export capacity (excluding UK-FR)	UK <-> NO	1,4	2,8	2,8
	UK <-> DK	1,4	1,4	1,4
	UK <-> DE	1,4	1,4	1,4
	UK <-> NL	1	3	3
	UK <-> BE	1	2,4	2,4
	IE <-> FR	0,7	0,9	0,9
	Total	**6,9**	**11,7**	**11,7**
France's export capacity (excluding UK and IE)	FR -> DE	4,8	4,8	4,8
	FR -> BE	4,3	6,3	6,3
	FR -> CH	3,7	5,2	6,2
	FR -> IT	4,35	4,35	5,1
	FR -> ES	5,1	8	8
	Total	**22,3**	**28,7**	**30,4**
France's import capacity (excluding UK and IE)	DE -> FR	4,8	4,8	4,8
	BE -> FR	2,8	4,8	4,8
	CH -> FR	1,4	1,9	2,9
	IT -> FR	2,16	2,16	3
	ES -> FR	5,2	8	8
	Total	**16,4**	**21,7**	**23,5**

Other assumptions

			2030			2040			2050		
			S1	S2	S3	S1	S2	S3	S1	S2	S3
FR Generation fleet	Nuclear	[GW]	59			50	50	46	29	29	25
	Gas	[GW]	11,5			5	5	11,5	0,5	0,5	9,7
	Hydrogen turbines	[GW]	0			1,6	2,9	0	18	4,5	1,8
	Onshore wind	[GW]	33	33	28	51,6	40,5	31,6	70	52	40
	Offshore wind	[GW]	5,2			33,1	19	19,1	61	36	33
	Solar	[GW]	35	35	30	93,6	61	52,5	149	90	80
	Fuel oil	[GW]	0	0	2,6						
FR demand	Electrical demand excluding electrolysis	[TWh el]	483			568	534	504	665	595	545
	Electrical demand for electrolysis	[TWh el]	25,0	25,0	10	64	37	20	103	55	30
	Electrolyzer capacity	[GW H2]	6,5	6,5	2,6	13	8,5	4,6	22	11	5,9
	Average electrolyzer load factor	[%]	30%	30%	30%	39%	36%	36%	40%	43%	43%
UK Generation fleet	Nuclear	[GW]	4,6			12	13	11	15,3	12,9	14,5
	Gas	[GW]	35,8	35,7	44,8	15,3	17,4	56,6	3,3	14,1	64
	Biomass	[GW]	1,1	0,55	0	10	9,4	2,2	11,8	10	5,2
	Hydrogen turbines	[GW]	1,2	1,38	0	10,62	14,21	0	18,8	22	1,8
	Onshore wind	[GW]	28,6	24,7	21,2	41,1	31,2	27,9	47,2	34,1	29,5
	Offshore wind	[GW]	44,5	40,4	31,3	90,6	83,6	63,1	110	98	74
	Solar	[GW]	31,4	25,2	17,3	57	43,2	27,6	79,3	57,4	34,3
	Other renewables	[GW]							7,5	8,7	4,8
UK demand	Electrical demand excluding eletrolysis	[TWh]	335	309	322	536	426	433	584	476	556
	Electrical demand for electrolysis	[TWh]	4	15,4	1	43	87	4,1	152	244	7,4
	Electrolyzer capacity	[GW H2]	0,72	2,99	0,32	6,9	17,1	0,68	26	52	1,6
	Average electrolyzer load factor	[%]	44%	41%	25%	51%	41%	49%	50%	39%	40%
Amenities prices	Natural gas prices	[€/MWh]	40			40			40		
	Carbon price	[€/t]	70			90			168		

Appendix 2 – Supplementary analysis: impact of congestion in the UK power grid on benefits of interconnection projects

Summary

Internal congestion in the UK grid could result in a significant reduction in the volume of wind power generation located in the north of Great Britain that can be exported via interconnectors with France, and thus the value of any new interconnectors on this border.

However, we are not in a position to quantify this impact, which depends on a complex combination of factors relating to UK internal grid reinforcements, potential delays to such investments, and the geographic distribution of wind power capacity across the UK.

Without claiming to quantify this impact precisely, we have conducted an additional simulation, representing an extreme situation, a kind of "worst case". This extreme situation is based on the assumption that the increase in interconnection capacity does not enable British generation to be used on the continent (i.e. the increase in interconnection capacity only takes place in the direction from France to Great Britain, the current capacity being retained for the direction from Great Britain to France).

These simulations lead to the following conclusions:

- Overall social welfare gains over the whole geographical scope are reduced by a factor of 10 to 20 for all scenarios considered by 2030, and by a factor of 4 to 6 by 2040.
- The drop in overall social welfare is mainly localized in Great Britain.
- Social welfare for France resulting from increased interconnection capacity is impacted, but to a much lower degree.

Finally, it should be pointed out that if Great Britain were subject to a significant level of internal congestion, a change in market design with the creation of regional market zones would seem possible. Such a change would have a strong impact on benefits from increased interconnection capacity between France and Great Britain (as well as on existing interconnections).

Analysis

i. Estimation of a lower bound - interconnection benefits in case of capacity increase only in the France to Great Britain direction

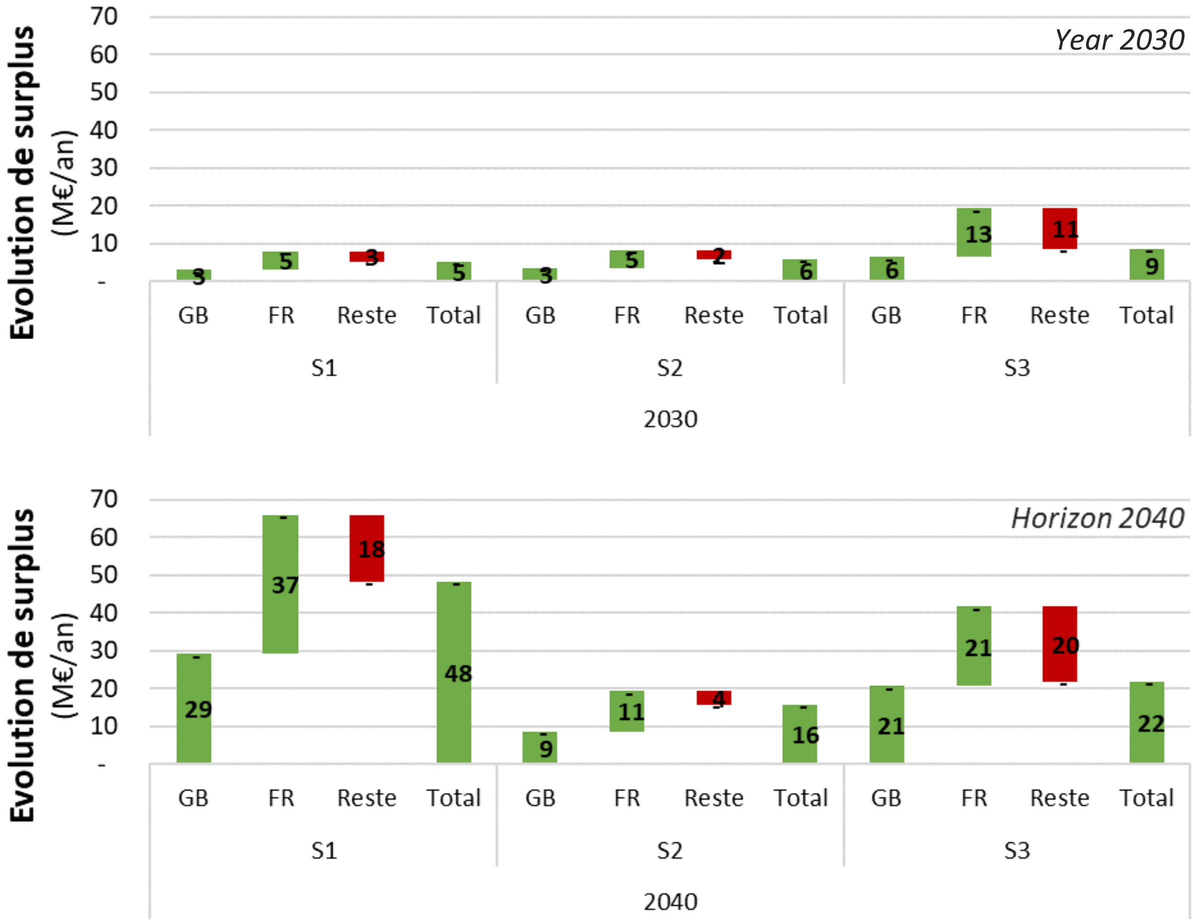


Figure 56 - Variations in overall social welfare by geographical area, for the first interconnection project, when it can only operate in the France to Great Britain direction.

The first interconnection project, operating only in the direction from France to Great Britain, generates overall social welfare gains of respectively 48, 16 and 22 M€/year/GW over the whole geographical scope in 2040.

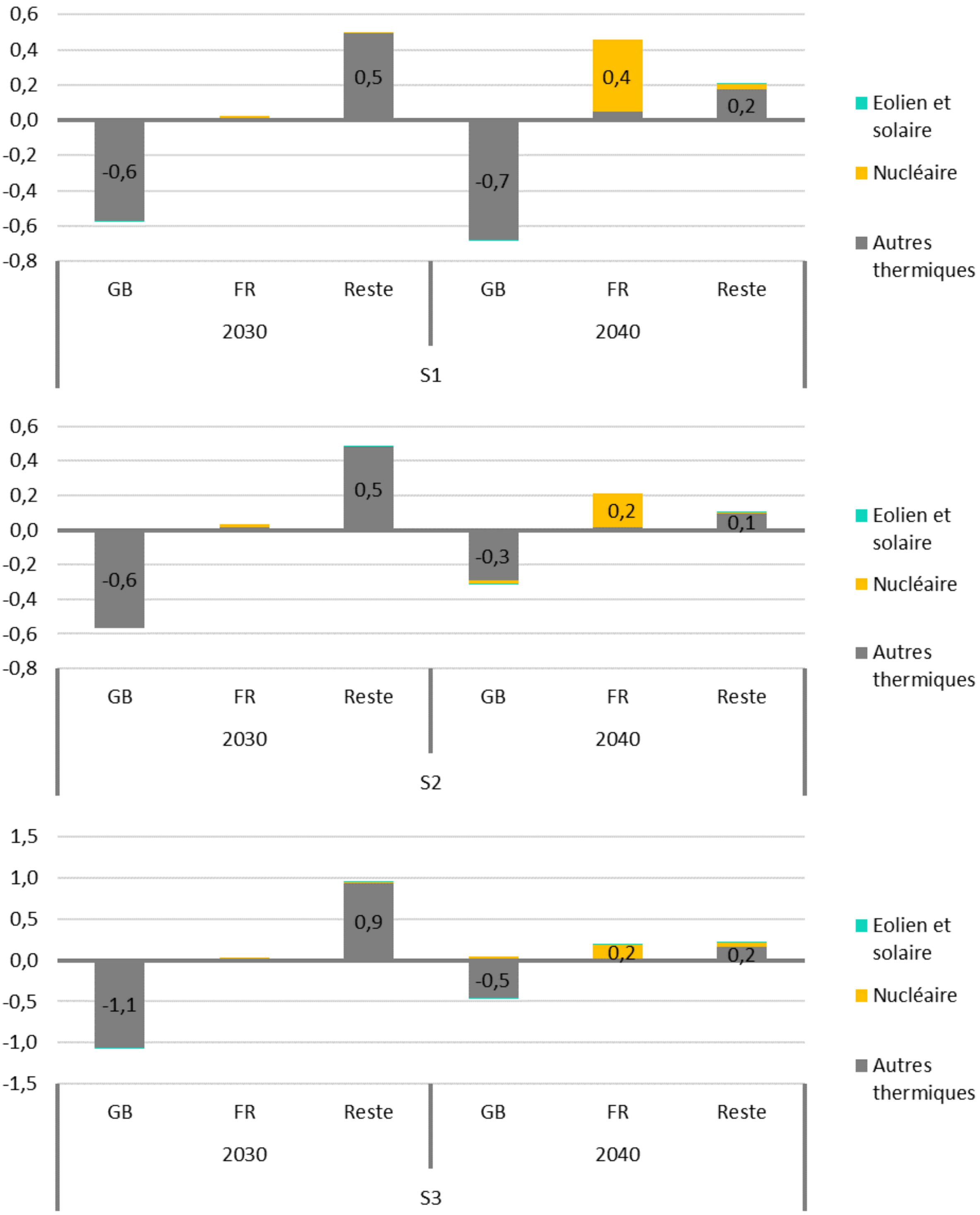


Figure 57 - Variations in generation by sector and by geographical area for the addition of the first interconnection project, when it can only operate in the direction France to Great Britain (TWh/year)

Figure 57 illustrates the variations in generation by sector and by geographical area, when the addition of the first interconnection project can only operate in the direction from France to Great Britain. By 2030, an increase in interconnection capacity will only make it possible to substitute thermal generation in Great Britain with slightly cheaper thermal generation in the rest of Europe, and in small quantities. This explains why the benefits of interconnection are limited (between 5 and 9 M€/year/GW over the whole scope).

By 2040, the increased capacity will also make it possible to increase French nuclear exports to Great Britain (to substitute thermal generation). The benefits of interconnection are therefore greater by 2040.

ii. Comparison with central scenario results

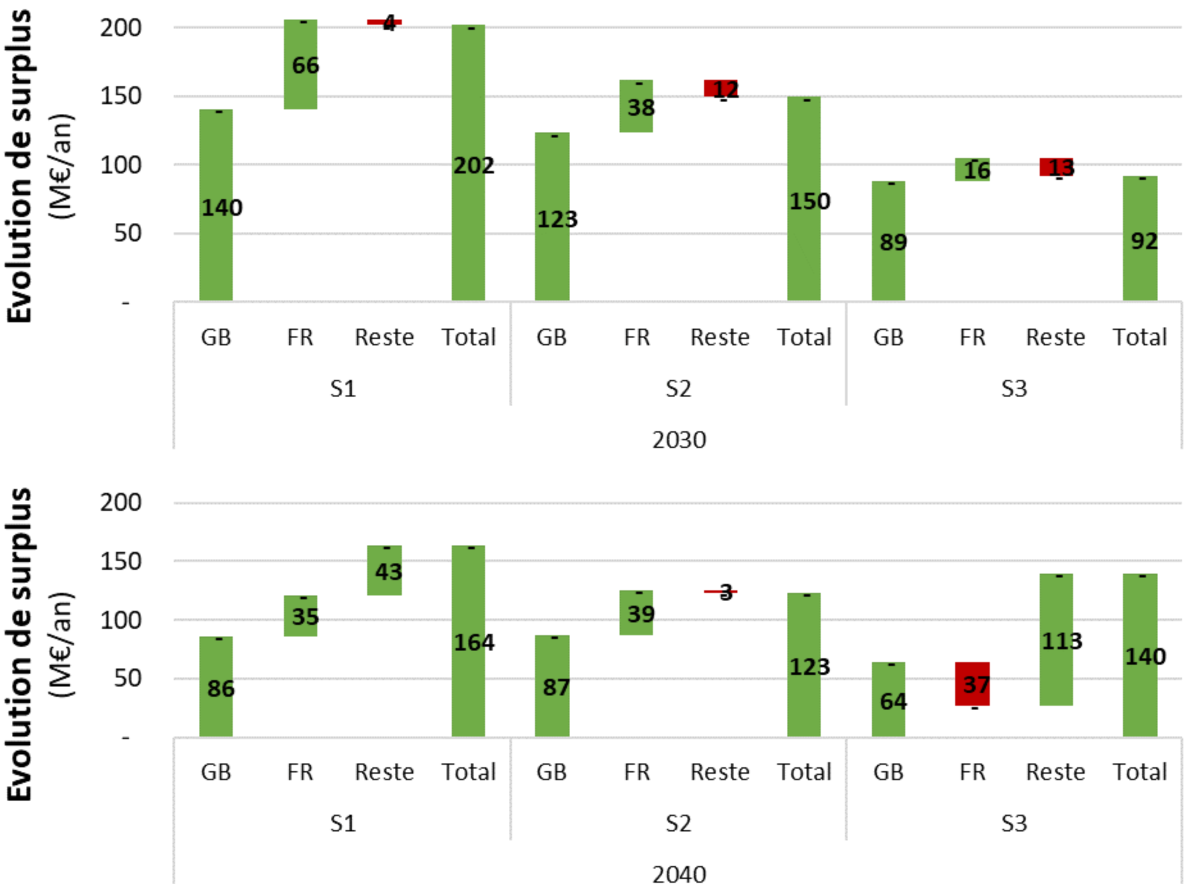


Figure 58 - Variations in overall social welfare by geographical area, for the addition of the first interconnection project, when it can only operate in both directions (results presented in the main report)

Forcing the additional interconnector to operate only in the direction France to Great Britain (which represents a form of "worst case" situation where internal congestion in Great Britain prevents any form of additional export to France) greatly reduces the overall social welfare gains. In the second scenario, they fall from 123 to 16 M€/year/GW. **In all three scenarios, the overall social welfare gain over the entire geographical scope is reduced by a factor of 10 to 20 by 2030, and by a factor of 4 to 6 by 2040.**

Nevertheless, by 2040, the impact on social welfare trends for France is less pronounced: in scenario 1, the overall social welfare gain for France increases slightly, from 35 to 37 M€/year/GW. In scenario 2, it falls from 39 to 11 M€/year/GW. In scenario 3, it rises sharply, from -37 M€ to 21 M€/year/GW.

To summarize, while increasing the interconnection capacity exclusively in the direction from France to Great Britain significantly reduces social welfare gains over the whole geographical scope, the impact on France appears to be more limited. **From the point of view of the benefits brought by a new interconnector, France thus appears to be much less exposed to the risk of internal congestion in the British network than either Great Britain or the rest of Europe.**

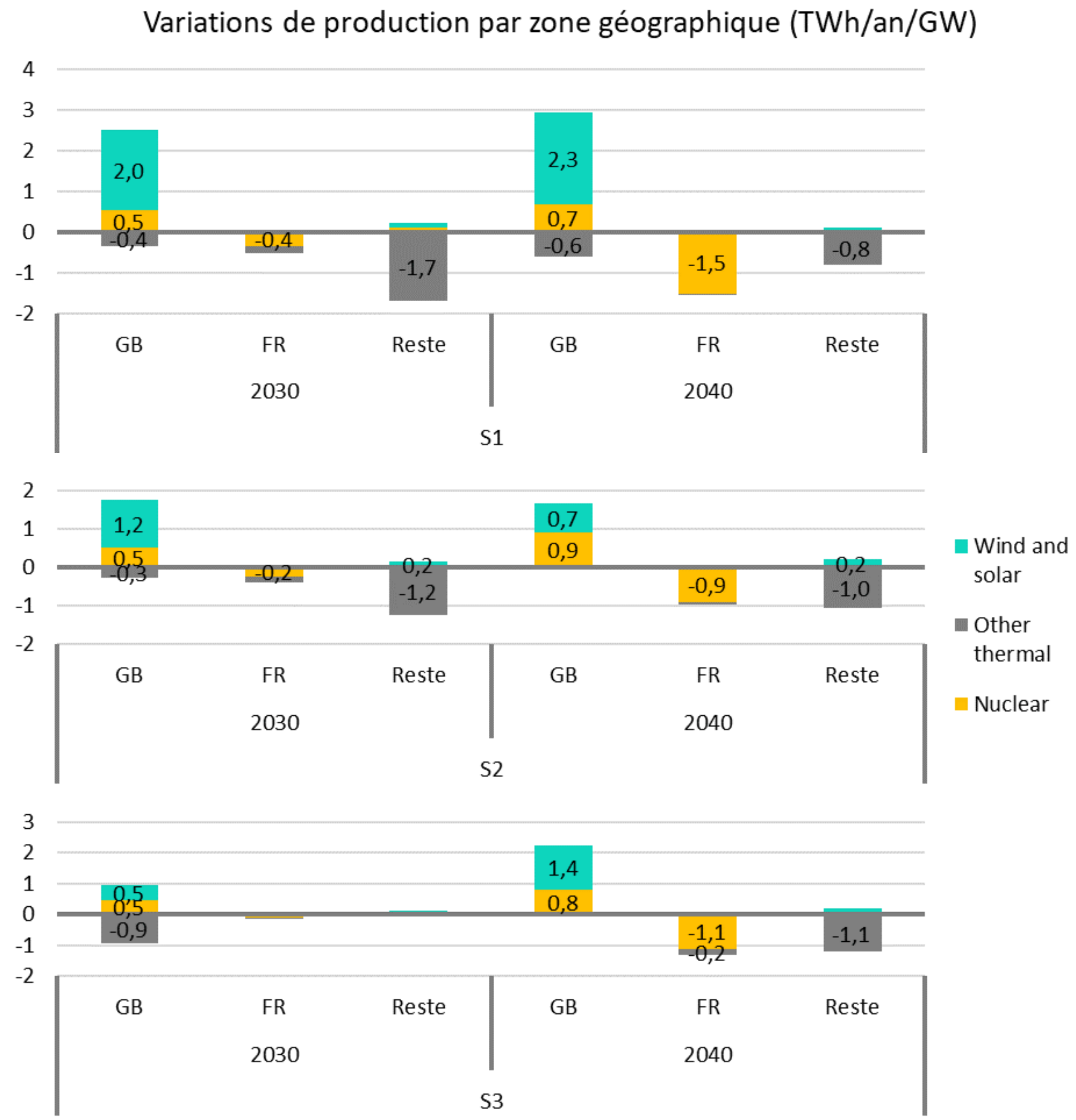


Figure 59 - Generation variations by sector and geographical area for the first interconnection project in the central scenarios (i.e., when the capacity increment is not limited to the France to Great Britain direction)

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