FINAL REPORT

# Impacts of increased electricity interconnection on achievement of Ireland’s 2030 and post-2030 climate and energy objectives

## DECC – Department of the Environment, Climate and Communications

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# 1 EXECUTIVE SUMMARY

## 1.1 Background

The Irish Government has committed to update its interconnection policy, first published in 2018, during 2023 in view of several developments, including: Ireland's increased 2030 and post 2030 climate and energy ambition, the revision of the European guidelines for trans-European energy infrastructure, and the emerging understanding of the benefits of hybrid / multi-purpose interconnectors.

It is in the context of the increased climate and energy ambition contained in the Programme for Government[1] and the Climate Action Plan[2] that the Department of the Environment, Climate and Communications (DECC) seeks to understand what the impacts of additional interconnection on Irish energy system could be in order to substantiate the update to Ireland's interconnection policy. To this end, DECC commissioned a study from DNV to identify what are the most likely implications for the Irish electricity sector from further cross-border interconnection and to indicate, based on a quantitative modelling, what are the optimal and realistic interconnection capacities with the objective of maximising socio-economic benefits.

This DNV study investigates the economic, financial, climate and technical impacts of additional interconnection capacities with three countries identified as potential candidates for interconnection with the island of Ireland's Single Electricity Market (SEM system), namely, Great Britain, France and Spain. Three study reference years are considered, namely 2030, 2040 and 2050. By 2030, an additional link with Great Britain is assumed as the only plausible opportunity for further interconnection beyond those projects currently operational or at an advanced stage of development. Towards 2040 and 2050 however, it is reasonable to expect significant growth in cross-border capacity not only with Great Britain, but also with France and Spain.

## 1.2 Findings

DNV together with DECC has selected nine metrics to evaluate each of the examined cases of interconnector capacity with respect to the economic impact for the society and the Transmission System Operators (TSOs), the overall success of renewables integration, and the guarantee of security of supply. From an extensive quantitative analysis, the following conclusions are drawn:

- Additional interconnection capacity in 2030, beyond existing projects or those at advanced development stage, has significant economic benefits for the SEM system. Developing a new interconnector with Great Britain is justified both from the developer and societal perspectives. Furthermore, it supports the achievement of Ireland's 2030 energy objectives and de-risks offshore wind development.
- The development of significant further interconnection between the island of Ireland and all countries within the study's scope by 2050 is economically justified, as it delivers sizeable socio-economic welfare gains for the SEM and other countries in scope. The impact on achieving net zero is negligible as the model shows that it would be achieved regardless. Nevertheless, additional interconnection facilitates a very significant reduction in SEM curtailment allowing it to export surplus green electricity to the countries where it is needed, and thereby de-risking renewables development. Considering the benefit-to-cost ratio of additional interconnectors with all modelled countries, DNV finds all of the 2050 connections to be economically justified and beneficial to consumers in the SEM and the connected countries. Provided they can be implemented as hybrid links and result in savings in wind farm connection costs, the connections with Great Britain are seen by DNV as the most attractive in relative terms to the investment costs.
- Sensitivity studies show that development of significant additional interconnection for the 2050 reference year continues to deliver a large increase in socio-economic welfare in a scenario where the level of renewable energy

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[1] https://www.gov.ie/en/publication/7e05d-programme-for-government-our-shared-future/

[2] https://www.gov.ie/en/publication/7bd8c-climate-action-plan-2023/

deployment underperforms against Government ambitions. These benefits impact the SEM and all countries in scope.

- Congestion revenues are a part of the SEW, yet they have been analysed separately since, from the perspective of the interconnector developer, they are an important indicator to judge the financial attractiveness of a project. DNV analysis shows that the present value of lifetime annual congestion rents on all of the assessed links outweighs the lifetime costs of building these links. In most cases, investments would pay back already in 15 years, assuming stable annual congestion rent and a 7% discount rate.
- The SEM system achieves high RES shares in the electricity generation mix even without additional interconnection capacity, which are sufficient for Ireland to fulfil its 2030 and 2050 climate objectives. The increase in RES generation share enabled by additional interconnectors is minor. Nevertheless, sizeable benefits in terms of the RES utilisation are enabled by additional interconnection capacity with Great Britain in 2030 and with Spain and France beyond 2030. In addition, interconnection allows for large reductions in the volumes of SEM RES curtailment providing export opportunities to other countries.
- Further interconnection results in a sizeable reduction in total power system costs within the SEM. Additional interconnectors between the SEM and Great Britain are beneficial in 2030 (12% reduction in SEM system costs), but cause an increase in system costs by 2040 and, depending on the interconnector capacity, by 2050. Interconnections with Spain and France yield the largest total power system savings for the SEM (up to 30%) in power system costs in 2040 and 2050, respectively.
- Whilst the study did not entail a stochastic network modelling to assess system security, DNV noted that the SEM system is expected to have a large share of variable renewables in the future. Any additional interconnector capacity, if placed strategically, will contribute to growing the portfolio of flexible capacities.  Furthermore, voltage and reactive power are expected to be a challenge too. HVDC-based interconnectors are beneficial as they often possess active voltage regulation, frequency response, grid forming and black start capabilities.
- From the cost perspective, interconnectors with Great Britain are the most attractive due to shorter distances and opportunities to develop hybrid assets. Considering the benefits, all four countries experience sizeable positive economic impacts, even in cases when they do not get directly connected with the SEM. Provided that smart agreements on cross-border cost sharing and compensation mechanisms were in place, DNV would recommend the development of interconnectors with France and Spain as economically attractive in the time period beyond 2030 and focusing on interconnection with Great Britain towards 2030.

# 2 INTRODUCTION

## 2.1 Background and objective

A first National Policy Statement on Electricity Interconnection[3] articulating the Irish Government's policy position on electricity interconnection was published by DECC in 2018. The Irish Government has committed to update its interconnection policy during 2023 in view of several developments, including: Ireland's increased climate and energy ambition, the revision to the EU TEN-E Regulation[4],, and the emerging understanding of the benefits of hybrid / multi-purpose interconnectors. It is in the context of the wider Programme for Government[5] and the Climate Action Plan[6] that DECC seeks to understand what the impacts of additional interconnection on Irish energy system could be, to substantiate the update to Ireland's interconnection policy.

Whilst the starting point for the study is the EU and Member State policies, the ultimate focus is on quantifying and modelling the future Irish system with higher levels of interconnection, beyond the existing projects and the planned Celtic (700 MW) and Greenlink (500 MW) interconnectors (ICs). The EU has established an interconnection target[7] of 15% by 2030, highlighting that each proposed interconnector project should undergo a socio-economic cost-benefit analysis to assess its value[8]. This study shall, therefore, focus on the high-level view of the potential socio-economic benefits of further interconnection and its impacts on the energy objectives set for 2030 and 2050. Ireland's 2030 objectives are to reach 80% renewable electricity with 5 GW of new offshore wind capacity and to curb the carbon emissions for electricity production between 2 and 4 million tonnes, compared to 30% and 10.1 million tonnes in 2018, respectively. The 2050 goal is to achieve climate neutrality.

With the above in mind, the ultimate objective for the project outcomes is as follows:

*"To identify what are the most likely implications on the Irish electricity sector from further cross-border interconnection. Based on a quantitative modelling, to indicate what are the optimal and realistic, given the prevailing policy, interconnection capacities with each of the countries with the objective of maximising socio-economic benefits."*

In particular, the study considers:

1. The economic rationale and the impact of further interconnection on the achievement of Ireland's 2030 energy objectives and de-risking future offshore renewables development.
2. The economic rationale for developing further interconnection and the impact of increased interconnection on achieving Ireland's longer-term energy objectives, including achieving net zero by 2050.
3. The extent to which further interconnection can contribute to the decarbonisation of Irish power generation and electricity consumed in Ireland, through the replacement of domestic fossil fuel generation.
4. The impact of further interconnection on total power system costs.
5. Security of supply benefits associated with development of further interconnection capacity.
6. Consideration of the optimal countries/markets for Ireland to interconnect with, and an analysis as to whether priority should be placed on developing further interconnection with Great Britain, the EU Internal Energy Market, or both.

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[3] https://www.gov.ie/en/publication/3e988-national-policy-statement-on-electricity-interconnection/

[4] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R0869&from=EN

[5] https://www.gov.ie/en/publication/7e05d-programme-for-government-our-shared-future/

[6] https://www.gov.ie/en/publication/7bd8c-climate-action-plan-2023/

[7] Implying that each country should have sufficient interconnection capacity to allow at least 15% of electricity produced within its borders to be exported. https://energy.ec.europa.eu/topics/infrastructure/electricity-interconnection-targets_en

[8] Regulation 2018/1999 on the Governance and Climate Action. Article 4 (d) (1) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R1999&from=EN

## 2.2 Scope and methodology of the study

Given the geographic position of Ireland, DNV selected three countries as potential candidates for an interconnection with the island of Ireland (SEM system) – Great Britain, France and Spain. Analysis on the impacts of interconnection between the SEM and alternative countries is beyond the scope of this study. Likewise, the impact of increased cross-border transmission lines between Ireland and Northern Ireland, within the SEM, are beyond the scope of this study.

In terms of the temporal scope, in line with the objectives of the study, three study reference years are considered, namely 2030, 2040 and 2050. Given the limited opportunity to significantly increase the interconnection capacity with the selected countries by 2030, it is assumed that it is only plausible to implement additional links with Great Britain, due to its proximity and experience of commissioning interconnectors between the two countries. For 2040 and 2050 however, it is reasonable to expect significant growth in cross-border capacity.

The methodology of the study has techno-economic cost-benefit analysis as its cornerstone. Within this analysis, DNV broadly follows ENTSOE CBA 3.0 guidelines, yet with less detail in some instances. In order to address the main study questions, DNV performs a number of market simulations. As a main tool for the simulations. DNV utilises its proprietary PLEXOS-based European Power Market Model. A central scenario is defined to represent the most likely development of national energy sectors in selected countries (SEM system, Great Britain, France and Spain) and their neighbouring member states. In addition, two sensitivity runs are performed to test how robust the results are. The results of the study are presented through a number of key performance indicators (KPIs), primarily based on the ENTSOE guidelines, which allow addressing the main study objective. These KPIs represent economic, financial, climate and technical impacts of additional interconnection capacities.

## 2.3 Report structure

As a foundation for the study, the report gives an overview of the study cases that will be analysed in Chapter 3. Chapter 4 reviews the national interconnection policies and other relevant documents that help to define what the realistic cross-border capacities might be in 2030, 2040 and 2050, given the prevailing policy regime, TSO plans, and system needs in each of the selected countries. Next, Chapter 5 details the scenario input data, the assumptions and the structure of the model that is utilised to perform the market simulations and evaluate the KPIs for the different study cases. Having defined what will be analysed and how, Chapter 6 presents the detailed methodology for the KPI evaluation and the results of our analysis, including sensitivities. Finally, Chapter 7 is a summary of the obtained results, including the discussion of the impacts of additional interconnection on each of the six study objectives introduced above.

# 3 THE STUDY CASES

In order to establish the foundation for the study, this section specifies the alternative interconnection configurations that will be analysed and assessed.

## 3.1 Geographic scope

Given the geographic position of Ireland, DNV and DECC agreed that for the purposes of this modelling exercise, three countries would be analysed as potential candidates for additional interconnection with Ireland – Great Britain, France and Spain. Analysis on the impacts of interconnection between Ireland and alternative countries is beyond the scope of this study.

Unless explicitly stated otherwise, Ireland and Republic of Ireland (ROI) are used interchangeably in this study, whereas all-island wholesale electricity market – the SEM - includes both Ireland and Northern Ireland (NI). The scope of this study does not include cross-border transmission lines between the two jurisdictions that comprise the SEM.

**Temporal scope**

In terms of the temporal scope, in line with the objectives of the study, two study years are considered, namely 2030 and 2050. Whilst there is a limited opportunity to significantly increase the interconnection capacity with the selected countries by 2030, it is assumed that it is plausible to implement additional links with Great Britain, due to its proximity and experience of commissioning interconnectors between the two countries. For 2050 however, it is reasonable to expect significant growth in cross-border capacity.

As the study progressed, the temporal scope has been extended to cover 2040 as well.

## 3.2 Study cases

In order to assess the impact of the additional interconnection capacity on the achievement of Ireland’s energy system and economy, DNV established counterfactual cases for 2030 and 2050. The counterfactuals are deemed to represent the cross-border capacity between the SEM and other countries that DNV assumes to be realised under the current government policy. In contrast, the “factuals” are the study cases where DNV assumes plausible additional cross-border capacity beyond currently envisaged projects to be built, but that could possibly require or be expedited by a more accommodative Irish Government interconnection policy[9]. Based on the comparison of factuals and counterfactuals, the impact of additional interconnection capacity is investigated through a set of Key Performance Indicators (KPIs), which are described in Chapter 6.

For each of the three candidate countries for additional interconnection development, potential interconnection capacities are defined. For both 2030 and 2050, this is done based on national policies and targets, as well as TSO network development plans available in the public space, which is further elaborated upon in Chapter 4.

Given the relatively short timeframe between now and 2030, a single study case is assumed for this year, noting that a limited number of candidate interconnection projects could realistically be implemented by that time. Hence, the assessment focuses on those, not expecting any new projects to materialise since it would require longer development time. For 2050 the uncertainty is higher, hence a minimum and a maximum case are considered.

As the study progressed, three study cases have been added for year 2040, one for each country. The candidate interconnection capacities have been designed to fit within the boundaries of 2030 and 2050 values and, at the same time, representing realistic potential projects.

An overview of the study cases is summarised in Table 3-1.

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[9] NB: This study makes no judgement on the efficacy of the Irish Government’s existing interconnection policy.

**Table 3-1 Overview of the study cases- Additional cumulative IC capacity for the SEM beyond EWIC, Moyle, Greenlink and Celtic. See Section 4.6 for more details.**

| Study cases | SEM-GB | SEM-FR | SEM-ES |
|---|---|---|---|
| **Counterfactual 2030** | 0 | 0 | 0 |
| **Factual 2030** | 1,250 | 0 | 0 |
| **Counterfactual 2040** | 1,250 | 0 | 0 |
| **Factual 2040** | 1,300 | 1,050 | 1,000 |
| **Counterfactual 2050** | 1,250 | 0 | 0 |
| **Factual 2050 min** | 1,300 | 2,100 | 1,500 |
| **Factual 2050 max** | 2,300 | 3,100 | 1,900 |

The assessment investigates the impacts of increased interconnection between the SEM and each country independently in order to be able to clearly attribute the impacts to a respective country and answer the question of which countries are the most optimal to connect with. In addition, simulations with all interconnectors connected at once are run for 2040 and for 2050.

# 4 POLICY REVIEW AND INTERCONNECTOR CAPACITIES

This chapter reports on the results of the policy review conducted to investigate what are the current plans and outlooks for the level of interconnection capacity in SEM, Great Britain, Spain, and France. The outcome of this review informs our study case definition by identifying plausible interconnection capacities for 2030 and 2050 for the selected countries. The interconnection for 2040 was defined based on 2030 and 2050 assumptions.

## 4.1 Summary

The result of our review is a complete envelope of defined study cases for 2030 and 2050. The underlying rationale is given further below in this section. As the study progressed, three study cases have been added for year 2040, one for each country. The candidate interconnection capacities have been designed to fit within the boundaries of 2030 and 2050 values and, at the same time, representing realistic potential projects.

**Table 4-1 Additional cumulative IC capacity beyond EWIC, Moyle, Greenlink and Celtic.**

| [MW] | SEM-GB | SEM-FR | SEM-ES | Total SEM |
|---|---|---|---|---|
| **Counterfactual 2030** | 0 | 0 | 0 | 0 |
| **Factual 2030** | 1,250 (750+500) | 0 | 0 | 1,250 |
| **Counterfactual 2040** | 1,250 (750+500) | 0 | 0 | 1,250 |
| **Factual 2040** | 1,300 (800*+500) | 1,050 (1,050) | 1000 (1000) | 3,350 |
| **Counterfactual 2050** | 1,250 (750+500) | 0 | 0 | 1,250 |
| **Factual 2050 min** | 1,300 (800*+500) | 2,100 (1,050+1,050) | 1,500 (1,500) | 4,900 |
| **Factual 2050 max** | 2,300 (750+500+1,050*) | 3,100 (1,050+1,050+1,000) | 1,900 (900+1,000) | 7,300 |

* part of a hybrid link

## 4.2 The island of Ireland (SEM system)

### 4.2.1 Documents reviewed

The following key documents have been identified and reviewed for the SEM system:

- All-Island Ten-Year Transmission Forecast Statement[10]
- Ofgem Notice of Grant of an Interconnector Licence[11]
- Mares-Connect Non-technical Summary webpage[12]
- Transmission Investment LirIC Interconnector Project[13]
- SONI & EirGrid Shaping Our Energy Future[14]
- EirGrid Tomorrow's Energy Scenarios (2019)[15]
- ENTSO-E Ten Year Network Development Plan
- DECC Electricity Interconnection Policy – Technical Consultation[16]

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[10] https://www.eirgridgroup.com/site-files/library/EirGrid/All-Island-Ten-Year-Transmission-Forecast-Statement-TYTFS-2021.pdf
[11] https://www.ofgem.gov.uk/publications/maresconnect-limited-notice-grant-electricity-interconnector-licence
[12] https://maresconnect.ie/non-technical-summary/
[13] https://tinv.com/intercon-projects/liric/
[14] https://www.eirgridgroup.com/site-files/library/EirGrid/Shaping_Our_Electricity_Future_Roadmap.pdf
[15] http://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid-TES-2019-Report.pdf
[16] https://www.gov.ie/en/consultation/ca3b4-electricity-interconnector-policy-technical-consultation/

## 4.2.2 Current IC capacity with other countries

The SEM system currently has two electricity interconnectors with a combined capacity of **1 GW**. Details of these were published in EirGrid's 2021 All-Island Ten-Year Transmission Forecast Statement in August 2022. The East West Interconnector (EWIC) is a **500 MW** HVDC link running between the ROI and Wales. The Moyle Interconnector is a **500 MW** HVDC link between NI and Scotland. Note that for the purposes of this analysis the proposed North South Interconnector between NI and the ROI has been excluded as the SEM treats this more as an internal transmission link.

**Table 4-2 Existing interconnectors with SEM**

| Project name | Connecting countries | Capacity [MW] | Delivery date |
|---|---|---|---|
| **Moyle** | NI and Scotland | 500 | 2002 |
| **EWIC** | ROI and Wales | 500 | 2012 |
| **TOTAL** | | 1,000 | |

EirGrid de-rates the capacity of Moyle and the EWIC to 60% for planning purposes, representing the availability of the interconnector and of generation in GB.

## 4.2.3 2030 planned capacity

Four more interconnectors for the SEM are projected by the project developers to be added in the next decade totalling **2.6 GW** of capacity. The planned 500 MW Greenlink Interconnector between the ROI and Wales is assumed to be in place by 2024.

EirGrid is progressing plans for the 700 MW Celtic Interconnector between the ROI and France, which has EU Project of Common Interest status and has been awarded a €530 million grant from the European Commission. It is expected to commission in 2026 and be available to the market in 2027.

There are two further proposed interconnectors at pre-construction development phase that are not widely discussed in EirGrid documents. The MaresConnect interconnector between the ROI and UK (Wales) is projected to provide 750 MW. Ofgem published a Notice to grant of an electricity interconnector licence for MaresConnect in July 2022, and according to the developer, the interconnector will be operational by 2027. There is also the proposed LirIC interconnector between NI and the UK (Scotland), which will provide 500-700 MW of capacity. It is projected to connect in 2028. It is worth noting, however, that in the 2021 edition of Shaping Our Energy Future (SOEF), SONI and EirGrid did not assume MaresConnect or LirIC to connect before 2030.

**Table 4-3 Planned interconnectors with SEM to be added by 2030**

| Project name | Connecting countries | Capacity [MW] | Delivery date |
|---|---|---|---|
| **Greenlink** | ROI and Wales | 500 | 2024 |
| **Celtic** | ROI and France | 700 | 2026 |
| **MaresConnect** | ROI and Wales | 750 | 2027* |
| **LirIC** | NI and Scotland | 500-700 | 2028* |
| **TOTAL** | | 2,450-2,650 | 2030 |

** not included in SOEF*

## 4.2.4 2050 planned and potential capacity

There is very little official documentation on the expected Irish interconnector capacity for 2050. In its 2019 Tomorrow's Energy Scenarios document, EirGrid projected one additional interconnector to GB by 2040 in one scenario, and two more in another. This document did not include MaresConnect or LirIC in its base case, so it is possible these would fulfil these needs.

DNV notes that Ireland has expressed its commitment to achieving the EU's policy on interconnection in its technical consultation on interconnector policy without explicitly stating it will meet the non-binding EU target for member states to be able to export 15% of their maximum generation output via interconnectors. DNV believes that it is reasonable to assume that Ireland will aim to at least meet this level in the future, providing a base case for assumed interconnector capacity versus assumed generation capacity. Ireland has stated it intends to build 37 GW of offshore wind by 2050 as outlined by a recent joint statement of the North Seas Energy Cooperation.[17] Some of this will be dedicated to electrolysers for hydrogen production, but there will still likely be a large onshore renewables industry as well. As of early December 2022, this is currently expected to include around 5.5 GW of solar and 8 GW of onshore wind by 2030, so Ireland will need to find export routes to European markets for this excess generation.

Based on these assumptions DNV proposes a minimum of the interconnectors already planned to connect before 2030, which includes EWIC, Moyle, Greenlink, Celtic, Mares Connect and LirIC, which totals up to 3.65 GW of capacity. Out of these, MaresConnect and LirIC will be considered as additional capacity for the purpose of this study. For a maximum value, DNV assumes that renewable capacity will be the deciding factor. Taking into account the current ambition[18] (47.5 GW of installed renewables; onshore and offshore wind, solar) and the current European interconnection target of 15% of installed capacity, a value of 7.1 GW of interconnector capacity is reached.

### 4.2.5 Hybrid interconnections

There are currently no planned Irish hybrid interconnector projects (which are defined as connecting two separate jurisdictions to a large offshore generator). However, National Grid in GB has plans through its National Grid Ventures entity to build a 1.4 GW interconnector between GB and Belgium which will give both markets access to 2.8 GW of offshore wind generation capacity.[19] For the Irish case, it is possible that a similar configuration of hybrid interconnection could be connected between Ireland and GB.

## 4.3 Great Britain

### 4.3.1 Documents reviewed

The following key documents have been identified and reviewed for Great Britain:

- GB National Grid ESO FES 2022 publication (July 2022), p179, 219[20]
- GB Ofgem Interconnector Policy Review (2021)[21]
- Ofgem Interconnectors webpage, consulted September 2022[22]
- Application Guidance for the Third Cap and Floor Window for Electricity Interconnectors (July 2022)[23]
- Energy white paper: Powering our net zero future (December 2020)[24]
- Statnett – NSL interconnector to have reduced capacity until February (June 2021)[25]

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[17] https://energy.ec.europa.eu/system/files/2022-09/220912_NSEC_Joint_Statement_Dublin_Ministerial.pdf

[18] Value provided by EirGrid during an interview conducted at the beginning of the study.

[19] https://www.nationalgrid.com/national-grid-ventures/interconnectors-connecting-cleaner-future/nautilus-interconnector

[20] GB National Grid ESO FES 2022 publication (July 2022)

[21] GB Ofgem Interconnector Policy Review (2021)

[22] Ofgem Interconnectors webpage, consulted September 2022

[23] Application Guidance for the Third Cap and Floor Window for Electricity Interconnectors (July 2022)

[24] Energy white paper: Powering our net zero future

[25] Statnett – NSL interconnector to have reduced capacity until February (June 2021)

- Future Energy Scenarios 2022 by NG ESO[26]

### 4.3.2 Current IC capacity with other countries

Great Britain's electricity market has **8.4 GW** of electricity interconnector capacity, of which **1 GW** is connected to the SEM through the Moyle IC that connects Scotland and Northern Ireland and the East West interconnector (EWIC) connecting the ROI with Wales. Table 4-4 lists existing interconnectors with Great Britain which connect with France, the Netherlands and Belgium. In addition, the NSL 1.4 GW interconnector between the UK and Norway has entered Trial Operations in 2021, continuing in 2022.

**Table 4-4 Existing interconnectors with Great Britain**

| Project name | Connecting country | Capacity [MW] | Delivery date |
|---|---|---|---|
| **IFA** | France | 2,000 | 1986 |
| **Moyle** | Northern Ireland | 500 | 2002 |
| **BritNed** | Netherlands | 1,000 | 2011 |
| **EWIC** | Ireland | 500 | 2012 |
| **Nemo Link** | Belgium | 1,000 | 2019 |
| **IFA2** | France | 1,000 | 2021 |
| **ElecLink** | France | 1,000 | 2022 |
| **NSL** | Norway | 1,400 | 2021 |
| **TOTAL** | | 8,400 | |

### 4.3.3 2030 planned capacity and potential capacity with the SEM

The British government aims to deliver at least **18 GW** of interconnection capacity by 2030, representing a more than two-fold increase from 2020 levels. To fulfil these ambitions, Ofgem is incentivising the development of electricity interconnection by hedging developers from electricity market price risk through a regulatory mechanism known as Cap and Floor. Currently, a third cap and floor scheme is welcoming applications until the end of January 2023 for interconnector projects, aiming for projects to start operation prior to the end of 2032. Furthermore, a pilot cap and floor regulatory framework for hybrid interconnectors, also known as Multi-Purpose Interconnectors (MPIs) is running in tandem.

There is currently only one additional interconnector project between Great Britain and Ireland with regulatory approval to be delivered before 2030 – Greenlink being developed by Element Power & Partners Group. Its **500 MW** capacity has a delivery date of 2024. The table below lists the future electricity interconnectors with GB with regulatory approval.

**Table 3-4-5. Planned interconnectors with GB to be added by 2030**

| Project name | Connecting countries | Capacity [MW] | Delivery date |
|---|---|---|---|
| **Viking Link** | Denmark | 1,400 | 2023 |
| **GreenLink** | Ireland | 500 | 2024 |
| **GridLink** | France | 1,400 | 2024 |
| **NeuConnect** | Germany | 1,400 | 2024 |
| **NorthConnect** | Norway | 1,400 | 2025 |
| **FAB Link** | France | 1,400 | 2025 |
| **TOTAL** | | 7,500 | 2030 |

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[26] https://www.nationalgrideso.com/document/263951/download

### 4.3.4 2050 planned capacity and potential capacity with the SEM

There is very little official documentation on the expected British interconnection capacity for 2050. National Grid's Future Energy Scenarios foresee between **16-27 GW** of interconnection capacity to export excess renewable generation to other electricity markets in the Net Zero Scenarios by 2050. Their modelling includes the 8 interconnectors currently operational, and a pipeline of 19 other projects, mostly coming live before 2035.

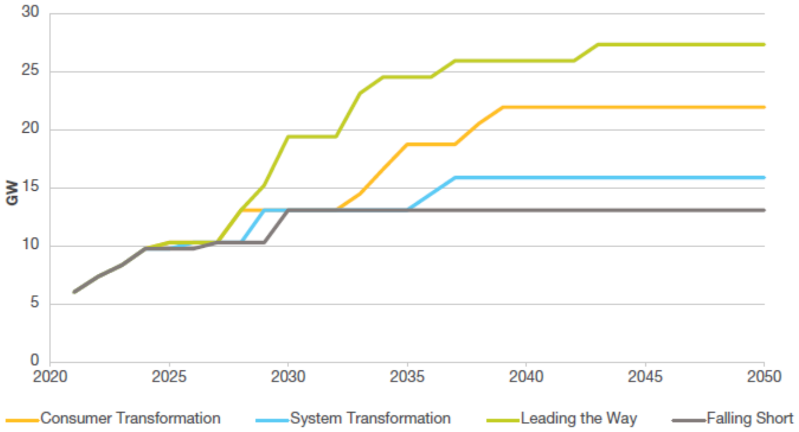

**Figure 4-1 National Grid's Future Energy Scenarios foreseen installed interconnection capacity**

## 4.4 France

### 4.4.1 Documents reviewed

- National energy and climate plans – France, Commission´s individual assessment[27]
- France National Energy and Climate Plan (2020)[28]
- France 2021 – International Energy Agency, Energy Policy Review (2021)[29]
- French Transmission Network Development Plan (2019)[30]
- France's ten-year network development plan (SDDR) Chapter 5 – Interconnection (2019)[31]
- RTE – Futurs Énergétiques 2050 (October 2021)[32]
- TYNDP 2022 Implantation Guidelines (July 2022)[33]

### 4.4.2 Current IC capacity with other countries

Current French interconnector capacity is approximately **18 GW**. The French National Energy and Climate Plan accounts for 17.4 GW in exports and 12.5 GW in imports, resulting in an interconnection level of 11.4%, which is above the European

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[27] https://energy.ec.europa.eu/system/files/2021-01/staff_working_document_assessment_necp_france_en_0.pdf

[28] https://energy.ec.europa.eu/system/files/2022-08/fr_final_necp_main_en.pdf

[29] https://iea.blob.core.windows.net/assets/7b3b4b9d-6db3-4dcf-a0a5-a9993d7dd1d6/France2021.pdf

[30] https://assets.rte-france.com/prod/public/2020-07/Sch%C3%A9ma%20d%C3%A9cennal%20de%20d%C3%A9veloppement%20de%20r%C3%A9seau%202019%20-%20Synth%C3%A8se%20%E2%80%93%20English%20version.pdf

[31] https://assets.rte-france.com/prod/public/2020-07/SDDR%202019%20Chapitre%2005%20-%20Les%20interconnexions.pdf

[32] https://assets.rte-france.com/prod/public/2021-10/Futurs-Energetiques-2050-principaux-resultats_0.pdf

[33] https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2022/public/CBA-IG.pdf

target of 10% by 2020, measured as the imports over installed generation capacity. At the moment, there is no interconnector capacity with SEM.

**Table 4-6. Existing interconnectors with France**

| Connecting countries | Capacity [MW] |
|---|---|
| **Great Britain** | 4,000 |
| **Germany** | 3,000 |
| **Belgium** | 2,800 |
| **Switzerland** | 1,300 |
| **Spain** | 2,800 |
| **Italy** | 4,100 |
| **TOTAL** | 18,000 |

### 4.4.3 2030 planned capacity and potential capacity with the SEM

In France, a further addition of around **11 GW** of interconnection capacity compared to existing capacity is foreseen, resulting in an interconnectivity of around **29 GW** by 2030. This corresponds to a 16.5% interconnection level, which is above the 15% EU target. The TYNDP Implementation Guidelines published in July 2022 list the projects planned to be commissioned before 2030, in permitting or under construction. Only the 1000 MW project with Belgium remains still under consideration. With Ireland, France has one Project of Common Interest of **700 MW** capacity, the Celtic Interconnector, owned by RTE & EirGrid that is expected to go live in 2027.

France has two potential interconnectors with Great Britain – FAB link and GridLink. Whilst they are not in the TYNDP 2022 reference grid, they have both received regulatory approval in GB. GridLink received a rejection for financing from CRE (the French national regulatory authority) but is committed to address the issues raised and was not put on hold as such.[34] We, therefore, believe that both projects can realistically be delivered by 2030 and include them in our list.

**Table 4-7. Planned interconnectors with France included in the TYNDP 2030 reference grid.**

| Project name | Connecting countries | Capacity [MW] | Commissioning year |
|---|---|---|---|
| **Biscay Gulf** | Spain | 2,200 | 2027 |
| **FR-ES Project -Navarra-Landes** | Spain | 1,500 | 2029 |
| **Muhlbach – Eichstetten** | Germany | 300 | 2026 |
| **Vigy - Uchtelfangen area** | Germany | 1,500 | 2029 |
| **R-BE I: Avelin/Mastaing-Avelgem-Horta HTLS** | Belgium | 1,000 | 2022 |
| **FR-BE: study Lonny-Achene-Gramme** | Belgium | 1,000 | 2030 |
| **Celtic interconnector** | Ireland | 700 | 2027 |
| **FAB Link** | Great Britain | 1,400 | 2025 |
| **GridLink** | Great Britain | 1,400 | 2025 |
| **TOTAL** | | 11,000 | 2030 |

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[34] https://gridlinkinterconnector.com/cre-publishes-decision-on-investment-request-2/

### 4.4.4 2050 planned capacity and potential capacity with the SEM

RTE's study on the evolution of the electricity system, 'Energy Futures 2050,' foresees a level of **39 GW** of import capacity by 2050, considering what would the economic feasibility and realistic technical and political parameters.

This same report highlights the flexible capacity needs contributing to security of supply by 2050, and the economic interest for France and Europe to widely develop the interconnection capacity. It sets the minimum potential interconnection capacity at **33 GW**, and the economic optimum at **44 GW**, that is considered the maximum potential interconnection capacity installed.

## 4.5 Spain

### 4.5.1 Documents reviewed:

- Spain Long-term strategy on how it plans to achieve greenhouse gas emission reduction[35]
- Spain National Energy and Climate Plan[36]
- Spain Red Electrica Network Development Plan 2021-2026[37]
- The Spanish Electricity System Preliminary report 2021[38]

### 4.5.2 Current IC capacity with other countries

Currently the interconnection ratio of Spain is lower than 5%, making it the only country not achieving the 10% IC ratio EU objective. In the present, the Spanish electricity system is interconnected with France, Portugal, Morocco, and Andorra, with the total capacity of 6,800 MW.

- The interconnection with **France** consists of 5 lines: Hernani-Argia 400 kV, Arkale-Argia 220 kV, Biescas-Pragnères 220 kV, Vic-Baixas 400 kV and Santa Llogaia-Baixas 400 kV. The Santa Llogaia-Baixas line is direct current and was put into service in October 2015 through the eastern Pyrenees. This allows for electricity exchange capacity of **2,200-2,800 MW**.
- The interconnection with Portugal is made up of 11 lines: Cartelle-Lindoso 400 kV 1 and 2, Conchas-Lindoso 132 kV, Aldeadavila-Lagoaça 400 kV, Aldeadavila-Pocinho 1 and 2 220 kV, Saucelle-Pocinho 220 kV, Cedillo-Falagueira 400 kV Badajoz-Alcáçovas 66 kV, Brovales-Alqueva 400 kV, Rosal de la Frontera-V. Ficalho 15 kV and Puebla de Guzmán-Tavira 400 kV. Finally, the interconnection Ponte Lima – Vila Nova Famalicão - Recarei and Beariz – Fontefría, commissioned in 2021, will allow the interconnection capacity to increase to up to **3,000 - 3,200 MW**.[39]
- The interconnection with Andorra is carried out with the 110 kV line (information on capacity not public, but likely to be in a range of 150-250 MW).
- The interconnection with Morocco is made through 2 submarine lines of 400 kV, which in total provide an exchange capacity of about **800 MW**.

**Table 4-8 Existing interconnectors with Spain**

| Connecting country | Capacity [MW] |
|---|---|
| **France** | 2,800 |
| **Portugal** | 3,200 |

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[35] https://ec.europa.eu/clima/sites/lts/lts_es_es.pdf

[36] https://energy.ec.europa.eu/system/files/2020-04/es_final_necp_main_es_0.pdf

[37] https://www.planificacionelectrica.es/sites/webplani/files/2022-04/REE_Plan_Desarrollo.pdf

[38] https://www.ree.es/en/datos/publications/annual-system-report/the-spanish-electricity-system-preliminary-report-2021

[39] https://www.ren.pt/files/2018-02/2018-02-19172504_4c65f7f1-2e56-4968-a1af-585420fa64e0$$e127f718-8018-4fb5-b93e-f5d4e9726e3e$$dfd6b11e-90f0-4680-9373-5e5c9eb78d9c$$en_gb__file$$pt$$1.pdf

| | |
|---|---|
| **Morocco** | 800 |
| **TOTAL** | **6,800** |

### 4.5.3 2030 planned capacity and potential capacity with the SEM

Spain aims to reach the 15% IC ratio with Member States (MS) by 2030 by expanding their interconnections with Portugal and France. There are no plans to interconnect Spain and Ireland.

- The construction of a new 400 kV line between Spain and **Portugal** will allow a total exchange capacity of **4,200 MW**
- New interconnections with **France** should increase interconnection capacity to 8,000 MW. One project, however, is included in the Spain National Energy and Climate Plan but is not included in the TYNDP 2022. As TYNDP 2022 is issued later, a value of **6,500 MW** is used as the interconnection capacity with France.
- The total capacity of interconnectors in Spain will therefore reach around 11.5 GW.

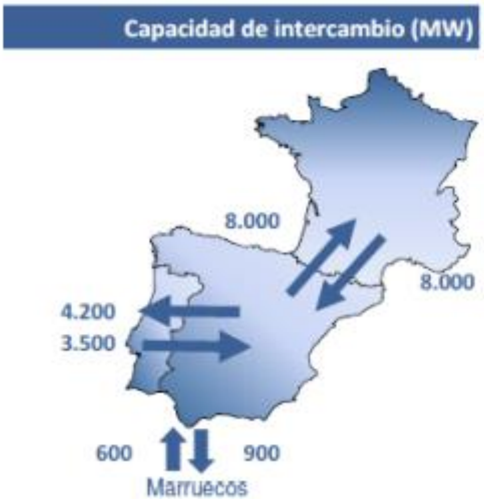

**Figure 4-2 Foreseen interconnection capacity by 2030 in Spain (Source: Spain National Energy and Climate Plan)**

**Table 4-9 Planned interconnector capacity in Spain to be added by 2030**

| Project name | Connecting countries | Capacity [MW] | Commissioning year |
|---|---|---|---|
| **Biscay Gulf** | France | 2,200 | 2026-2027 |
| **Interconnection between Aragón (ES) y Atlantic Pyrenees (FR)** | France | 1,500 | 2029-2030 |
| **Interconnection between Navarra (ES) y Landes (FR)** | France | 1,500[40] | 2029-2030 |
| **Interconnection Spain - Portugal North** | Portugal | 1,000 | 2023-2024 |
| **TOTAL** | | 4,700 | |

### 4.5.4 2050 planned capacity and potential capacity with the SEM

The Spanish government does not have clear plans or views beyond 2030. In the report “Spain Long-term strategy on how it plans to achieve greenhouse gas emission reduction”, it is indicated that analysis must be carried out on the levels of interconnection for 2050 that would be technically and economically suitable, within the framework of the integration of

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[40] This is not mentioned in TYNDP 2022, hence we are NOT including it

the Community Electricity Market and depending on the compliance with the various National Energy and Climate Plans of the different European countries.

To estimate the interconnector capacity in Spain by 2050, the current 15% IC capacity target is assumed. According to the Ministry for the Ecological Transition and the Demographic Challenge, to achieve the climate neutrality scenario, RES capacity needs to cover 100% of the electricity generation (Figure 4-3). This translates to roughly 230 GW of installed RES capacity in Spain by 2050. The IC capacity by 2050 would therefore amount to **34.5 GW**.

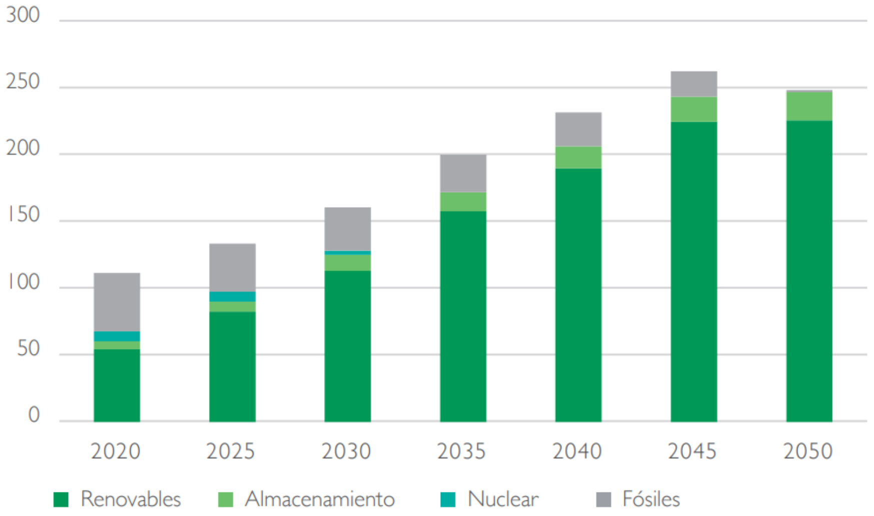

**Figure 4-3 Electricity generation capacity for climate neutrality scenario (Source: Ministry for the Ecological Transition and the Demographic Challenge)**

## 4.6 Additional interconnector capacities

This final part of the chapter collates the outcomes of the conducted review to identify what the realistic interconnector capacities can be in each of the study cases defined in Table 3-1.

In the 2030 Counterfactual it is assumed that no additional interconnection capacity is developed beyond EWIC, Moyle, Greenlink and Celtic, which in total add up to 2,200 MW. Therefore, the additional capacity between the SEM and each of the countries is equal to zero. For the 2030 factual, we assume the MaresConnect and LirIC will be realised. While MaresConnect will have a 750 MW capacity, the LirIC capacity is uncertain and varies between 500 to 700 MW. In order for 2050 counterfactual to have SEM to GB capacity value lower than in 2050 min case, we opt for the lower boundary of LirIC capacity, i.e., 500 MW. This results in the total SEM to GB interconnection capacity of 1,250 MW, thus similar to the 2030 factual case, yet with a different generation and demand background corresponding to the 2050 system. It is assumed that no interconnectors are developed between SEM and France or Spain in 2050 counterfactual.

Two factors are utilised to define the interconnection capacities in 2050 min and max:

1. EU interconnection target of 15% achieved by SEM system in 2050 min and 20% target achieved in 2050 max. The percentage is calculated from the total RES generation capacity installed in RoI, which in 2050 reaches ~47.5 GW.[41]
2. Consideration of national interconnection plans and mutual complementarity of national power systems in the considered countries (we prefer to realise more interconnection between countries with different generation and load profiles).

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[41] The value was provided as input by EirGrid during an interview conducted at the beginning of the study. This is different from the final total RES capacity used in our market model (~68 GW for SEM in total, out of which ~60 GW for RoI). The fact that another RES capacity value was used to determine additional IC capacity cases has no impact on the study outcomes.

For 2050 minimum case we assume that the SEM achieves the EU 15% interconnection target, where 15% is calculated from the total renewable capacity of ~47.5 GW resulting in 7,125 MW. Having subtracted the 2,200 MW of EWIC, Moyle, Greenlink and Celtic, this leaves us with ~5 GW of additional capacity between SEM and other countries. We assume that the total 7,125 MW of interconnection capacity should be distributed in the following approximate ratio – GB receiving ~40%; France receiving ~40% and Spain receiving ~20%. As a result, SEM to GB and SEM to France total capacities amount to 2,800 MW, and SEM to Spain amounts to 1,500 MW. Taking into account the four interconnectors assumed to be operational, we obtain additional interconnection capacity between SEM and GB to be equal to 1,300 MW; between SEM and France to be equal to 2,100 MW; and between SEM and Spain to be equal to 1,500 MW.

For 2050 maximum case, a similar logic is utilised, except that a 20% interconnection to RES ratio is assumed. This results in additional capacity between SEM and GB to be equal to 2,300 MW between SEM and France to be equal to 3,100 MW; and between SEM and Spain to be equal to 1,900 MW.

For 2040, we have designed the capacities such that they fit within the boundaries of 2030 and 2050 values, at the same time representing realistic potential projects, rather than arbitrary numbers. 2040 counterfactual is the same as 2050 counterfactual in what concerns interconnection capacities - it assumes that no additional links are developed beyond those currently planned.

The above-given interconnector capacities for different study cases are summarised in the table below.

**Table 4-10 Additional cumulative IC capacity beyond EWIC, Moyle, Greenlink and Celtic.**

| [MW] | SEM-GB | SEM-FR | SEM-ES | Total SEM |
|---|---|---|---|---|
| **Counterfactual 2030** | 0 | 0 | 0 | 0 |
| **Factual 2030** | 1,250 | 0 | 0 | 1,250 |
| **Counterfactual 2040** | 1,250 | 0 | 0 | 1,250 |
| **Factual 2040** | 1,300 | 1,050 | 1,000 | 3,350 |
| **Counterfactual 2050** | 1,250 | 0 | 0 | 1,250 |
| **Factual 2050 min** | 1,300 | 2,100 | 1,500 | 4,900 |
| **Factual 2050 max** | 2,300 | 3,100 | 1,900 | 7,300 |

### Maximum Loss of Infeed limit

In order to properly evaluate the costs of additional interconnection capacity, one needs to split the total capacity into individual projects. This requires careful consideration of the maximum loss of infeed (LoI) limit, which is the maximum size of an individual interconnector's capacity that can be connected to the SEM while maintaining system security. Having consulted with EirGrid network experts, we assume that in 2050, a maximum of 1,050 MW single loss on the system will be allowed. This allows using 2,100 MW HVDC bipole with dedicated metallic return (DMR) connections safely. The inherent feature of this type of DC connection is that in case one pole fails, i.e., 1,050 MW is lost, it is still possible to continue power transfer through the remaining healthy pole at a level of 1,050 MW, not violating the LoI limit.[42]

### Hybrid interconnectors

DNV considers that it is realistic to assume hybrid links[43] to be developed post 2030, thus, to be featured in 2040 and 2050 study cases, assuming all necessary legislative and regulatory frameworks at the national and EU level will be in place by then. Furthermore, we are of an opinion that it is currently not realistic to expect hybrid links with any other country than GB.[44] Given the large distances between the island of Ireland and France or Spain, it would be very risky and complex for project developers to implement hybrid links between these countries. Therefore, in consultation with DECC, DNV

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[42] See p.146 for further details https://www.promotion-offshore.net/fileadmin/PDFs/D12.4_-_Final_Deployment_Plan.pdf

[43] Combining generation evacuation and trading functionalities

[44] This assumption could change with possible future technological advances and development cost reductions

assumed a hybrid link featuring 1,600 MW Irish offshore wind farm (OWF) with two legs of 800 MW to be connected to SEM and GB will be assessed in 2050 min case; and a hybrid link featuring 2,100 MW Irish OWF with 1,050 MW legs to SEM and GB will be assessed in 2050 max case.

As a result, the following split of the total additional interconnection capacity into individual projects is proposed by DNV.

**Table 4-11 Split of additional cumulative IC capacity beyond EWIC, Moyle, Greenlink and Celtic into individual projects.**

| [MW] | SEM-GB | SEM-FR | SEM-ES | Total SEM |
|---|---|---|---|---|
| **Counterfactual 2030** | 0 | 0 | 0 | 0 |
| **2030** | 1,250 (750+500) | 0 | 0 | 1,250 |
| **Counterfactual 2040** | 1,250 (750+500) | 0 | 0 | 1,250 |
| **2040** | 1,300 (800*+500) | 1,050 (1,050) | 1000 (1000) | 3,350 |
| **Counterfactual 2050** | 1,250 (750+500) | 0 | 0 | 1,250 |
| **2050 min** | 1,300 (800*+500) | 2,100 (1050+1050) | 1,500 (1500) | 4,900 |
| **2050 max** | 2,300 (750+500+1050*) | 3,100 (1050+1050+1000) | 1,900 (900+1000) | 7,300 |

* part of a hybrid project.

Figure 4-4, Figure 4-5 and Figure 4-6 below provide visual representations of all study cases.

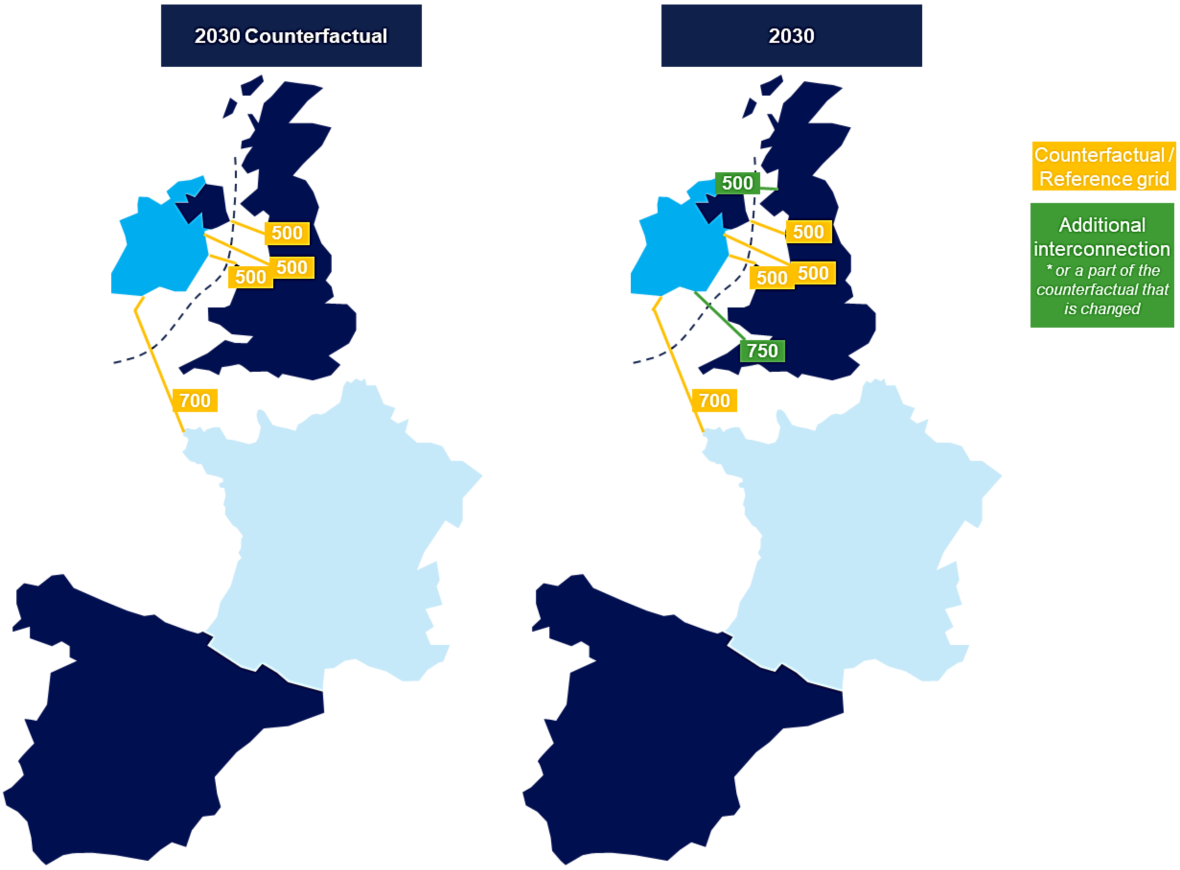

**Figure 4-4 Map of 2030 Study cases**

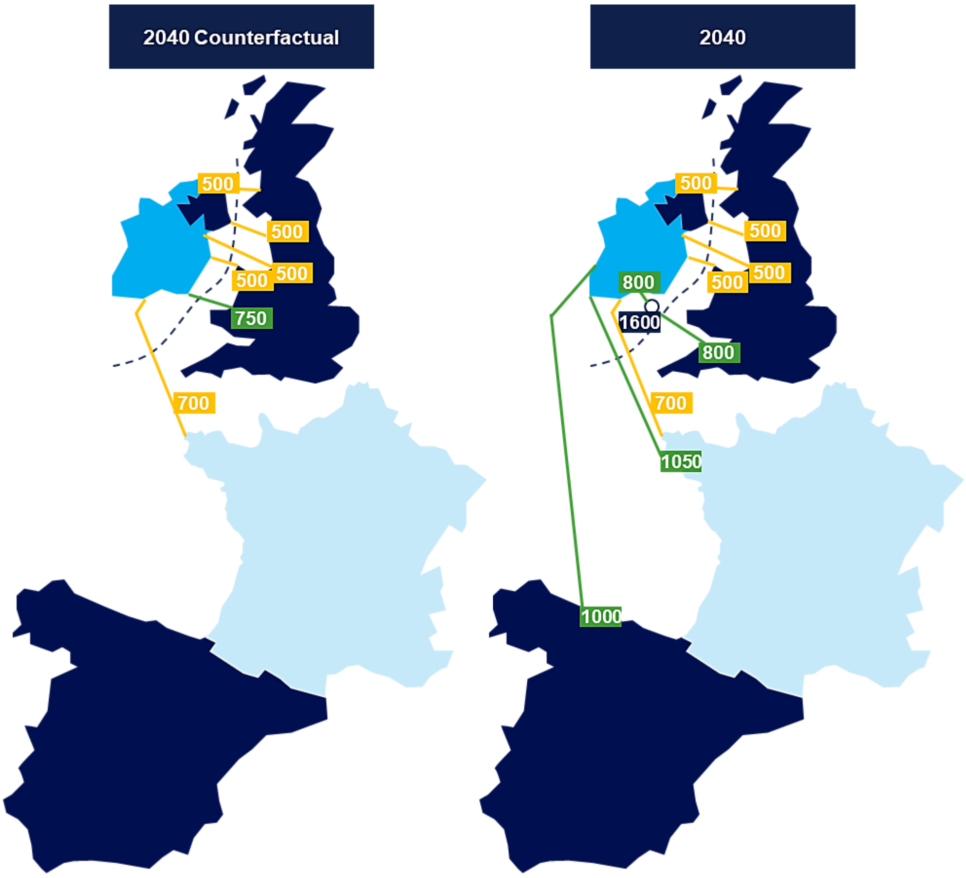

Figure 4-5 Map of 2040 Study cases

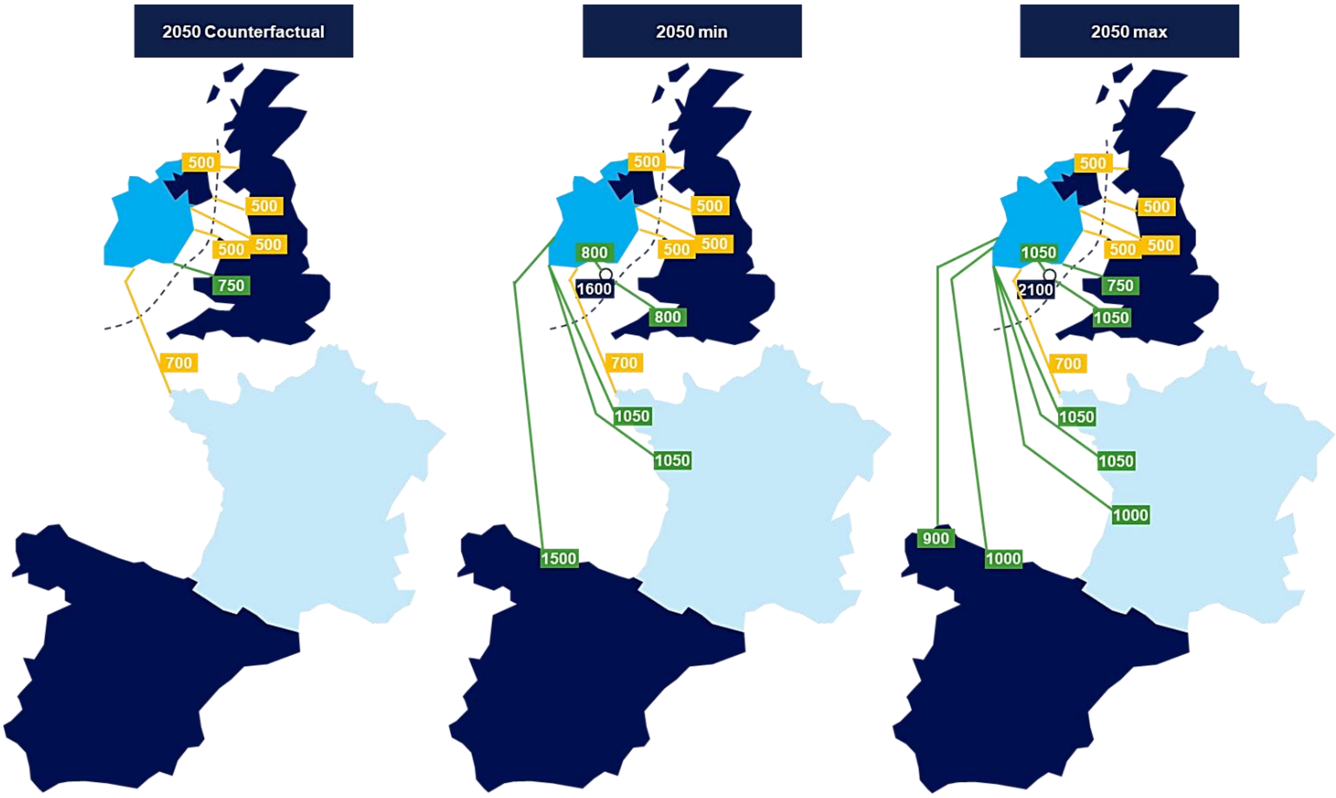

Figure 4-6 Map of 2050 Study cases

# 5 MODEL SETUP AND INPUT DATA

## 5.1 Approach

DNV has used its European Market Model, a fundamental market model that simulates the day-ahead spot price by optimising the unit commitment and economic dispatch of electricity generation. The simulations are performed on an hourly time-resolution containing a detailed representation of generation, commodity prices and demand for all bidding zones in Europe, based on the following modelling assumptions:

- Generation capacities are modelled on an individual basis with detailed techno-economic characteristics such as, but not limited to, heat rates, ramping ability, minimum stable level, fuel cost, other variable operating costs, maintenance and forced outage rates, etc.
- Renewable generation takes volatility into account through the use of historical or re-analysed time series of, for example, data on wind speed and solar irradiation for different locations. These profiles take geographical correlation into account.
- Market exchanges between countries (i.e., bidding zones) are defined based on Net Transfer Capacities. The increase in available transmission capacity is based on available projections announced by individual TSOs and/or ENTSO-E. Transmission and distribution constraints within bidding zones are not modelled.
- The demand consists of an hourly fixed demand profile, flexible demand-side management components and other flexible load originated by front-of-the-meter applications such as utility-scale batteries. Flexible demand is optimised against certain constraints within the model – e.g., electric vehicles (EVs) need to be charged by a certain volume within a specified period (e.g., within one day).
- The model set-up assumes that all flexible demand and generation is exposed to the market.

DNV European Market Model is built on PLEXOS® Integrated Energy Modelling software, an industry state-of-art power market and transmission network modelling framework developed by Energy Exemplar.

## 5.2 Scenario data

The input data and assumptions considered in this study are based on several sources, mainly ENTSO-E Ten Year Network Development Plan 2022 (TYNDP), specific national targets and studies, and DNV insights. Considering these sources, DNV has defined the inputs to the European Market Model, which can be divided into installed capacity, electricity demand, demand side flexibility, and interconnector capacities.

### 5.2.1 Installed capacity

The focus of the study is on the the SEM system (Republic of Ireland and Northern Ireland), and the neighbouring countries to which additional interconnections are analysed, i.e. Great Britain, France, and Spain. For these selected countries, DNV has considered the following assumptions regarding installed capacities.[45]

#### 5.2.1.1 Republic of Ireland

The installed generation capacities assumed for the Republic of Ireland are shown in Figure 5-1.

- Renewable installed capacity: renewable installed capacity increases from 2030 to 2050, especially offshore wind. Wind offshore reaches 37 GW installed capacity by 2050. Onshore wind is the main renewable source in 2030 with 7.1 GW, from 2040 onwards offshore wind replaces it as the main renewable source. Solar PV installed capacity is assumed to almost double from 2030, reaching 9.5 GW in 2050.

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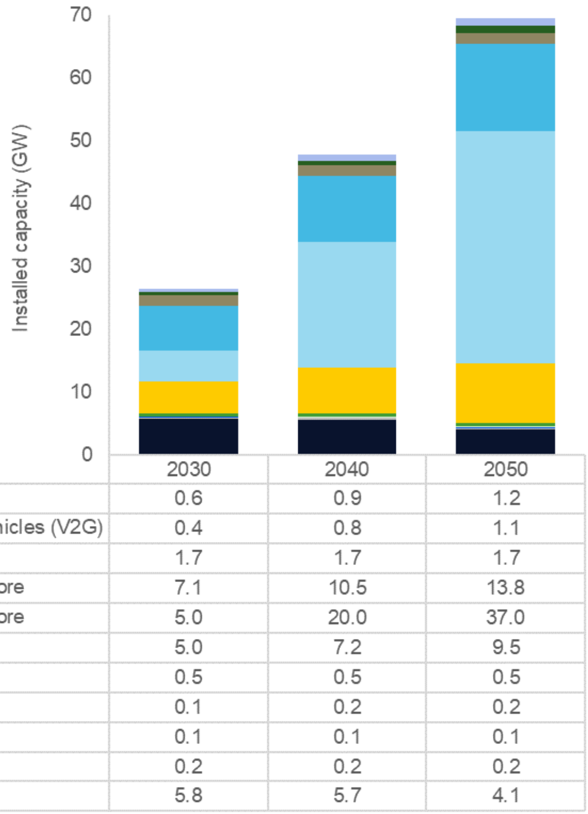
[45] Generation capacities were determined before the publication of Ireland's Climate Action Plan 2023 and EirGrid's updated Shaping Our Electricity Future report.

- Thermal installed capacity: natural gas power plants represent about 5.8 GW of Ireland installed capacity in 2030-2040, reducing slightly to 4.1 GW in 2050.



| | 2030 | 2040 | 2050 |
|---|---|---|---|
| DSR | 0.6 | 0.9 | 1.2 |
| Electric vehicles (V2G) | 0.4 | 0.8 | 1.1 |
| Batteries | 1.7 | 1.7 | 1.7 |
| Wind onshore | 7.1 | 10.5 | 13.8 |
| Wind offshore | 5.0 | 20.0 | 37.0 |
| Solar | 5.0 | 7.2 | 9.5 |
| Hydro | 0.5 | 0.5 | 0.5 |
| Biomass | 0.1 | 0.2 | 0.2 |
| Other | 0.1 | 0.1 | 0.1 |
| Oil | 0.2 | 0.2 | 0.2 |
| Gas | 5.8 | 5.7 | 4.1 |

**Figure 5-1 Installed capacity Republic of Ireland**

- Demand side flexibility: electric vehicles (V2G) and Industrial DSR increase from 2030 onwards, reaching 1.1 GW and 1.2 GW respectively in 2050. Battery capacity remains constant during the period 2030-2050 with 1.7 GW. Section 5.2.3 presents in more detailed the demand side flexibility technologies considered in the study, and their characteristics.

The installed capacities assumed for the Republic of Ireland are based on DNV data for individual power plants in 2030, and the information presented in EirGrid and SONI reports “Shaping our electricity future” (2021)[46], and “Ireland Capacity Outlook 2022-2031” (2022).[47] For 2040 and 2050, the scenario TYNDP 2022[48] Distributed Energy is used for DSR, oil, and hydro installed capacities. Natural gas installed capacity assumptions for 2050 are based on TYNDP 2022 Global Ambition scenario, while 2040 values are estimated ensuring consistency with 2030 and 2050 assumptions. Renewable installed capacities are based on inputs provided by DECC in November 2022.

### 5.2.1.2 Northern Ireland

The installed generation capacities assumed for Northern Ireland are shown in Figure 5-2.

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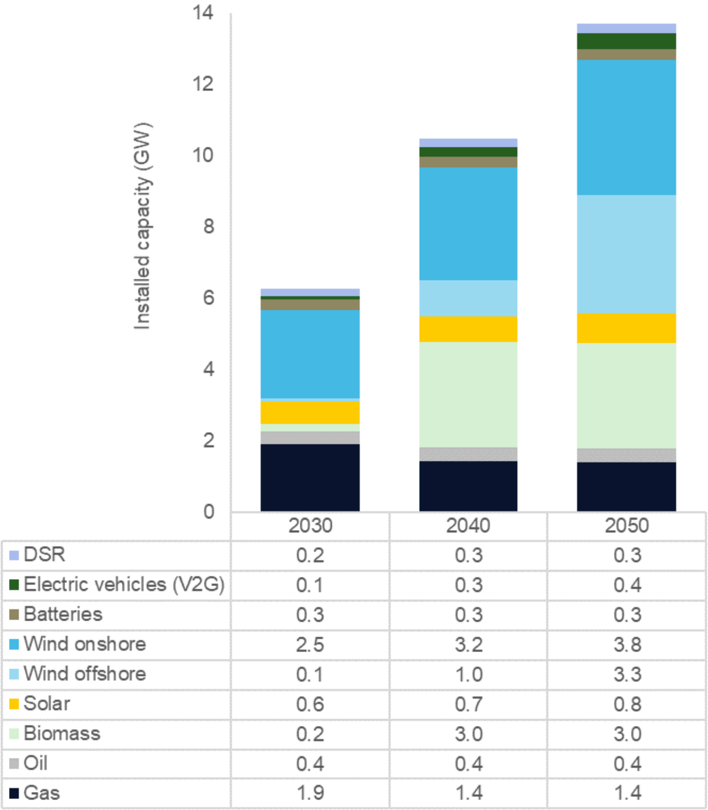
[46] https://www.eirgridgroup.com/site-files/library/EirGrid/Shaping_Our_Electricity_Future_Roadmap.pdf

[47] https://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid_SONI_Ireland_Capacity_Outlook_2022-2031.pdf

[48] https://2022.entsos-tyndp-scenarios.eu/download/



| | 2030 | 2040 | 2050 |
|---|---|---|---|
| DSR | 0.2 | 0.3 | 0.3 |
| Electric vehicles (V2G) | 0.1 | 0.3 | 0.4 |
| Batteries | 0.3 | 0.3 | 0.3 |
| Wind onshore | 2.5 | 3.2 | 3.8 |
| Wind offshore | 0.1 | 1.0 | 3.3 |
| Solar | 0.6 | 0.7 | 0.8 |
| Biomass | 0.2 | 3.0 | 3.0 |
| Oil | 0.4 | 0.4 | 0.4 |
| Gas | 1.9 | 1.4 | 1.4 |

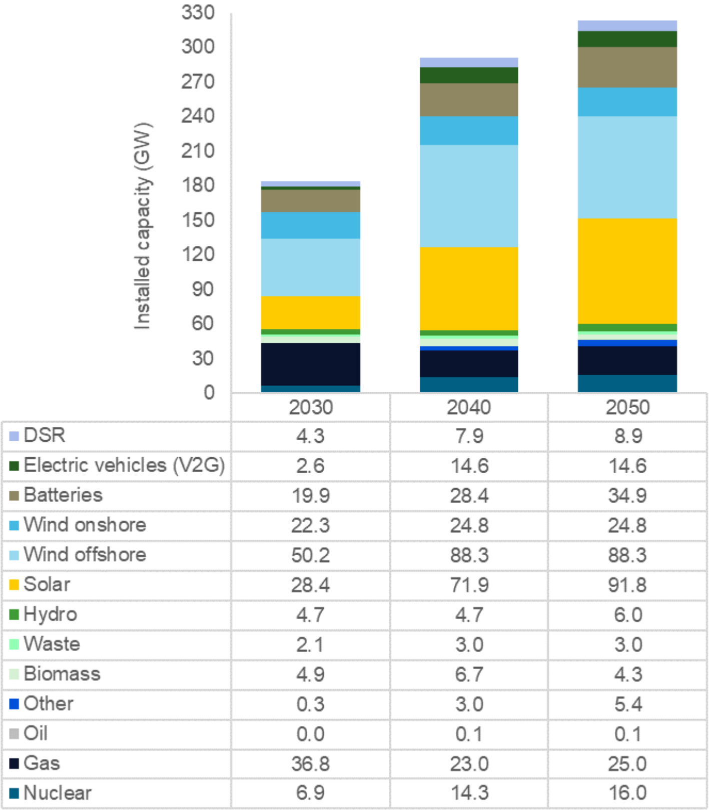
**Figure 5-2 Installed capacity Northern Ireland**

- Renewable installed capacity: renewable installed capacity increases in the period 2030 – 2050. Wind experiences the main increases, reaching 3.8 GW wind offshore capacity and 3.3 GW wind onshore capacity in 2050. Solar development experiences a lower increment.
- Thermal installed capacity: natural gas-fired installed capacity is expected to decline from 2030 to 2040 influenced by decommissioning of existing power plants.
- Demand side flexibility: electric vehicles (V2G) and Industrial DSR increase from 2030 onwards, reaching 0.4 GW and 0.3 GW respectively in 2050. Battery capacity remains constant during the period 2030-2050 with 0.3 GW. Section 5.2.3 presents in more detailed the demand side flexibility technologies considered in the study, and their characteristics.

The installed capacities assumed for Northern Ireland are based on DNV data for individual power plants in 2030, and the information presented in EirGrid and SONI reports “Shaping our electricity future” (2021)[46], and “Ireland Capacity Outlook 2022-2031” (2022)[47]. For 2040 and 2050, the scenario TYNDP 2022[48] Distributed Energy is used for DSR, oil, biomass, wind, and solar installed capacities, combined with the natural gas installed capacity presented in TYNDP 2022 Global Ambition scenario. Renewable installed capacities for 2050 are based on TYNDP 2022 Distributed Energy, same as wind offshore 2040 estimates. 2040 values of wind onshore and solar PV are estimated ensuring consistency with 2030 and 2050 assumptions.

#### 5.2.1.3 Great Britain

The installed generation capacities assumed for Great Britain are shown in Figure 5-3.



| | 2030 | 2040 | 2050 |
|---|---|---|---|
| DSR | 4.3 | 7.9 | 8.9 |
| Electric vehicles (V2G) | 2.6 | 14.6 | 14.6 |
| Batteries | 19.9 | 28.4 | 34.9 |
| Wind onshore | 22.3 | 24.8 | 24.8 |
| Wind offshore | 50.2 | 88.3 | 88.3 |
| Solar | 28.4 | 71.9 | 91.8 |
| Hydro | 4.7 | 4.7 | 6.0 |
| Waste | 2.1 | 3.0 | 3.0 |
| Biomass | 4.9 | 6.7 | 4.3 |
| Other | 0.3 | 3.0 | 5.4 |
| Oil | 0.0 | 0.1 | 0.1 |
| Gas | 36.8 | 23.0 | 25.0 |
| Nuclear | 6.9 | 14.3 | 16.0 |

**Figure 5-3 Installed capacity Great Britain**

- Renewable installed capacity: renewable installed capacity is expected to significantly increase during the period 2030-2050 driven by the developments of solar PV and wind offshore. In 2050, installed capacity from renewable energy sources is expected to reach 205 GW in total.
- Thermal installed capacity: natural gas installed capacity is expected to decline during the period 2030-2040. However, nuclear installed capacity is expected to increase towards 2050 with the commissioning of new power plants. Therefore, the total thermal capacity is expected to decrease in 2040 to then increase towards 2050, remaining relatively stable during the period 2030-2050.
- Demand side flexibility: electric vehicles (V2G) and Industrial DSR increase from 2030 to 2050 reaching 14.6 GW and 8.9 GW respectively in 2050. Battery capacity is expected to almost double from the values of 2030, accounting for 34.9 GW in 2050. Section 5.2.3 presents in more detailed the demand side flexibility technologies considered in the study, and their characteristics.

The installed capacities assumed for Great Britain are based on DNV data for individual power plants in 2030, and the information presented on the study of National Grid ESO, “Future Energy Scenarios” (2021-2022).[49] For 2040 and 2050, the scenario TYNDP 2022[48] Distributed Energy is used for DSR, oil, biomass, and hydro installed capacities, combined with the nuclear, and natural gas installed capacities presented in TYNDP 2022 Global Ambition scenario. Renewable and battery installed capacities are based on FES 2022 Leading the way scenario.

#### 5.2.1.4 France

The installed generation capacities assumed for France are shown in Figure 5-4.

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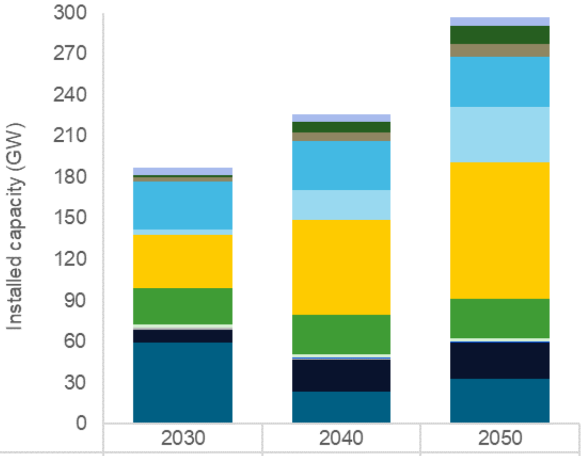
[49] https://www.nationalgrideso.com/future-energy/future-energy-scenarios



| | 2030 | 2040 | 2050 |
|---|---|---|---|
| ■ DSR | 5.5 | 5.5 | 6.2 |
| ■ Electric vehicles (V2G) | 1.9 | 7.5 | 13.2 |
| ■ Batteries | 3.1 | 6.1 | 9.0 |
| ■ Wind onshore | 34.6 | 35.8 | 37.0 |
| ■ Wind offshore | 4.4 | 22.2 | 40.0 |
| ■ Solar | 38.2 | 69.1 | 100.0 |
| ■ Hydro | 27.0 | 28.5 | 28.5 |
| ■ Biomass | 2.2 | 2.4 | 2.4 |
| ■ Other | 0.2 | 1.0 | 1.0 |
| ■ Oil | 1.4 | 0.4 | 0.0 |
| ■ Gas | 8.9 | 23.7 | 26.4 |
| ■ Nuclear | 59.5 | 23.5 | 32.6 |

**Figure 5-4 Installed Capacity France**

- Renewable installed capacity: renewable installed capacity is expected to significantly increase during the period 2030-2050 driven by the developments of solar PV and wind offshore. In 2050, installed capacity from renewable energy sources is expected to reach 177 GW in total.
- Thermal installed capacity: natural gas installed capacity is expected to increase during the period 2030-2050. Nuclear installed capacity is expected to decrease towards 2050 due to the decommissioning of some of the existing power plants.
- Demand side flexibility: electric vehicles (V2G) and Industrial DSR increase from 2030 onwards, reaching 13.2 GW and 6.2 GW respectively in 2050. Battery deployment is expected to increase, accounting for 9 GW in 2050. Section 5.2.3 presents in more detailed the demand side flexibility technologies considered in the study, and their characteristics.

The installed capacities assumed for France are based on DNV data for individual power plants in 2030, and the national targets for renewable energy, including the "Joint statement on the North Seas energy cooperation" (2022)[50]. For 2040 and 2050 the scenario TYNDP 2022[48] Distributed Energy is used for DSR, oil, biomass, natural gas, and hydro. Battery installed capacities for 2040-2050 are based on the study "RTE – Futurs Énergétiques 2050"[51]. Renewable and nuclear

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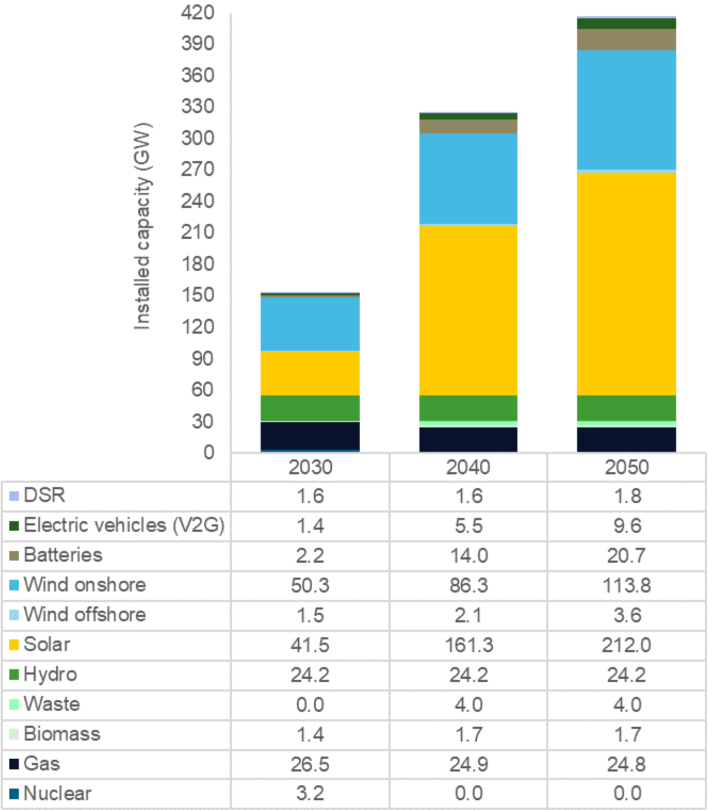
[50] https://energy.ec.europa.eu/system/files/2022-09/220912_NSEC_Joint_Statement_Dublin_Ministerial.pdf

[51] https://assets.rte-france.com/prod/public/2021-10/Futurs-Energetiques-2050-principaux-resultats_0.pdf

installed capacities are based on national targets recently announced for 2050[52][53], while 2040 values are estimated ensuring consistency with 2030 and 2050 assumptions.

### 5.2.1.5 Spain

The installed generation capacities assumed for Spain are shown in Figure 5-5.



| | 2030 | 2040 | 2050 |
|---|---|---|---|
| DSR | 1.6 | 1.6 | 1.8 |
| Electric vehicles (V2G) | 1.4 | 5.5 | 9.6 |
| Batteries | 2.2 | 14.0 | 20.7 |
| Wind onshore | 50.3 | 86.3 | 113.8 |
| Wind offshore | 1.5 | 2.1 | 3.6 |
| Solar | 41.5 | 161.3 | 212.0 |
| Hydro | 24.2 | 24.2 | 24.2 |
| Waste | 0.0 | 4.0 | 4.0 |
| Biomass | 1.4 | 1.7 | 1.7 |
| Gas | 26.5 | 24.9 | 24.8 |
| Nuclear | 3.2 | 0.0 | 0.0 |

**Figure 5-5 Installed capacity Spain**

- Renewable installed capacity: renewable installed capacity is expected to significantly increase during the period 2030-2050 mostly due to an increase in solar PV deployment. In 2050, installed capacity from renewable energy sources is expected to reach 329 GW in total.
- Thermal installed capacity: natural gas installed capacity is expected to remain stable, only decreasing about 2 GW in the period 2030 - 2050. Nuclear power plants are expected to be decommissioned after 2030.
- Demand side flexibility: electric vehicles (V2G) and Industrial DSR increase from 2030 to 2050, reaching 9.6 GW and 1.8 GW respectively in 2050. Battery deployment is expected to increase, accounting for 20.7 GW in 2050. Section 5.2.3 presents in more detailed the demand side flexibility technologies considered in the study, and their characteristics.

The installed capacities assumed for Spain are based on DNV data for individual power plants in 2030, and the national targets presented in PNIEC 2021-2030 (2020)[36]. For 2040 and 2050, installed capacities are based on the scenario TYNDP 2022[48] Distributed Energy.

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[52] https://www.banquedesterritoires.fr/relance-du-nucleaire-et-essor-de-leolien-en-mer-et-du-solaire-les-choix-energetiques-demmanuel

[53] https://renewablesnow.com/news/macron-targets-over-100-gw-of-solar-in-france-by-2050-772845/

## 5.2.2 Electricity demand

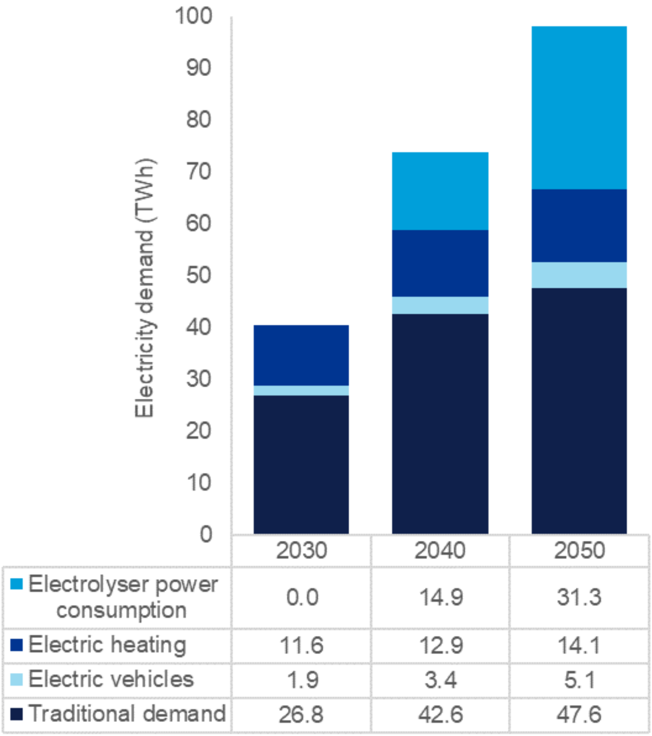
The electricity demand is considered in the analysis by differentiating the traditional demand for electricity from the additional demand due to the electrification of passenger transport and heating, and from electrolysers for power-to-hydrogen conversion.

- Traditional demand encompasses, for example, household, commercial and industrial power demand, categories already considered nowadays.
- Electrification of passenger transport[54] is driven by support schemes and by technological and infrastructure developments and expected cost degression.
- Electrification of heating consists of both space heating and industrial heating.
- Power-to-hydrogen entails the electricity demand required by electrolysers.

Based on the above categories we have considered the following values for electricity demand in the selected countries.

### 5.2.2.1 Republic of Ireland

The annual electricity demand assumed for the Republic of Ireland is shown in Figure 5-6.



| | 2030 | 2040 | 2050 |
|---|---|---|---|
| ■ Electrolyser power consumption | 0.0 | 14.9 | 31.3 |
| ■ Electric heating | 11.6 | 12.9 | 14.1 |
| ■ Electric vehicles | 1.9 | 3.4 | 5.1 |
| ■ Traditional demand | 26.8 | 42.6 | 47.6 |

**Figure 5-6 Electricity demand Republic of Ireland**

Electricity demand in the Republic of Ireland is expected to increase from 40 TWh in 2030 to 74 TWh in 2040, and 98 TWh in 2050, mostly driven by an increase in traditional demand and electrolyser consumption.

The assumptions regarding electricity demand data for the Republic of Ireland are based on DNV ETO 2021 values for electric vehicles, total electricity demand for 2030 from EirGrid and SONI report “Ireland Capacity Outlook 2022-2031”

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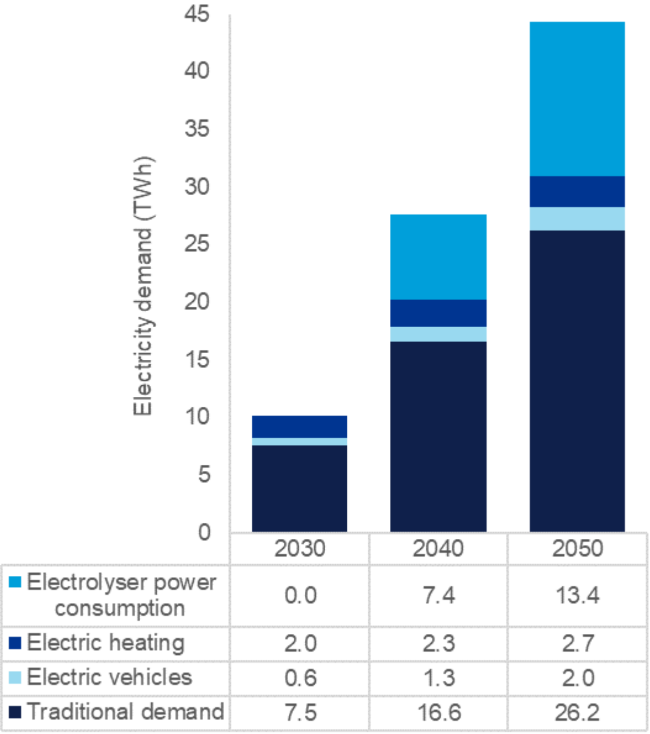
[54] In our model this is limited to passenger EVs

(2022)47, and TYNDP 2022[48] Distribute Energy scenario for electric heating assumptions. For 2040 and 2050, the total electricity demand corresponds to TYNDP 2022 Distributed Energy scenario, as well as the electrolyser capacity and electric heating assumptions.

### 5.2.2.2 Northern Ireland

The annual electricity demand assumed for Northern Ireland is shown in Figure 5-7.



| | 2030 | 2040 | 2050 |
|---|---|---|---|
| ■ Electrolyser power consumption | 0.0 | 7.4 | 13.4 |
| ■ Electric heating | 2.0 | 2.3 | 2.7 |
| ■ Electric vehicles | 0.6 | 1.3 | 2.0 |
| ■ Traditional demand | 7.5 | 16.6 | 26.2 |

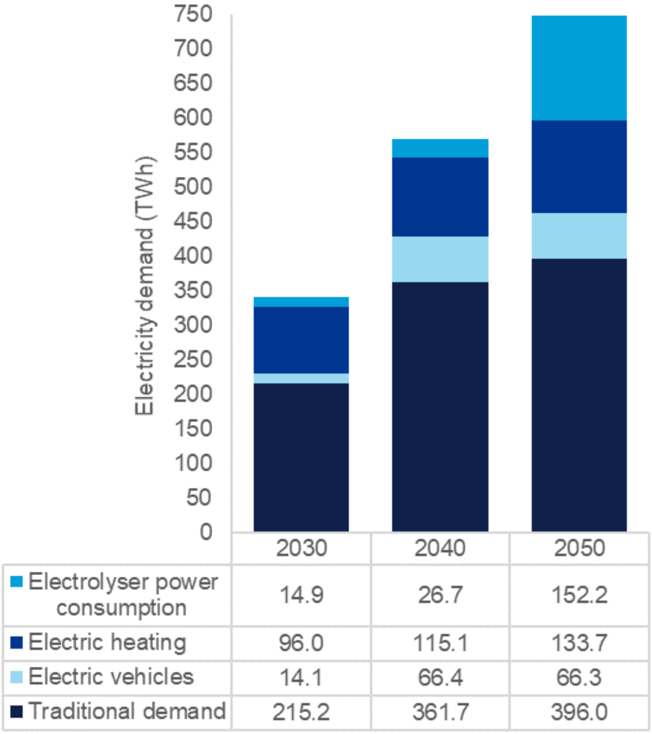
**Figure 5-7 Electricity demand Northern Ireland**

Electricity demand in Northern Ireland is expected to increase from 10 TWh in 2030 to 28 TWh in 2040, and 44 TWh in 2050, mostly driven by an increase in traditional demand and electrolyser consumption.

The assumptions regarding electricity demand data for Northern Ireland are based on DNV ETO 2021 values for electric vehicles, total electricity demand for 2030 from EirGrid and SONI report “Ireland Capacity Outlook 2022-2031” (2022)[47], and TYNDP 2022[48] Distribute Energy scenario for electric heating assumptions. For 2040 and 2050, the total electricity demand is aligned with TYNDP 2022 Distributed Energy scenario while ensuring consistency with 2050 assumptions. Electrolyser capacity and electric heating assumptions are based on TYNDP 2022 Distributed Energy scenario.

### 5.2.2.3 Great Britain

The annual electricity demand assumed for Great Britain is shown in Figure 5-8.



| | 2030 | 2040 | 2050 |
|---|---|---|---|
| ■ Electrolyser power consumption | 14.9 | 26.7 | 152.2 |
| ■ Electric heating | 96.0 | 115.1 | 133.7 |
| ■ Electric vehicles | 14.1 | 66.4 | 66.3 |
| ■ Traditional demand | 215.2 | 361.7 | 396.0 |

**Figure 5-8 Electricity demand Great Britain**

Electricity demand in Great Britain is expected to increase from 340 TWh in 2030 to 570 TWh in 2040, and 748 TWh in 2050, with sectors like electric mobility and electrolyser consumption experiencing the highest increment.

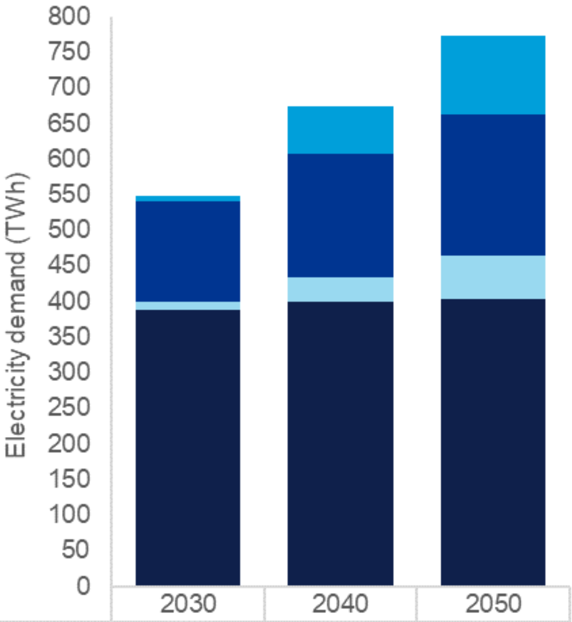
The assumptions regarding electricity demand data for Great Britain are based on DNV ETO 2021 values for electric vehicles, and electrolyser capacity for 2030, total electricity demand (excluding electrolyser consumption) for 2030 based on National Grid ESO, “Future Energy Scenarios” (2022)[49], and TYNDP 2022[48] Distribute Energy scenario for electric heating assumptions. For 2040 and 2050, the total electricity demand corresponds to TYNDP 2022 Distributed Energy scenario, as well as the electrolyser capacity and electric heating assumptions.

#### 5.2.2.4 France

The annual electricity demand assumed for France is shown in Figure 5-9.

Electricity demand in France is expected to increase from 548 TWh in 2030 to 674 TWh in 2040, and to 773 TWh in 2050, with sectors like electric mobility and electrolyser consumption experiencing the highest increment.

The assumptions regarding electricity demand data for France are based on DNV ETO 2021 values for electric vehicles, traditional demand, and electrolyser capacity for 2030, and TYNDP 2022[48] Distributed Energy scenario for electric heating assumptions. For 2040 and 2050, the total electricity demand corresponds to TYNDP 2022 Distributed Energy scenario, as well as the electrolyser capacity and electric heating assumptions.



| | 2030 | 2040 | 2050 |
|---|---|---|---|
| 🟦 Electrolyser power consumption | 7.7 | 66.9 | 110.1 |
| ■ Electric heating | 142.0 | 173.2 | 199.0 |
| 🟦 Electric vehicles | 10.3 | 33.9 | 59.7 |
| ■ Traditional demand | 388.4 | 399.9 | 403.7 |

**Figure 5-9 Electricity demand France**

#### 5.2.2.5 Spain

The annual electricity demand assumed for Spain is shown in Figure 5-10.

Electricity demand in Spain is expected to increase from 264 TWh in 2030 to 394 TWh in 2040, and 474 TWh in 2050, with sectors like electric mobility and electrolyser consumption experiencing the highest increment.

The assumptions regarding electricity demand data for France are based on DNV ETO 2021 values for electric vehicles, traditional demand and electrolyser capacity for 2030, and TYNDP 2022[48] Distribute Energy scenario for electric heating assumptions. For 2040 and 2050, the total electricity demand corresponds to TYNDP 2022 Distributed Energy scenario, as well as the electrolyser capacity and electric heating assumptions.

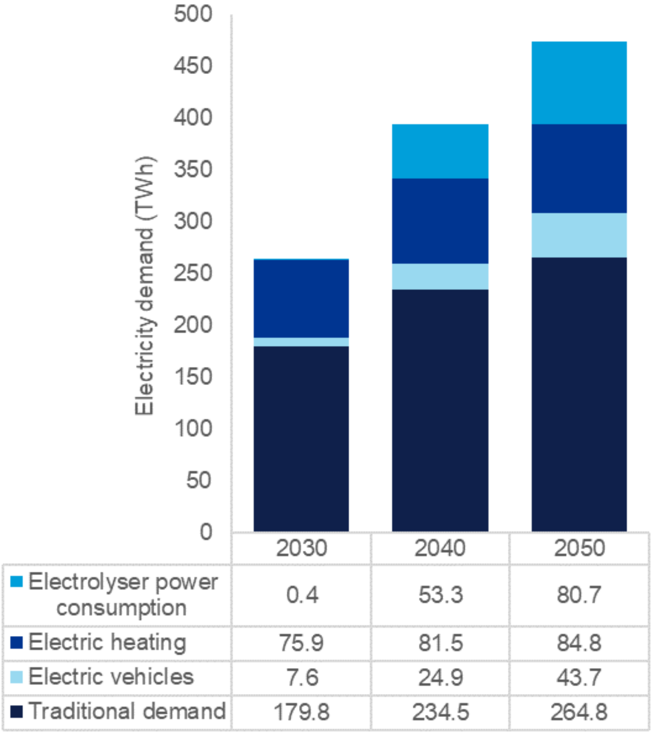


**Figure 5-10 Electricity demand Spain**

## 5.2.3 Demand side flexibility

Demand side flexibility (DSF) is considered in the analysis by including the following flexible technologies: industrial demand-side response (DSR), residential electric heating, batteries (BESS), electric vehicle smart charging, vehicle-to-grid (V2G), and electrolysers.

Next, we provide more details on the assumption and modelling implementation for each DSF technology.

### 5.2.3.1 Industrial DSR

Industrial DSR is an industrial electric heating load that can (partially) shut down its consumption. Industrial DSR is defined per country and distinguished in five types of industrial load. Each type is defined by a maximum curtailable load in MW, a cost of shutting down the industrial load in euro/MWh, and a maximum number of consecutive hours the industrial load can be curtailed.

When the entire cheaper generation capacity is already fully committed, industrial DSR acts as a last resort to prevent unserved load.

### 5.2.3.2 Residential electric heating

Residential electric heating represents residential and commercial space heating electricity demand. It is considered as a shiftable load with a minimum and maximum consumption over a 12-hour day/night period.

Residential electric heating load is optimised in the market model. However, it is subject to a 12-hour load equality constraint that cannot be violated. Two 12-hour periods are defined, namely, day period from 9 a.m. to 9 p.m. and night period from 9 p.m. to 9 a.m. Therefore, it can provide flexibility by shifting the consumptions while respecting the 12-hour load requirement.

#### 5.2.3.3 BESS

Batteries are modelled with a simplified approach: one large scale battery is considered at each node, which represents all BESS installation in the country. The BESS charging and discharging efficiency is considered 97.5% which represents the most common efficiency of LI-Ion batteries. A minimum state of charge of 20% and an initial SOC of 50% are assumed.

BESS charge and discharge are optimized in the market model depending on the power price, while satisfying some constraints, namely, maximum charging/discharging power, maximum storage capacity, and minimum state of charge. For the battery to be activated, the power price needs to show a sufficiently large spread in one day look-ahead to overcome the cost of energy due to efficiency losses.

#### 5.2.3.4 Electric vehicle smart charging

Electric vehicles are distinguished between EVs following a fixed charging profile and EVs with daily energy consumption and flexible charging profiles. While the modelling approach is similar for both types, only the latter offers DSF. The share of EVs offering daily flexibility (i.e. smart charging) is assumed to increase towards 2050 and reach 50% in 2050[55]. Therefore, the share of EVs following a fixed charging profile is assumed to decrease down to 50% in 2050.

The total number of EVs per country is estimated based on DNV insights on European passenger and commercial EV uptakes as well as vehicle statistics per country. The annual energy consumption per EV is estimated at 2.26 MWh/year, assuming 0.2 kWh/km and 11300 km/year. The EV power and energy capacity are assumed equal to 10 kW and 63.9 kWh, respectively. Additionally, given the total number of EVs per country, the number of (office and residential) charging points is half the EV number. An availability profile representing the hourly share of charging points occupied by a vehicle is also modelled.

The charging profile of the EVs offering daily flexibility is determined in the market model depending on the power price, while satisfying some constraints, namely, maximum charging power based on the availability profile, maximum storage capacity, and daily energy demand to be satisfied. The daily demand is assumed constant throughout the year.

#### 5.2.3.5 V2G

Electric vehicles may also offer vehicle-to-grid. It is assumed that 10% of the EV infrastructure provides V2G possibility by 2050, based on DNV insights.

V2G generation and consumption are determined in the market model based on the power price, while satisfying some constraints, namely, maximum charging/discharging power based on the availability profile, maximum storage, and a maximum number of daily cycles of 2. For V2G to be activated, the power price needs to show a sufficiently large spread to overcome operating inefficiencies and costs (VO&M cost of 0.01 euro/MWh).

#### 5.2.3.6 Electrolysers

Electrolyser consumption is considered a shiftable load. Electrolyser consumption is determined in the market model based on the power price, while satisfying some constraints, namely, maximum load and monthly consumption. The maximum load corresponds to the installed electrolyser capacity, whereas the monthly consumption is assumed constant and calculated based on the following number of full-load hours (FLH):

- In 2030, for all countries, 3,000 FLH;
- In 2050, for countries bordering the North Sea, the Nordic countries, Ireland, and North Ireland, 4,500 FLH; and
- In 2050, for all other countries, 3,000 FLH.

Electrolyser consumption may be curtailed to prevent unserved energy.

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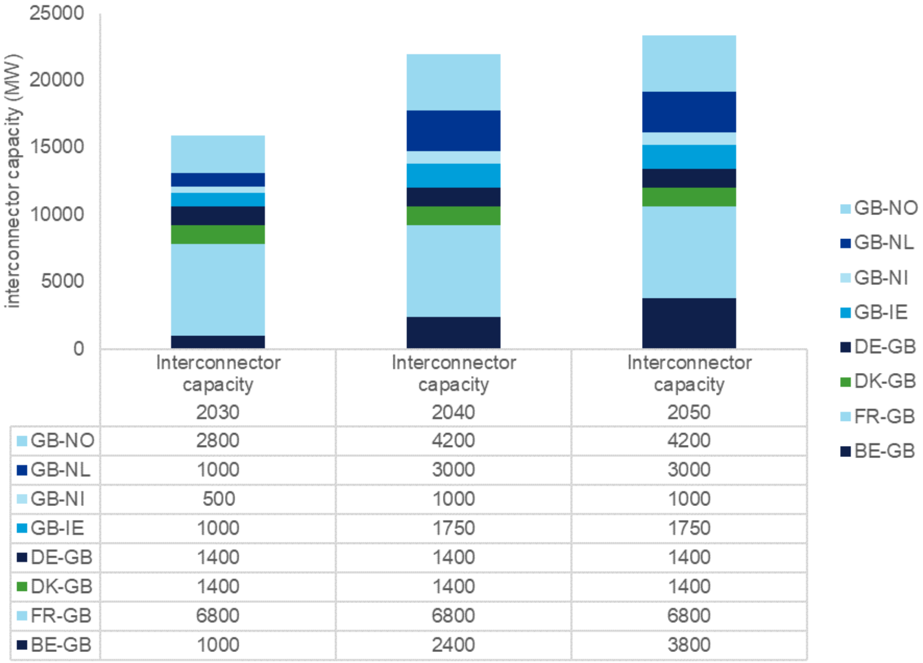
[55] https://www.nationalgrideso.com/document/263951/download

## 5.2.4 Interconnector capacities

The total interconnector capacity (as part of the reference /counterfactual grid) for Great Britain, France, and Spain are presented below. We do not distinguish between import and export capacity; the highest value is used for both directions.

### 5.2.4.1 Great Britain

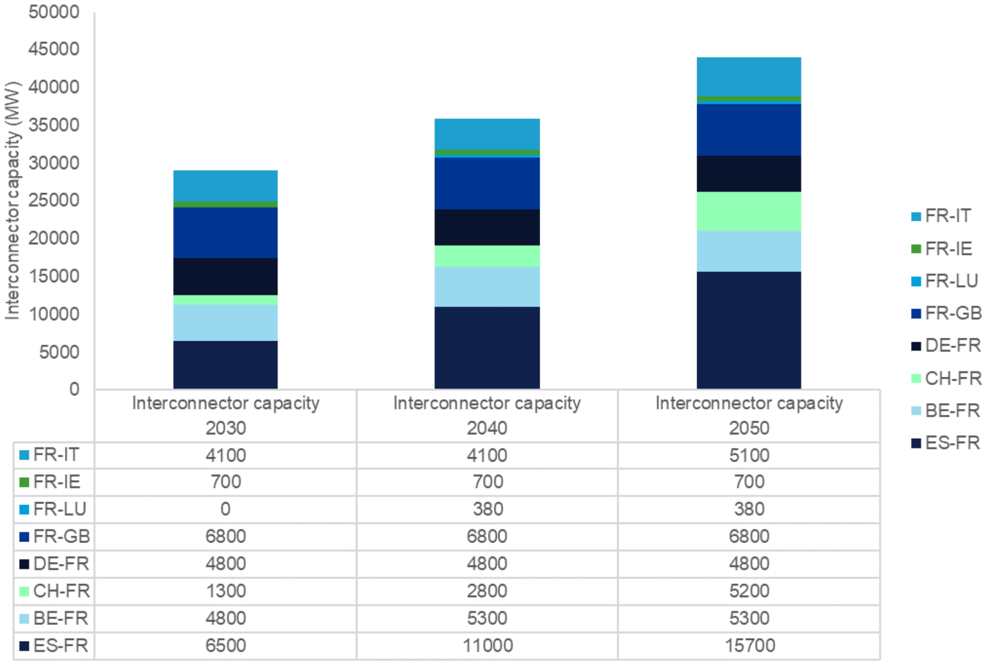


| | Interconnector capacity 2030 | Interconnector capacity 2040 | Interconnector capacity 2050 |
|---|---|---|---|
| GB-NO | 2800 | 4200 | 4200 |
| GB-NL | 1000 | 3000 | 3000 |
| GB-NI | 500 | 1000 | 1000 |
| GB-IE | 1000 | 1750 | 1750 |
| DE-GB | 1400 | 1400 | 1400 |
| DK-GB | 1400 | 1400 | 1400 |
| FR-GB | 6800 | 6800 | 6800 |
| BE-GB | 1000 | 2400 | 3800 |

**Figure 5-11 Interconnector capacities Great Britain**

The total import/export limit for Great Britain in 2030, 2040 and 2050 is 15.9 GW, 22.0 GW and 23.4 GW, respectively. For more details on the assumption for 2030 and 2050, please refer to Section 4.3.3 and Section 4.3.4, respectively. The expected interconnection capacity in 2040 is mostly based on TYNDP 2022[48] Distributed Energy scenario, while ensuring consistency with 2050 assumptions.

### 5.2.4.2 France

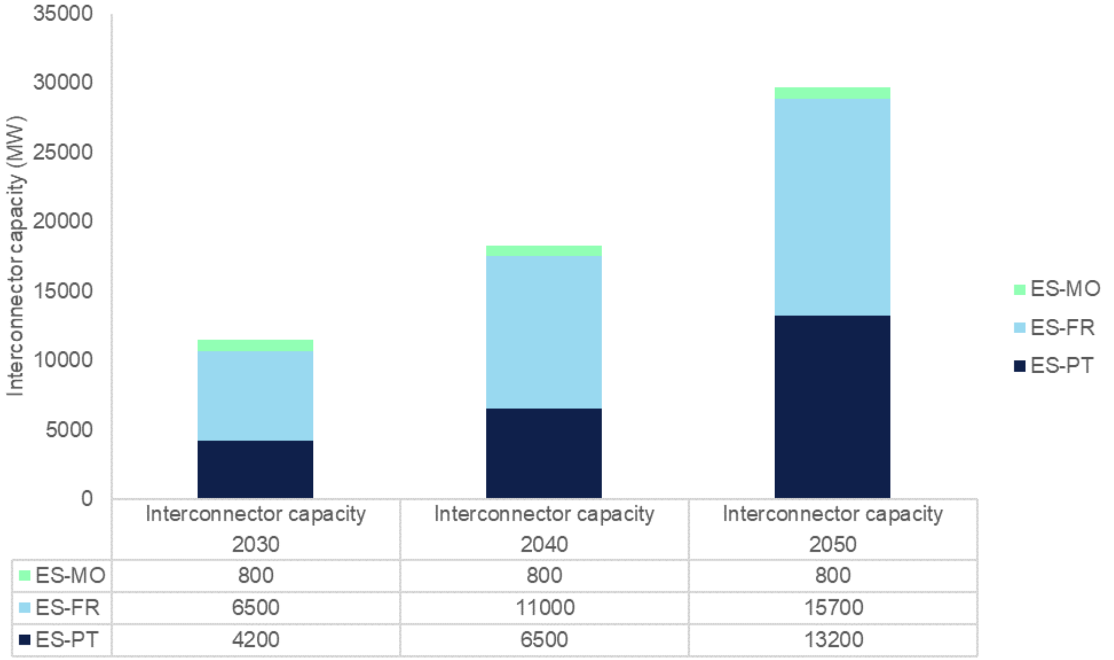


| | Interconnector capacity 2030 | Interconnector capacity 2040 | Interconnector capacity 2050 |
|---|---|---|---|
| FR-IT | 4100 | 4100 | 5100 |
| FR-IE | 700 | 700 | 700 |
| FR-LU | 0 | 380 | 380 |
| FR-GB | 6800 | 6800 | 6800 |
| DE-FR | 4800 | 4800 | 4800 |
| CH-FR | 1300 | 2800 | 5200 |
| BE-FR | 4800 | 5300 | 5300 |
| ES-FR | 6500 | 11000 | 15700 |

**Figure 5-12 Interconnector capacities France**

The total import/export limit for France in 2030, 2040 and 2050 is 29.0 GW, 35.5 GW and 44.0 GW, respectively. For more details on the assumption for 2030 and 2050, please refer to Section 4.4.3 and Section 4.4.4, respectively. The expected interconnector capacity in 2040 is mostly based on TYNDP 2022[48] Distributed Energy scenario.

### 5.2.4.3 Spain



| | Interconnector capacity 2030 | Interconnector capacity 2040 | Interconnector capacity 2050 |
|---|---|---|---|
| ES-MO | 800 | 800 | 800 |
| ES-FR | 6500 | 11000 | 15700 |
| ES-PT | 4200 | 6500 | 13200 |

**Figure 5-13 Interconnector capacities Spain**

The total import/export limit for Spain in 2030, 2040 and 2050 is 11.5 GW, 18.3 GW and 29.7 GW, respectively. For more details on the assumptions for 2030 and 2050, please refer to Section 4.5.3 and Section 4.5.4, respectively. The expected interconnector capacity in 2040 is mostly based on TYNDP 2022[48] Distributed Energy scenario. The interconnector capacity between Spain and Portugal is estimated by DNV to ensure a consistent trend towards 2050, while assuming that most of the capacity will be added after 2040.

# 6 ASSESSMENT

In this chapter DNV present the main results from the analysis. We provide numerical and qualitative evidence to what the impacts of additional interconnection could be based on the envelope of the study cases that we defined. Several KPIs are assessed for each study cases, in combination allowing us to draw conclusions about the costs and benefits of different interconnection configurations, compared to the status quo and among themselves.

## 6.1 Summary

The content of the assessment chapter is twofold, firstly to introduce the main objectives of this study and secondly to present the overall results of this study.

As part of explaining the main objectives, the relevant methodology which has been used to assess the pre-defined KPIs is mentioned as well. Overall, DNV together with DECC has selected nine KPIs which serve as important metrics to evaluate the main objectives of this study. In particular, the KPIs are designed to support describing the economic impact for the society and the TSOs, the overall success of the RES integration, and the guarantee of security of supply for each of the examined cases of interconnector capacity.

The results chapter entails an assessment of the KPIs for the main study cases and two sensitivity runs which examined the impact of the RES share in the SEM and the nuclear share in France in greater detail. The outcomes per KPI are displayed as the difference between the counterfactual case (no additional interconnector capacity) and the factual cases (additional interconnector capacity depending on the individual cases; see Section 4.6) for each examined year (2030, 2040 and 2050).

Overall, for 2030, 2040 and 2050, the results indicate that additional interconnection capacity enables a generation mix in the SEM that relies less on fossil fuels and integrates more RES, which is shown by a reduction in RES curtailment in the SEM irrespective of the study case. Yet, the impact on RES share in the SEM generation mix is overall minor, owing to the fact that even without additional interconnectors, the SEM generates 88% of its electricity from renewables in 2030 and above 90% from 2040 onwards.

Additional interconnection with France leads to the highest reduction of curtailment. Based on DNV scenario assumptions on the decommissioning plan of French nuclear power plants, fossil fuel share (gas fired power plants) in the French generation mix towards 2040 and 2050 is expected to be relatively high (around 7% in 2040 and 2.5% in 2050), hence enabling large export opportunities for the SEM. Among the other selected countries, France benefits the most from the additional links in terms of both $CO_2$ and system costs reduction.

Furthermore, a reduction in carbon emissions is visible across all examined interconnection cases across all selected countries. Additional links between the SEM and France and between the SEM and Spain lead to the highest $CO_2$ reduction in the SEM in both absolute values and per MW of additional IC capacity. A reduction in carbon emissions translates into a cost reduction for both the producers and the whole society.

The economic impact of the additional interconnection capacity is measured in terms of system costs, which herein refer to the sum of the total running costs of all generators (fuel and O&M costs), plus the total variable O&M costs for BESS and the costs for flexible demand (fuel, emission start/shutdown), and of revenues enabled by the use of the interconnectors. Additional interconnection capacity leads in almost all study cases to a decrease in system costs across all selected countries for 2030, 2040, and 2050, and for the SEM in particular This is due to additional opportunities for all countries to share low-carbon generation among them, which replaces expensive and polluting fossil fuel generation. Interconnections with France and Spain enable the largest environmental benefit, while creating revenues linked to imports and exports between the SEM and the connected country. Obviously, additional interconnection capacity requires investment costs, which increase with the length and capacity of the link. The interconnectors with Great Britain are, therefore, the cheapest.

Finally, additional interconnections are expected to increase system flexibility. In practice, the results show that additional interconnection capacity may indeed prevent the SEM system from resorting to its most expensive resources by providing additional import capacity from neighbouring countries.

## 6.2 Objectives and methodology

To be able to identify relevant Key Performance Indicators (KPIs), it is important to address first the main objectives of this study. Table 6-1 provides an overview of the selected objectives for this analysis. In addition, the relevant metrics to support the analysis are also illustrated, which are identical to the applied KPIs. It is worth noticing that in analyses herein we use “system costs” to refer to the sum of the total running costs of all generators (fuel and O&M costs), plus the total variable O&M costs for BESS and the costs for flexible demand (fuel, emission start/shutdown).

**Table 6-1 Overview of main objectives of this study and relevant KPIs.**

| Objective | KPIs (metrics to support the analysis) |
|---|---|
| **Impact on achieving 2030 goals** | RES integration / curtailment; Carbon Emissions |
| **Impact on achieving goals beyond 2030 (net zero 2050)** | RES integration / curtailment; Carbon Emissions |
| **Economic rationale around 2030 including de-risking offshore wind** | SEW (Generation costs, BESS costs and DSM costs); Congestion revenues; Interconnector utilisation; Interconnector CAPEX |
| **Economic rationale towards 2050** | SEW (Generation costs, BESS costs and DSM costs); Congestion revenues; Interconnector utilisation; Interconnector CAPEX |
| **Impact on RES integration / $CO_2$ emissions** | RES integration / curtailment; Carbon Emissions |
| **Replacement of domestic fossil fuel generation** | RES integration / curtailment; Carbon Emissions; Fuel mix |
| **Impact on total power system costs** | SEW (Generation costs, BESS costs and DSM costs); Avoided $CO_2$ emission costs; Fuel savings due to integration of RES; Interconnector CAPEX; Congestion revenues |
| **Optimal countries Ireland should connect with** | Comparison across the simulated cases |
| **Security of supply** | EENS; Security of supply impacts |

Based on the objectives of this study, DNV selected a number of metrics to assess the primary impacts of additional interconnection on the SEM system. Table 6-2 presents the list of KPIs which have been assessed in this study. Some of the KPIs are direct outputs of the simulations (based on market modelling in PLEXOS software) and others are partly based on simulation outputs with some post-processing calculations. Only capital cost (CAPEX) KPI is assessed using DNV in-house data. DNV has a dynamically updated database of CAPEX of global HVDC projects, including the distribution of total costs per component type.

These KPIs are designed to help explain the economic impact for the society on Socio-Economic Welfare (SEW) and the TSOs (via congestion revenue and interconnector CAPEX), the success of RES integration (via RES curtailment, fuel mix, carbon emissions and interconnector utilization) and guarantee of security of supply (via the EENS and Security of Supply impacts) for each of the examined scenarios of interconnector capacity. The majority of these KPIs are adopted from the ENTSOE CBA Guidelines as explained in the following section.[56]

**Table 6-2 Overview of the assessed KPIs**

| KPI within our study | Description | Assessed based on: |
|---|---|---|
| 1. Socio-Economic Welfare (SEW) | The change in SEW is calculated as the difference in the total running costs of all generators (fuel and O&M costs), plus the total variable O&M costs for BESS and the costs for flexible demand (fuel, emission start/shutdown) across the study cases. | Direct output of PLEXOS |
| *1.1. Avoided $CO_2$ emission costs* | As part of the SEW, the avoided costs for $CO_2$ emission are evaluated between factual and counterfactual cases per assessed year. Thereby, the assumed ETS values for 2030 and 2050 are 91.8 EUR/tonne $CO_2$ and 118.1 EUR/tonne $CO_2$, respectively. | Calculated based on PLEXOS outputs ($CO_2$ emissions) and assumed ETS values |
| *1.2. Fuel savings due to integration of RES* | As part of the SEW, the saved fuel costs due to RES integration are evaluated between factual and counterfactual cases per assessed year. The methodology for the evaluation can be found in section 4.1.1 in the ENTSOE TYNDP Implementation Guidelines 2022[57]. | Calculated based on PLEXOS outputs (RES generation & availability; nodal prices) and by using the demand weighted average marginal price per bidding zone |
| 2. Congestion revenues | Congestion revenues across the interconnectors connecting the SEM to other countries (evaluated per individual link). | Calculated based on PLEXOS outputs (power flows; nodal prices) |
| 3. Interconnector CAPEX | CAPEX estimates for each individual interconnector taking into account the onshore HVDC converter and the HVDC cable. For the hybrid assets, only the transmission part is considered. | Calculated by making use of DNVs internal database of CAPEX/OPEX costs of current HVDC projects. |
| 4. RES Curtailment | The curtailment rates for each of the renewable types as well as for the total renewable generation in the system. Results are displayed in percentages of curtailment and in absolute values. | Calculated based on PLEXOS outputs (RES generation; RES availability) |
| 5. Carbon emissions | The sum of $CO_2$ emissions in tonnes across a simulated year. | Direct output of PLEXOS |
| 6. Interconnector utilisation | The ratio (in percentage) between the annual average power flow and the maximum possible flow (installed capacity) per interconnector. Provided for information purposes only and does not indicate any cost or benefit. | Calculated based on PLEXOS outputs (power flows) and assumed installed capacity of Interconnectors |
| 7. Fuel mix | The annual share of each of the fuel types in the final generation mix. | Direct output of PLEXOS |
| *8. Expected Energy Not Served (EENS) | Depending on the outcome of simulation we will evaluate either:<br>a) The unserved energy demand (in case present) to assess the energy volumes (GWh) and duration (hrs) of foreseen 'loss of load' events.<br>b) The number of hours when all system generators are operating at maximum to indicate the level of generation scarcity | Direct output of PLEXOS |
| 9. Security of supply impacts | Qualitative | Qualitative |

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[56] https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/CBA/210322_3rd_ENTSO-E_CBA_Guidelines.pdf

[57] https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2022/IG/220304_TYNDP2022-Implementation-Guidelines.pdf

As explained in Chapter 3, various study cases are analysed depending on different interconnector capacities between countries in 2030 and 2050. Table 6-3 provides an overview on the assessed study cases. The counterfactual cases represent the base case which are used to assess the impact of the other study cases (factual cases). For the counterfactual cases, the simulations consider only the expected interconnector capacities among all countries (SEM (ROI & NI), GB, FR and ES), thus, resulting in one single simulation per assessed year. The factual cases, however, are individual simulation runs whereby the specific interconnection capacity between two countries is increased (either min or max capacity scenario). Thus, the factual simulations resulted in six individual runs for 2050, three for 2040 and one for 2030 (in 2030 only SEM-GB capacity is increased in the factual case). In addition, for 2040 and 2050 we also performed simulations with connections to all countries reflected in the model – All IC min and All IC max for 2050, and All IC for 2040.

**Table 6-3 Overview of the study cases, based on the additional Interconnection capacities [MW], as introduced in Chapter 4.6**

| Study cases | SEM-GB | SEM-FR | SEM-ES |
|---|---|---|---|
| **Counterfactual 2030** | 0 | 0 | 0 |
| **Factual 2030** | 1,250 | 0 | 0 |
| **Counterfactual 2040** | 1,250 | 0 | 0 |
| **Factual 2040** | 1,300 | 1,050 | 1,000 |
| **Counterfactual 2050** | 1,250 | 0 | 0 |
| **Factual 2050 min** | 1,300 | 2,100 | 1,500 |
| **Factual 2050 max** | 2,300 | 3,100 | 1,900 |

The results are presented for each study case individually and according to the pre-defined KPIs. The results are shown in absolute values and per MW of additional interconnector capacity. By indicating the results per MW of additional capacity, the values of the KPIs can be better compared across the study cases which vary in terms of additional IC capacity.

## 6.2.1 Detailed methodology for KPI evaluation

Table 6-4 includes explanations of the calculation methodology applied in this study for each of the KPIs, as well as their relation to the ENTSO-E CBA 3.0 metrics.

**Table 6-4 Overview of the calculation methodology per KPI and how it relates to the ENTSO-E CBA 3.0**

| KPI within our study | How it is calculated in this study | Reference to ENTSOE CBA 3.0 draft 2021[58] | Reference to ENTSOE TYNDP Implementation Guidelines 2022[59] |
|---|---|---|---|
| 1. Interconnector CAPEX | Initial CAPEX of interconnectors.<br>Expressed in mlnEUR in 2022 money.<br>Calculated for all additional links, assuming average distance between the connected countries. | See KPI C1, C1a (p110). Only C1a will be evaluated using DNV's in-house equipment cost database. 2022 equipment cost values are used. | For hybrid links between IE and GB, we will assess the CAPEX of legs to shore, as well as the offshore platform and substation. OWF generation CAPEX is not assessed.<br>RES is assumed to be operational both in the 2050 counterfactual and 2050 factuals, whereby in the counterfactual it is assumed to be radially connected. The cost of the offshore platform and substation is assumed to be the same in both cases. We will evaluate the CAPEX savings due to avoided |

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[58] https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/CBA/210322_3rd_ENTSO-E_CBA_Guidelines.pdf

[59] https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2022/IG/220304_TYNDP2022-Implementation-Guidelines.pdf

| KPI within our study | How it is calculated in this study | Reference to ENTSOE CBA 3.0 draft 2021[58] | Reference to ENTSOE TYNDP Implementation Guidelines 2022[59] |
|---|---|---|---|
| | | | need to build a radial connection for the OWF.<br>This is different from the TYNDP guidelines, since we assume that RES will be implemented in any case, whether the hybrid project is present or not. The comparison between the counterfactual and 2050 min and max will show the effect of hybridising an interconnector to GB (that would otherwise be a point-to-point link) and CAPEX savings in OWF connection that are enabled in this way.<br>See section 9.3.2 (p81, 82) |
| 2. Socio-Economic Welfare (SEW) | The sum of all generators, BESS systems and flexible demand variable (fuel, emission start/shutdown) and O&M costs over a year.<br>Expressed in mlnEUR/yr.<br>Calculated per country or bidding zone for Ireland, Northern Ireland, France, Great Britain and Spain. | See KPI B1. Follows the generation cost approach (p 65-67), where "Total generation costs are equal to the sum of thermal generation costs (fuel plus $CO_2$ ETS costs), and DSR costs."<br>Further, the effects of $CO_2$ emissions, based on assumptions regarding emission costs, are monetised and reported as additional information based on emission reduction calculated in KPI 5 Carbon Emissions.<br>The effects of RES integration on SEW due to the reduction of curtailment and lower short-run variable generation costs is monetised and reported as additional information based on RES integration (avoided curtailment) calculated in KPI 4 RES Curtailment. | Follows Method 1 (p50) and methodology 4.1.1 for fuel savings due to integration of RES (p56) and 4.1.2 for avoided $CO_2$ emission costs (p56). |
| 3. Congestion revenues | Product of flow over an interconnector times price differential over a year on an hourly basis.<br>Expressed in mlnEUR/yr.<br>Calculated per line and summed up per border. | Not needed to be explicitly reported when generation cost approach is followed for KPI B1 SEW as this benefit is captured.<br>Will be reported in this study as an additional information, not to be considered as an additional benefit. | NA |
| 4. RES Curtailment | Reduction in total annual curtailment of RES generation.<br>Expressed in MWh/yr. | See KPI B3. Calculated for interconnectors within this study, thus for projects that increase the capacity in the system itself (p75). | NA |

| KPI within our study | How it is calculated in this study | Reference to ENTSOE CBA 3.0 draft 2021[58] | Reference to ENTSOE TYNDP Implementation Guidelines 2022[59] |
|---|---|---|---|
| | Calculated per country or bidding zone for Ireland, Northern Ireland, France, Great Britain and Spain. | | |
| 5. Carbon emissions | Sum of all emissions from fossil fuel powered generation over a year.<br>Expressed in $CO_2$ tonnes/yr.<br>Monetised under KPI 1; also monetised under this KPI as an additional societal benefit).<br>Calculated per country or bidding zone for Ireland, Northern Ireland, France, Great Britain and Spain. | See KPI B2 (Additional Societal benefit due to $CO_2$ variation).<br>To be monetised based on the societal cost of $CO_2$ less the ETS $CO_2$ price to avoid double counting with KPI 1. (p71, 72).<br>ETS price assumed to be 91.8 EUR/tonne $CO_2$ in 2030, 104.1 EUR/tonne $CO_2$ in 2040 and 118.1 EUR/tonne $CO_2$ in 2050 within this study. | Follows KPI B2 approach (p57). Societal cost of $CO_2$ to be equal 100 EUR/ton for 2030 and 269 EUR/ton for 2040 and 2050 (p 58).<br>Only market studies are taken into account, see 4.2.1 (p59). |
| 6. Interconnector utilisation | Volume-weighted average percentage of total transport capacity used over a year as the actual hourly flow divided by the maximum possible flow.<br>Expressed in %.<br>Calculated per line and summed up per border. | Not required to be explicitly reported. | NA |
| 7.Fuel mix | Total fuel consumption per year.<br>Expressed in MWh/yr/fuel type.<br>Calculated per country or bidding zone for Ireland, Northern Ireland, France, Great Britain and Spain. | Not required to be explicitly reported. | NA |
| *8. EENS | Unserved energy demand over a year. Expressed in GWh/yr. | See KPI B6. A much-simplified approach is taken – EENS is only reported if it is present in the simulation results. | NA. A much-simplified approach is taken. |
| 9. Security of supply impacts | Qualitative | See KPIs B7, B8 and B9. Table 10 (KPI B8) could be used to comment on the impacts on stability in a qualitative manner (p 101).<br>As we do not run any quantitative network simulations, we will reflect in a broad manner comments received from EirGrid on the operational challenges that interconnectors could help to address. | NA |

## 6.2.2 Hybrid links

As discussed in Section 4.6, a number of the 2040 and 2050 links between the SEM and GB are assumed to be of a hybrid type. This means that they serve a dual purpose – exporting offshore wind energy to shore and providing cross-border capacity between the countries. It is important to elaborate on how these links are treated within our assessment.

2050 counterfactual features 40.3 GW of offshore wind connected to the SEM system (37 GW to ROI and 3.3 GW to NI). In 2040 and 2050 cases where connections between the SEM and GB are modelled, we assume that the offshore wind capacity of the hybrid asset is taken away from the total SEM offshore wind. In this way the total installed offshore wind capacity is kept the same in the counterfactual and factual cases. The offshore wind farm is represented as a separate offshore bidding zone from a market perspective, yet it belongs to the SEM offshore wind capacity.

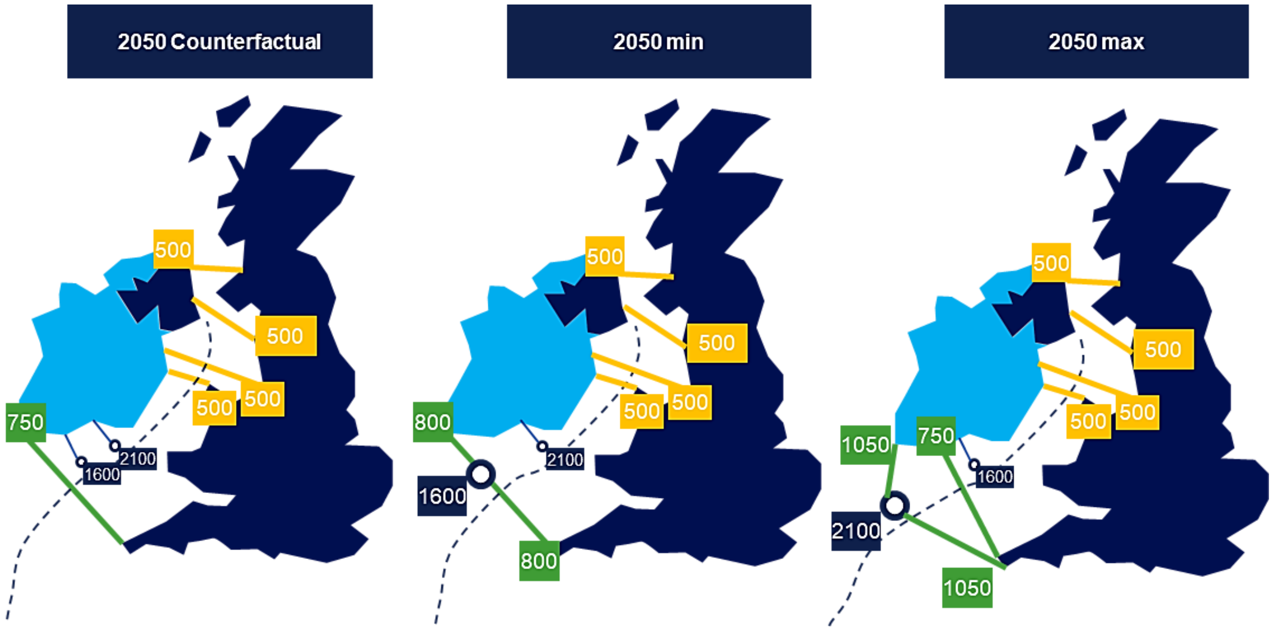

Figure 6-1 Illustration of hybrid interconnectors for 2050

The difference is in how this generation capacity is connected. For example, in 2050 min, a 1,600 MW wind farm is assumed to be integrated into a hybrid asset with two links of 800 MW to the SEM and GB. This means that compared to the counterfactual, the SEM system has 800 MW less offshore wind directly connected to it and GB has 800 MW more. Similarly, in 2050 max, a 2,100 MW wind farm is modelled to be a part of a hybrid asset. In the counterfactual we assume that this capacity connects directly to the SEM system, while in the factual the connection to the SEM is only 1,050 MW, and the other 1,050 MW are connected directly to GB.

This has an impact on the SEW indicator, as the system effectively has 800 MW less of supply directly available to it (excluding interconnection capacity). In periods when the SEM system has high demand, and all interconnectors are already importing, the system will have to run extra 800 MW of conventional generation to compensate. This will affect the total cost of generation and the volume of $CO_2$ emissions.

Congestion revenues will be affected as well. Where in counterfactual we counted them on a point-to-point link between SEM and GB, in 2040 and 2050 factual cases we are adding up the congestion rents on two legs of the hybrid asset.

The fact that the offshore wind farm belongs to Irish offshore wind means that its generation is still tagged as SEM system RES production. Hence, even though e.g., in 2050 min only half out of 1,600 MW of hybrid offshore wind asset is directly connected to SEM, the generation output still counts as belonging to SEM renewable production, even when it flows straight to GB.

It is also worth explaining how we treat the hybrid asset in our CAPEX estimate. As explained in Table 6-4, we assess the CAPEX of legs to shore and onshore converter stations. Offshore wind farm generation, offshore platform and offshore converter station CAPEX is not assessed. As mentioned above, we assume that the offshore wind farm is operational both in the 2050 counterfactual and 2050 factuals, hence the offshore substation and its support structure will be required in any case. In the counterfactual the wind farm is assumed to be radially connected. From the perspective of entire society (consumers, developers, TSO), developing a hybrid asset in 2050 min case helps to avoid the need to build the radial connection of 1,600 MW from the wind farm to shore. Instead, two connections of 800 MW are developed. The costs of the offshore platform and HVDC converter are the same in both cases, hence not calculated. In our assessment we evaluate the CAPEX savings due to avoided need to build a radial connection for the OWF. This approach is different from the TYNDP guidelines, since we assume that RES will be implemented in any case, whether the hybrid project is present or not. The comparison between the counterfactuals and factuals for 2040 and 2050 will show the effect of hybridising an interconnector to GB (that would otherwise be a point-to-point link) and CAPEX savings in OWF connection that are enabled in this way.

## 6.3 Results

In this section we present the results of KPI assessment and provide argumentation and rationale for them. Most of the results and underlying charts are expressed in terms of differences between the factual and counterfactual cases rather than in absolute values. This allows us to analyse whether proposed interconnection increases deliver benefit against the status quo development for 2030, 2040 and 2050.

The results are presented for the simulations, where we tested the impact of additional interconnection with a particular country and with all countries. An example of the former is 2050 IC min GB, in which case only additional interconnectors with GB in accordance with the minimum boundary of potential 2050 interconnection capacity are reflected in the model. For the latter case, we run a simulation assuming that all additional interconnections with all countries (Great Britain, France and Spain) are implemented. An overview of cumulative IC capacity is given in Figure 6-2.

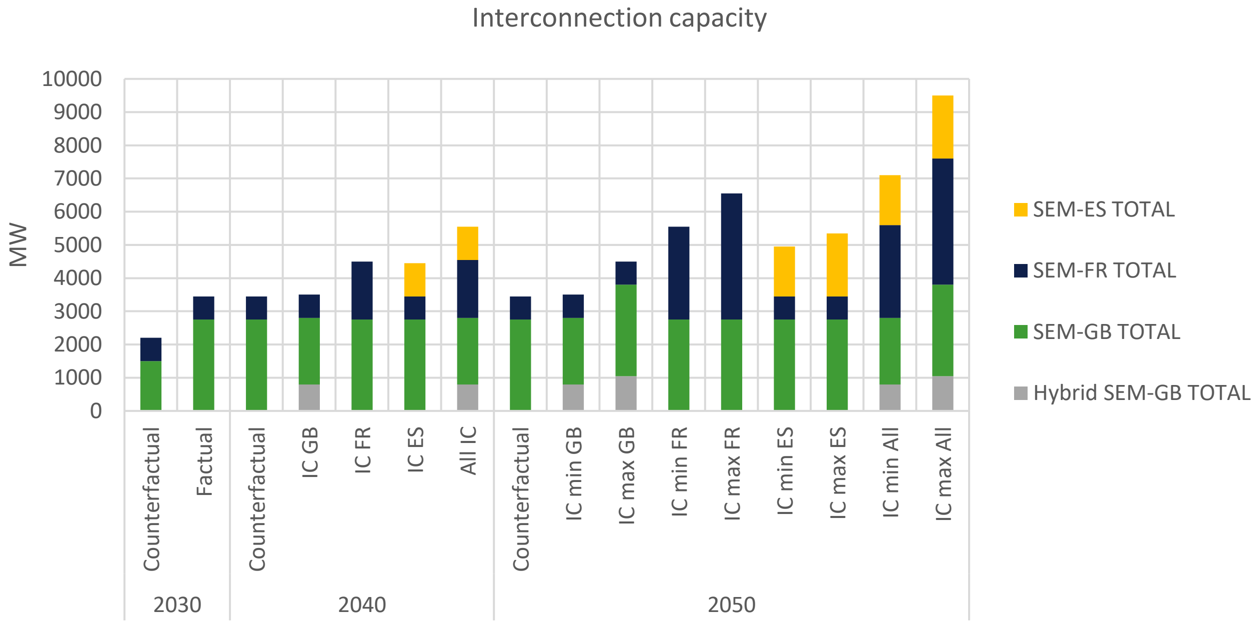

**Figure 6-2 Overview of IC capacity in different simulation cases**

The difference in IC capacity between the factual and counterfactuals is given in Figure 6-3.

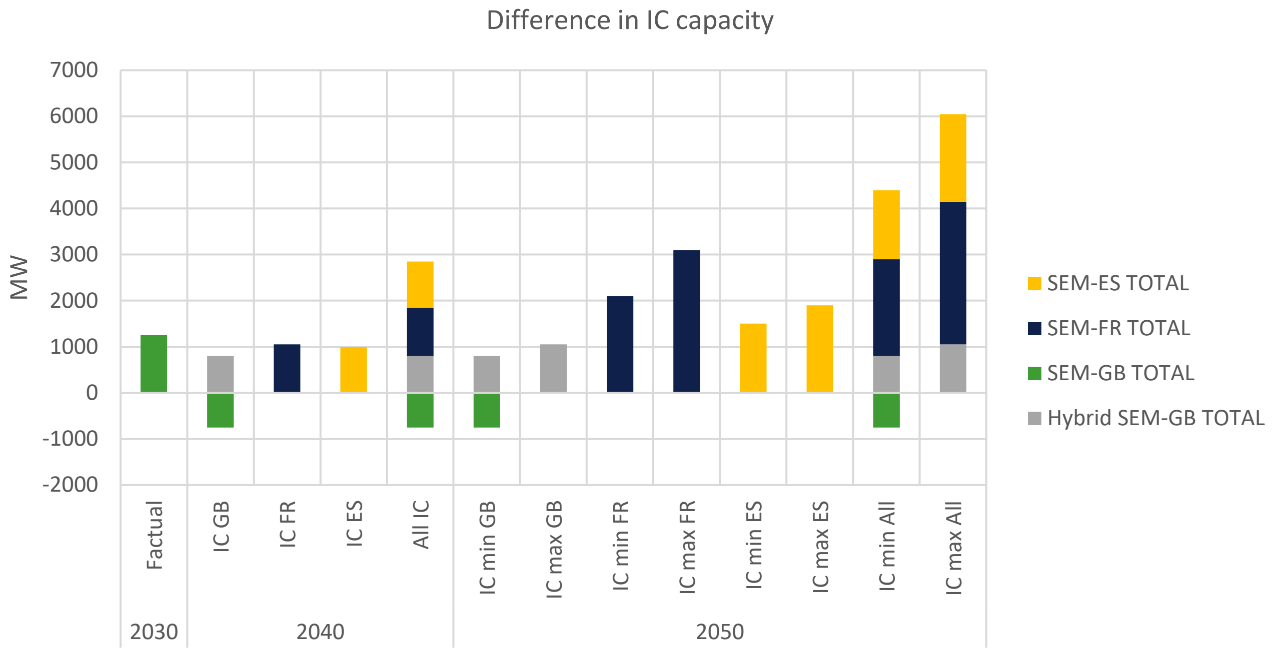

**Figure 6-3 Overview of the difference in IC capacity between factuals and counterfactual**

### 6.3.1 Interconnector costs (CAPEX)

CAPEX assessment provides an indication of the total investment costs of interconnectors.[60] It reflects the total costs of the primary assets that constitute an interconnector – onshore HVDC converter stations and subsea HVDC cables. The costs that are captured under this indicator cover equipment manufacturing, transportation, and installation, as well as project management and contingency costs (see Annex for more detail). It is worth noticing that the CAPEX costs are the upfront investment for the interconnection, not annualised investment costs.

**Summary**

Our assessment of 2050 shows that in absolute values interconnections to France and Spain are more expensive than those to GB. This is mainly driven by higher interconnection capacities and distances between the connected countries. When considering the cost per MW of additional interconnection capacity, France and Spain also exhibit higher costs, at the same time benefitting from economies of scale (max cases are cheaper than min cases in CAPEX per MW). Hybrid links between the SEM and GB allow to realise savings in CAPEX compared to the counterfactual. They increase cross-border capacity while also integrating offshore wind farms, thus avoiding the costs of offshore wind grid connection systems and of an alternative point-to-point link. This comes with a caveat that unlike for normal point-to-point interconnections, cross-border capacity of hybrid links is variable and depends on wind generation profile. They can only act as conventional point-to-point interconnectors at moments when the wind farm production is zero.

The absolute additional CAPEX for 2030 is 687 mlnEUR; for 2040 case where all interconnectors are implemented – 1,452 mlnEUR; for 2050 min case with all interconnectors – 2,974 mlnEUR; for 2050 max case with all interconnectors – 4,441 mlnEUR. In relative terms this translates to 549 kEUR per MW for 2030; 692 kEUR per MW for 2040 case with all interconnectors; 815 kEUR per MW for 2040 min case with all interconnectors; and 734 kEUR per MW for 2050 max case with all interconnectors.

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[60] Since the identification of exact onshore connection points falls out of scope, to evaluate the cost of cables we assumed the following average distances: RoI to GB – 200 km; NI to GB – 135 km; RoI to France – 520 km; RoI to Spain – 950 km; RoI to the offshore wind farm, part of a hybrid asset – 75 km; GB to the offshore wind farm, part of a hybrid asset – 140 km.

**Explanation**

Figure 6-4 presents the results of CAPEX assessment per component type.

Additional interconnectors result in extra CAPEX in 2030, estimated to reach 687 mlnEUR. Most of the cost is attributed to onshore converters, given that the distance between the SEM and GB is relatively low and the share of cable costs is minor.

The hybrid connection between the SEM and GB is already present by 2040 (for the IC GB case) which results in actual CAPEX savings compared to the counterfactual case. This is mainly due to the shift from the conventional radial link to the hybrid connection while the capacity of the link solely increases marginally by 50 MW between the counterfactual and the IC GB case. Among all cases, the connection towards Spain (IC ES) leads to the largest CAPEX differences compared to the counterfactual case with an additional expenditure of 970 mlnEUR which is mainly due to increased cable expenses triggered by the larger distance between SEM and ES (assume average distance is 950 km) vs. SEM and FR (assume average distance is 520 km), while the additional capacity for both cases are comparable (IC ES: 1,000 MW additional IC; IC FR: 1,050 MW additional IC).

Like in 2040, in 2050 we see that connections with GB that are hybridised enable savings in CAPEX compared to the counterfactual case. The fact that the hybrid connection replaces alternative radial link from the windfarm to shore results in savings in GB min case (see Section 6.2.2 for how hybrid links are treated). Analysing the absolute values of additional CAPEX for connections with France and Spain we see that France max case (additional 3,100 MW of IC) leads to the highest expenditure. Notably, the difference between the CAPEX of Spain min and max case is negligible, i.e., less than 3%, owing to a trade-off between cable costs and onshore converter costs, where the former decrease while the latter increase when one single line of larger capacity and higher voltage is added compared to the case with two lines of smaller capacity and lower voltage. It may be, therefore, that all else equal, it can be attractive to implement higher capacity with Spain with the configurations proposed in this study (1,000+900 MW vs 1,500 MW). The cases with all ICs connected come at the highest CAPEX expenditure.

Given the difference in additional IC capacity between the countries, it is more meaningful to analyse the value of KPIs per MW of additional IC capacity as presented in Figure 6-5 (also in the following KPIs across this section we follow this approach). The outliers in the negative part of the graph represent the savings that one achieves by developing the hybrid asset. The values are so large because the added IC capacity in these cases is only 50 MW (both for the IC GB case in 2040 and the IC min GB case in 2050), which is much smaller than in all other cases, hence when normalised by the additional IC capacity, the results for IC GB (2040) and IC min GB (2050) case are always going to stand out. Looking at the other cases, we see that the relative CAPEX for additional interconnection capacity is the lowest for GB max, which is a direct outcome of the short distance between the two countries. Connections with Spain are more expensive than those to France following the same rationale. The average distance that we assume between the SEM and Spain is 950 km, while for France this value is around 520 km.

The underlying values and equipment count are presented in Appendix (section 8.1).

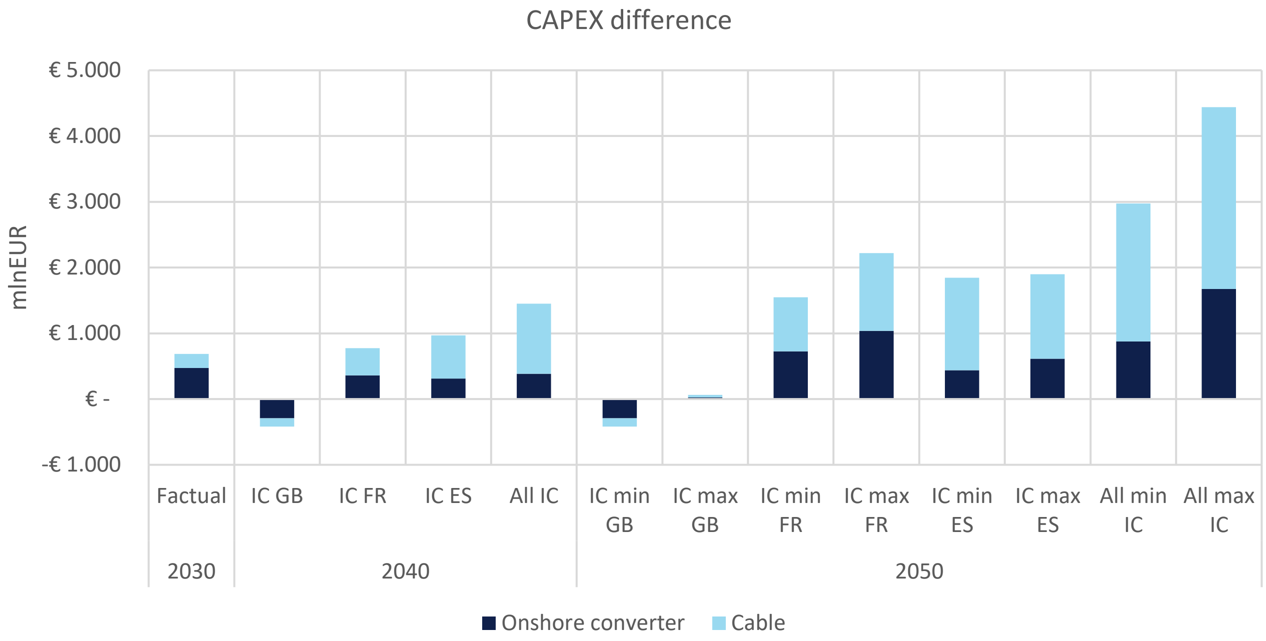

Figure 6-4 CAPEX difference between factual and counterfactual per component type (in mlnEUR)

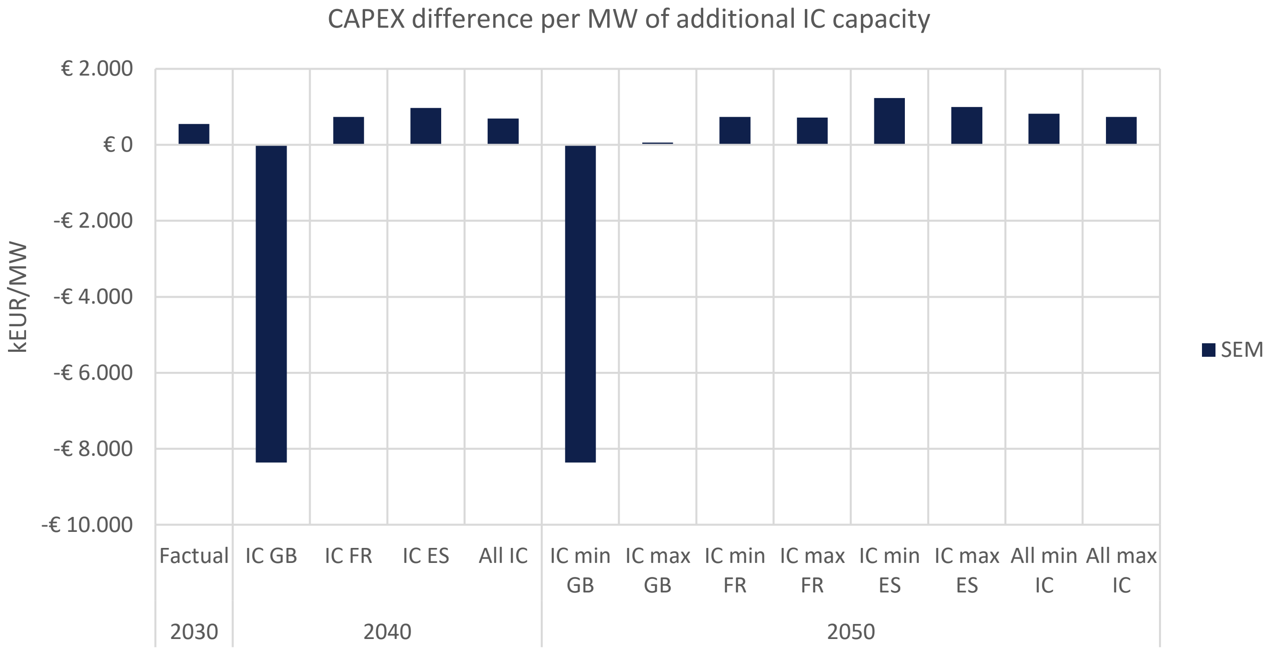

Figure 6-5 CAPEX difference between factual and counterfactual, per MW of additional interconnection capacity (in kEUR/MW)

A complete CAPEX breakdown in absolute values is presented in Figure 6-6.

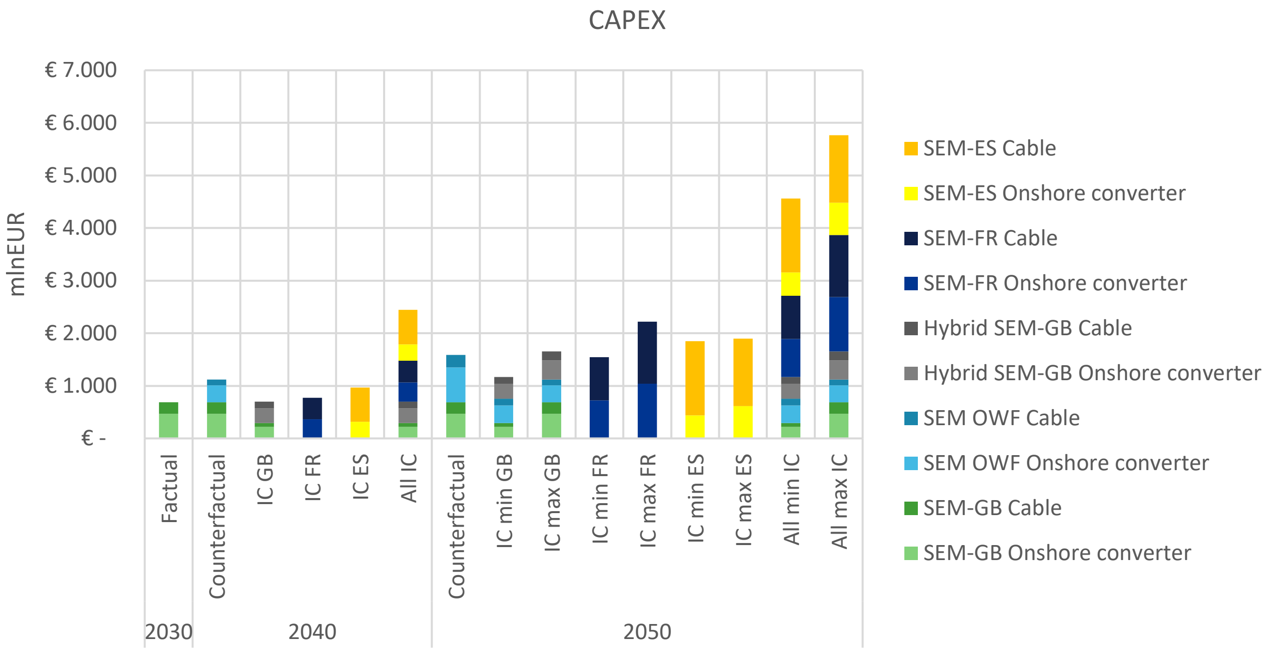

**Figure 6-6 Absolute CAPEX breakdown per component type (in mlnEUR)**

## 6.3.2 Socio-Economic Welfare (SEW)

### 6.3.2.1 Overall SEW

Socio-Economic Welfare (SEW) is a measure of the economic benefits that the whole society (in the context of power sector comprised of consumers, producers, and grid owners) enjoys. Additional transmission projects will affect the SEW in both countries that are connected. As the two power markets become integrated, consumers and producers in both markets benefit from access to the other market's generation and demand, respectively. This affects the volume of generation by each technology, and therefore the total system costs. For the sake of clarity, it is worth repeating that, in this study, system costs and SEW account for the total running costs of all generators (fuel and O&M costs), plus the total variable O&M costs for BESS and the costs for flexible demand (fuel, emission start/shutdown). Interconnector costs are not accounted for in SEW.

**Summary**

Overall, there are Socio-Economic Welfare (SEW) benefits among all connection cases visible in 2030 (102 mlnEUR/year), 2040 (largest SEW: 464 mlnEUR/year All IC case) and 2050 (largest SEW: 891 mlnEUR/year IC max All case), confirming that further interconnection of SEM results in a very significant reduction in system costs (see Figure 6-7). These benefits do not account for the required interconnector costs linked to the additional capacity, which are reported in Figure 6-4. The differences between the countries and cases for 2040 and 2050 are less significant when examined per unit of additional interconnection capacity (see Figure 6-8). Compared to GB, interconnection of SEM with France and Spain result in slightly larger SEW benefits per MW of additional interconnection capacity, with France and SEM system being the main beneficiaries. Given a minor increase of IC capacity by 50 MW compared to the counterfactual, hybrid connection with GB in 2050 min study case yields the largest benefits per MW of additional interconnection capacity – it does not only interconnect the markets but also results in a significantly different dispatch.

**Explanation**

The 2030 factual case results in an increased SEW of 102 mlnEUR/year, compared to the counterfactual case, whereby SEM benefits with the largest share of 56 mlnEUR/year followed by GB with 35 mlnEUR/year (see Figure 6-7). For SEM, such an increase in SEW corresponds to 12% reduction in power system costs compared to the counterfactual case.

Among the 2040 factual cases, the connections towards France and Spain result in the most significant increase in SEW compared to the factual case across all selected countries, with 250 mlnEUR/year and 253 mlnEUR/year, respectively. In both cases (IC FR and IC ES) France is the core country which is benefitting the most in terms of SEW (220 mlnEUR/year in IC FR and 123 mlnEUR/year in IC ES). In fact, among all 2040 cases France benefits the most compared to the other selected countries owing to the fact that France imports either directly or indirectly wind power from SEM and, thus, reduces its rather high system costs. The rather comparable increase in overall SEW between the IC FR and IC ES cases can be explained by the fact that both cases assume a similar additional interconnection (IC FR: 1,050 MW additional IC; IC ES: 1,000 MW additional IC). The IC GB case, on the other hand, assumes only a minor increase in IC of 50 MW, compared to the factual case, thus, resulting in a low benefit in terms of SEW (5 mlnEUR/year). SEM benefits in 2040 only in the IC ES case, which leads to a 25 mlnEUR increase in SEW, i.e. 7% reduction in system costs. This could be triggered due to rather complementary renewable generation profiles between Spain (predominantly solar PV) and SEM (predominantly wind) which could result in solar power imports during times when wind generation is low in SEM, thus, increasing SEW.

In 2050, the largest increase in SEW in absolute figures is achieved when connecting SEM to France and Spain which display significantly larger values compared to the connection towards GB (both for the min and max cases). This outcome is due to a better integration of RES generation, which leads to a reduction in $CO_2$ and fuel costs (see Section 6.3.2.2 and 6.3.2.3 for further details). As expected, the cases which consider all connections combined (IC min/max All) result in the largest SEW increase since the SEW benefits are in general increasing with IC capacity. The difference with the counterfactual reaches 891 mlnEUR/year (IC max All) in 2050. Among all factual cases in 2050 (except IC max GB), France is the country that benefits the most in terms of SEW growth, ranging from 23 mlnEUR/year in IC min GB and 223 mlnEUR in IC max FR to 430 mlnEUR/year in IC max all. This is mainly due to the generally very significant system costs in France, which are a result of the high share of thermal generation in the country in comparison with other countries where renewable generation presents higher shares in the generation mix. France system costs are by far the largest among all examined countries in the counterfactual case for 2050 (3,854 mlnEUR/year), thus the additional import/export has a rather big impact on its SEW, since renewable generation imported from neighbouring countries replace expensive fossil fuel generation. Worth noting is also that Great Britain benefits more when SEM is connected to France than to Great Britain itself (120 mlnEUR/year in IC max FR and 62 mlnEUR/year in IC max GB). The reasoning could be that, due to the already implemented and rather extensive IC between SEM and GB, the additional IC does not result in significantly more imported wind power, especially since both countries display rather similar dynamics in the wind generation profile. The connection to France, on the other hand, allows Great Britain to increase its imports from France (mainly baseload nuclear power) during times when France is importing vast amounts of wind from SEM and thereby enhancing its SEW. Compared to the 2040 cases, SEM benefits from all 2050 cases in terms of SEW and except for the IC min GB case. In particular, SEM benefits the most when connecting to France and Spain, leading to an increase in SEW of 89 mlnEUR/year and 86 mlnEUR/year for the max cases, respectively, which correspond to about 30% reduction in SEM system costs.

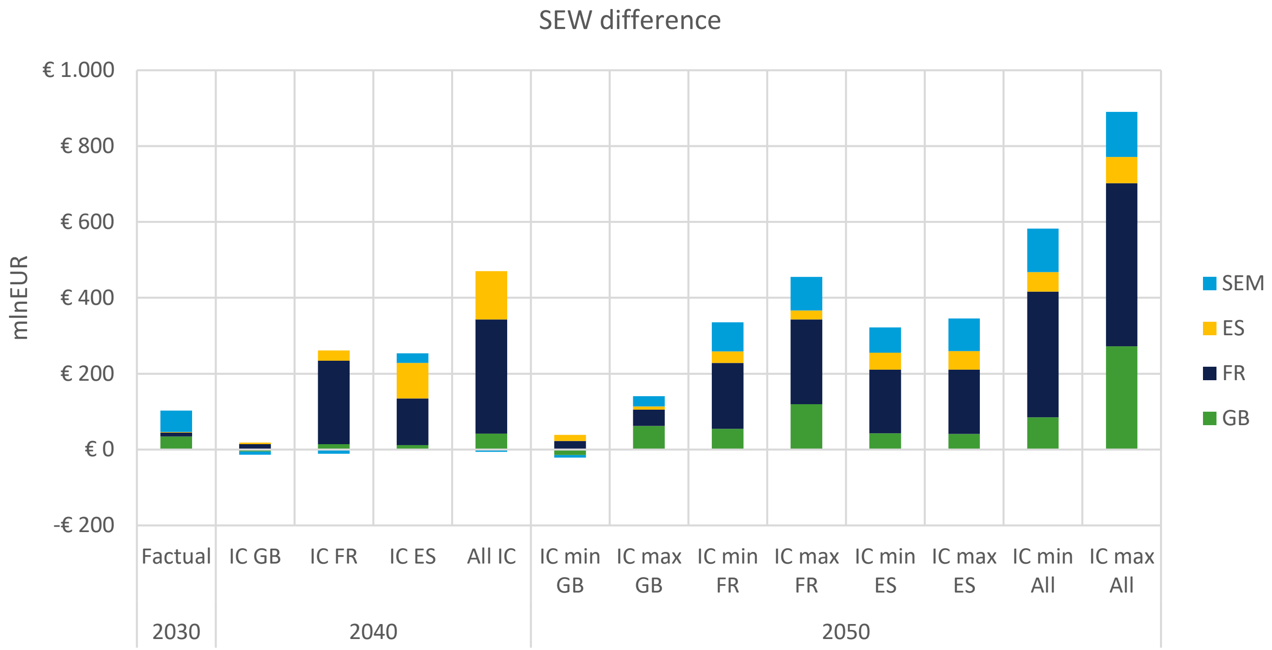

**Figure 6-7 SEW difference between factual and counterfactual, per absolute value (in mlnEUR). (Positive value implies gain in SEW compared to the counterfactual)**

In terms of SEW per additional interconnector capacity, whereas the 2040 values are rather comparable, there are slightly larger values for the Spain cases compared to the French ones in 2050 (see Figure 6-8). These differences are mainly due to larger assumed absolute interconnector capacity values for SEM-FR (2,100 MW 2050min; 3,100 MW 2050max) than for SEM-ES (1,500 MW 2050min; 1,900 MW 2050max) which results in slightly lower values when examine the SEW per additional IC (159 kEUR/MW/year in IC min FR and 214 kEUR/MW/year in IC min ES). Similar to the absolute values (figure above), SEM solely benefits in the IC ES case in 2040 with 25 kEUR/MW/year of additional IC. In 2050, SEM benefits among all cases (except IC min GB) regarding enhanced SEW, whereby the connection to Spain results in the highest values with 45 kEUR/MW/year of additional IC for the IC max ES case.

Notably, the IC GB 2040 and the IC min GB 2050 cases represents outliers and are triggered by the fact that the factual and counterfactual interconnection capacity for these specific cases differs only by 50 MW (1,250 MW counterfactual; 1,300 MW factual) which subsequently leads to higher number per MW. In addition, it does not only provide cross-border capacity but also integrates part of Irish offshore wind (800 MW) directly into GB system. We highlight that a similar spike for the 2040 IC GB and 2050 IC min GB cases occurs for most of the KPIs evaluated in this study when analysing the relative change per MW of additional IC capacity. This happens because the change is only 50 MW, while other cases have increases in a range of ~1,000 MW, hence when normalising by such different values, the results vary a lot.

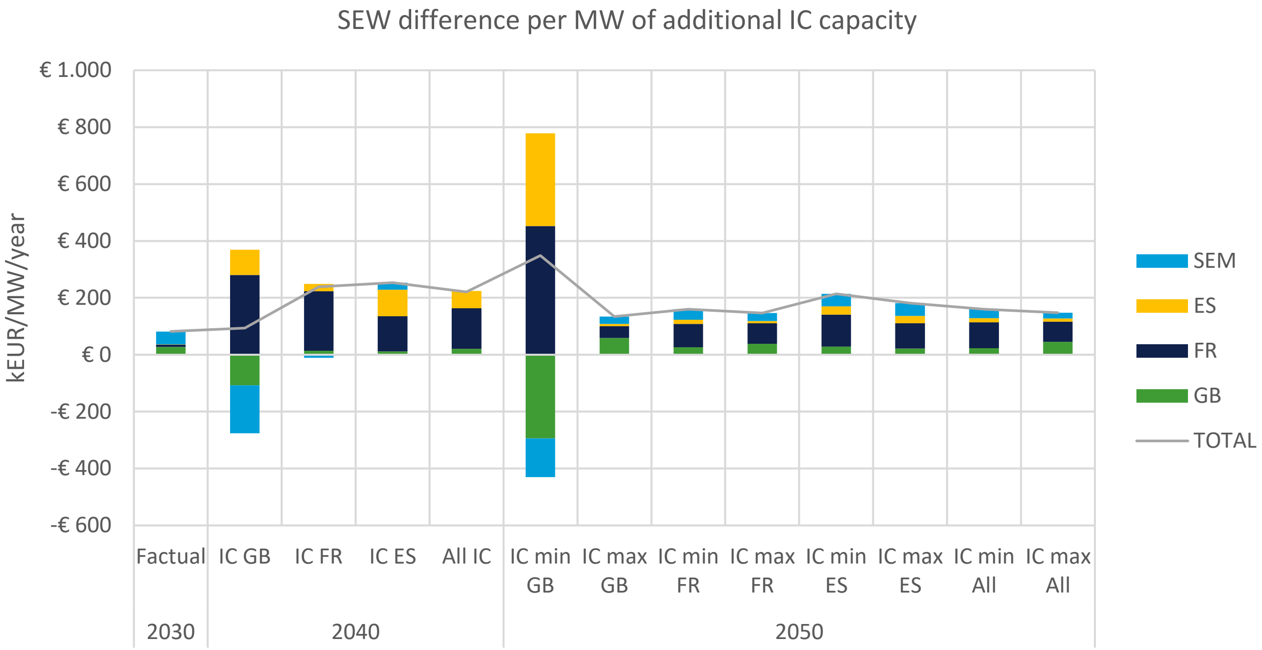

**Figure 6-8 SEW difference between factual and counterfactual, per MW of additional interconnection capacity (in kEUR/MW/year)**

In addition to considering SEW gains in isolation, it can be interesting to look at the ratio of SEW gain to CAPEX spent, which is commonly referred to as Benefit-to-Costs Ratio (BCR indicator). This can be used to validate whether developing an interconnector is attractive from the perspective of society as it shows whether societal benefits (SEW gain) outweigh the costs (CAPEX) Note that this does not capture all benefits – the SEW gain calculation within our study only considers wholesale market welfare benefits (the other ones would include utilisation of an interconnector to provide ancillary services, avoid onshore grid reinforcements etc). Equally, CAPEX costs are not the only costs that would be incurred throughout the lifetime (OPEX costs are not taken into account in this study but would normally be considered).

Figure 6-9 presents the results of this high-level assessment, whereby the outcomes are given in total (total SEW benefit divided by the total CAPEX) and for each connection separately (SEW benefit from both connecting country combined divided by the total CAPEX). It is important to note that these results are highly dependent on the assumed CAPEX values for this study (see Section 6.3.1).

We obtain a value of 0.32 EUR and 0.2 EUR of total annual welfare gain across the four considered systems for each 1 EUR of CAPEX investment for the 2040 All IC and 2050 All IC cases, respectively. Assuming this benefit would stay on average stable across the lifetime of 25 years (conservative estimate of interconnector lifetime by DNV), at 7% discounting rate, we arrive at 3.7 EUR and 2.3 EUR of welfare gain for each 1 EUR of investment for 2040 and 2050 cases, respectively. For 2030, the total annual welfare is around 0.15 EUR per year per 1 EUR of CAPEX spent. The same logic allows us to calculate a welfare gain of 1.75 EUR per 1 EUR of CAPEX spent brought by the suggested 2030 additional interconnector capacity. Among most cases, the connection between France and SEM leads to the largest values in terms of enhanced SEW (in France and SEM) per overall CAPEX spent. The IC max GB represents an outlier among all cases (including the total value) which is due to the only minimal increase in CAPEX spent between the counterfactual and the IC max GB cases (see Figure 6-4). The only marginal increase in CAPEX is strongly dependent on the assumed cost values of the hybrid link in the factual case compared to the conventional radial connected interconnector in the counterfactual case.

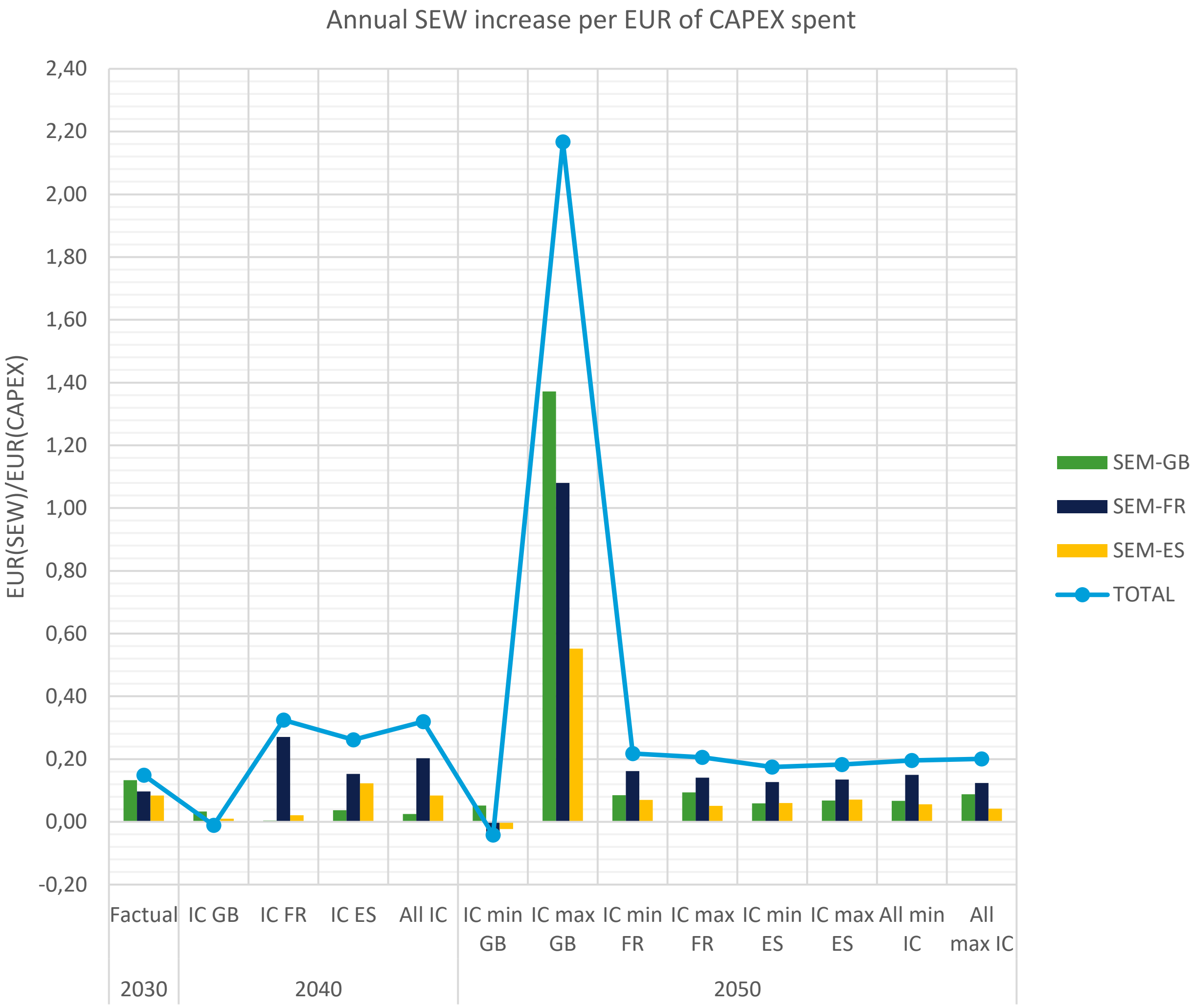

Figure 6-9 High-level assessment of annual SEW gains per CAPEX incurred

### 6.3.2.2 Benefits attributed to $CO_2$ reduction

According to ENTSOE CBA Guidelines the benefits from SEW increase can be attributed to two factors - the first one is reduction of $CO_2$ emissions as clean renewable technology replaces conventional thermal power plants. These benefits are captured in this section. Given that producers have to buy ETS certificates to compensate for their emissions, it is possible to monetise this benefit by using the representative ETS price. According to TYNDP guidelines, these benefits are not to be considered as additional to SEW change, as they are an underlying part thereof. Benefits attributed to $CO_2$ reduction are, therefore, reported here for information purposes and are included in SEW benefits (see Table 6-4).

**Summary**

The benefits attributed to $CO_2$ reduction show a similar behaviour as the SEW figures. Overall, there are benefits among all connection cases visible in terms of avoided $CO_2$ emission costs (see Figure 6-10) as interconnections allow the dispatch of more renewable generators on the system. We observe less significant differences among the factual cases when evaluating the avoided $CO_2$ emission costs per additional interconnection capacity (see Figure 6-11).

**Explanation**

The avoided $CO_2$ emission costs across all selected countries in the 2030 factual costs represent 33 mlnEUR/year compared to the counterfactual case, of which 21 mlnEUR/year are saved in SEM (see Figure 6-10).

Due to the same reasoning explained in the SEW KPI, the 2040 cases connecting France and Spain lead to higher avoided $CO_2$ emission costs compared to the GB case, resulting in 91 mlnEUR/year and 89 mlnEUR/year of avoided $CO_2$ emission costs among all selected countries, respectively. Only the IC ES case results in benefits for SEM in terms of saved $CO_2$ emission costs of 6 mlnEUR/year.

Also in 2050, the largest avoided $CO_2$ emission cost is achieved when connecting to France and Spain, which display significantly larger values compared to the connection towards GB (both for the min and max case) (see Figure 6-10). As expected, the cases which consider all connections combined (IC min/max All) result in the largest avoided $CO_2$ emission costs, up to 299 mlnEUR/year (IC max All) compared to the counterfactual case in 2050. Similar to the SEW analysis, France shows the largest benefit among most factual cases in 2050, ranging from 7 mlnEUR/year in the IC min GB case up to 67 mlnEUR/year in the IC max FR case. This is mainly due to the generally very significant carbon emissions in France which are, together with Great Britain, by far the largest among all other analysed countries in the counterfactual case for 2050 (6,045 ktonne $CO_2$ France; 5,314 ktonne $CO_2$ GB) and, thus, the additional import of pre-dominantly wind power has a rather big impact on the overall carbon emissions. The sources of these carbon emissions are mainly the power generation from conventional fossil-fuel based power plants, such as natural gas which still display some minor shares, especially in France and Great Britain by 2050, in the counterfactual case (Natural gas: 18.4 TWh in FR (2.6 % of total generation supply); 12 TWh in GB (1.8 % of total generation supply) compared to 0.9 TWh in ES (0.1 % of total generation supply); 1.3 TWh in SEM (0.8 % of total generation supply)). Like in the SEW KPI, SEM benefits among all examined cases with the exception of the IC min GB case. Beside the IC min/max All cases, the IC max FR/ES cases lead to the largest benefit for SEM with 23 mlnEUR/year of avoided $CO_2$ emission costs (or saved ETS certificates).

In terms of avoided $CO_2$ emission per MW of additional interconnector capacity, there are slightly larger values for the interconnection with Spain compared to France in 2050, whereas the 2040 values are rather comparable (see Figure 6-11). These differences are mainly due to larger assumed absolute interconnector capacity values for SEM-FR (2,100 MW in 2050min; 3,100 MW in 2050max) than for SEM-ES (1,500 MW in 2050min; 1,900 MW in 2050max). As in the assessment of SEW, the IC GB 2040 and IC min GB 2050 cases are outliers due the only minor increase of the interconnection capacity by 50 MW between factual and counterfactual in 2050 (1,250 MW in the counterfactual; 1,300 MW in 2040 IC GB and 2050 min GB) which subsequently results in inflated numbers per MW.

This KPI is calculated based on the $CO_2$ emissions (retrieved from the Carbon emission KPI; see Section 6.3.5) utilising an ETS price value of 91.8 EUR/tonne$CO_2$, 104.1 EUR/tonne$CO_2$ and 118.1 EUR/tonne$CO_2$ by 2030, 2040 and 2050 respectively.

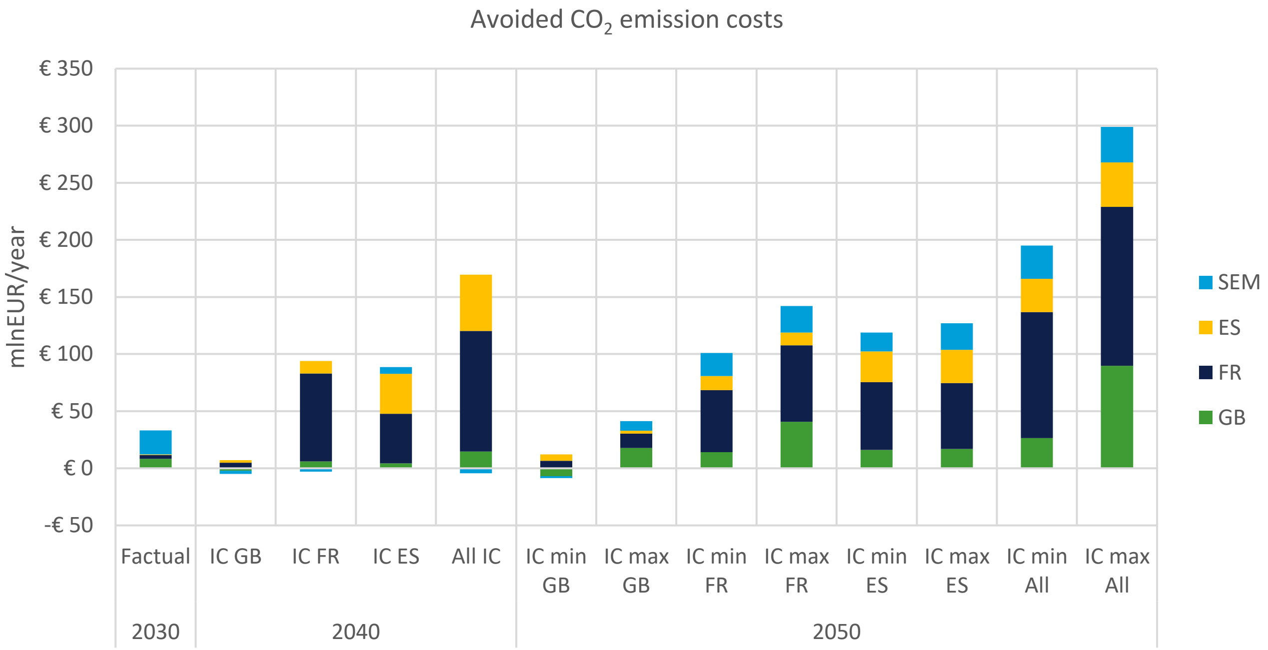

**Figure 6-10 Avoided $CO_2$ emission costs between factual and counterfactual, per absolute value (in mlnEUR/year)**

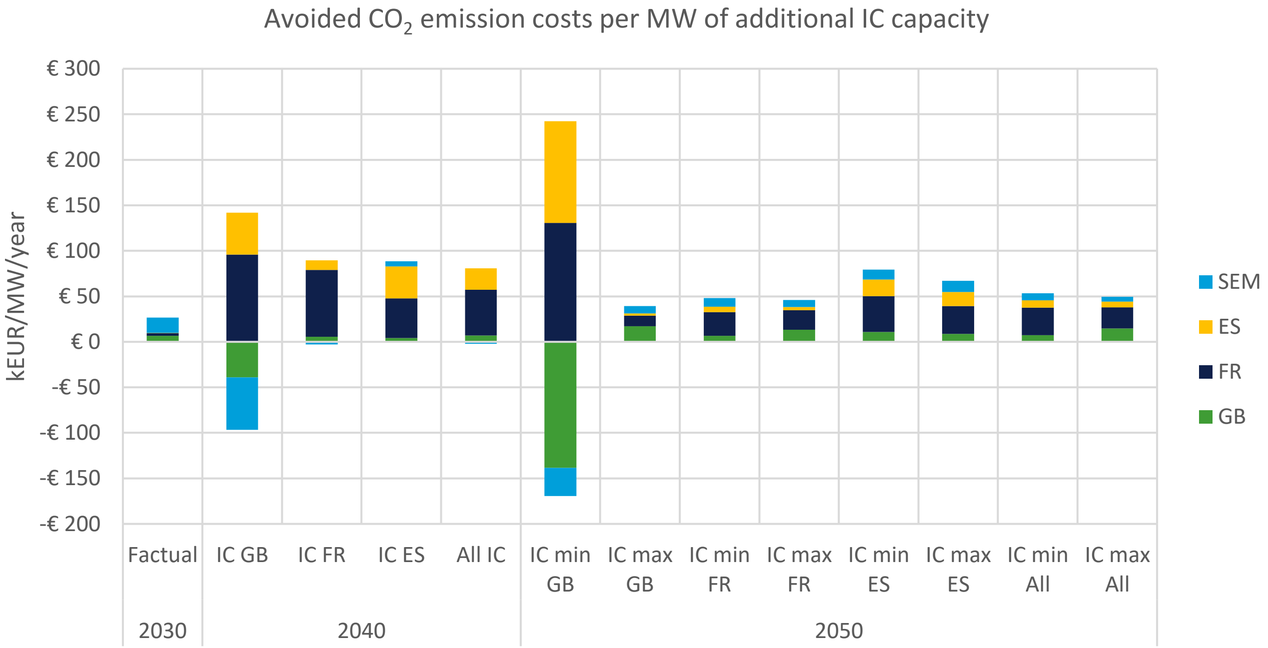

**Figure 6-11 Avoided $CO_2$ emission costs between factual and counterfactual, per MW of additional interconnection capacity (in kEUR/MW/year)**

#### 6.3.2.3 Benefits attributed to RES integration

The second factor which accounts for the SEW increase is related to RES integration. This reflects the fact that RES technologies such as wind and solar have no fuel costs, hence, generally speaking, they are a cheaper way of producing electricity compared to thermal generation. It is possible to monetise this benefit using the demand weighted average marginal price. According to TYNDP guidelines, these benefits are not to be considered as additional to SEW change, as they are an underlying part thereof. Benefits attributed to RES integration are, therefore, reported here for information purposes and are included in SEW benefits (see Table 6-4).

**Summary**

The fuel savings due to the integration of RES (onshore wind, offshore wind, and solar PV) for each assessed case are illustrated in Figure 6-12. As expected, there are benefits among all interconnection cases visible, in terms of benefits attributed to RES integration, suggesting that additional interconnector capacity is facilitating the integration of RES into the system. However, this benefit is mainly experienced in SEM and not in the other investigated countries. Less significant differences among the factual cases are observed when analysing the fuel cost savings per additional interconnection capacity (see Figure 6-13).

**Explanation**

The fuel savings due to the integration of RES results in the 2030 factual case to 88 mlnEUR, compared to the factual case, whereby solely SEM is benefitting from the additional link.

In 2040, the largest fuel cost savings across all countries, besides the All IC case, are reflected in the case where France gets connected to the SEM (105 mlnEUR/year). In the SEM, 92 mlnEUR/year are saved in fuel costs thanks to RES integration. Overall, the SEM is benefiting most in terms of fuel cost savings due to the integration of RES which is due to significant curtailment values in SEM (2040 counterfactual case curtailment levels: 34 TWh/year SEM, 4.7 TWh/year GB, 0 TWh/year FR). Moreover, Spain benefits rather significantly from fuel saving costs among the 2040 cases, triggered by large curtailment values of 95 TWh/year in the counterfactual case.

Also in 2050, the largest fuel cost savings due to the integration of RES are achieved when connecting to France, among the individual cases. As expected, the cases which consider all connections combined (IC min/max All) result in the largest overall fuel cost savings attributed to RES integration, up to 267 mlnEUR/year (IC max All) compared to the counterfactual case in 2050. Among all examined cases, the SEM is by far the largest beneficiary in terms of RES integration, whereby the connections to France lead to the highest values among the individual cases with 107 mlnEUR/year and 158 mlnEUR/year for the IC min FR and IC max FR cases, respectively (see Figure 6-12). This is mainly due to the fact that solely in the SEM, and a lesser extent also in Spain, RES curtailment occurs. Since there is no RES curtailment in Great Britain and France, for either the factual or counterfactual cases, there is also no fuel cost savings due to RES integration visible with increased interconnection capacity.

In terms of fuel cost savings due to the integration of RES per unit of additional interconnector capacity, there are only minor differences visible among the different connection cases in 2040 and in 2050 (see Figure 6-13). Again, the IC GB 2040 and the IC min GB 2050 cases stand out due to the minor increase of interconnection capacity between the counterfactual and factual by 50 MW.

This KPI is calculated based on RES curtailment (retrieved from the RES curtailment KPI; see 6.3.4) and multiplying it with the demand weighted average marginal price per bidding zone.

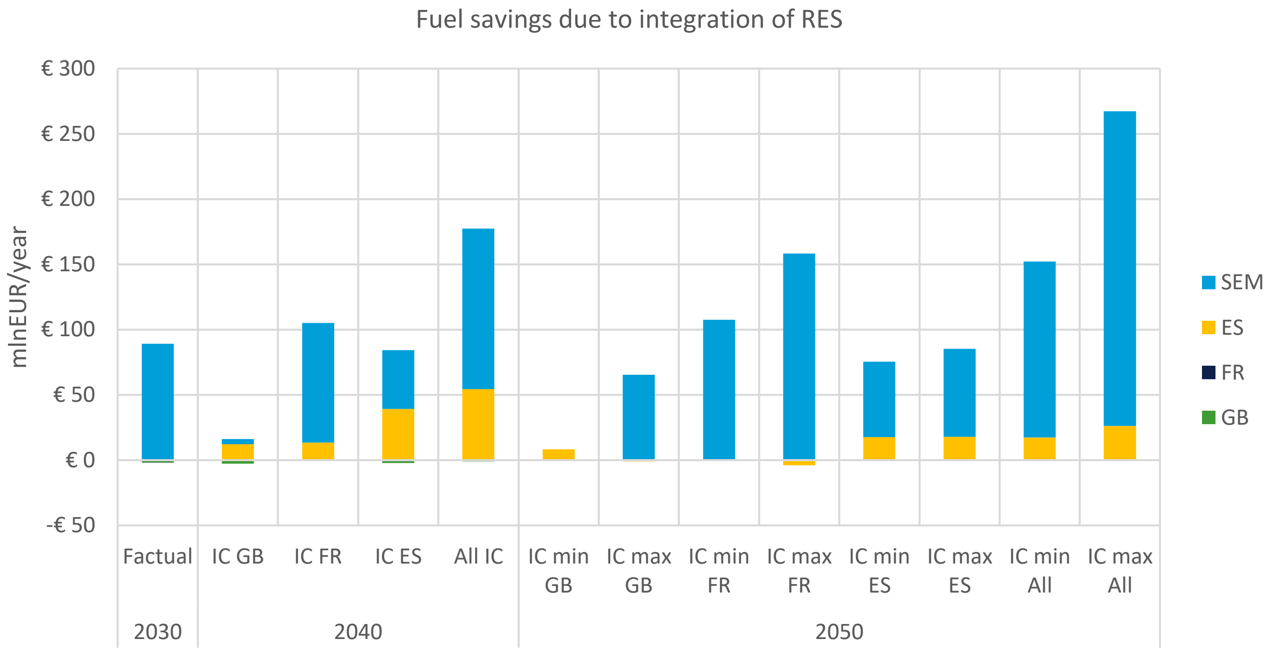

**Figure 6-12 Fuel savings due to the integration of RES, indicated as the difference between factual and counterfactual, per absolute value (in mlnEUR/year)**

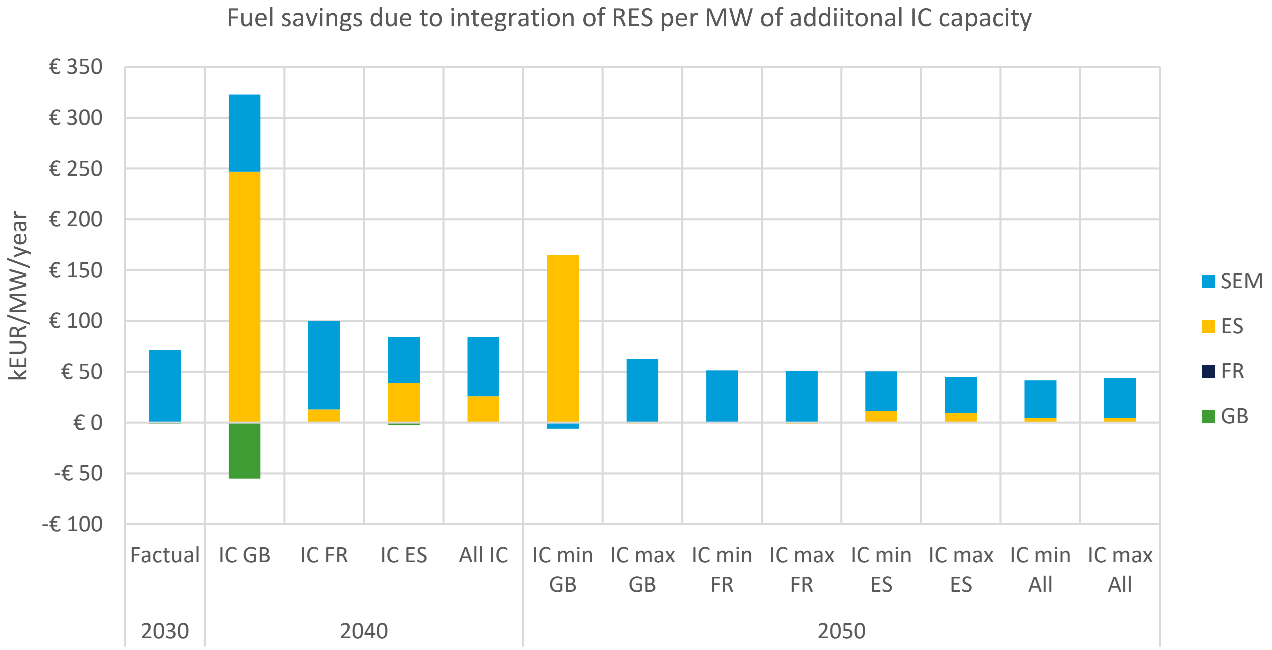

**Figure 6-13 Fuel savings due to the integration of RES, indicated as the difference between factual and counterfactual, per MW of additional interconnection capacity (in kEUR/MW/year)**

### 6.3.3 Congestion rents

Congestion rents in energy economics reflect the value of an interconnector that integrates two different markets. They are equal to the annual sum of hourly products of electricity flow and the price differential between the two markets. The higher the power flow on a line, or the price difference at each end, the higher the value of an interconnector, and hence the congestion rents. Congestion rents are normally captured by network owners, and under European regulation, in most cases should be used to finance future network development.

**Summary**

The differences between the factual and counterfactual congestion rents for each studied interconnection case are presented in Figure 6-14. It can be seen that the connections between SEM-FR, SEM-ES and Hybrid SEM-GB result in significant growth of congestion revenues in 2040 and 2050, while in 2030 they are actually decreasing compared to the 2030 counterfactual case. Among all cases, the SEM-GB links have lower congestion revenues in the factual compared to the counterfactual case, since additional interconnectors cannibalise on already existing links between SEM and GB. The congestion revenues per additional interconnection capacity result in similar values for the individual connection cases in 2040 and in 2050 but shows outliers for the 2040 All IC and 2050 IC min/max All (all combined connected) (see Figure 6-15).

**Explanation**

In 2030 factual congestion rents declined compared to the counterfactual case, suggesting that the additional inks resulted in a good price convergence between the SEM and GB, and SEM and France. This reduction in congestion rents, however, should not necessarily be interpreted as reflecting the non-commercial viability of developing further interconnection capacity between the SEM and GB for 2030. The absolute value of annual congestion rent on additional interconnectors in the 2030 factual case amounts to 74 mlnEUR. With CAPEX estimated at 687 mlnEUR, such an investment would pay back in 15 years (assuming stable annual congestion rent and 7% discount rate). Another point worth highlighting is that the total congestion rents on the SEM-GB border decreased by 2 mlnEUR/year between the counterfactual and factual (not visible on the graph). This is indeed one of the possible outcomes as additional interconnectors cannibalise on the business case of the existing ones – even though there is more capacity and, thus, more power flowing through the border, the price convergence may become stronger, hence the total congestion rents, calculated as the product of the flow and price difference, may go down.

In 2040, among the individual cases, the SEM-FR connection leads to the largest increase in congestion revenues with 309 mlnEUR/year. This result is in line with the expectations and previous observation since the additional interconnection with France boosts power flows from the SEM to France. The shift from the radial- to the hybrid connection in the IC GB case results in a minor overall gain of 6 mlnEUR/year in congestion revenues (hybrid SEM-GB: 113 mlnEUR/year; SEM-GB: -102 mlnEUR/year; SEM-FR: -5 mlnEUR/year). Overall, the All IC case results in the largest increase in congestion revenues with 443 mlnEUR/year (including the decrease of 156 mlnEUR/year congestion revenues on the SEM-GB links). The French interconnection enables the largest increase in congestion revenue, followed by Spain.

Similar to the analysis for 2040, the 2050 IC min/max All cases show that the highest increase in congestion revenues occurs for the SEM-France interconnections, followed by SEM-Spain and the Hybrid SEM-GB. Among the individual cases, the connection to France for both the min and the max cases lead to the largest congestion revenue increase, i.e., 318 mlnEUR/year and 444 mlnEUR/year, respectively, compared to the counterfactual case in 2050. The reduction in congestion revenues for the SEM-GB connections is mainly due to the fact that even in the counterfactual case in 2050 the interconnectors between SEM and GB were not running at their limit (average utilization rate of 86%), thus, additional capacity does not result in more congestion revenues. Another important factor is that the introduction of the Hybrid SEM-GB connection means that some of the cross-border flows which originally went via the SEM-GB border are now flowing over the Hybrid connection. Overall, when the SEM-GB and Hybrid SEM-GB are combined, the congestion revenues for the combined connections between SEM and GB are still increasing between factual and counterfactual.

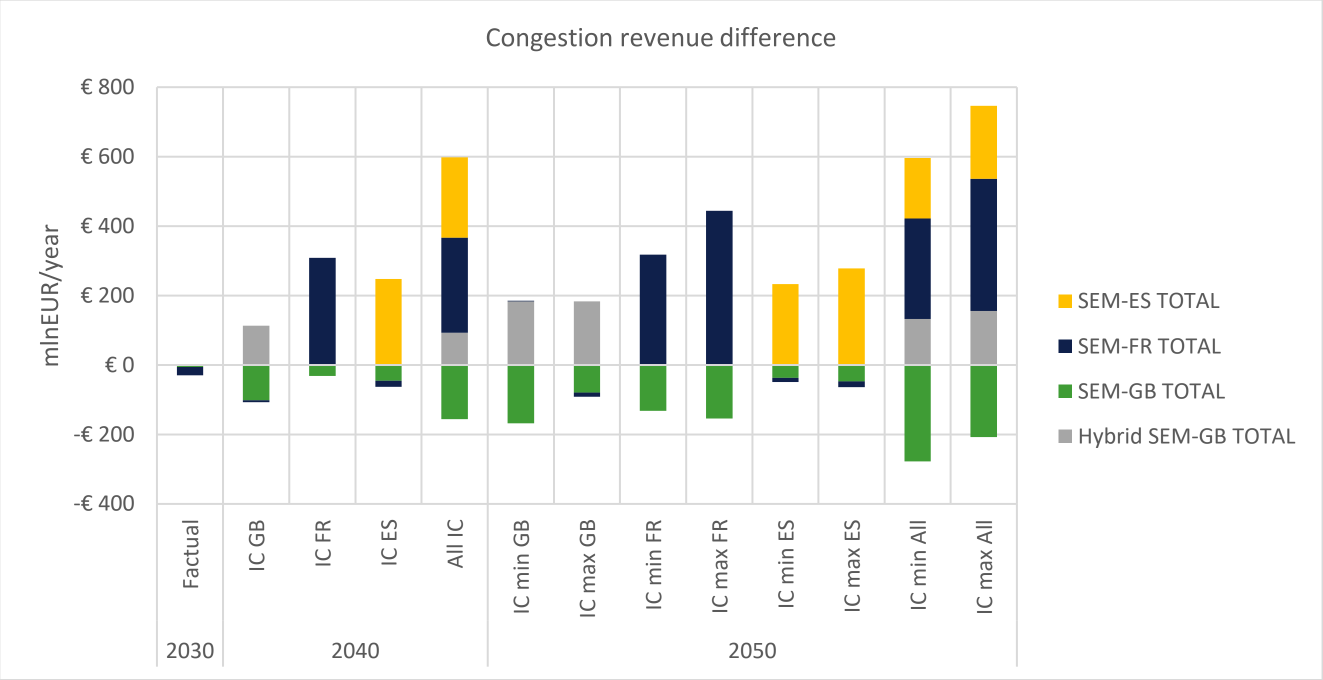

**Figure 6-14 Congestion revenue difference between factual and counterfactual, per absolute value (in mlnEUR/year)**

The difference in congestion revenues per additional IC capacity results in similar values among the individual cases in 2040 and in 2050, with SEM-FR still being the largest value in 2040 (293 kEUR/MW/year) and Hybrid SEM-GB representing the largest increase in 2050 (229 kEUR/MW/year) (see Figure 6-15). However, the 2040 All IC and 2050 IC min/max All cases represent outliers with overall the largest values. This suggests that when all connections are considered simultaneously, the overall congestion revenues increase more significantly than the IC capacity compared to the individual cases. Important to note is, that the negative values for the SEM-GB (in the cases: IC GB 2040, IC min GB 2050 and IC min All 2050) do not suggest a reduction in congestion revenue per additional IC capacity but should be seen as reduced congestion revenues per lost IC, since the IC between the counterfactual and factual cases declines (750 MW less IC between SEM-GB in the factual compared to counterfactual cases).

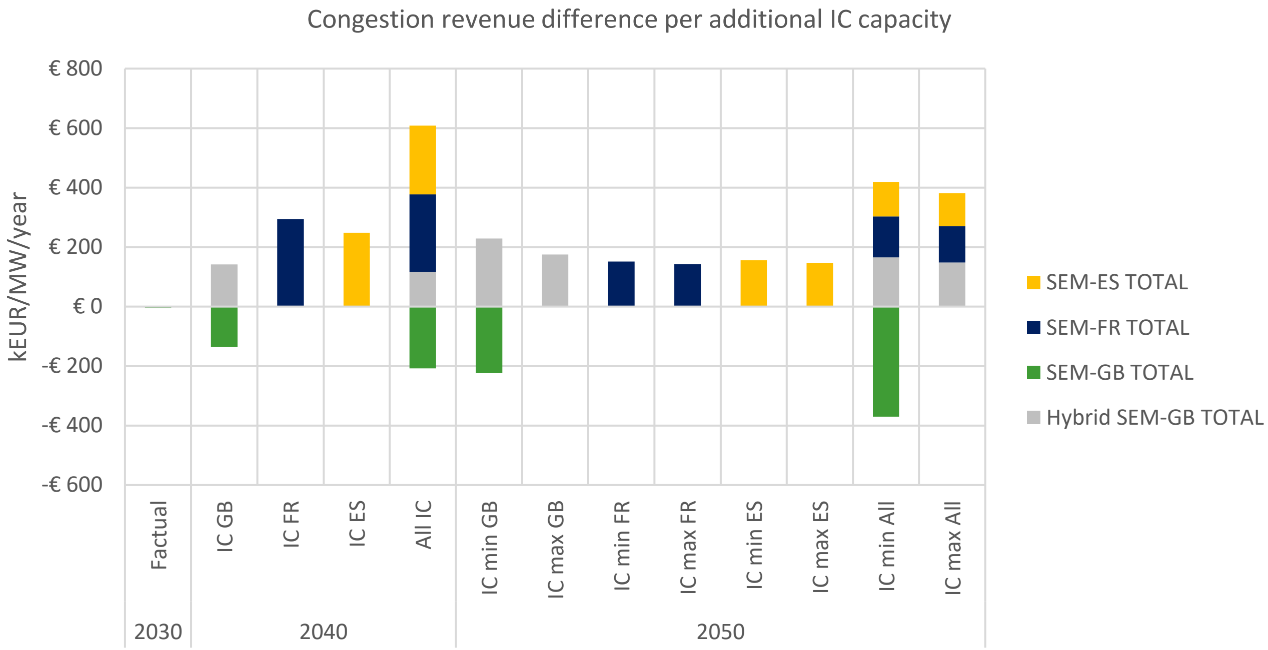

**Figure 6-15 Congestion revenue difference between factual and counterfactual, per MW of additional interconnection capacity (in kEUR/MW/year)**

### 6.3.4 RES curtailment

RES curtailment is a measure of how much renewable electricity generation is not effectively consumed but has to be wasted because the system is a) not able to deliver it from generation to consumption due lack of network capacity – ‘’bottlenecks’, or b) not able to consume because the volume of demand is lower than the total volume of renewable power generated in a certain time period – ‘overproduction’. In order to achieve a Net Zero system, the SEM will have to evolve to cope with these two challenges and effectively utilise all of the available renewable energy without curtailing it. Interconnectors help to achieve this objective as they provide additional export capacities to transport the energy at times of overproduction and import capacities to benefit from renewable energy in other countries, when there is lack of own zero-carbon generation.

**Summary**

Overall, additional interconnection capacity reduces renewable curtailment in all cases in the SEM and Spain. This effect is already visible in 2030, when the increase of interconnection capacity with GB reduces the curtailment of renewables in the SEM by 2.2 TWh/year. In 2040 and 2050, the cases which consider all connections combined (All IC, IC min/max All) show, as expected, the highest reduction of curtailment in both the SEM and Spain. This reduction in curtailment across all scenarios highlights the likely positive impact of additional interconnection on the cost of developing renewables generation, which is evident most clearly within the SEM.

**Explanation**

In 2030, additional interconnection capacity contributes to reduce the annual RES curtailment in the SEM by 2.2 TWh. Reduction in curtailment facilitated by additional interconnectors de-risks the development of renewables, in particular offshore wind as shown in Section 6.3.7, and is likely to have positive impact on Ireland achieving its climate ambitions for 2030.

The highest increase of interconnection capacity in 2040, All IC, achieves a curtailment reduction of 8.9 TWh/year across all countries, and especially in the SEM. Additional interconnection with France allows for further integration of renewables in the SEM, as it reaches the highest curtailment reduction in the SEM of all individual connection cases, i.e., 4.3 TWh/year. The link with Spain reduces renewable curtailment in both the SEM and Spain. Also, the additional 50 MW of interconnection capacity with GB achieves a decrease in curtailment in the SEM, yet it is significantly lower than in other connection cases.

In 2050, across all cases, the area which experiences the largest decrease in curtailment is the SEM, influenced by a high share of renewable installed capacity compared to its electricity demand. The additional interconnection with France, as shown in both min and max cases, brings the highest reduction of RES curtailment in the SEM, reaching 14.7 TWh/year reduction in comparison to 2050 counterfactual, in the max case. The interconnection with Spain shows that curtailment is reduced in Spain as well as the SEM, as a result of different renewable generation patterns between the countries. A complex interplay of two factors plays a role here. Interconnection with GB allows to achieve great price convergence between the SEM and GB, yet it does not necessarily help to integrate RES to the same extent as the connections with continental Europe, where weather profiles are more complimentary to Irish ones. At the same time, the fact that in both cases with connection to GB part of the infrastructure is hybrid means that some of the Irish offshore wind capacity is connected directly to GB. This offshore wind capacity benefits from having a connection to two markets, thereby minimising its curtailment. Hence, there is a visible curtailment reduction not only when connecting to the continental Europe, but also to GB, provided that some of the connections are hybrid.

While this comparison refers to the absolute values of curtailment reduction, not all the cases have the same additional interconnection capacity. Therefore, Figure 6-16 presents the RES curtailment reduction per MW of additional interconnection in comparison to counterfactual cases. In this regard, the additional interconnections with GB in 2040 and 2050 min case are characterised by the highest overall potential. Focusing on the potential to reduce curtailment in the SEM, the additional connections to France show the highest potential in both 2040 and 2050.

Note that for 2040 and 2050 min and max, the offshore wind farm that is part of the hybrid asset SEM-GB is considered to add up to Irish generation, hence its curtailment, if any, is accounted for in the figures for the SEM.

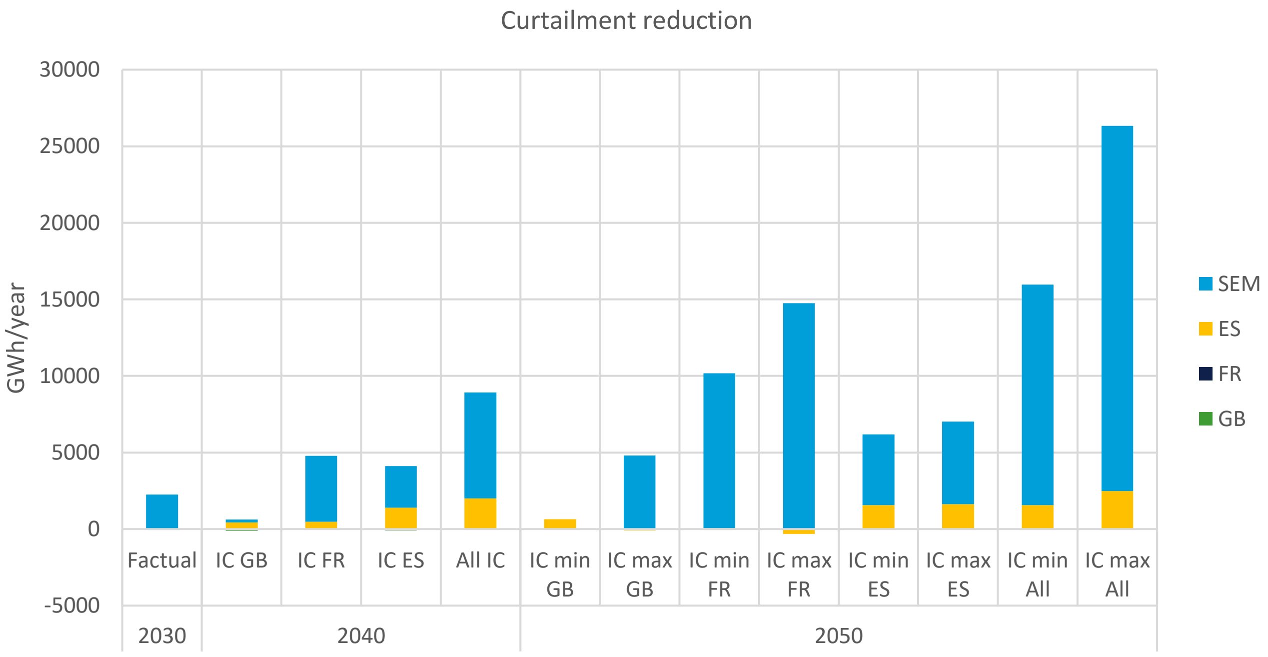

Figure 6-16 RES curtailment reduction difference between factual and counterfactual (in GWh/year)

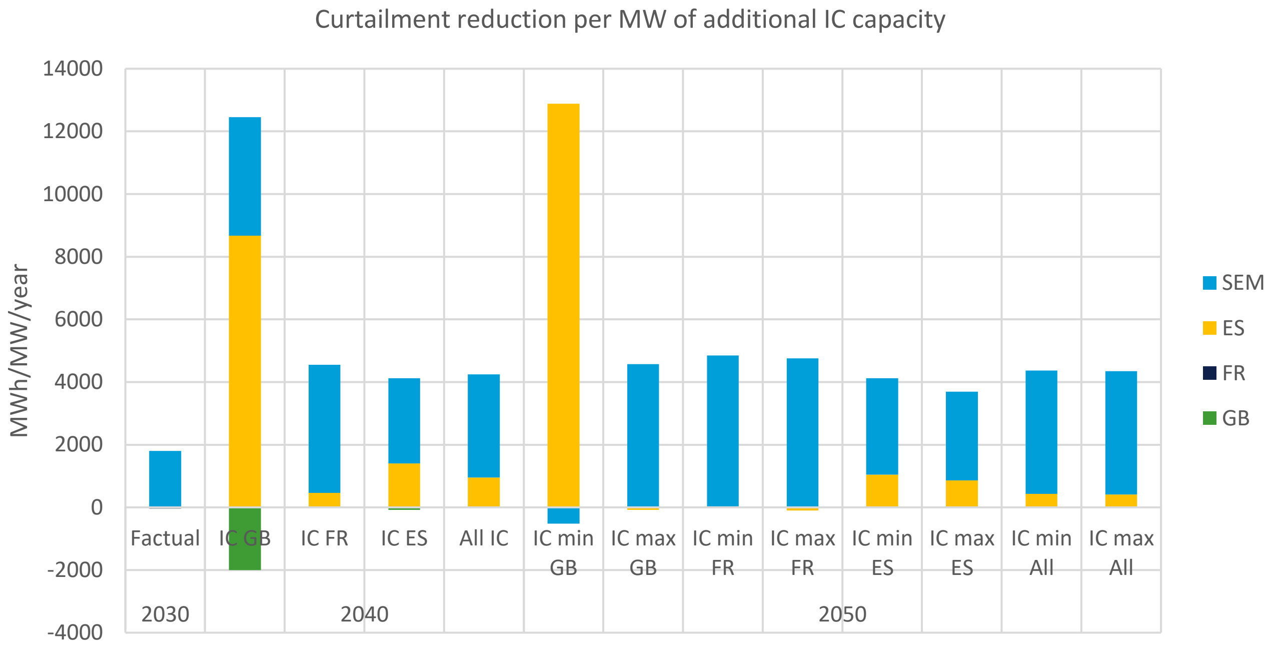

**Figure 6-17 RES curtailment reduction difference between factual and counterfactual, per MW of additional interconnection capacity (in MWh/MW/year)**

## 6.3.5 Carbon emissions

This KPI measures the volume of carbon emitted by the thermal generators from electricity production. The lower the carbon emissions are, the more decarbonised and clean the power system is. Interconnectors provide access to other markets, where there might be available green generation to replace local carbon emitting options.

### 6.3.5.1 Carbon emissions reduction

**Summary**

There are carbon emission reductions visible across all examined interconnection cases, as interconnections allow to dispatch more renewable generators in the system. The SEM benefits significantly in 2030, while in 2050 the largest beneficiary is France regardless of the interconnection case. The differences between the respective 2040- and 2050-factual cases, when evaluating the reduced carbon emission per additional interconnection capacity, are less significant compared to the absolute values, apart from the IC GB 2040 and IC min GB 2050 outliers.

**Explanation**

In 2030, the factual case leads to 363 ktonne/year reduced carbon emission compared to the counterfactual case. Thereby, the SEM benefits by far from the largest reduction in carbon emission with 230 ktonne/year, followed by Great Britain, which reduces its carbon emissions by 91 ktonne/year.

The carbon emission reductions, considering all selected countries, in the 2040 factual cases are similar between the IC FR and IC ES cases (875 ktonne $CO_2$/year and 851 ktonne $CO_2$/year, respectively) which follows expectations, since both cases assume a similar addition of IC (IC FR: 1,050 MW; IC ES 1,000 MW). Among all individual cases, the largest reduction in carbon emission is experienced within France in the IC FR case (739 ktonne $CO_2$/year). The IC GB case, on the other hand, results in a very low value (22 ktonne $CO_2$/year reduction) which is triggered by the only minor increase in IC between counterfactual and factual of 50 MW. The SEM solely benefits, in terms of carbon emission reduction, when connecting to Spain in the IC ES case (56 ktonne $CO_2$/year).

Among the factual and country specific cases in 2050, the largest reduction in carbon emission is achieved when connecting to France and Spain which display significantly larger reduction values compared to the connection towards GB (both for the min and max case) (see Figure 6-18). As expected, the cases which consider all connections combined (IC min/max All) result in the largest reduction in carbon emissions across all selected countries, i.e., up to 2,531 ktonne $CO_2$/year (IC max All), compared to the counterfactual case in 2050. The SEM benefits among all cases in 2050 (except the IC min GB case) regarding reduced carbon emissions, whereby both the IC max FR and the IC max ES result in the largest reduction among the individual cases, i.e., 197 ktonne $CO_2$/year.

As shown under the avoided $CO_2$ costs KPI (see 6.3.2.2), France also shows the largest benefit among all factual cases in 2050 (except for the GB connection cases) in terms of reduced carbon emissions. Again, this is mainly due to the generally high carbon emissions in France which are, together with Great Britain, by far the largest among all other examined countries in the counterfactual case for 2050 (6,045 ktonne $CO_2$/year France; 5,314 ktonne $CO_2$/year GB) and, thus, the additional import of pre-dominantly wind power has a rather big impact on the overall carbon emission. The sources of these carbon emissions are mainly the power generation from conventional fossil-fuel based power plants, such as natural gas, which still display some minor shares, especially in France and Great Britain by 2050, in the counterfactual case (Natural gas: 18.4 TWh in FR (2.6 % of total generation supply); 12 TWh in GB (1.8 % of total generation supply) compared to 0.9 TWh in ES (0.1 % of total generation supply); 1.3 TWh in the SEM (0.8 % of total generation supply)). The reason why France benefits even when connections with Spain are considered is because France and Spain are assumed to be very well interconnected, so part of the benefits from interconnectors between the SEM and Spain spill over to France.

In terms of reduced carbon emission per additional unit of interconnector capacity, whereas the 2040 values are rather comparable, there are slightly larger values for the interconnection with Spain compared to France in the 2050 cases visible (see Figure 6-19). An important driver for this finding is the larger assumed absolute interconnector capacity values for SEM-FR (2,100 MW in 2050 min; 3,100 MW in 2050 max) than for SEM-ES (1,500 MW in 2050 min; 1,900 MW in 2050 max). Again, the IC GB 2040 and the IC min GB 2050 cases are outliers due to the only minor increase of interconnection capacity by 50 MW between factual and counterfactual (1,250 MW in the counterfactual; 1,300 MW in 2040 IC GB and 2050 IC min GB) which subsequently results in inflated numbers per MW. The SEM benefits with 56 tonne$CO_2$ per additional IC in 2040 when connecting to Spain. Also in 2050, the SEM reduces the most carbon emission per additional IC when connecting to Spain (IC max ES: 104 tonne$CO_2$/MW/year).

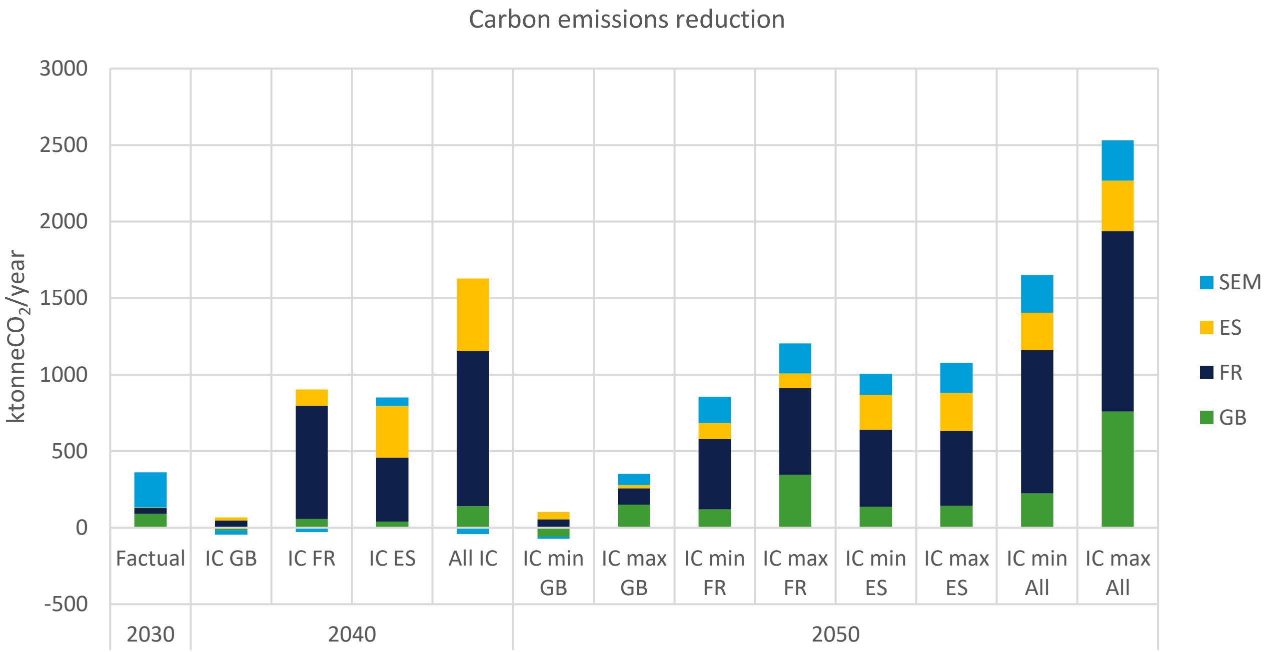

**Figure 6-18 Carbon emission reduction, indicated as the difference between factual and counterfactual, per absolute value (in ktonne CO$_2$/year)**

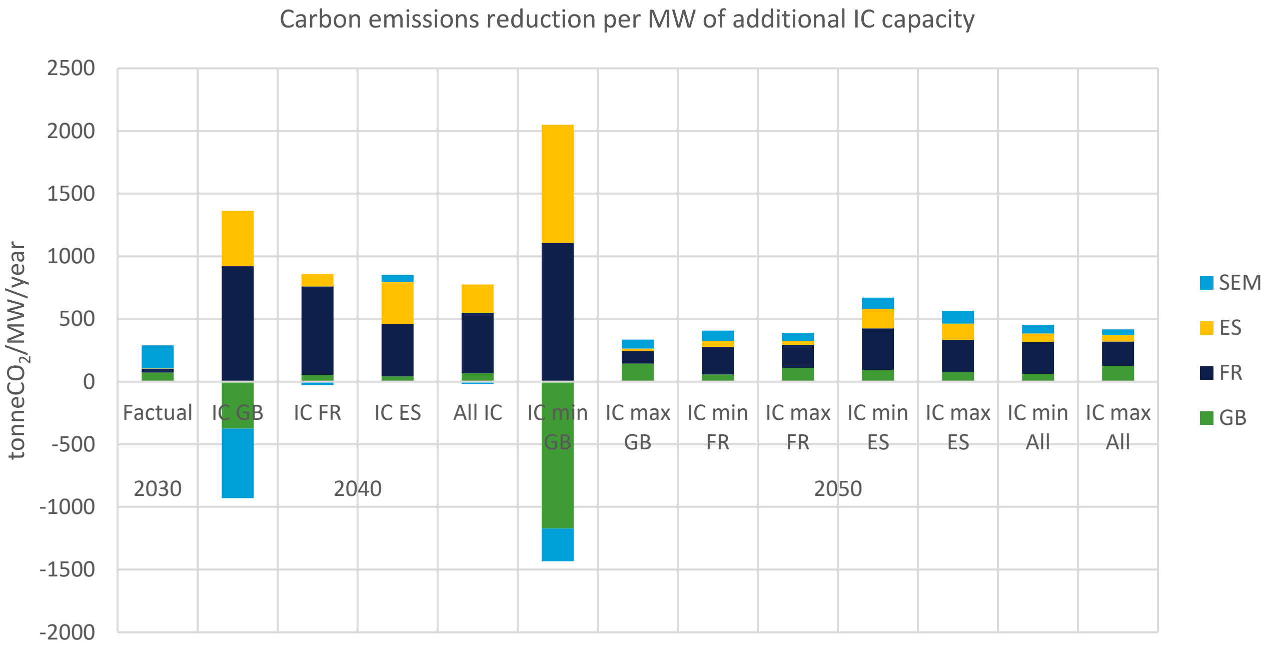

**Figure 6-19 Carbon emission reduction, indicated as the difference between factual and counterfactual, per MW of additional interconnection capacity (in tonneCO$_2$/MW/year)**

#### 6.3.5.2 Additional Societal Benefit due to CO$_2$ emissions reduction

Carbon emissions are an externality of electricity production. They have a negative impact on the society as they pollute the atmosphere, which has impacts on our health and well-being. ENTSOE recommends monetising the carbon emissions using the societal cost of carbon, to indicate what the benefits of additional interconnection are with respect to reducing the volume of CO$_2$ in the atmosphere.

**Summary**

The additional societal benefit due to the reduction in $CO_2$ emissions follows, as expected, a very similar pattern compared to the carbon emission figures (see Section 6.3.5.1). This is a monetised representation of the impacts that society incurs from the reduced carbon emissions.[61] Overall, there are benefits visible across all examined cases (see Figure 6-20). The differences between the factual cases when evaluating the societal benefit due to $CO_2$ emission reduction per additional interconnection capacity are less significant (see Figure 6-21).

**Explanation**

In 2030, the factual case leads to only 3 mlnEUR/year additional societal benefit due to $CO_2$ emission reduction, compared to the counterfactual case. This rather low value is due to the only minor difference in the assumed societal cost (100 EUR/tonne$CO_2$) and ETS price (91.8 EUR/tonne $CO_2$) in 2030 which serves as basis for calculating this KPI (see further down a more detailed explanation of this KPIs calculation).

The additional societal benefit due to the reduction in carbon emission, among all countries combined, in the 2040 factual cases are similar between the IC FR and IC ES cases (144 mlnEUR/year and 140 mlnEUR/year, respectively) which follows expectations since both cases assume a similar addition of IC (IC FR: 1,050 MW; IC ES 1,000 MW). Among the individual cases, France represents the country with the largest increase in additional societal benefits due to $CO_2$ emission reduction with up to 122 mlnEUR/year in the IC FR case. The IC GB case, on the other hand, results in a very low value (4 mlnEUR/year) which is due to the solely minor increase in IC between counterfactual and factual of 50 MW.

Among the factual and country specific cases in 2050, the largest additional societal benefit due to $CO_2$ reduction is achieved when connecting to France and Spain which display significantly larger reduction values compared to the connection towards GB (both for the min and max case) (see Figure 6-20). Among all individual cases, the IC max FR case results in the overall largest benefit among all selected countries, resulting in 181 mlnEUR/year of additional societal benefit. As expected, the cases which consider all connections combined (IC min/max All) result in the largest additional societal benefit due to $CO_2$ emission reduction, up to 382 mlnEUR/year (IC max All) compared to the counterfactual case in 2050. Again, France shows the largest benefit among all factual cases in 2050 (except for the GB cases). These outcomes can be explained based on the same argumentation as in the previous subsection (6.3.5.1: Carbon emission reduction). The SEM benefits among all 2050 cases (expect IC min GB), whereby the connection to France lead to the highest values among the individual cases (30 mlnEUR/year in the IC max FR case).

In terms of additional societal benefit due to $CO_2$ emission reduction per additional interconnector capacity, there are slightly larger values for the interconnection with Spain compared to France visible in 2050 (see Figure 6-21). Again, the same explanation as introduced in the previous subsection (6.3.5.1: Carbon emission reduction) holds true here. Whereases the SEM benefits among most of the 2050 cases, only the IC ES case leads to additional societal benefit due to $CO_2$ emission reduction in SEM in 2040, by 9 kEUR/year per additional IC.

This KPI is calculated by monetising the societal benefit of the reduces $CO_2$ emissions. Thereby, the carbon emission reduction per case is multiplied with the additional societal cost of emitted $CO_2$. To avoid double counting with the KPI reduction in $CO_2$ emission costs (see Section 6.3.2.2), only the difference between the assumed societal costs of $CO_2$ (100 EUR/tonne$CO_2$ in 2030 and 269 EUR/tonne$CO_2$ in 2040 and 2050) and the assumed ETS price (91.8 EUR/tonne $CO_2$ in 2030, 104.1 EUR/tonne $CO_2$ in 2040 and 118.1 EUR/tonne $CO_2$ in 2050) is used to calculate this KPI.

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[61] These benefits come on top of those estimated as part of SEW calculation in 6.3.2.2 (see 6.2.1 for detail).

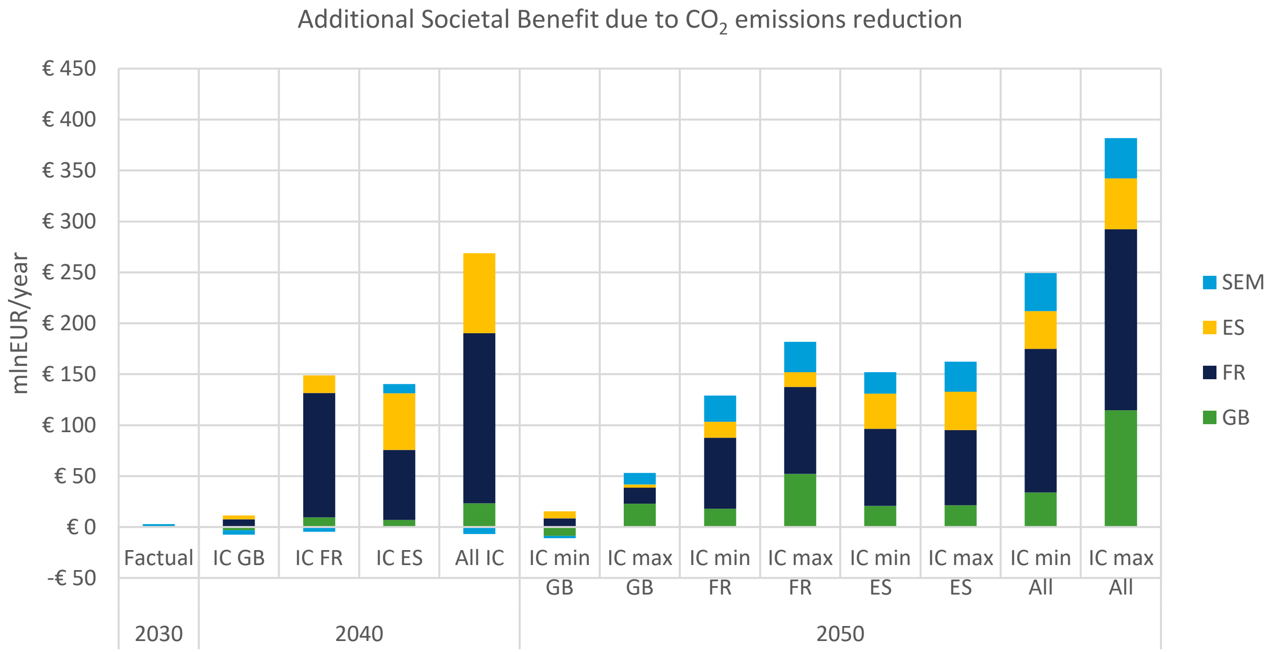

**Figure 6-20 Additional societal benefit due to CO₂ emissions reduction, indicated as the difference between factual and counterfactual, per absolute value (in mlnEUR/year)**

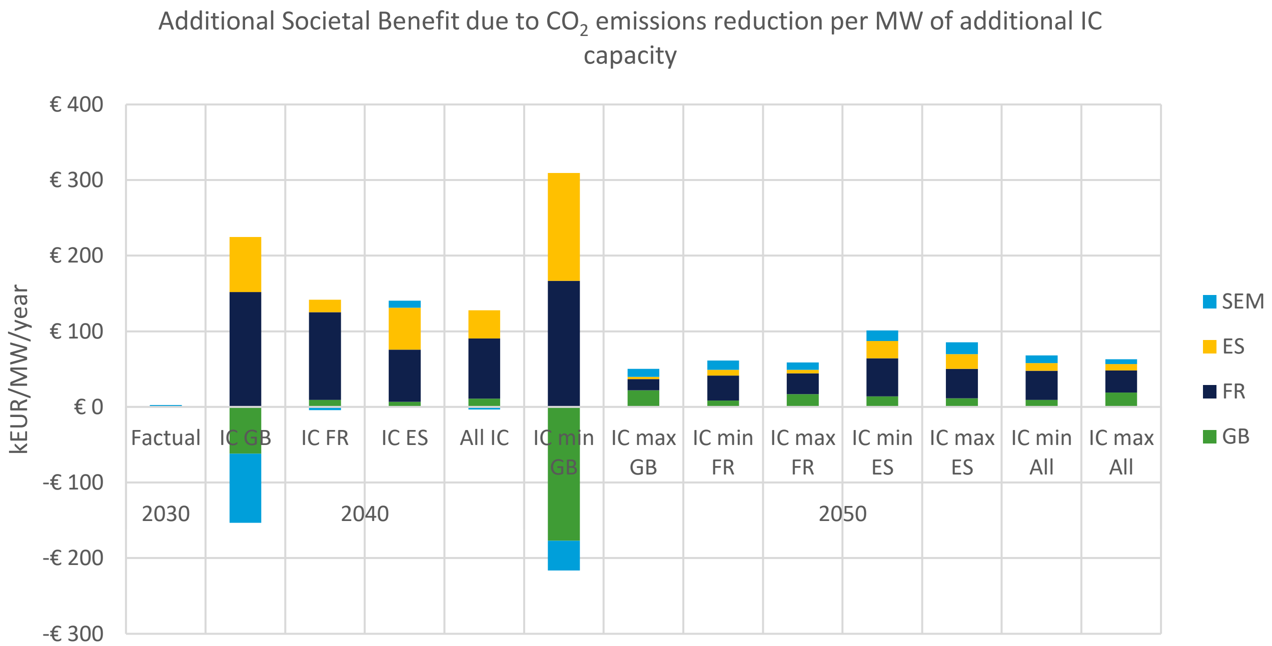

**Figure 6-21 Additional societal benefit due to CO₂ emissions reduction, indicated as the difference between factual and counterfactual, per MW of additional interconnection capacity (in kEUR/MW/year)**

### 6.3.6 Interconnector utilisation

Interconnectors are utilised when there is a need and an opportunity to transport power from one market to another, i.e., to trade power. Usually, trade on interconnectors occurs where there is an opportunity for price arbitrage, as one market has relatively cheap generation to meet (part of) the demand in the connected market. Interconnector utilisation is a measure of the percentage of time when an interconnector is utilised for trade, and hence it provides benefits in terms of market integration. As the total volume of interconnectors between the two markets grows, their utilisation will generally fall, as the value of each additional interconnector is lower than of the one built earlier. For this analysis, the average utilization across all interconnectors linked to the SEM is assessed.

**Summary**

The interconnection utilisation is generally higher in the counterfactual than in the factual cases, for 2030, 2040 and 2050.[62] This is due to higher available interconnection capacity in the factual cases, while in the counterfactual the interconnectors are congested, used at their maximum capacity, more often. When increasing the interconnection capacity, the usage of the interconnectors is more distributed, and the congestion of individual lines is reduced. Based on this, we can also observe that the case with the maximum increase of interconnection capacity, IC max All, is consequently the case with the lowest utilisation rate in 2050.

**Explanation**

In 2040, the connection case with France presents the highest utilisation rate, the same as in the counterfactual case. Therefore, even by increasing the interconnection capacity with France, the interconnectors are still highly utilised. The additional interconnection with Spain shows similar results, however slightly below the utilisation rate in the counterfactual case. The increase in the connection to GB reduces the utilisation rate by 9% in comparison to the counterfactual case; this is influenced by the additional interconnection which is a hybrid link, and it reaches low utilisation rates in the connection between the SEM and the offshore wind farm. IC All case, which introduces the highest increase in interconnection capacity, presents 8% lower utilisation rate than the counterfactual case.

In 2050, the additional interconnections to France and Spain are the cases which present the highest utilisation rate. IC min FR case shows a difference of 3% less utilisation than the counterfactual case, while IC min ES is 6% lower than in counterfactual. In the case of France, this shows that even with the increment in capacity the interconnections are still highly utilised. Further increase of the interconnection capacity with France, IC max FR, already shows a decrease in the interconnection utilisation, 80% in comparison to 82% for the IC min FR case. The additional connections with France are the cases with the highest interconnection capacity of SEM, across the individual connection cases. Therefore, the high utilisation rate in the IC min FR case in comparison to other cases like GB shows that the connection with France can boost cross-border exchanges.

Across all individual connection cases investigated in 2050, the minimum interconnection values present higher utilisation rates than the maximum cases. This reflects the decrease in the saturation of the lines by the increase in available capacity. The additional connections with GB reach the lowest utilisation rate with 73% and 70% for the min and max cases respectively. Spain shows higher utilisation rates, closer to those of France. Both Spain and France cases can benefit from a generation mix and renewable patterns complementing those observed in the SEM, thereby boosting exchanges across countries.

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[62] Note that this KPI is provided for informational purposes and does not indicate any additional cost or benefit.

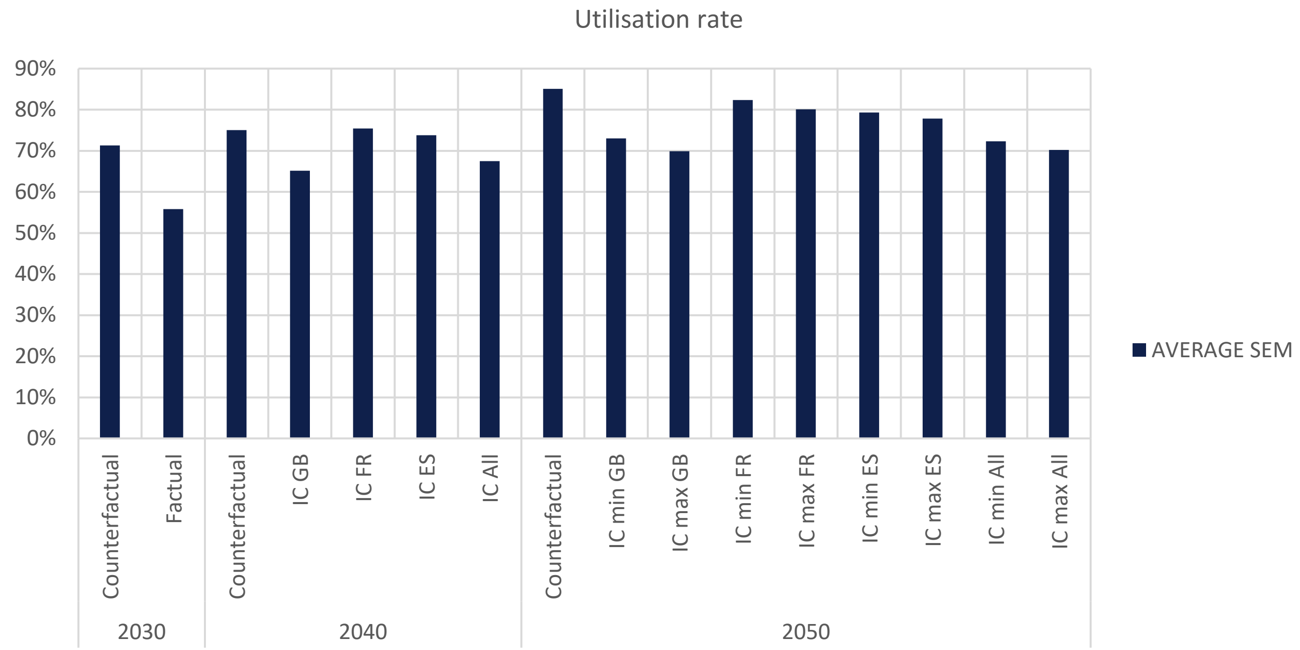

**Figure 6-22 The average annual utilisation rate among all considered interconnectors, indicated for each case separately (in average percentage over the year, whereby the individual utilisation rates are weighted depending on the corresponding IC capacity)**

## 6.3.7 Fuel mix

Fuel mix is used to showcase the proportion of different fuel types that are used to generate power to satisfy the total annual demand in a market. It provides and insight as to how ‘green’ the system is.

**Summary**

Overall, the additional interconnection capacity results in a generation mix with less thermal generation and an increase in the generation from renewable sources, similar to the outcomes described under the Section 6.3.4. Yet, compared to the counterfactual cases without additional IC, the increase in RES share in the SEM electricity generation mix is minor.

**Explanation**

In 2030, the additional interconnection with GB increases the renewable generation across the selected countries in comparison to the counterfactual case, especially offshore wind generation. The generation from thermal power plants is reduced in the factual case, mostly the generation from natural gas units. The SEM is the area that experiences most of the changes in the generation mix, particularly the increase in renewable generation. Yet, since the share of RES in the 2030 counterfactual case is already high, i.e. 88%, the benefits enabled by the additional interconnector between the SEM and Great Britain are minor, i.e. 2 percentage points.

In the 2040 counterfactual case, the SEM generates about 92% of its electricity from renewable sources. 2040 study case results show an increase in renewable generation across the selected countries thanks to the addition of interconnection. All IC case presents, as expected, the highest increment in renewable generation together with the largest decrease in thermal generation, especially generation for natural gas power plants. The additional interconnection with France achieves a higher integration of renewables, compared to the connection with Great Britain and Spain, both for all countries and for the SEM. The growth in renewable generation is mostly from offshore wind for the individual connection cases of France and Spain. However, in All IC case onshore wind experiences the highest increment across the selected countries. GB connection case shows a decrease in offshore wind generation due to that one offshore wind farms is connected in a hybrid manner, which affects its dispatch. Overall, the impact of additional interconnectors on the SEM RES share is minor, i.e. between -0.1 and +0.4 percentage point.

In the 2050 connection cases, the highest share of renewable generation across the selected countries is achieved in the case that considers all connections combined, IC max All. This case shows as well, the highest increase in renewable generation in comparison to the 2050 counterfactual case. Offshore wind is the renewable source experiencing the largest growth in generation in comparison to counterfactual values. Similarly, IC max All presents the lowest generation from thermal power plants, and the largest decrease in comparison to 2050 counterfactual. Nuclear generation exhibits the highest decrease in generation in comparison to counterfactual.

For the cases with individual increase of interconnection capacity, FR max case is characterised by the highest values of renewable generation and consequently the lowest share of thermal generation, as vast volumes of SEM renewable generation replace French conventional and nuclear generation. In comparison to the counterfactual case, offshore wind generation increases significantly by 12.2 TWh/year, while nuclear generation decreases by 5.2 TWh/year in total across the selected countries.

Figure 6-23 presents the total difference of generation per fuel type between factual and counterfactual across GB, SEM, France, and Spain. The values represent the annual generation per case of interconnection capacity. Overall, it can be seen that all cases result in increased shares of renewables (offshore wind, onshore wind and solar PV), whereby the increase in offshore wind generation is the most significant. Thereby, the additional generation of renewables replaces directly conventional power generation sources, such as natural gas, nuclear, waste and biomass.

A similar picture is visible, when looking at the difference in fuel mix within SEM (see Figure 6-24). Again, offshore wind generation displays the most significant growth among the cases, except for the IC min GB case, where the fact that one of offshore wind farms is connected in a hybrid manner, affects its dispatch, yet balanced out by increased onshore wind output. Nevertheless, it is worth noticing that the SEM RES share reaches 96% already in the counterfactual case without additional interconnectors. These allow for further increases and up to 97% when all links with maximum capacity are interconnected, hence indicating that additional interconnection is not vital to achieve Ireland's climate objectives and, overall, enables only minor benefits.

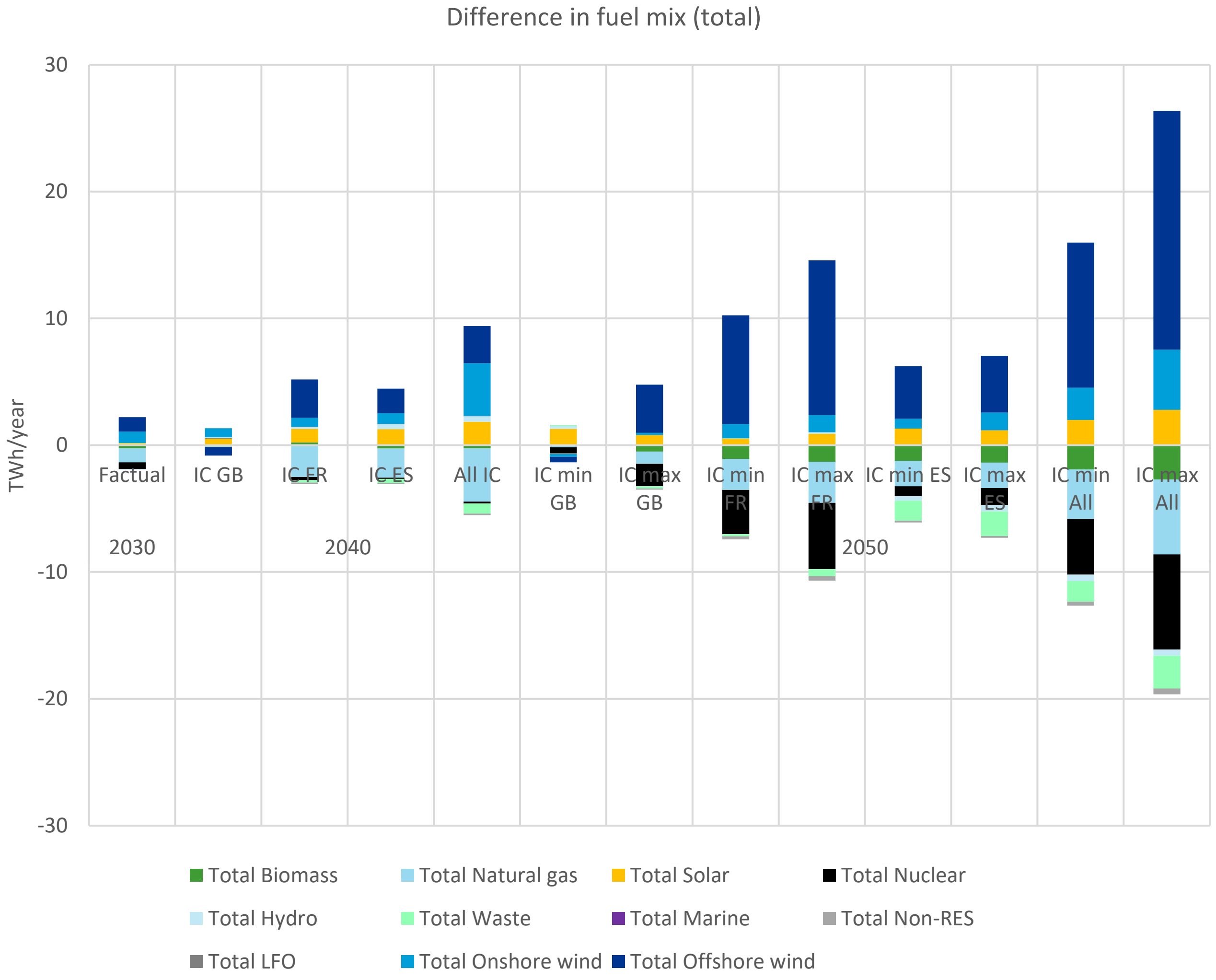

**Figure 6-23 Difference in fuel mix for each assessed case (factual and counterfactual) among all examined countries combined (in TWh/year)**

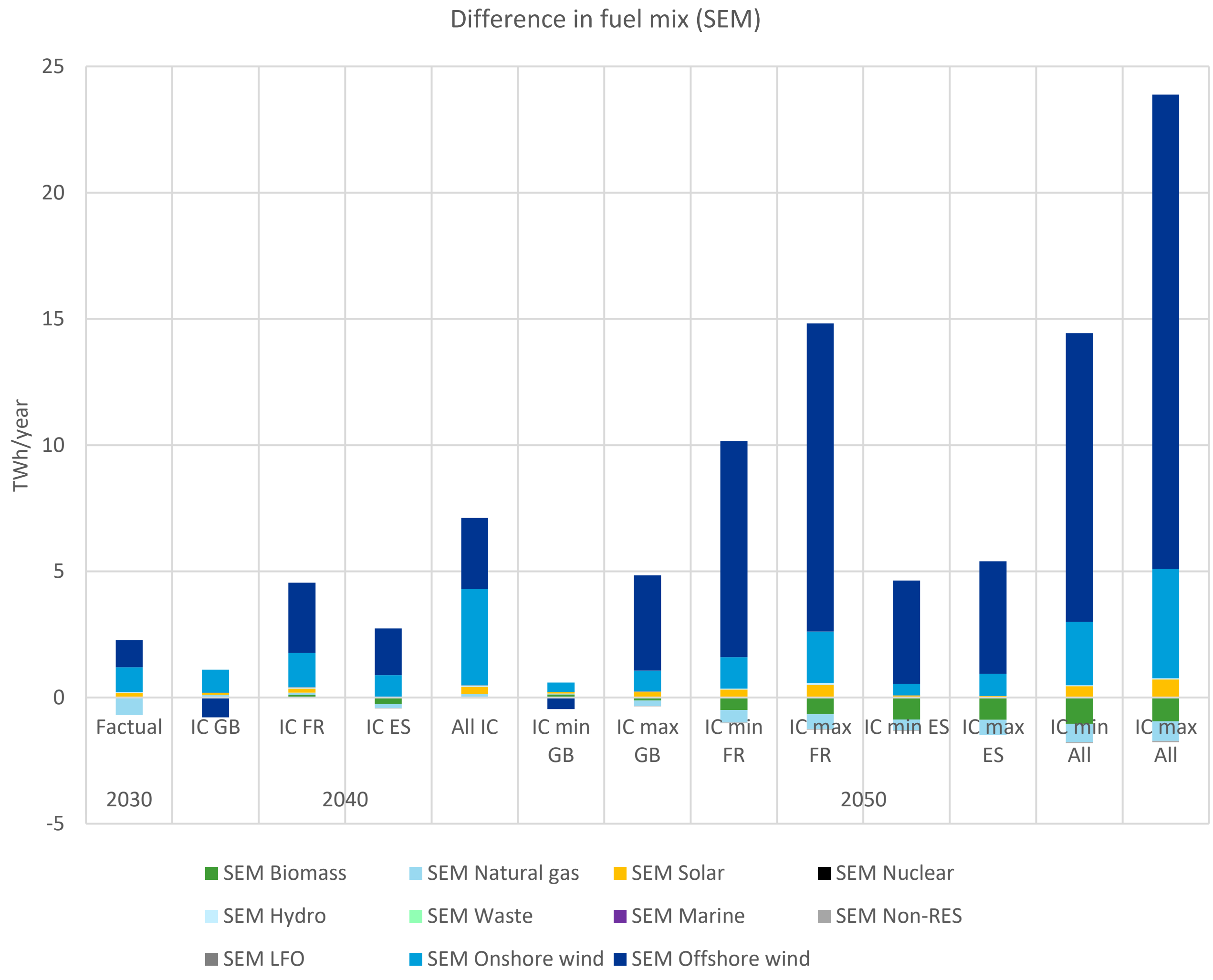

**Figure 6-24 Difference in fuel mix for each assessed case (factual and counterfactual) in the SEM (in TWh/year)**

### 6.3.8 Security of supply

The security of supply is an important indicator as it reflects how stable and reliable the transmission system is, which in its turn affects whether it is capable to deliver its main function, electricity transport from supply to demand. Generally speaking, interconnectors, if designed and integrated between the systems carefully, improve the security of supply as they provide opportunity for the connected systems to support each other in case of adverse conditions.

**Summary**

In order to properly assess the impact of additional interconnectors on the security of supply aspects, network modelling simulations are required. This is all outside of the scope of this study. DNV have discussed with EirGrid how they would normally assess the potential impacts and what are the typical operational challenges they expect interconnectors to (partially) address in the SEM system.

Normally, TSOs would run Monte Carlo simulations in their network modelling tools to investigate the operational conditions resulting from numerous combinations of weather, load and generation profiles in order to comment about the security of supply impacts of any additional cross-border capacity. An example is the ERAA process (European Resource

Adequacy Assessment) carried out by ENTSOE.[63] The ERAA is a pan-European monitoring assessment of power system resource adequacy of up to 10 years ahead. EirGrid has their own studies which are reported annually in EirGrid's Generation Capacity Statement reports, where the security of supply issues are investigated.[64]

DNV recognise that Security of Supply is important for understanding the full business case of interconnectors, yet it is not captured in our study. The value of contribution towards security of supply is captured and monetised at a level of TYNDP modelling which promoters necessarily have to carry at the project assessment phase. For Ireland, adequacy and flexibility are the most critical SoS aspects, given that the SEM is located on the periphery of Europe and does not benefit from large cross-border capacity with the neighbouring systems. As the SEM system is likely to have large share of RES in the future, its portfolio of flexible capacities needs to be sufficiently robust, both the type of capacity and its location will be of importance. Any additional interconnector capacity, if placed strategically will contribute to both of these aspects. Albeit ramp rates of HVDC-based interconnector technology are not as high as they are for AC interconnectors in Europe, the higher the volume of interconnectors in the SEM, the more flexible the system will be. Furthermore, voltage and reactive power are expected to be a challenge too. HVDC-based interconnectors are beneficial as they often possess active voltage regulation, frequency regulation, grid forming and black start capabilities.

In the context of our study, it is not possible to claim that one of the study cases is able to contribute more to the SoS than the other. As a general statement, any additional number of interconnectors will deliver SoS benefits.

**Explanation**

One aspect of the SoS which we were able to assess is the number of hours in which the SEM system is at limit. The system is considered at limit when all available generation capacity is fully used, and imports are at maximum level. In this case, an additional MWh of load would cause energy not served and, hence, it is priced at the value of loss of load (VoLL), which is 3,500 euro/MWh. Table 6-5 indicates that for 2040, this is the case when connecting the SEM to Great Britain and France; whereas for 2050, this is the case when connecting SEM to Great Britain and Spain.

**Table 6-5 Number of hours when all SEM generators are producing at their max limit and imports are at maximum level**

| Simulation | Hours when SEM is at limit |
|---|---|
| **2030 counterfactual** | - |
| **2030 factual** | - |
| **2040 counterfactual** | 7 |
| **2040 IC GB** | 5 |
| **2040 IC FR** | 7 |
| **2040 IC ES** | - |
| **2040 IC all** | - |
| **2050 counterfactual** | 8 |
| **2050 IC max GB** | 8 |

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[63] https://www.entsoe.eu/outlooks/eraa/

[64] https://www.eirgridgroup.com/newsroom/eirgrids-generation-capac/

| | |
|---|---|
| **2050 IC min GB** | 8 |
| **2050 IC max FR** | - |
| **2050 IC min FR** | - |
| **2050 IC max ES** | 7 |
| **2050 IC min ES** | 7 |
| **2050 IC max all** | - |
| **2050 IC min all** | - |

The SEM operates at limit in eight simulations, namely, 2040 counterfactual, 2040 IC GB, 2040 IC FR, 2050 counterfactual, 2050 IC max GB, 2050 IC min GB, 2050 IC max ES, and 2050 IC min ES. In all these simulations, the system reaches its limit on December 1st between 11 am and 6 pm (or 7 pm). All available generation capacity and import capacity are fully used, the latter being limited due to some lines being subject to forced outage.

In 2040, the additional interconnections with ES lead to the largest benefit for the SEM system, by preventing the system to reach its limit at any time. The additional links with GB reduce the number of hours in which the SEM operates at limit by two, whereas the additional links with FR has no impact.

On the contrary, in 2050, the additional interconnections with FR are the most beneficial for the SEM, leading to zero hours of operation at system limit. The interconnections with Spain reduce the number of hours in which the SEM operates at limit by one, whereas the additional links with GB have no impact.

The SEM prevents unserved energy by reducing electrolyser load, which is modelled with a bid price of 3,500 euro/MWh and, hence, it can be curtailed to prevent energy not served.

## 6.4 Sensitivity study 1 - Reduced RES in SEM 2050

In addition to the core energy system scenario described in Chapter 5, we have also tested how robust our 2050 results are by means of sensitivity runs. The interconnector capacities for all study cases are kept the same. Instead, we vary exogenous energy system variables and investigate the effects on the key KPIs.

### 6.4.1 Rationale

In this first sensitivity study, we investigate the impacts of reduced installed capacity of renewable energy sources (RES) in the SEM system. For this purpose, we compare the results from 2050 All IC min and All IC max cases in the core and adjusted scenarios. The overview of the assumed RES capacities is given in Table 6-6.

**Table 6-6 RES capacities Sensitivity study 1 - Reduced RES in the SEM in 2050**

| | Main scenario (GW) | Sensitivity (GW) |
|---|---|---|
| **Wind onshore** | 17.6 | 14.1 |
| **Wind offshore** | 40.3 | 32.3 |
| **Solar** | 10.3 | 8.3 |

The rationale for such a sensitivity is that the results of our assessment indicated large benefits from additional interconnection in what concerns RES integration, curtailment reduction and carbon emission reduction, especially for the SEM system. This sensitivity aims to challenge how robust the conclusions on the benefit of additional interconnection would be if the total volume of installed RES capacity in the SEM system would be less. Arguably, the need for additional interconnectors could decline. The need to test the outputs against the reduced RES assumption is also stipulated by the high uncertainty in how the renewable sector would develop in the SEM by 2050.

In order to study the impacts of this change in the scenario, the cases with all interconnectors (to Great Britain, to France and to Spain) being implemented are explored, i.e. All IC min and All IC max.

## 6.4.2 Results

This section presents the results in absolute values for the selected KPIs, in order to compare how the reduction in the SEM RES capacity affects the results in the counterfactual cases. Then the difference between factual and counterfactual for the base scenarios and the sensitivity is shown, in order to compare how the reduction in SEM RES capacity affects the magnitude of impacts from additional interconnection.

### 6.4.2.1 SEW

A reduction in SEM RES capacity leads to a significant increase in the SEM system costs in absolute values in both counterfactual and the cases with all additional interconnectors, when compared to the corresponding base scenario. The system costs of the other selected countries in absolute values are affected only to a minor extent (see Figure 6-25). Given the increase in system costs owing to a reduction in SEM RES capacity, the additional interconnection capacity has a larger benefit in terms of Socio-Economic Welfare in the SEM than in the base scenario. On the other hand, the other selected countries benefit less from the additional interconnection with the SEM, since less renewable generation is available to export (see Figure 6-26).

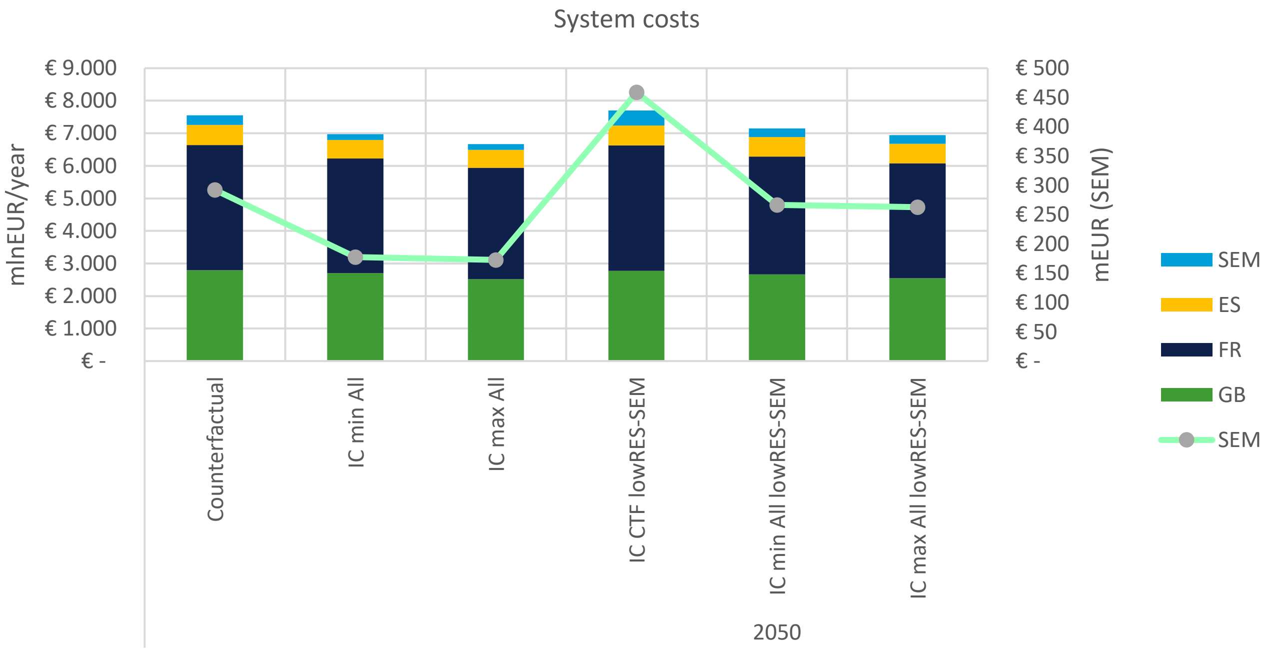

Figure 6-25 Sensitivity 1 - System costs comparison (mlnEUR/year)

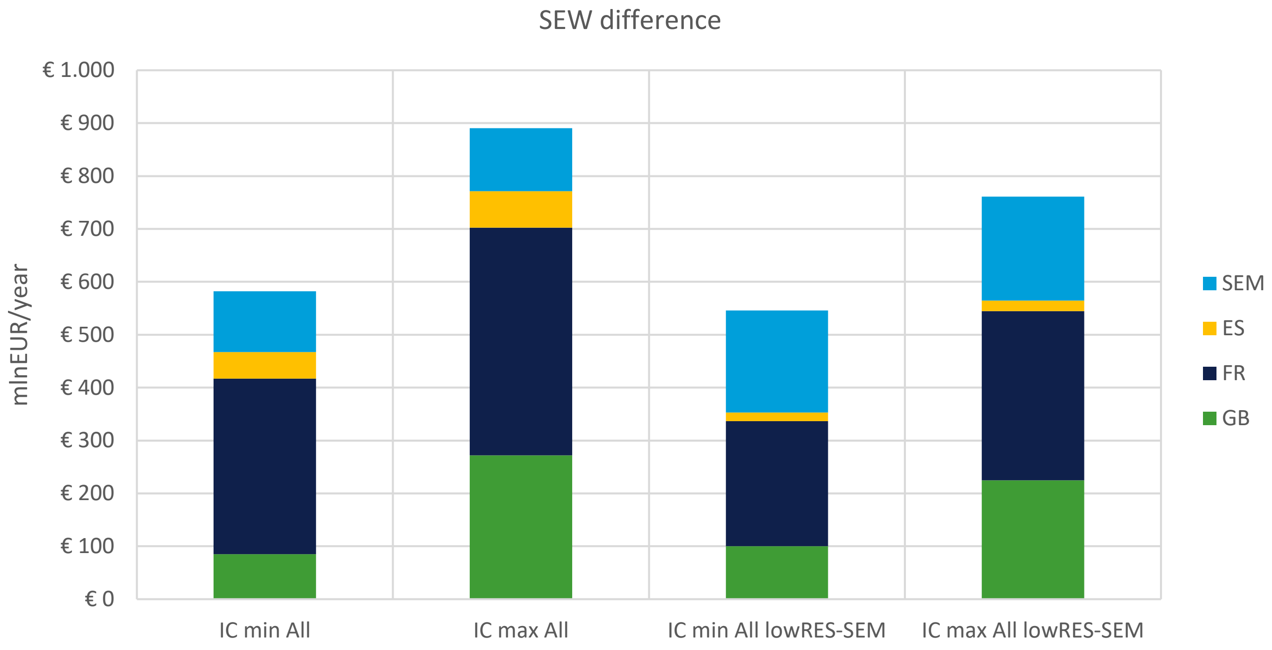

**Figure 6-26 Sensitivity 1 - SEW gain (factual and counterfactual difference) comparison**

#### 6.4.2.2 Congestion rents

A reduction in SEM RES capacity leads to a decrease in export from the SEM to the other selected countries, while the import increases. At the same time, the price differentials become smaller, mostly owing to a significant increase in SEM prices.

The Counterfactual shows an increase in congestion rents in absolute values for both the SEM-GB and SEM-FR interconnections, due to more power flowing towards the SEM (see Figure 6-27). On the other hand, the additional interconnectors enable smaller benefits in terms of congestion rents between SEM-FR, SEM-GB, and Hybrid SEM-GB when compared to the base scenario (see Figure 6-28). Contrarily, the SEM-ES interconnection shows an increase in congestion revenues owing to large power flows from Spain to the SEM. In fact, Spain becomes net exporter towards SEM, while it is net importer from the SEM in the base scenario.

Overall, with a reduction in SEM RES capacity, the additional interconnections enable lower benefits in terms of congestion revenue compared to the base scenario (see Figure 6-28).

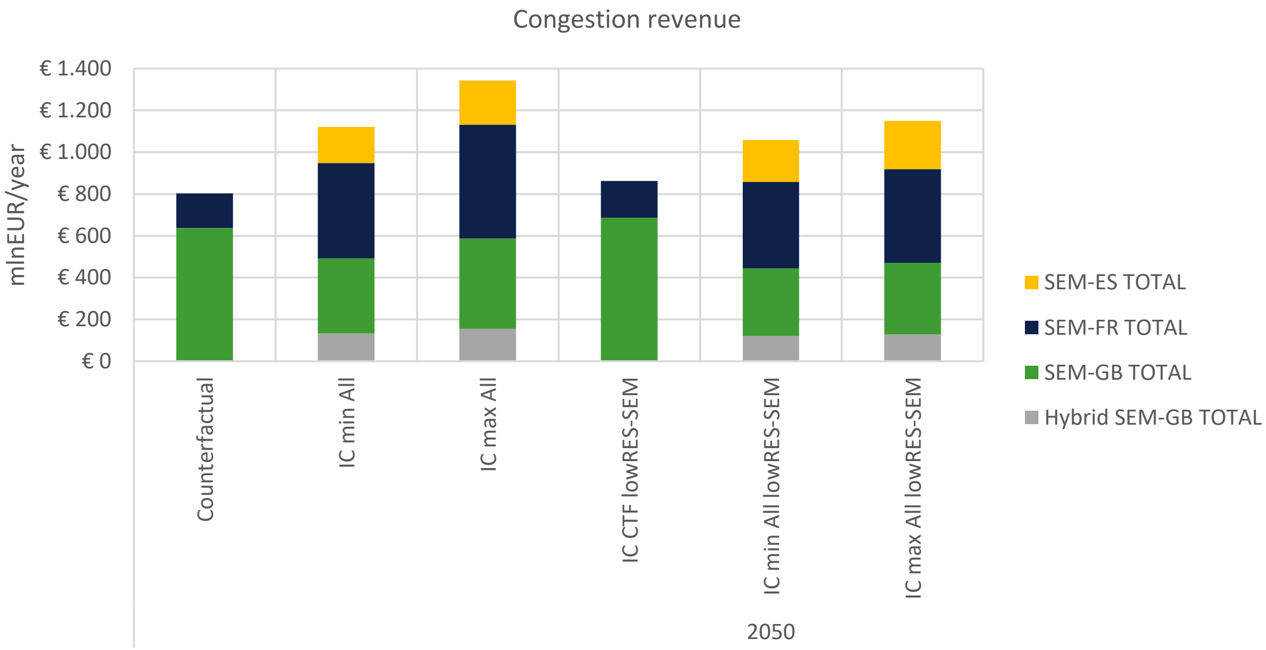

**Figure 6-27 Sensitivity 1 - Congestion revenue comparison**

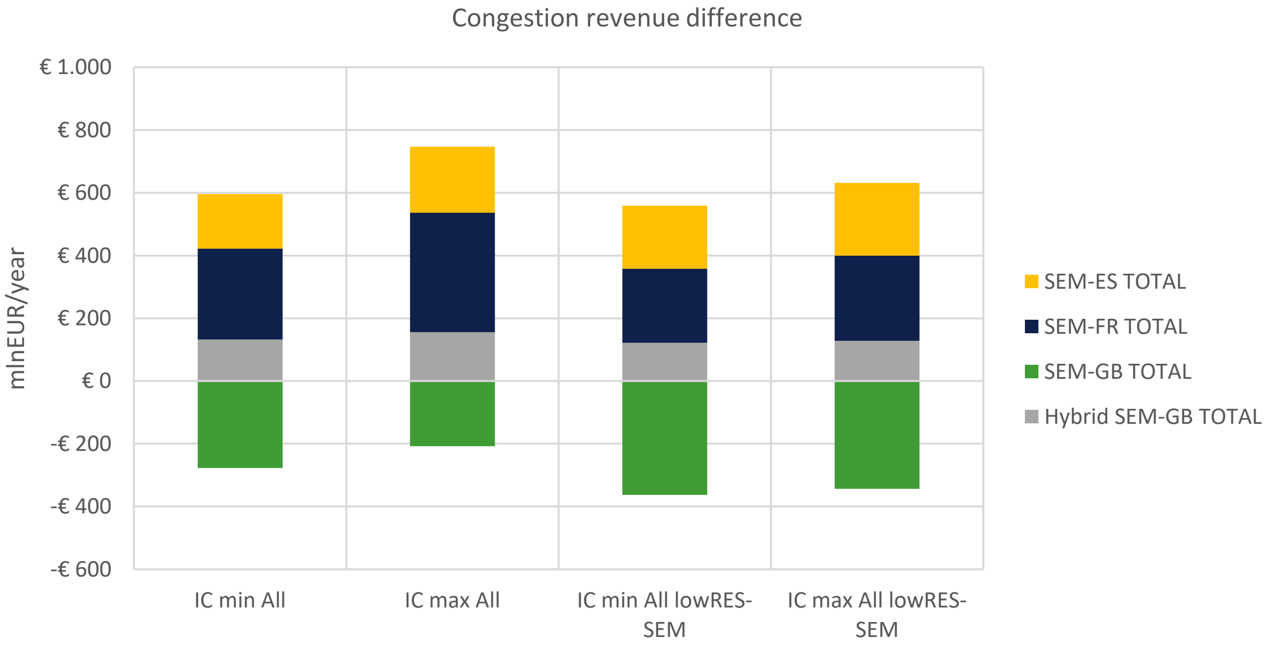

**Figure 6-28 Sensitivity 1 - Congestion revenue difference comparison**

#### 6.4.2.3 RES curtailment

The base scenario shows that only the SEM and Spain experience RES curtailment. As expected, a reduction in SEM RES capacity leads to a reduction in curtailment in the SEM in counterfactual (see Figure 6-29). Consequently, the additional interconnection capacity still reduces the RES curtailment, though to a lesser extent (see Figure 6-30).

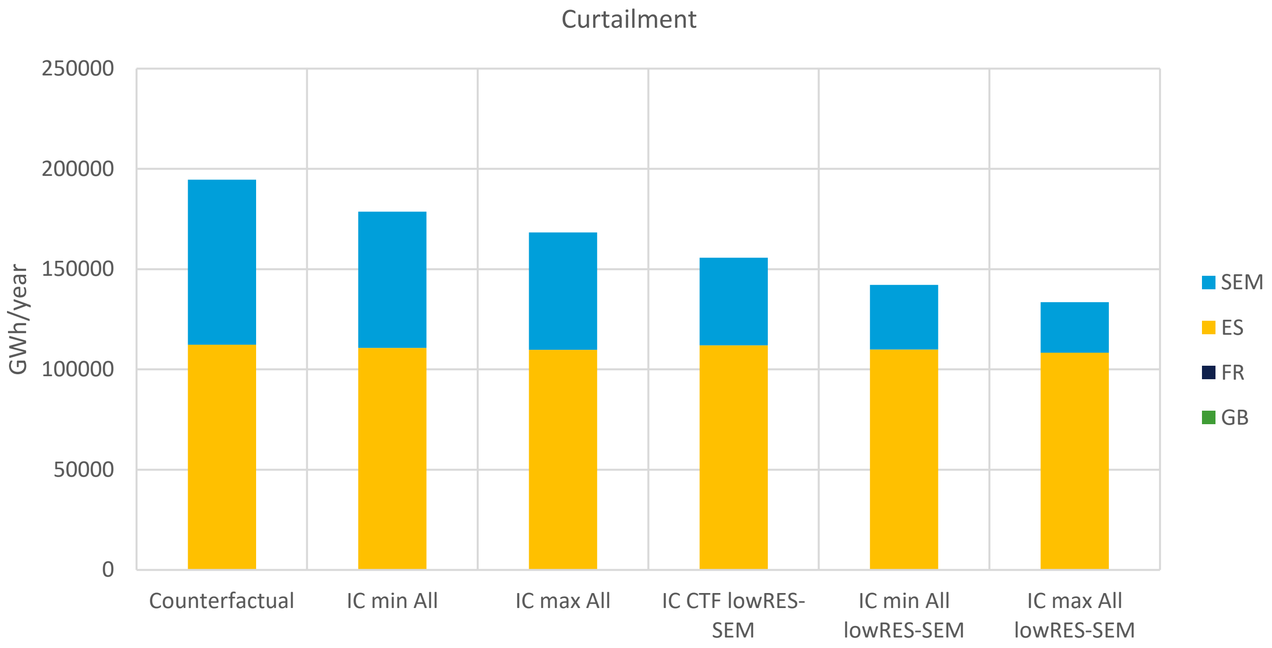

Figure 6-29 Sensitivity 1 – Curtailment comparison

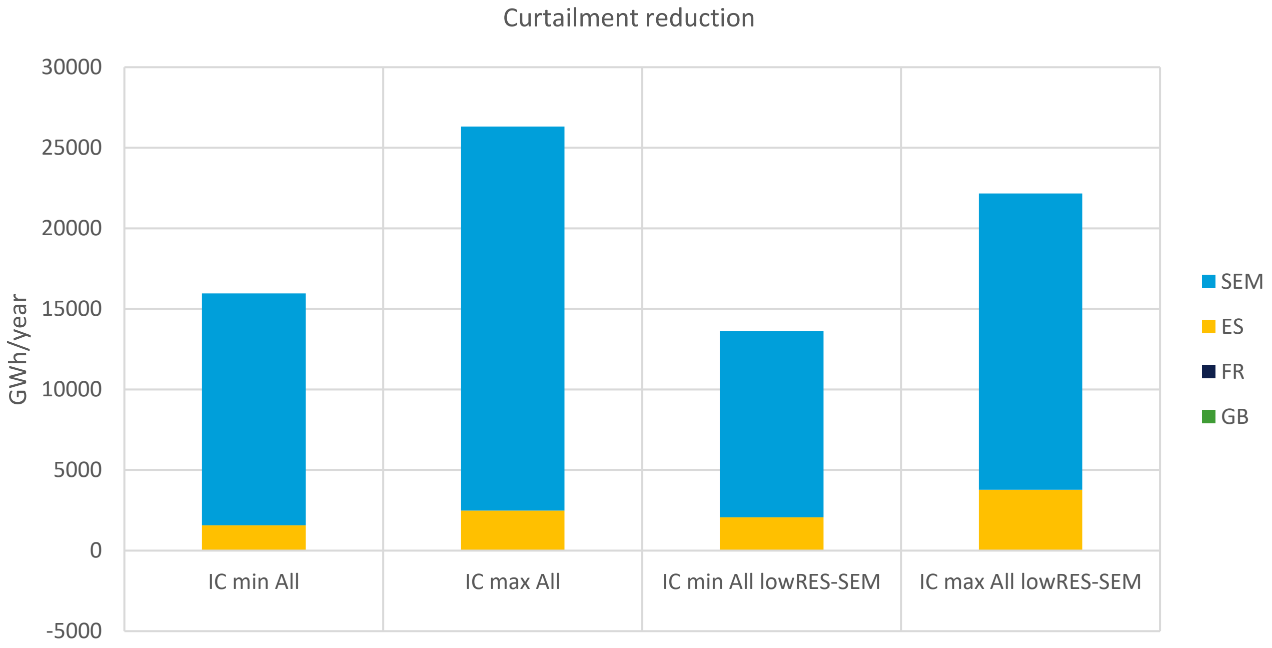

Figure 6-30 Sensitivity 1 – Curtailment reduction comparison

#### 6.4.2.4 Carbon emissions

A reduction in SEM RES capacity implies that alternative generation sources need to be used to satisfy the demand. Consequently, the carbon emissions in the SEM in the counterfactual case increases in absolute value, while the other selected countries experience no or minor changes (see Figure 6-31). All countries benefit in carbon emission reduction from the additional interconnection capacity, though to varying degree (see Figure 6-32). France, Spain and Great Britain benefit less than in the base scenario, owing to less renewable generation being imported from the SEM; at the same time, the SEM benefits more than in the base scenario, as imports from the other countries replace local fossil fuel generation.

Overall, the additional interconnection capacity allows for a visible reduction in carbon emissions in all countries and in the SEM in particular, hence partially counteracting the emission increase owing to less renewable generation.

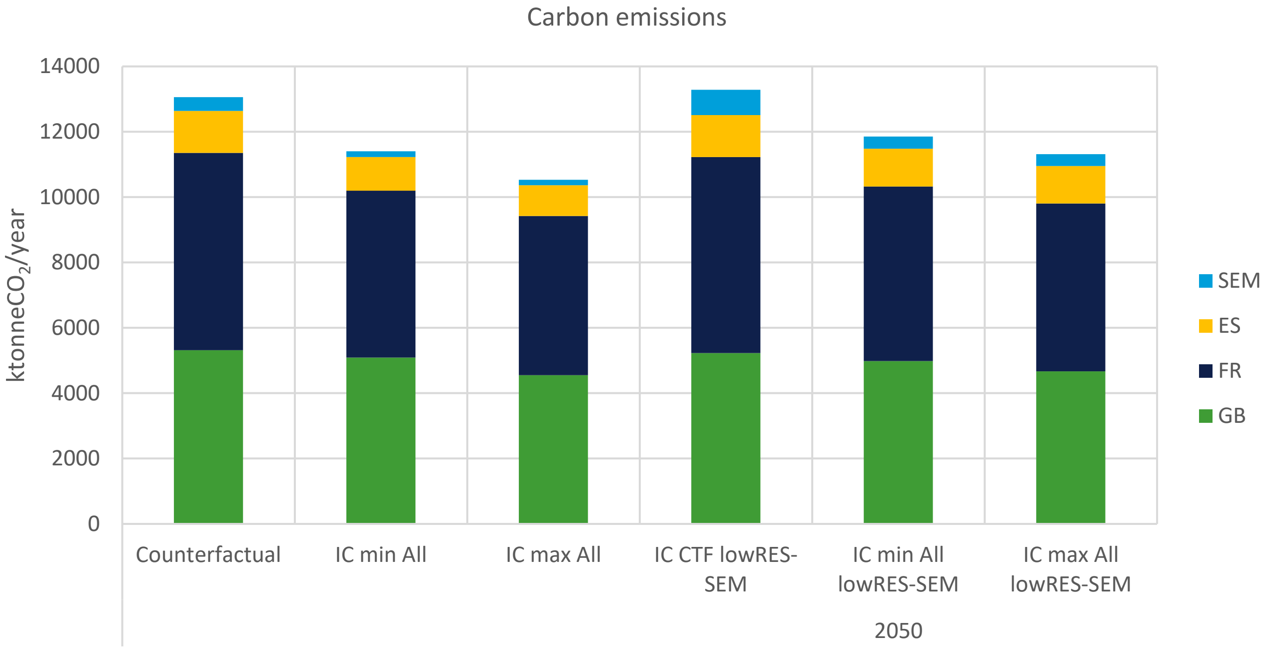

Figure 6-31 Sensitivity 1 - Carbon emissions comparison

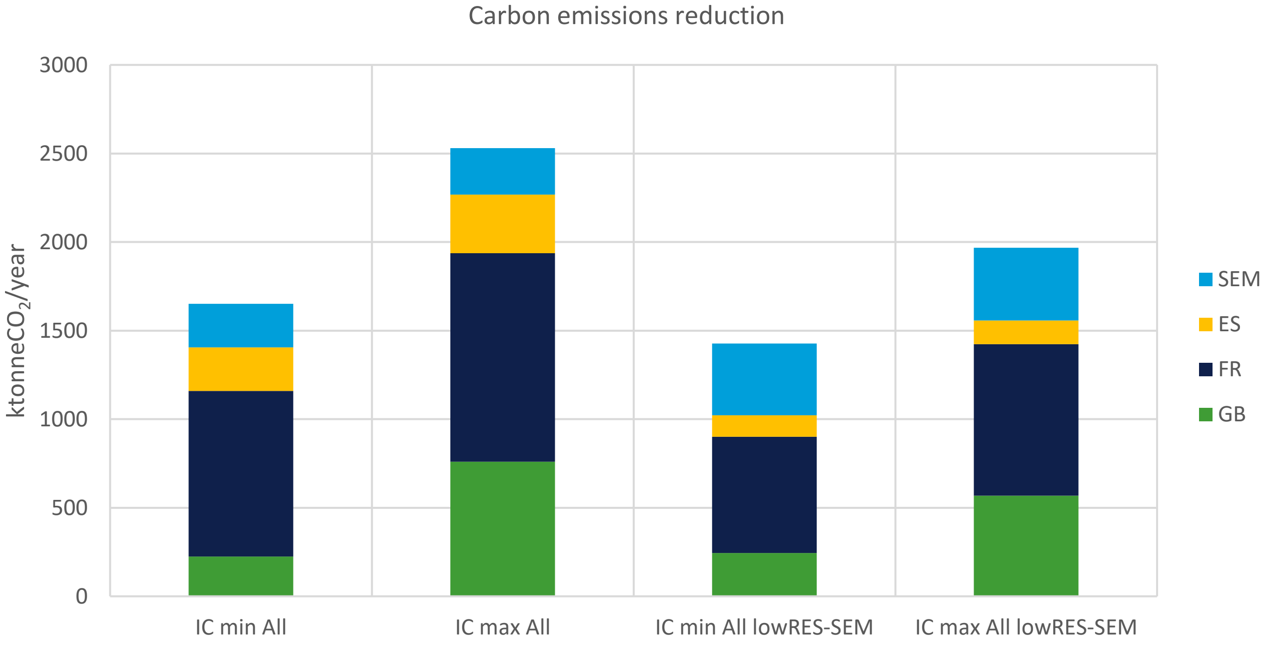

Figure 6-32 Sensitivity 1 - Carbon emissions reduction comparison

#### 6.4.2.5 Interconnector utilisation

The impact of a reduction of SEM RES capacity on the interconnector utilisation is minor, i.e., less than 2% lower than in the corresponding base scenario (see Figure 6-33). While the export from the SEM to the other selected countries decreases, the import to the SEM increases, hence leading to no significant changes in utilisation rate.

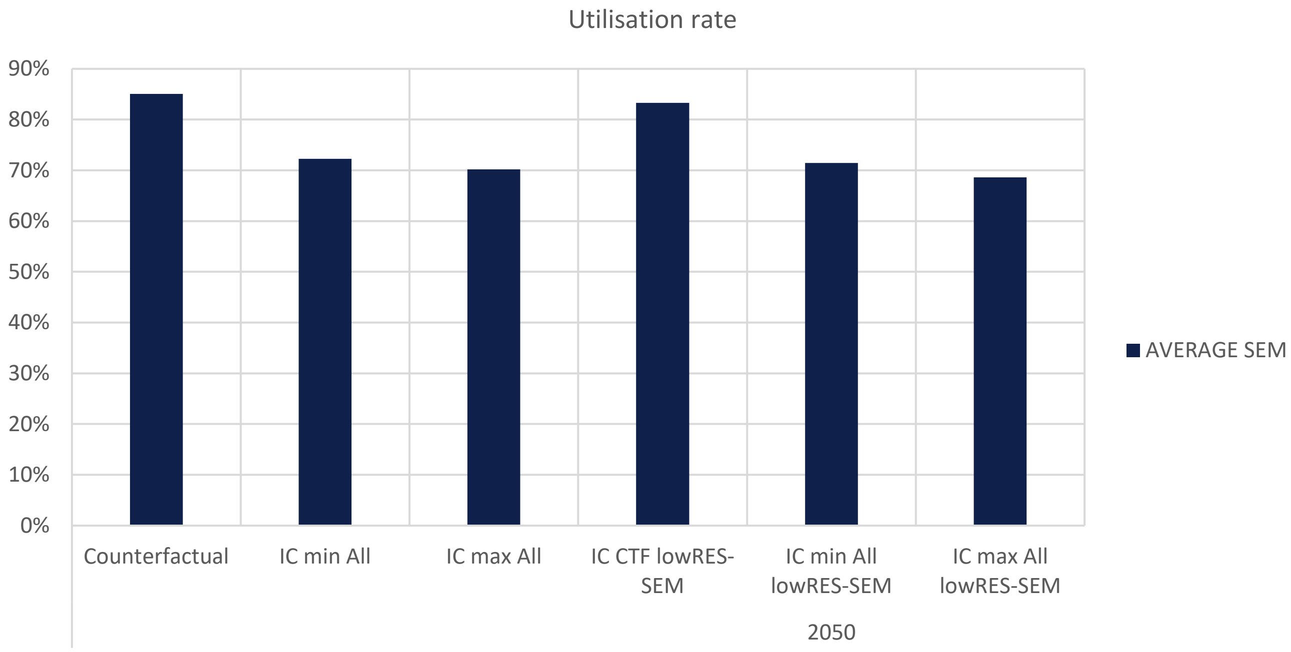

**Figure 6-33 Sensitivity 1 - Utilisation rate comparison**

#### 6.4.2.6 Fuel mix

The direct consequence of a reduction in SEM RES capacity is less RES generation in the SEM fuel mix, though renewables remain the major contributors to the SEM generation mix. In counterfactual, this reduction is about 8 TWh, which is partially compensated by an increase in generation from fossil-fuels (i.e., LFO and natural gas) and hydro. The additional interconnection capacity enables a reduction in RES curtailment in SEM and, hence, allows for more RES in the generation mix compared to counterfactual (see Figure 6-34).

Figure 6-35 shows that the additional interconnection capacity enables, in absolute values, a larger reduction of the fossil fuel share in the SEM fuel mix compared to the base scenario. Yet, the reduction in percentage of the actual fuel consumption is lower than in the base scenario, and the fossil fuel role in the fuel mix remains slightly more relevant (not visible in Figure 6-34).

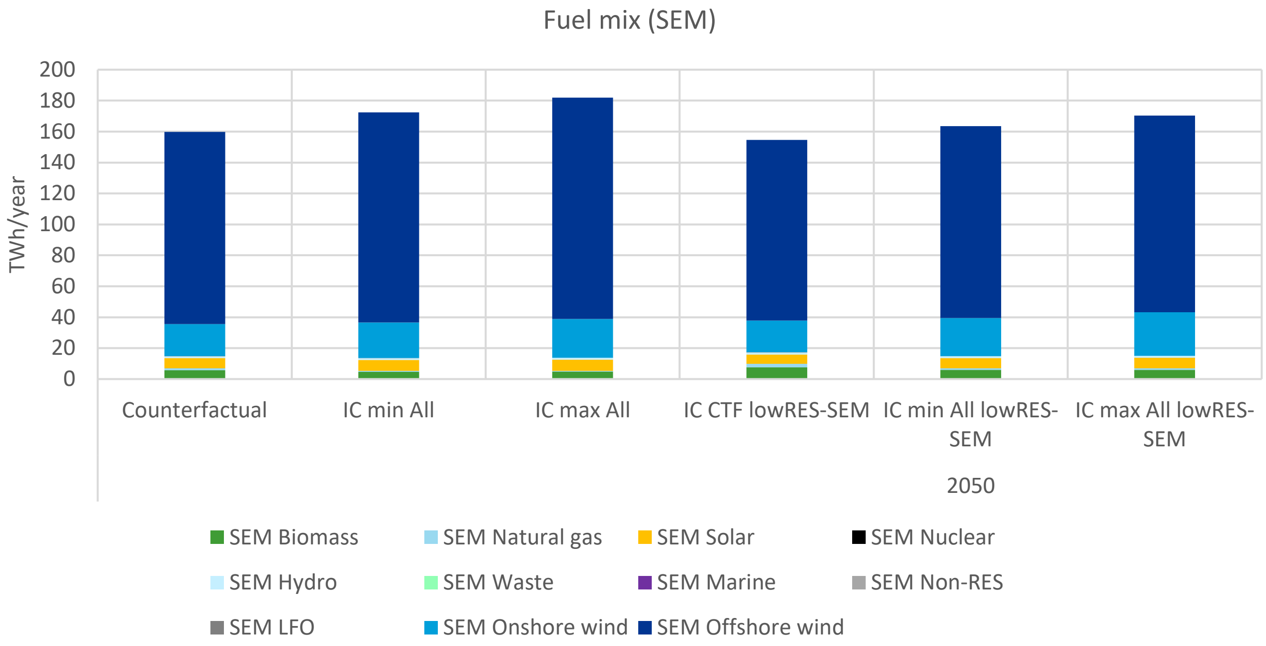

**Figure 6-34 Sensitivity 1 - Fuel mix comparison**

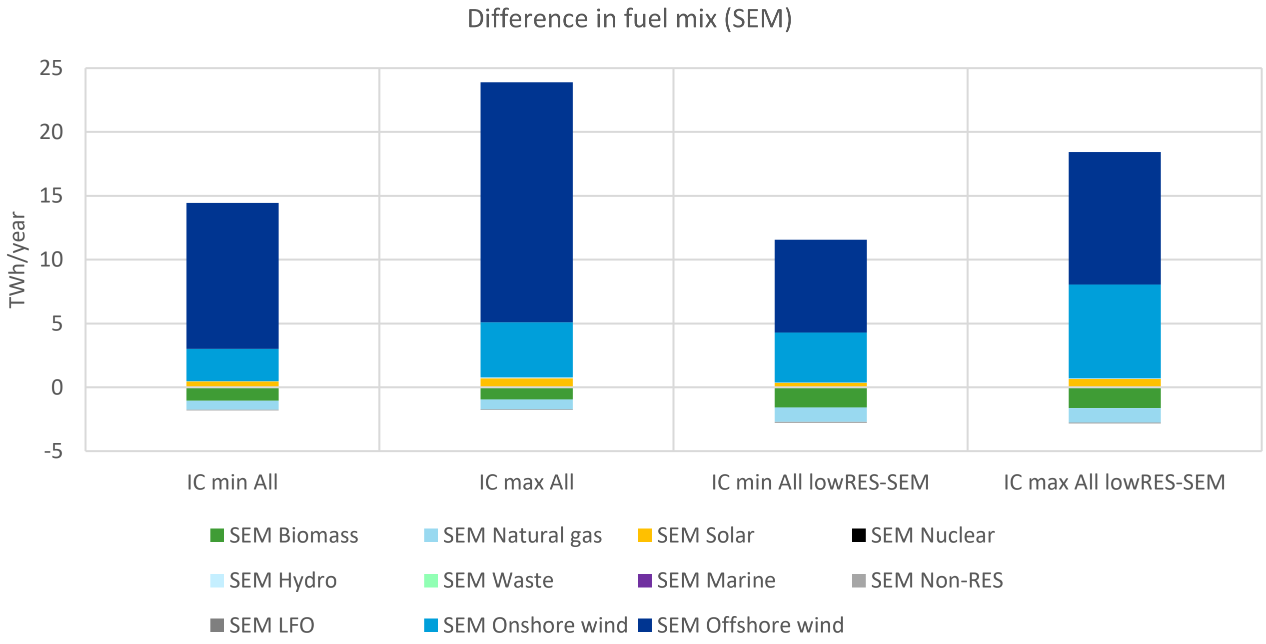

**Figure 6-35 Sensitivity 1 - Fuel mix difference comparison**

## 6.5 Sensitivity study 2 – Increased nuclear in France 2050

### 6.5.1 Rationale

This second sensitivity study investigates the impacts of increased nuclear generation capacity in France. For this purpose, the results from 2050 IC min FR and IC max FR cases in the core and adjusted scenarios are compared.

The rationale for such a sensitivity is that the results of our assessment indicate large benefits from additional interconnection in what concerns SEW increase and carbon emission reduction for France, and high congestion revenues and utilization rates for the France interconnection. This sensitivity aims to challenge how robust the conclusions on the benefit of additional interconnection would be if the French nuclear generation capacity was higher, owing to long-term operation (LTO) of existing nuclear power plants. In particular, the operating life of the power plants of Cattenom, Golfech, and Penly could be extended to 60 years, given that they entered operation at the end of the 80s or beginning of the 90s. The extension of the operating life of these power plants would result in additional 7.88 GW of nuclear generation capacity being available in 2050.

Arguably, the benefits of additional interconnection could decline, as France would rely less on gas-fired generation. This would lead to less carbon emissions, less generation costs, and less price spread between the SEM and France. The need to test the outputs against the increased nuclear generation capacity assumption is also stipulated by the recent renewed interest in potentially extending the lifespan of some exiting nuclear power plants beyond 50 years and in building six new nuclear reactors by 2050.[65]

To study the impacts of this change in the scenario, the cases with additional interconnectors to France being implemented, i.e., IC min FR and IC max FR, are explored.

## 6.5.2 Results

### 6.5.2.1 SEW

An increase in nuclear capacity in France leads to a decrease in system costs in all selected countries in both counterfactual and the cases with additional interconnections, when compared to the base scenario (see Figure 6-36). In counterfactual, system costs decrease by 15% in Spain, by 9% in France and Great Britain, and by 3% in the SEM system.

The additional interconnection capacity between SEM-FR still enables a benefit in terms of Socio-Economic Welfare (SEW) for all selected countries (see Figure 6-37). In the IC min FR LTO case, France and Spain benefit less than in the base scenario, while the SEM and Great Britain benefit more. In the IC max FR LTO case, France and Great Britain benefit less than in the base scenario, while the SEM and Spain benefit more. Overall, on the one hand, additional nuclear capacity in France increases the SEW benefits for the SEM by 14% to 29% compared to the base scenario with additional interconnection capacity between the SEM and France. On the other hand, the additional interconnection capacity is less beneficial for France, reducing the expected SEW benefits by 22% on average.

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[65] https://www.reuters.com/article/france-nuclear-safety-idAFL5N2X94GT

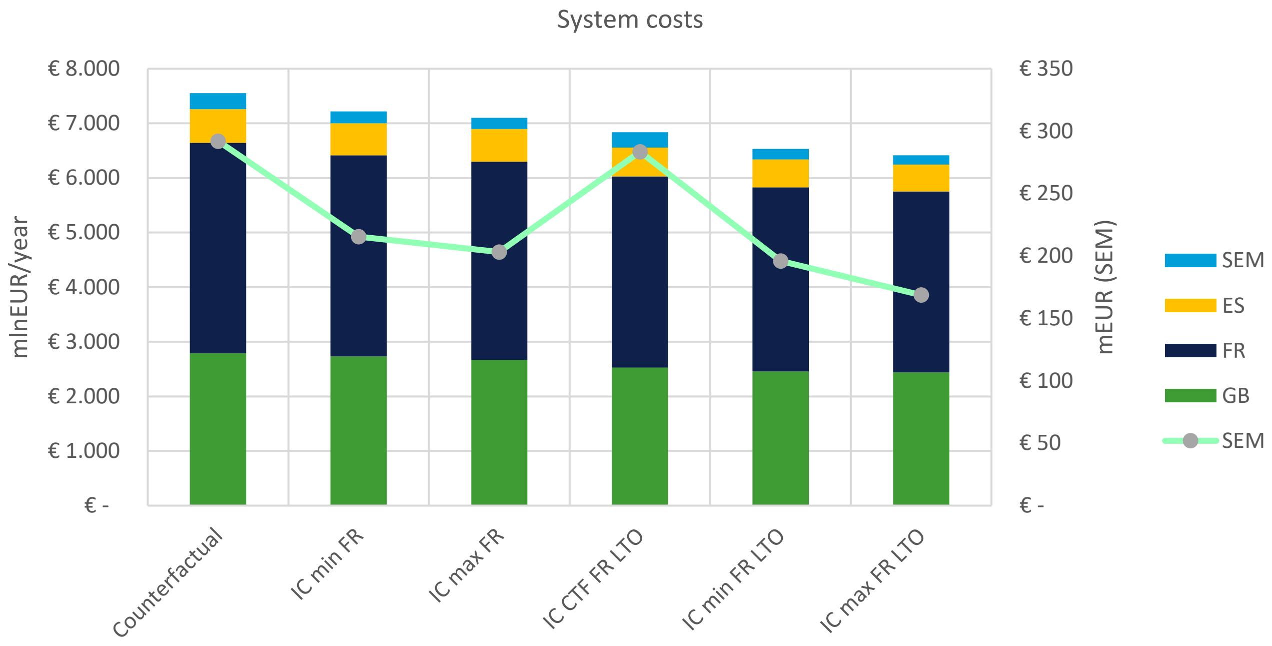

Figure 6-36 Sensitivity 2 - System costs comparison

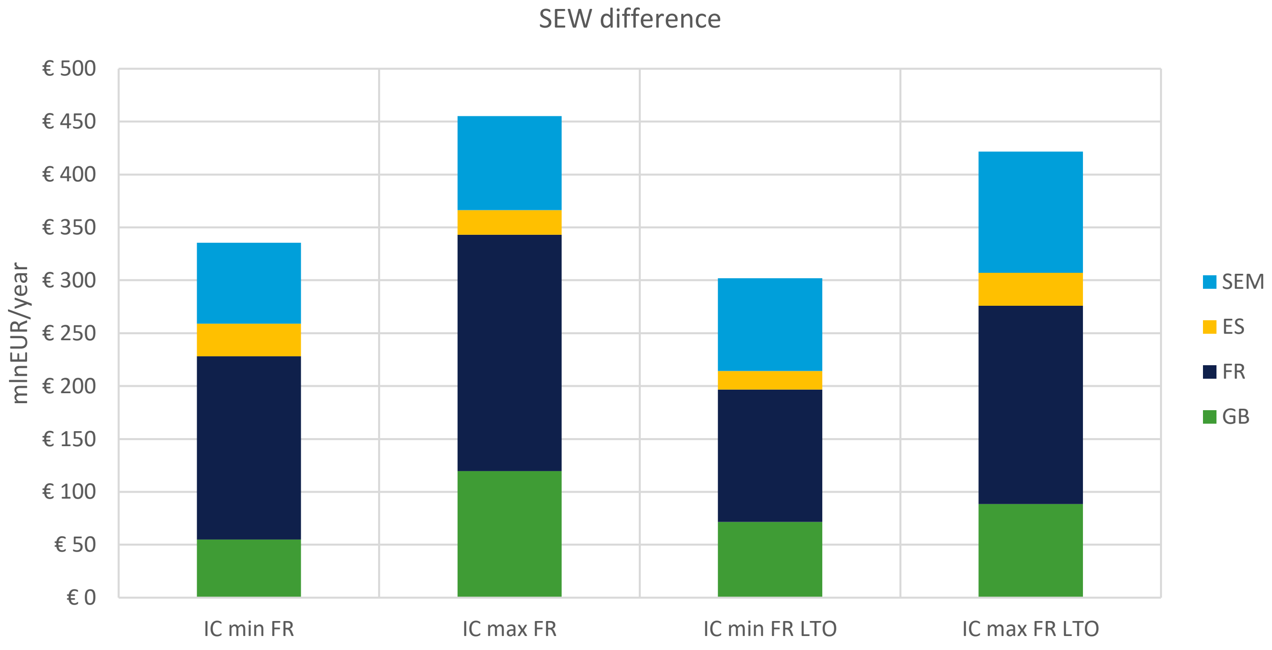

Figure 6-37 Sensitivity 2 - SEW difference comparison

### 6.5.2.2 Congestion rents

The additional nuclear capacity in France leads to a reduction in congestion revenues in all study cases when compared to the base scenario (see Figure 6-38). The reason mostly lies in France being less dependent on imports from neighbouring countries. The additional interconnection capacity between the SEM and France still enables an increase in congestion revenues compared to counterfactual, yet to a lesser extent than in the base scenario (see Figure 6-39). The congestion revenues for the SEM-GB border further decrease when more nuclear capacity is available in France because, as already mentioned for the base scenario, the additional interconnectors cannibalise on already existing links between the SEM and Great Britain, while the power flows towards France decrease.

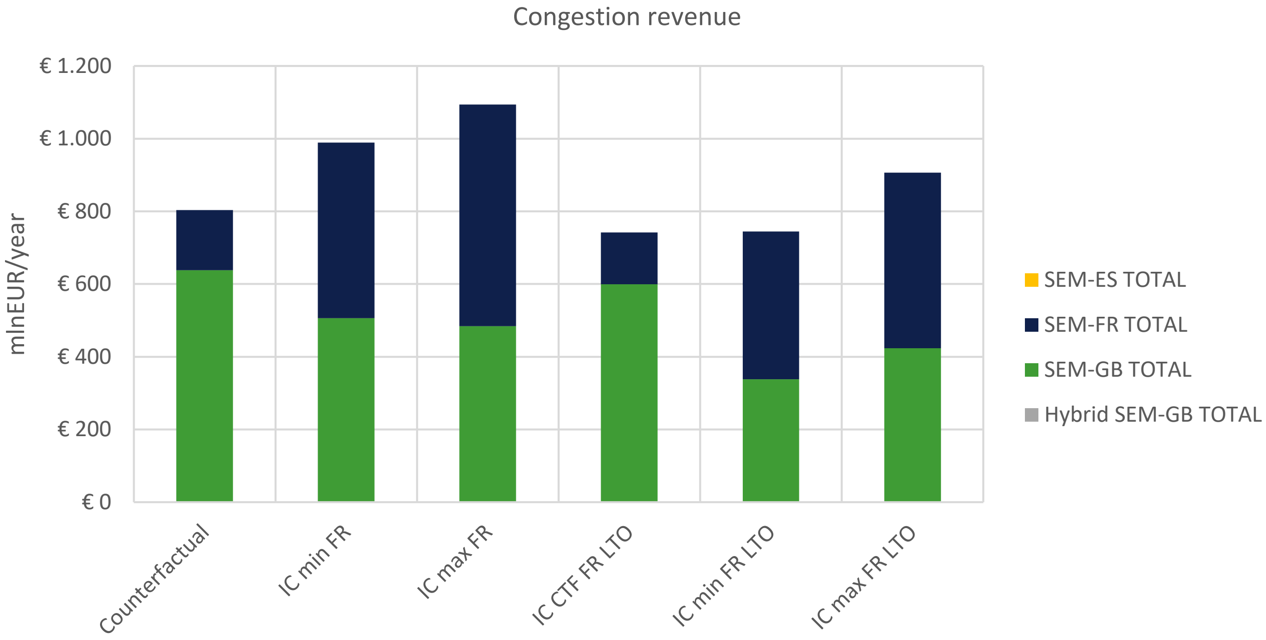

**Figure 6-38 Sensitivity 2 - Congestion revenue comparison**

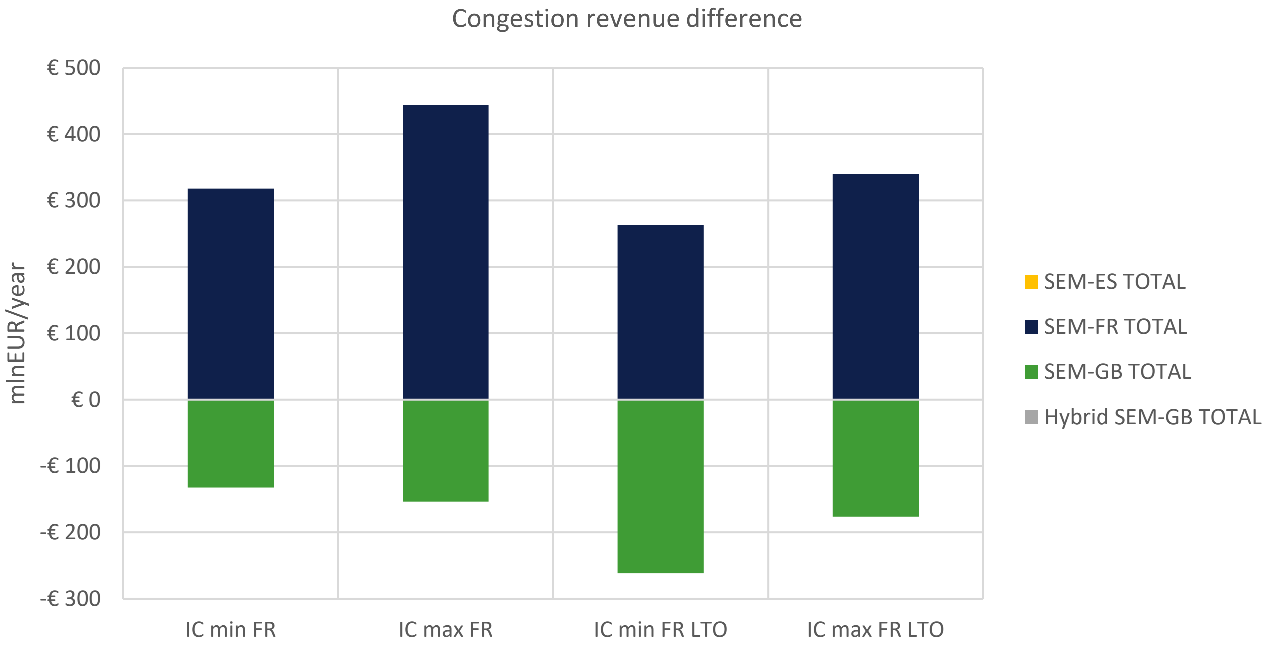

**Figure 6-39 Sensitivity 2 - Congestion revenue difference comparison**

### 6.5.2.3 RES curtailment

The impact of additional nuclear capacity in France on the RES curtailment in the SEM is minor and, overall, negligible (see Figure 6-40). The more visible effect is a slight increase in curtailment in Spain owing to less power flows from Spain to France (see Figure 6-41).

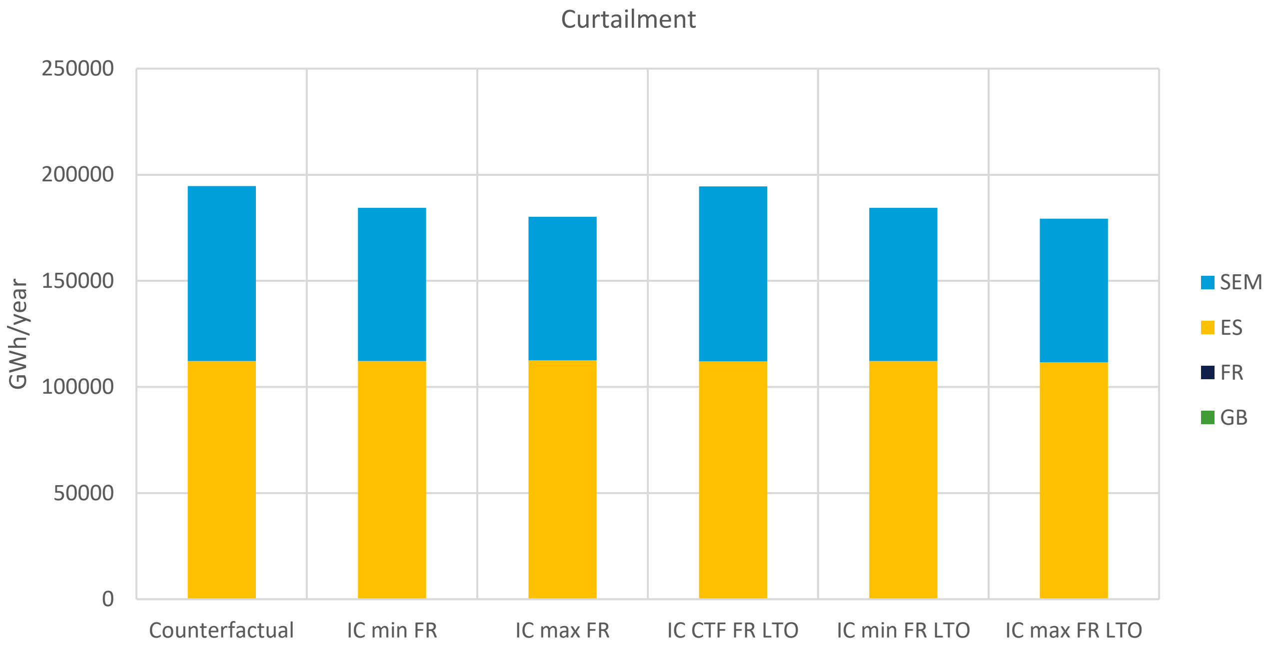

**Figure 6-40 Sensitivity 2 - RES Curtailment comparison**

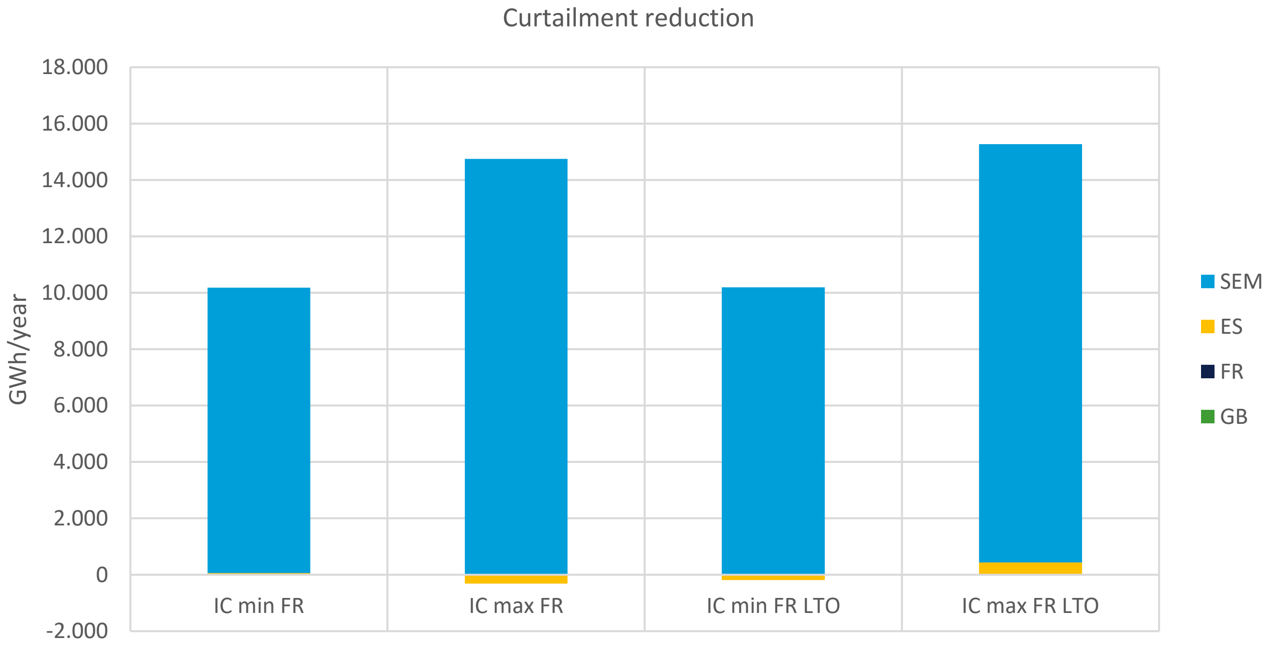

**Figure 6-41 Sensitivity 2 - Curtailment reduction comparison**

#### 6.5.2.4 Carbon emissions

Additional nuclear capacity in France enables a reduction in carbon emissions in all selected countries (see Figure 6-42). The total reduction in the counterfactual case is about 25%, with the largest reduction occurring in France (-31%) and the smallest in the SEM (-3%). The additional interconnection capacity between the SEM and France still leads to further carbon reduction in all selected countries (see Figure 6-43). For France, the additional benefit is smaller than in the base scenario (on average, -30%), while for the SEM is larger, i.e., +11% and +24% in the IC min FR and IC max FR cases, respectively.

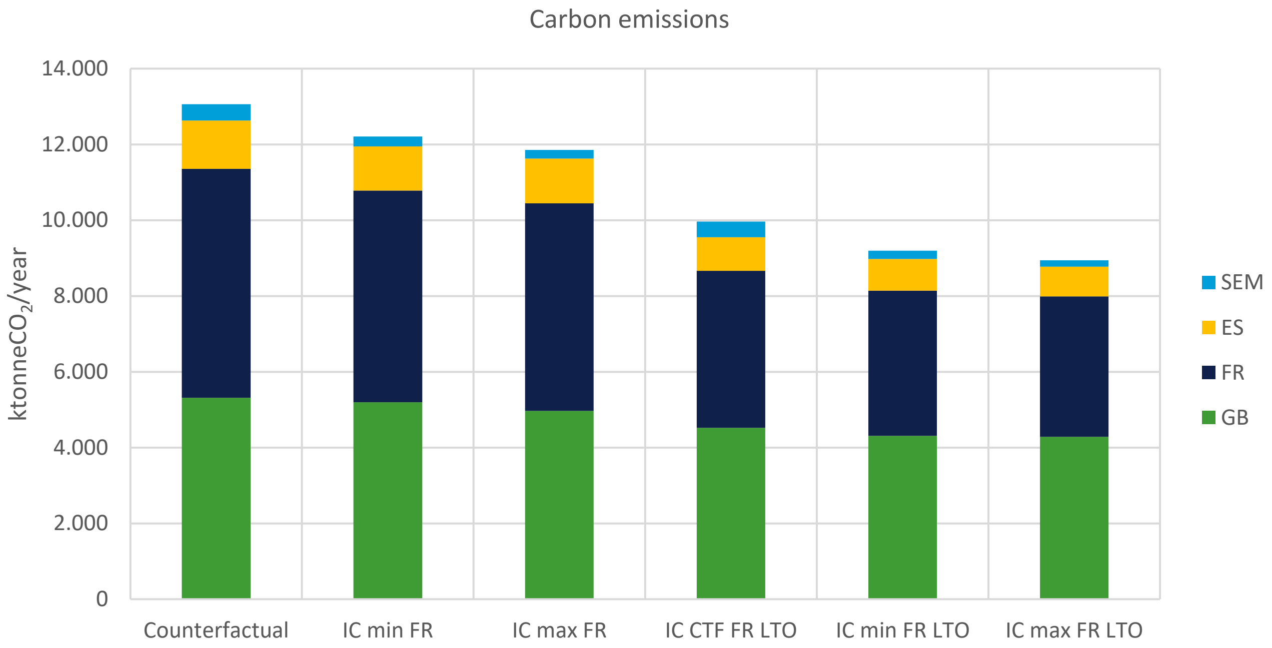

Figure 6-42 Sensitivity 2 - Carbon emissions comparison

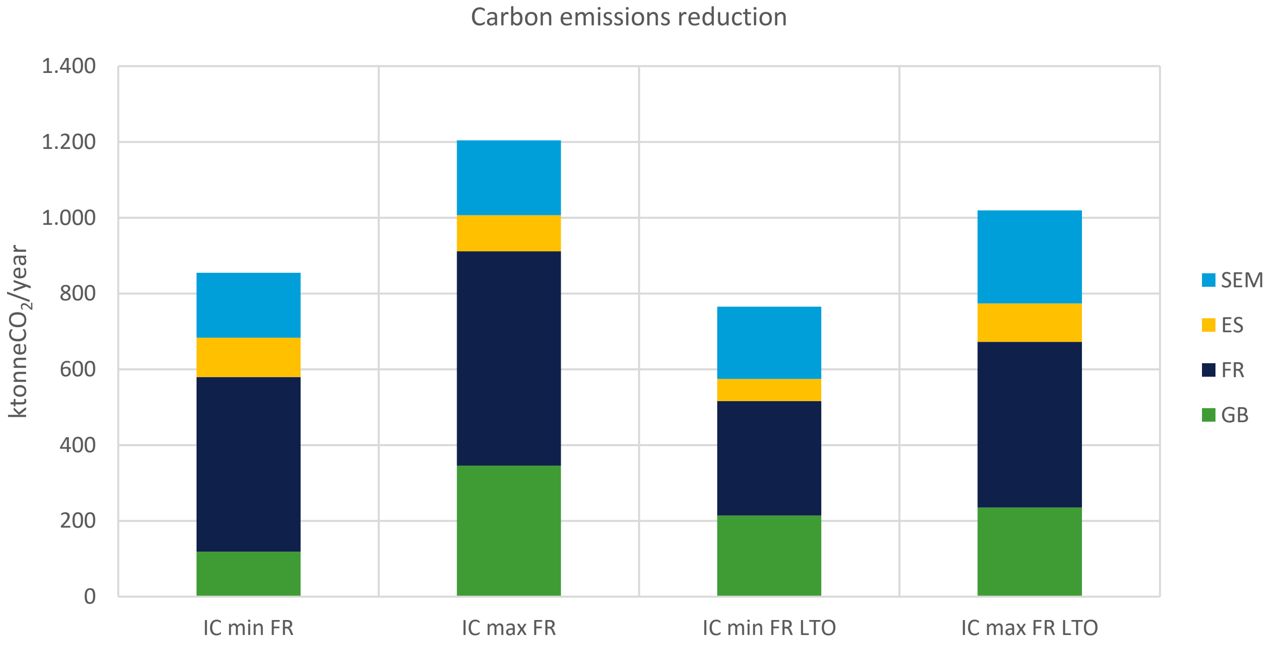

Figure 6-43 Sensitivity 2 - Carbon emission reduction comparison

### 6.5.2.5 Interconnector utilisation

The additional nuclear capacity in France leads to minor increase in the average utilisation rate of the interconnectors within the SEM system, namely, between 0.3% and 0.7%, compared to the base scenario.

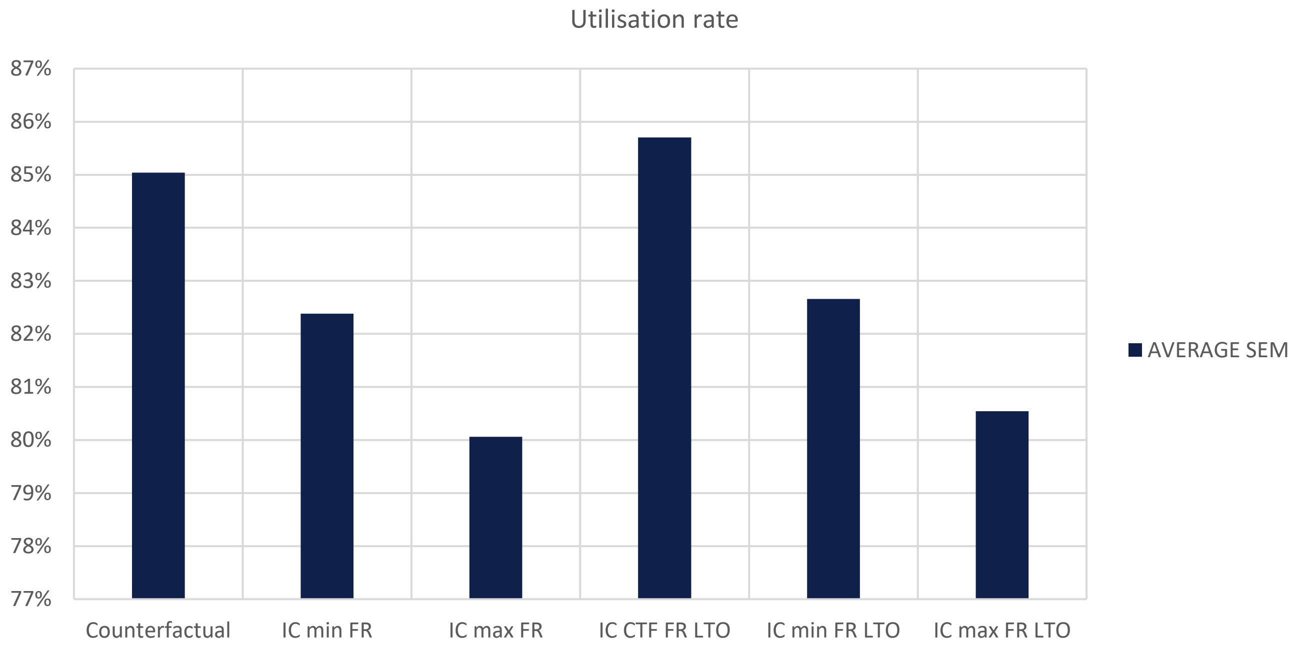

**Figure 6-44 Sensitivity 2 - Interconnector utilisation comparison**

### 6.5.2.6 Fuel mix

The impact of additional nuclear capacity in France on the SEM fuel mix is minor and, overall, negligible (see Figure 6-45). In the case of the maximum amount of additional interconnection capacity between the SEM and France being available, this sensitivity shows a further reduction in biomass and natural gas use in the SEM for electricity generation compared to the base scenario (see Figure 6-46).

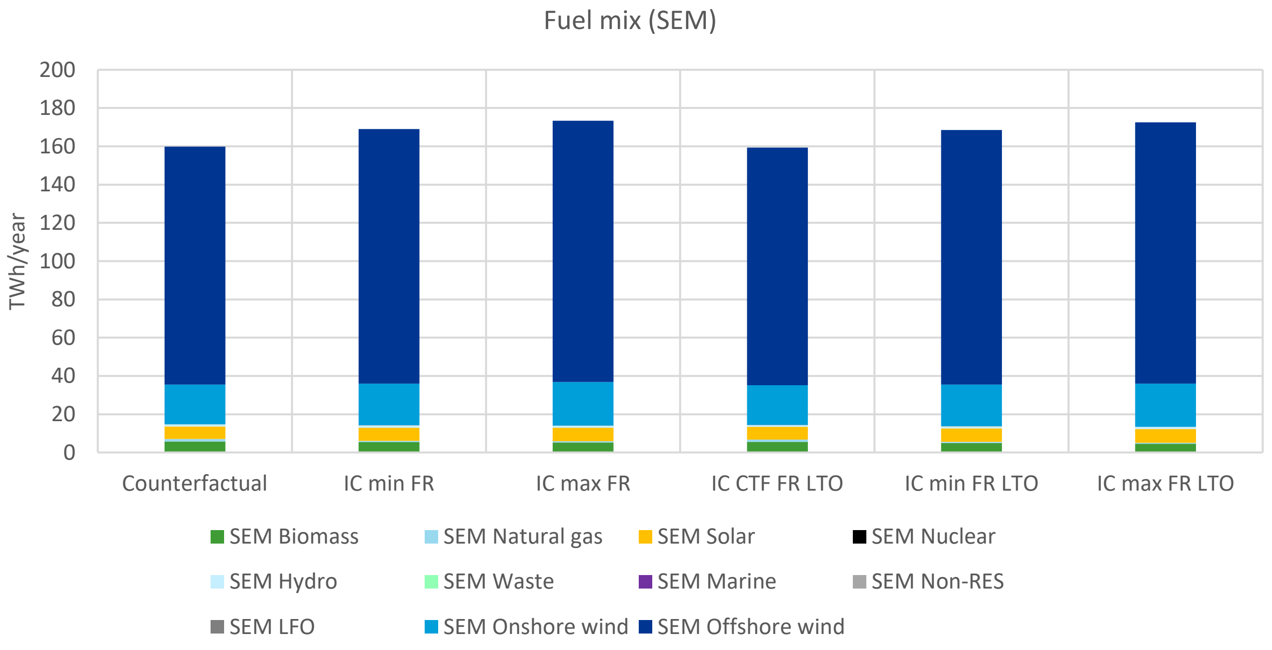

**Figure 6-45 Sensitivity 2 - Fuel mix comparison**

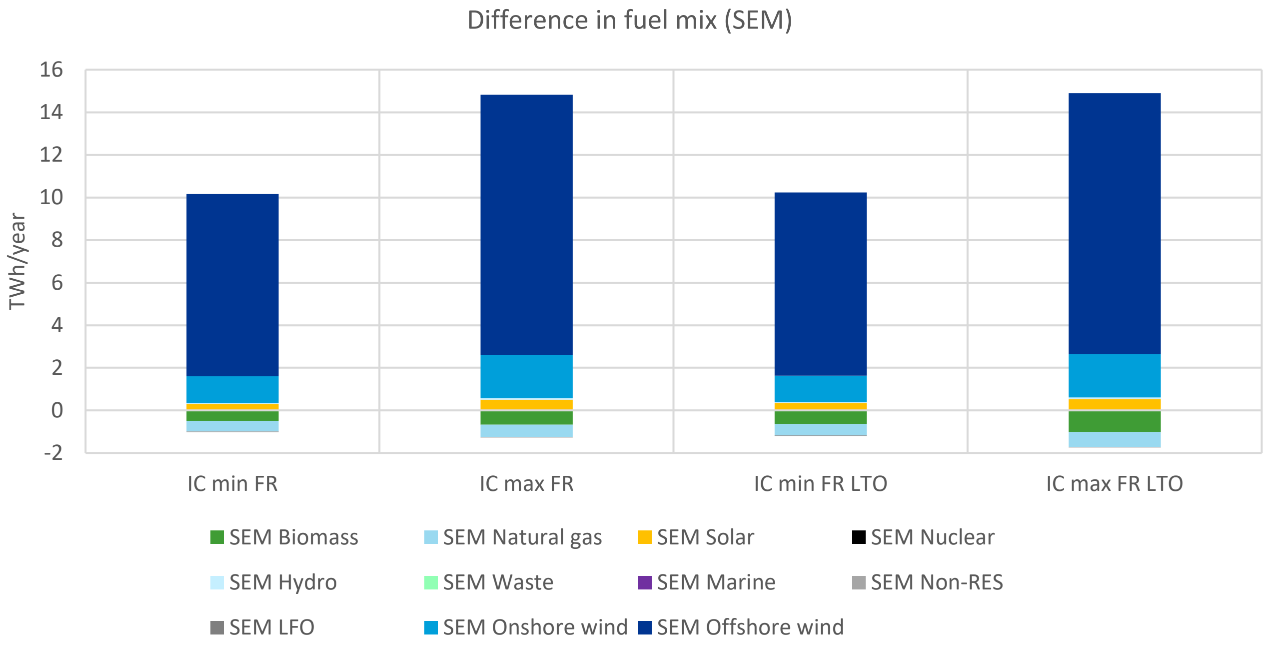

**Figure 6-46 Sensitivity 2 - Fuel mix difference comparison**

## 6.6 2030 Summary

For year 2030, DNV has analysed an additional interconnection between SEM and GB of 1,250 MW. The increase in interconnection capacity shows several benefits for the SEM, visible in the results of the different KPIs presented above. Overall, the additional interconnection facilitates renewable integration by reducing curtailment in the SEM by 2.2 TWh and in Spain, even though Spain and the SEM are not interconnected. This reduction of curtailment can be translated into fuel cost savings for the SEM equivalent to 88 mlnEUR/year.

In line with the decrease in renewable curtailment, the additional interconnection leads to a decrease of $CO_2$ emissions in the SEM power system. In 2030, the emissions are reduced by 230 ktonne $CO_2$/year, which avoids the cost of 21 mlnEUR/year that otherwise would be incurred as ETS certificates. The decrease in $CO_2$ emissions is not only visible in the SEM, but in all selected countries, especially GB. Therefore, even if GB does not directly benefit from higher integration of renewables by the additional interconnection, it does benefit from a decrease in $CO_2$ emissions of 91 ktonne $CO_2$/year.

The resulting SEM fuel mix after the integration of the connection with GB is characterised by an increase in renewable generation, especially offshore wind generation, while generation from natural gas power plants decreases. These results show the potential of additional interconnection to facilitate the achievement of Ireland's long term energy objectives and decarbonization of the power system.

The additional interconnection with GB introduces a CAPEX of 687 mlnEUR. At the same time, the SEM-GB connection leads to an economic benefit for the whole society expressed in terms of system cost reduction estimated at 56 mlnEUR/year for the SEM and at 35 mlnEUR/year for GB. As for the economic value of the interconnector in terms of congestion rents (which are a part of the SEW but have been analysed separately since they are an important indicator to judge the financial attractiveness of a project), the additional SEM-GB link leads to a decline in total congestion revenues compared to the counterfactual case. This suggests that a good price convergence is reached between the SEM and GB, and the SEM and France, and that the additional interconnectors cannibalise on already existing links. The latter is also shown by lower interconnector utilisation than in the counterfactual case. Nevertheless, the absolute value of annual congestion rent on additional interconnectors in the 2030 factual case amounts to 74 mlnEUR/year, leading to a payback period of 15 years (assuming stable annual congestion rent and 7% discount rate), which is comfortably within the anticipated lifetime of an interconnector asset.

In terms of security of supply, this study has not captured a specific quantitative KPI to reflect on this parameter. However, in general terms, additional interconnection will contribute to increased flexibility in the system and deliver SoS benefits.

## 6.7 2040 Summary

For the analysis of 2040, DNV has considered several additional interconnections with the SEM: SEM-GB of 50 MW, SEM-FR of 1,050 MW, and SEM-ES of 1,000 MW. Moreover, the case with all links included simultaneously has been analysed in order to estimate their combined effect on the system. Overall, the increase in interconnection capacity brings several benefits for the SEM, visible in the results of the different KPIs. However, differences among the various links are evident, which define the interconnection that could potentially be the most beneficial and lead the path towards 2050 goals.

In 2040 the SEM fuel mix shows an increase in renewable generation, mostly onshore and offshore wind. This trend is most prominent in the connection case with France, where renewable generation in the SEM is higher than in the counterfactual and other factual cases. However, the increase in renewable generation is not always complemented by a decrease in generation from conventional power sources in the SEM power system. In fact, the case of additional interconnection with Spain is the only factual case that shows a decrease of fossil fuel generation in the SEM in comparison to the counterfactual case.

The effect of interconnections on renewable integration and the decarbonization of the SEM system is also visible in other KPIs. In this regard, one can observe a reduction in renewable curtailment with the addition of interconnection in both the SEM and Spain. The case of additional links with France leads to the highest curtailment reduction in the SEM, both in absolute terms, 4.3 TWh/year, and relative terms (curtailment reduction per MW of additional interconnection).

This reduction of curtailment can be translated into fuel cost savings for the SEM equivalent to 92 mlnEUR/year. In terms of carbon emissions, and how further interconnection can facilitate their reduction and contribute towards Ireland's 2050 long term energy objectives (net zero 2050), the comparison between connection cases provides useful insights. The additional interconnections with Spain enable $CO_2$ emission reduction in all selected countries, and mainly in France and Spain. For the SEM the connection SEM-ES reduces carbon emissions by 56 ktonne $CO_2$/year, thereby avoiding 6 mlnEUR/year being spent in ETS certificates. While all the factual cases reduce the carbon emissions at least in some of the selected countries (the SEM, GB, FR, ES), only the interconnection with Spain achieves a decrease in the SEM system. Therefore, while additional interconnection with France could achieve higher integration of renewables in the SEM, the connections with Spain could boost the replacement of domestic fossil fuel power generation and reduction of carbon emissions.

The investment costs of interconnectors are higher for the links with Spain and France than those to GB. This is mainly driven by higher interconnection capacities and distances between the connected countries. Hybrid links between the SEM and GB enable savings in CAPEX compared to the counterfactual, since the cost of offshore wind grid connection systems is avoided. The connection towards Spain leads to the largest CAPEX differences compared to the counterfactual case, mainly caused by increased cable expenses triggered by the larger distance between the SEM and ES in comparison to the SEM and FR.

Additional interconnection can bring economic benefits for the whole society, Socio-Economic Welfare (SEW), as it can reduce the power system costs. All analysed connection cases present a decrease in total system cost and, hence, an increase in SEW for the whole group of studied countries in comparison to the counterfactual case. Yet, system cost savings in the SEM system are evident only in the connection case towards Spain and are estimated at 25 mlnEUR/year. Additionally, the link with Spain reaches the highest decrease in system cost for the selected countries as a whole, with France and Spain experiencing significant decrease.

As for the economic value of the interconnectors in terms of congestion rents, the additional interconnections with France achieve the highest increase in congestion rents, 278 mlnEUR/year, as well as the highest congestion revenues per additional interconnection capacity. This is due to France strongly relying on imports in order to reduce its fossil fuel generation and to larger average price differentials between the SEM and France than between the SEM and the other selected countries.

In terms of security of supply, DNV has not captured a specific quantitative KPI to reflect on this parameter. However, the numbers of hours in which the SEM system is at limit have been assessed. The counterfactual case as well as the cases with additional connections to GB and France present several hours where the SEM system is at limit, while the case with additional interconnections with Spain do not display any hour at limit. In general terms, additional interconnection will contribute to increase flexibility in the system and deliver SoS benefits.

## 6.8 2050 Summary

For year 2050, DNV has analysed several additional interconnections with the SEM: SEM-GB, SEM-FR, and SEM-ES. For the three different countries two connection values have been evaluated, a minimum and a maximum capacity addition. Moreover, the case with all links included simultaneously have been analysed in order to estimate their overall impact on the system. Overall, the increase in interconnection capacity brings several benefits for the SEM, visible in the results of the different KPIs presented above. However, differences among the various links are evident, which define the interconnection that could potentially be the most beneficial.

The SEM fuel mix in 2050 is characterised by a growing share of renewable generation, with offshore wind showing the most significant increasing trend. Consequently, the additional generation of renewables replaces conventional power generation sources, such as natural gas. This effect is visible in all interconnection cases, the link with France being the one that achieves the highest increase in renewable generation in SEM.

The resulted generation mix is also reflected in other KPIs which give insights into the renewable integration and the decarbonization of the SEM system. In this regard, renewable curtailment is always reduced with the integration of additional interconnections and up to a maximum of 14.7 TWh/year with the link SEM-FR (max case). Decrease in renewable curtailment is only visible in the SEM and Spain. In terms of RES curtailment reduction per additional MW of interconnection capacity, the difference across the connections is lower than in absolute terms, yet the interconnections with France show the highest potential to reduce curtailment in the SEM. The SEM-GB max case presents also high potential for reducing renewable curtailment in the SEM; in this case, part of the infrastructure is hybrid, hence this offshore wind capacity benefits from having a connection to two markets which minimises its curtailment. The reduction of curtailment can be translated into fuel cost savings equivalent to 158 mlnEUR/year in the case of maximum interconnection with France.

The decarbonization of the Irish power system by the introduction of additional interconnections is reflected in the comparison of carbon emissions across cases. On average, the interconnections with France lead to the highest decrease in $CO_2$ emissions in the SEM; yet the interconnection with Spain in the max case shows the same reduction as the SEM-FR max case. The difference between the cases is most notable in their potential to reduce emissions in other countries. The additional links to France (max case) show the highest decrease in carbon emissions across all selected countries, with France and GB showing the largest decrease. By analysing the decrease in carbon emissions per MW of additional interconnection, the links with Spain show higher values for the SEM than the ones with France. Both Spain and France are characterised by a generation mix and renewable patterns that are complementary to those observed in the SEM. Therefore, SEM-ES and SEM-FR interconnections enable a significant boost in renewable integration and a reduction in carbon emissions not only in the SEM, but also in all selected countries. In 2050, the additional interconnections with France or Spain allow the SEM to reduce its emission by 197 ktonne $CO_2$/year (FR and ES max cases), thereby avoiding 23 mlnEUR/year being spent in ETS certificates.

Similar to the results of the 2040 analysis, the investment costs of interconnectors are higher for the links with Spain and France than those to GB. This is mainly driven by higher interconnection capacities and distances between the connected countries. Hybrid links between SEM and GB actually allow savings in CAPEX compared to the counterfactual, since the cost of offshore wind grid connection systems is avoided.

Additional interconnection of the SEM system results in reduced system cost. The connection with France displays the largest decrease in SEM system cost, i.e., 89 mlnEUR/year, and in total for the selected countries. In relative terms, the links with Spain present the highest potential, enabling the largest decrease in the SEM system costs per MW of additional interconnection capacity. In terms of congestion revenues, the additional interconnection with France (max case) achieves the highest net increase in congestion rents, i.e., 290 mlnEUR/year. The congestion revenues per additional interconnection capacity shows that the hybrid connection SEM-GB reaches the highest congestion revenues per MW.

In terms of security of supply, this study has not captured a specific quantitative KPI to reflect on this parameter. However, the numbers of hours in which the SEM system is at limit have been assessed. The cases with additional connections to GB and Spain present several hours where the SEM system is at limit, while the cases with additional interconnections with France do not display any hour at limit. In general terms, additional interconnection will contribute to increased flexibility in the system and deliver SoS benefits.

The robustness of 2050 results discussed above have been tested by means of two sensitivities, the first assessing the influence of a reduction in SEM RES capacity, and the second an increase in French nuclear capacity. Overall, a reduction in SEM RES capacity leads to an increase in fossil fuel generation and system costs in the SEM, making the additional interconnection capacity all the more needed to enable SEW benefits and carbon emission reduction in the SEM. The additional links curb the system costs and fossil fuel consumption by amplifying the imports from neighbouring countries. At the same time, the SEM exports to the selected countries decline and the price differentials subside, hence reducing the congestion revenues generated by the additional links.

As for the second sensitivity, an increase in French nuclear generation leads to a slight decrease in SEM system costs, mostly owing to a decline in fossil fuel generation, which is replaced by imports from France. The effects are most evident with additional interconnection capacity installed between the SEM and France, which leads to an increase in carbon emission reduction in the SEM compared to the base scenario. On the other hand, SEM opportunities for export to France reduce, thereby curbing the congestion revenues not only for the SEM-FR links but also for the SEM-GB ones.

# 7 CONCLUSIONS

This chapter draws the main conclusions of the study according to the results presented in the previous chapter. The conclusions are presented in a "question – reply" format which addresses the key questions that motivated this study. It is worth noticing that, while the key questions mostly refer to the objectives set by the Government of Ireland, the result analyses carried out in this study focus on the SEM system, which encompasses the power system of both Ireland and Northern Ireland. For the sake of readability, the overview of the study cases presented in Table 6-3 is given here.

**Table 7-1 Overview of the study cases, based on the additional Interconnection capacities [MW], as introduced in Chapter 4.6**

| Study cases | SEM-GB | SEM-FR | SEM-ES |
|---|---|---|---|
| **Counterfactual 2030** | 0 | 0 | 0 |
| **Factual 2030** | 1,250 | 0 | 0 |
| **Counterfactual 2040** | 1,250 | 0 | 0 |
| **Factual 2040** | 1,300 | 1,050 | 1,000 |
| **Counterfactual 2050** | 1,250 | 0 | 0 |
| **Factual 2050 min** | 1,300 | 2,100 | 1,500 |
| **Factual 2050 max** | 2,300 | 3,100 | 1,900 |

### 1. The economic rationale and the impact of further interconnection, beyond the Celtic and Greenlink interconnectors, to be delivered by 2030 or soon thereafter, on the achievement of Ireland's 2030 energy objectives and de-risking future offshore renewables development.

**Additional interconnection capacity in 2030, beyond existing projects or those at advanced development stage, has significant economic benefits for the SEM system. Developing a new interconnector with Great Britain is justified both from the developer and societal perspectives. Furthermore, it supports the achievement of Ireland's 2030 energy objectives and de-risks offshore wind development.**

The Climate Action Plan 2023 sets out ambitious goals to reduce Ireland's greenhouse gas emissions and make Ireland carbon neutral by 2050. By 2030, the generation of electricity from renewable sources shall be 80% and the carbon emissions for electricity production shall be 2-4 million tonne, compared to 30% and 10.1 million tonne in 2018, respectively. Additionally, the offshore wind installed capacity shall increase up to 5 GW.[66] In line with these targets, this study assumes 5.1 GW of offshore wind installed capacity in SEM by 2030, of which 5 GW in the Republic of Ireland and 0.1 GW in Northern Ireland.

The results indicate that by 2030 88% of electricity generated in the SEM system comes from renewable sources, i.e. solar, wind, and hydro, with total production of up to 48 TWh/year. Yet, 9 TWh/year of renewable generation is curtailed when no additional interconnection capacity is developed. Curtailed offshore wind generation accounts for 4.5 TWh/year, corresponding to 20% of its potential contribution. Additional interconnection capacity with Great Britain, investigated in the 2030 Factual case, enables a reduction of renewable curtailment by 2.2 TWh/year, boosting the share of SEM electricity generation from renewable sources to 90%, well above the 2030 objective.

The economic impact of increasing renewable integration, including curtailment reduction and fossil generation displacement, is measured in terms of Socio-Economic Welfare (SEW). The additional 1,250 MW of interconnection capacity between the SEM and Great Britain enables an annual increase in SEW of 56 mlnEUR and 35 mlnEUR in the SEM and Great Britain respectively. These values account for cost reduction in ETS certificates owing to $CO_2$ emissions, and for fuel savings given that renewable generation is cheaper than generation based on (fossil) fuels. Although not taken into account by this study, the upcoming round of (onshore) renewable auctions will be compensating assets for any loss in revenue through the Unrealised Available Energy Compensation method.[67] This cost will ultimately be passed

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[66] https://www.gov.ie/en/policy-information/62d81a-electricity/

[67] https://assets.gov.ie/238476/2a77f83c-4b15-4fc3-89d4-89bae057e861.pdf

on to consumers. The reduction in renewable curtailment enabled by additional interconnectors will therefore translate into lower costs to consumers.

Congestion revenues are a part of the SEW, yet they have been analysed separately since, from the perspective of the interconnector developer, they are an important indicator to judge the financial attractiveness of a project. The additional link between the SEM and Great Britain enables a good price convergence between the two markets, but also between the SEM and France. This leads to a reduction in congestion rents for the links between the SEM and Great Britain, and those between the SEM and France, compared to the case with no additional interconnectors. On the SEM-GB border, the total congestion rents decrease by 2 mlnEUR/year, owing to additional interconnectors cannibalising the business case of the existing ones. This reduction in congestion rents, however, does not necessarily reflect the non-commercial viability of developing further interconnection capacity between the SEM and GB for 2030. The absolute value of annual congestion rent on additional interconnectors in the 2030 factual case amounts to 74 mlnEUR. With CAPEX estimated at 687 mlnEUR, such an investment would pay back already in 15 years, assuming stable annual congestion rent and a 7% discount rate.

To assess whether an interconnector is attractive from the perspective of the society, the ratio of SEW gain to CAPEX spent has been estimated. For 2030, the total annual welfare gain is about 0.15 EUR per year per 1 EUR of CAPEX spent. Assuming a conservative interconnector lifetime of 25 years and that this benefit would remain stable across the lifetime, a welfare gain of 1.75 EUR per 1 EUR of CAPEX spent is estimated (at 7% discount rate) which is a result of the suggested 2030 additional interconnector capacity.

Finally, additional interconnection capacity appears beneficial for de-risking future offshore renewable development This is evidenced by reductions in curtailment volumes of almost 50% compared to the 2030 Counterfactual case, dropping from 4.5 TWh/year to 2.2 TWh/year.

### 2. The economic rationale for developing further interconnection and the impact of increased interconnection on achieving Ireland’s longer term energy objectives, including achieving net zero by 2050.

**The development of significant further interconnection between the island of Ireland and all countries within the study’s scope by 2050 is economically justified, as it delivers sizeable socio-economic welfare gains for the SEM and other countries in scope. The impact on achieving net zero is negligible as the model shows that it would be achieved regardless. Nevertheless, additional interconnection facilitates a very significant reduction in SEM curtailment allowing it to export surplus green electricity to the countries where it is needed, and thereby de-risking renewables development. Considering the benefit-to-cost ratio of additional interconnectors with all modelled countries, DNV finds all of the 2050 connections to be economically justified and beneficial to consumers in the SEM and the connected countries. Provided they can be implemented as hybrid links and result in savings in wind farm connection costs, the connections with Great Britain are seen by DNV as the most attractive in relative terms to the investment costs.**

This study has investigated the impact of additional interconnection capacity in 2040 and 2050 (see Table 7-1). For the year 2040, three study cases have been defined, one assuming additional interconnection between the SEM and Great Britain (on top of the 1,250 MW included in the 2030 Counterfactual case), one between the SEM and Spain, and one between the SEM and France. For the year 2050, six study cases have been defined, where minimum and maximum capacity scenarios are investigated for each of the additional interconnection options, namely, SEM-GB, SEM-ES, and SEM-FR. Additional study cases with all potential links being developed have been investigated for both 2040 and 2050, and can be considered as the most optimistic development of interconnection capacity.

The results indicate that, with no additional interconnection capacity, the share of electricity generated from renewable sources reaches 92% in 2040 and 96% in 2050. Yet, SEM renewable curtailment amounts to 34 TWh/year and 82 TWh/year in 2040 and 2050 respectively, corresponding to 22% and 40% of the annual potential renewable generation. These high curtailment values could hinder the development of future renewable projects and lead to high costs for compensation of curtailment. All study cases for 2040 and 2050 show that additional interconnection capacity enables a reduction in renewable curtailment in the SEM, hence promoting a generation mix that relies less on fossil fuels and more on carbon-free sources. Additional interconnection with France leads to the highest reduction of renewable curtailment in the SEM; this is due to large export opportunities for the SEM towards France given the expected relatively high share of fossil fuel in the French generation mix towards 2040 and 2050 (around 7% in 2040 and 2.5% in 2050). In the French study cases, SEM share of renewables in the generation mix reaches 92% in 2040 and 96% in 2050, and renewable curtailment is reduced by up to one fifth.

In the 2040 case with connection to France, the 92% reduction of curtailment can be monetised in terms of fuel cost savings equivalent to 92 mlnEUR/year. Nevertheless, an increase in SEM socio-economic welfare is evident only in the interconnection case with Spain and is estimated at 25 mlnEUR/year, corresponding to a 7% reduction in system costs. The impact on SEM SEW from connecting with Great Britain or France in 2040 is negligible. In the case with connection to Spain, the SEM benefits from a reduction in carbon emissions of 56 ktonne/year, the highest among all 2040 study cases. Therefore, while additional interconnection with France facilitates higher utilisation of renewables in the SEM, the connections with Spain could boost the replacement of domestic fossil fuel power generation and reduction of carbon emissions. In fact, the share of renewables in SEM generation mix in the counterfactual case is already so high that additional interconnection capacity to France or Spain has a beneficial yet almost negligible impact, increasing the RES share by 0.2 to 0.5 percentage points. It is worth noting that, among all selected countries, France is the one country that benefits the most from the additional links in terms of both $CO_2$ and system costs reduction. Additional interconnection with the SEM enables France to import renewable generation which replaces expensive, polluting fossil fuel generators. Large power flow volumes from the SEM to France translate into high congestion rents, which total up to 278 mlnEUR/year, the highest net value across all 2040 study cases.

In 2050, the largest increase in SEW for the SEM is achieved when connecting to France, which is estimated between 76 mlnEUR (min case) and 89 mlnEUR (max case) per year. These values correspond to a sizeable decrease in SEM system costs of 26% to 30%, compared to the counterfactual case. Similar results are achieved when connecting the SEM to Spain with the maximum capacity. Both Spain and France are characterised by a generation mix and renewable patterns that are complementary to those observed in the SEM. Therefore, SEM-ES and SEM-FR interconnections enable a significant boost in renewable integration and a reduction in carbon emissions not only in the SEM, but in all selected countries. Additional interconnection capacity to France or Spain in the max cases allows the SEM to achieve 97% RES share in the generation, corresponding to an increase of one percentage point compared to the counterfactual case. One cannot conclude that additional interconnection is vital for Ireland to achieve its climate goals, as even in the counterfactual case, the goals are met. Nevertheless, the economic impact from reduced curtailment in the SEM is large, since interconnectors allow to export the surplus of green electricity generated in Ireland to the countries where it is needed.

The impact of increased interconnection on achieving the 2050 objective is, however, subject to uncertainty in both the development of the renewable sector in the SEM and of the nuclear sector in France. Overall, a reduction in SEM renewable capacity curbs SEM export opportunities, while the price differentials with other markets subside, reducing the congestion revenues generated by the additional links. Similarly, an increase in French nuclear generation reduces French needs for import from the SEM, hence curbing the congestion revenues not only for the SEM-FR links, but also for the SEM-GB ones. The SEM experiences a slight decrease in system costs due to a reduction in carbon emissions owing to a decline in fossil fuel generation which is replaced by imports from France.

The results indicate that the additional interconnections to France and Spain deliver the largest benefits in absolute figures and, on average, in terms of annual welfare gain per 1 EUR of CAPEX spent. Yet, among the 2050 study cases, the largest annual increase in SEW per 1 EUR of CAPEX spent is achieved by the hybrid SEM-GB interconnection with maximum capacity. Despite a cannibalisation effect with the links already existing, the hybrid link yields an annual welfare gain of 2.17 EUR per year per 1 EUR of CAPEX spent, and of 20 EUR per 1 EUR of CAPEX spent over 25 years of lifetime (at 7% discount rate). The hybrid interconnection avoids building a radial connection to the offshore wind farm, yielding additional investment costs between the 2050 Counterfactual and the factual cases which are negligible compared to the other 2050 study cases. CAPEX benefits of developing hybrid interconnectors would indicate that they are a priority.

The regulatory landscape for these is, however, limited. Great Britain is only just considering making them a licensable activity in the Energy Bill 2022[68], and other aspects of their operation are not currently possible. A priority should, therefore, be placed on developing the regulatory and operation parameters of multi-purpose interconnectors.

### 3. The extent to which further interconnection can contribute to the decarbonisation of Irish power generation and electricity consumed in Ireland, through the replacement of domestic fossil fuel generation.

**The SEM system achieves high RES shares in the electricity generation mix even without additional interconnection capacity, which are sufficient for Ireland to fulfil its 2030 and 2050 climate objectives. The increase in RES generation share enabled by additional interconnectors is minor. Nevertheless, sizeable benefits in terms of the RES utilisation are enabled by additional interconnection capacity with Great Britain in 2030 and with Spain and France beyond 2030. In addition, interconnection allows for large reductions in the volumes of SEM RES curtailment providing export opportunities to other countries.**

The results indicate that SEM system achieves high RES shares in the generation mix in line with Ireland's climate objectives for 2030 and 2050 even without additional interconnection capacity. The RES share in the counterfactual cases increases from 88% in 2030 to 92% in 2040 and reaches 96% in 2050, The study cases connecting the SEM to one of the other selected countries enable a further increase of about 2 percentage points in 2030, up to 0.5 percentage points in 2040, and up to 1 percentage point in 2050. The increase in generation from renewable sources enabled by additional interconnectors is minor. Additionally, not all study cases enable a reduction in domestic fossil fuel generation. In the 2030 factual case, the additional link between the SEM and Great Britain reduces the natural gas generation in the SEM by 700 TWh/year, corresponding to a 13% reduction. Yet, among the 2040 factual cases, only the additional link with Spain facilitates a decrease in fossil fuel generation, i.e., -9%, while an increase in fossil fuel generation occurs in both the study cases with additional interconnection with Great Britain and France, i.e., +5%. Among the 2050 study cases, all but the one with minimum additional capacity with Great Britain enable a replacement of domestic fossil fuel generation in the SEM, with the largest reduction of 46% being reached with maximum additional capacity with Spain and France. The replacement of domestic fossil fuel generation translates into carbon emission reduction. As already mentioned, in both 2040 and 2050, France is the core country that benefits the most in terms of $CO_2$ reduction across all study cases but the one with maximum hybrid SEM-GB interconnection. Additional interconnection can, therefore, contribute not only to the decarbonisation of the Irish power generation but also of the other countries, which, in fact, may be the largest beneficiaries.

### 4. The impact of further interconnection on total power system costs.

**Further interconnection results in a sizeable reduction in total power system costs within the SEM. Additional interconnectors between the SEM and Great Britain are beneficial in 2030 (12% reduction in SEM system costs), but cause an increase in system costs by 2040 and, depending on the interconnector capacity, by 2050. Interconnections with Spain and France yield the largest total power system savings for the SEM (up to 30%) in power system costs in 2040 and 2050, respectively.**

Most of the study cases enable a reduction in power system costs and, hence, an increase in SEW. The additional interconnector between the SEM and Great Britain in 2030 leads to a 56 mlnEUR/year decrease in total power system costs in the SEM, corresponding to 12% reduction compared to the counterfactual case. Towards 2040, further interconnection capacity with Great Britain causes a slight increase of 2% in SEM system costs. Similarly, the interconnection with France yields an increase in SEM power system costs of 3%. On the other hand, additional interconnection with Spain enables savings in power system costs for 25 mlnEUR/year, corresponding to -7% compared to the counterfactual case. Among the 2050 study cases, all additional interconnectors but the hybrid SEM-GB link with minimum capacity enable a sizeable reduction in SEM power system costs. The hybrid SEM-GB link with maximum capacity yields savings for 27 mlnEUR/year, i.e., -9% in power system costs. The largest benefits are enabled by the additional interconnectors with maximum capacity with France and estimated at 89 mlnEUR/year, corresponding to a 30% reduction in SEM power system costs.

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[68] https://www.gov.uk/government/publications/energy-security-bill-factsheets/energy-security-bill-factsheet-multi-purpose-interconnectors

### 5. Security of supply benefits associated with development of further interconnection capacity.

**Whilst the study did not entail a stochastic network modelling to assess system security, DNV noted that the SEM system is expected to have a large share of variable renewables in the future. Any additional interconnector capacity, if placed strategically, will contribute to growing the portfolio of flexible capacities. Furthermore, voltage and reactive power are expected to be a challenge too. HVDC-based interconnectors are beneficial as they often possess active voltage regulation, frequency response, grid forming and black start capabilities.**

This study does not feature a quantitative metric to reflect on the security of supply (SoS). To properly assess the impact of additional interconnectors on this aspect, stochastic network modelling simulations are required. This falls outside of the scope of this study. DNV recognise, however, that SoS is important for understanding the full business case of interconnectors.

For Ireland, adequacy and flexibility are the most critical SoS aspects, given that the SEM is located at the periphery of Europe and does not benefit from large cross-border capacity with the neighbouring systems. As the SEM system is expected to have large share of renewables in the future, its portfolio of flexible capacities needs to be sufficiently robust, and both the type of capacity and its location will be of importance. Any additional interconnector capacity, if placed strategically, will contribute to both these aspects. Albeit ramp rates of HVDC-based interconnector technology are not as high as they are for AC interconnectors in Europe, the higher is the volume of interconnectors in the SEM, the more flexible the system will be. Furthermore, voltage, frequency response and reactive power are expected to be a challenge too. HVDC-based interconnectors are beneficial as they often possess active voltage regulation, frequency response, grid forming and black start capabilities.

In this study, only the numbers of hours in which the SEM system is at limit have been assessed. The system is considered operating at limit when all available generation capacity is fully used, and imports are at maximum level. In this case, an additional MWh of load would cause energy not served and, hence, it is priced at the value of loss of load (VoLL), which is 3,500 EUR/MWh. In 2030, the SEM never operates at limit, while in 2040 and 2050 Counterfactual case it happens in 7 and 8 hours, respectively. In 2040, the additional interconnections with Spain lead to the largest benefit for the SEM system, by preventing the system to reach its limit at any time. In 2050, the most beneficial additional interconnections in terms of operating conditions are those with FR.

### 6. Consideration of the optimal countries/markets for Ireland to interconnect with, and an analysis as to whether priority should be placed on developing further interconnection with Great Britain, the EU Internal Energy Market, or both.

One of the findings from the analysis is that the impact of additional interconnectors on RES integration is negligible in all cases. The SEM system achieves high RES shares in the final energy mix even without additional interconnection capacities, which allows Ireland to meet its climate objectives for 2030 and 2050. Therefore, in determining the optimal countries/markets to interconnect with, DNV primarily focus on the economic aspect.

**From the cost perspective, interconnectors with Great Britain are the most attractive due to shorter distances and opportunities to develop hybrid assets. Considering the benefits, all four countries experience sizeable positive economic impacts, even in cases when they do not get directly connected with the SEM. Provided that smart agreements on cross-border cost sharing and compensation mechanisms were in place, DNV would recommend the development of interconnectors with France and Spain as economically attractive in the time period beyond 2030 and focusing on interconnection with Great Britain towards 2030.**

The analysis shows that the costs of additional interconnection are the lowest for Great Britain across all time periods. This is enabled by shorter distance and opportunity to make those links hybrid, meaning that one saves on the costs of wind farm connection. Connections to Spain in France, which DNV analysed for 2040 and 2050, are of a similar magnitude in CAPEX, with connection to Spain being slightly more expensive per MW of capacity due to the larger distance. Purely from the cost perspective, connections with Great Britain are, therefore, the most attractive.

Considering the benefits side, additional interconnection brings SEW benefits to the SEM system from connecting with Great Britain in 2030 and 2050, connecting to Spain in 2040 and 2050, and connecting to France in 2050. From this perspective, it can be attractive to focus on the interconnector development with Great Britain in the shorter-term, and to develop interconnectors with Spain and France towards 2040 and beyond to maximise the benefits for the SEM.

Analysing this further, the key observation that DNV makes is that there are sizeable positive economic impacts on all four countries, even in cases when they do not get directly connected with the SEM. From a larger, European perspective, interconnectors between the SEM and France or the SEM and Spain yield the highest total savings in system cots across the considered selected countries. France and Spain are the largest beneficiaries from additional interconnectors in 2040, and in 2050 this role is shared between France and Great Britain. In fact, France is the main beneficiary across all 2050 cases. In 2040, even though the SEM does not have SEW benefits from the connection with France, the benefits to France are very large (220 mlnEUR/year).

The benefits to Great Britain in terms of SEW increase and reduction of carbon emissions are also sensible when the SEM connects to France and Spain. Likewise, as a result of large cross-border capacity between these countries, France and Spain benefit economically when the SEM connects to either of them. Thus, it is crucial that political discussions around future interconnectors between the SEM and any of the analysed selected countries involve representative from the four sides (Island of Ireland, Great Britain, France and Spain). Provided that smart agreements on cross-border cost sharing and compensation mechanisms were in place, DNV would recommend the development of interconnectors with France and Spain as economically attractive in the time period beyond 2030.

# 8 APPENDIX

## 8.1 Transmission costs background

### 1. General Background to the DNV cost estimates

The input data for the transmission equipment unit cost is taken from the DNV in-house transmission equipment database. The database is developed based on public data about the offshore wind- and interconnector projects realised in the North Sea. This primarily concerns German, Dutch and British projects. The database is continuously updated with the most recent data from newly built projects, in this way ensuring its adequacy for the latest developments.

### 2. Component specific considerations

For HVDC cables, DNV will consider two separate cables (plus and minus pole) which will be laid in parallel to connect the HVDC converter station with symmetric monopole or rigid bipole topology. A third metallic return cable will be considered if the topology of “bipole with metallic return” is selected for the HVDC converters.

For HVDC converters DNV considers half-bridge voltage source converters (HB VSC), except for the topology Option 1C, where full-bridge configuration is applied (FB VSC). For HVDC converters with identical technology, the most important technical parameters are among others the DC voltage and power rating. It is assumed that converters with identical DC voltage level and power rating will have similar costs in terms of power electronics components. It is expected that control & protection will be more complex and converter transformers will be more demanding in bipole (both rigid bipole and bipole with dedicated metallic return) topology than their counterparts in the symmetric monopole topology. Such differences will be addressed in the cost estimation. All required DC switchgear and DC busbars are included as a part of the converter costs.

The type of platform design impacts the platform cost. There are three main types of platform design: jacket, jack-up and gravity-based solution (GBS). Jacket is expected to be in the lower range of the cost interval, while jack-up and GBS design are more expensive. The platform cost increases with the water depth; a taller substructure is needed for deeper water. More complex seabed increases the installation cost. Higher wind and/or wave load increases the need for a stronger and heavier substructure. The transportation and installation costs differ depending on the installation concept.

DCCBs are relatively new components with limited installations, the cost estimation of DCCB was done in a bottom-up approach based on our understanding of the most promising solutions (mechanical DCCB).

1. Factors contributing to CAPEX

What follows shows the cost breakdown for different elements contributing to the total cost of each equipment type with their corresponding percentage. The cost elements include the cost of equipment, installation and transportation, civil works, project management, right of ways, risk contingency and profit margin. The R&D cost is also included but differs between mature technology and new technology. In this project, DNV does not include any products still under development, so the R&D portion is low. The cost is implicitly included in the cost of equipment. The cost level shown in the report is inflation-adjusted to year 2021. The project management cost is included in cost breakdown for each category by component/subsystem, as such not as separate cost items to the high-level project cost.

Below is an overview of CAPEX breakdown for primary components per category.

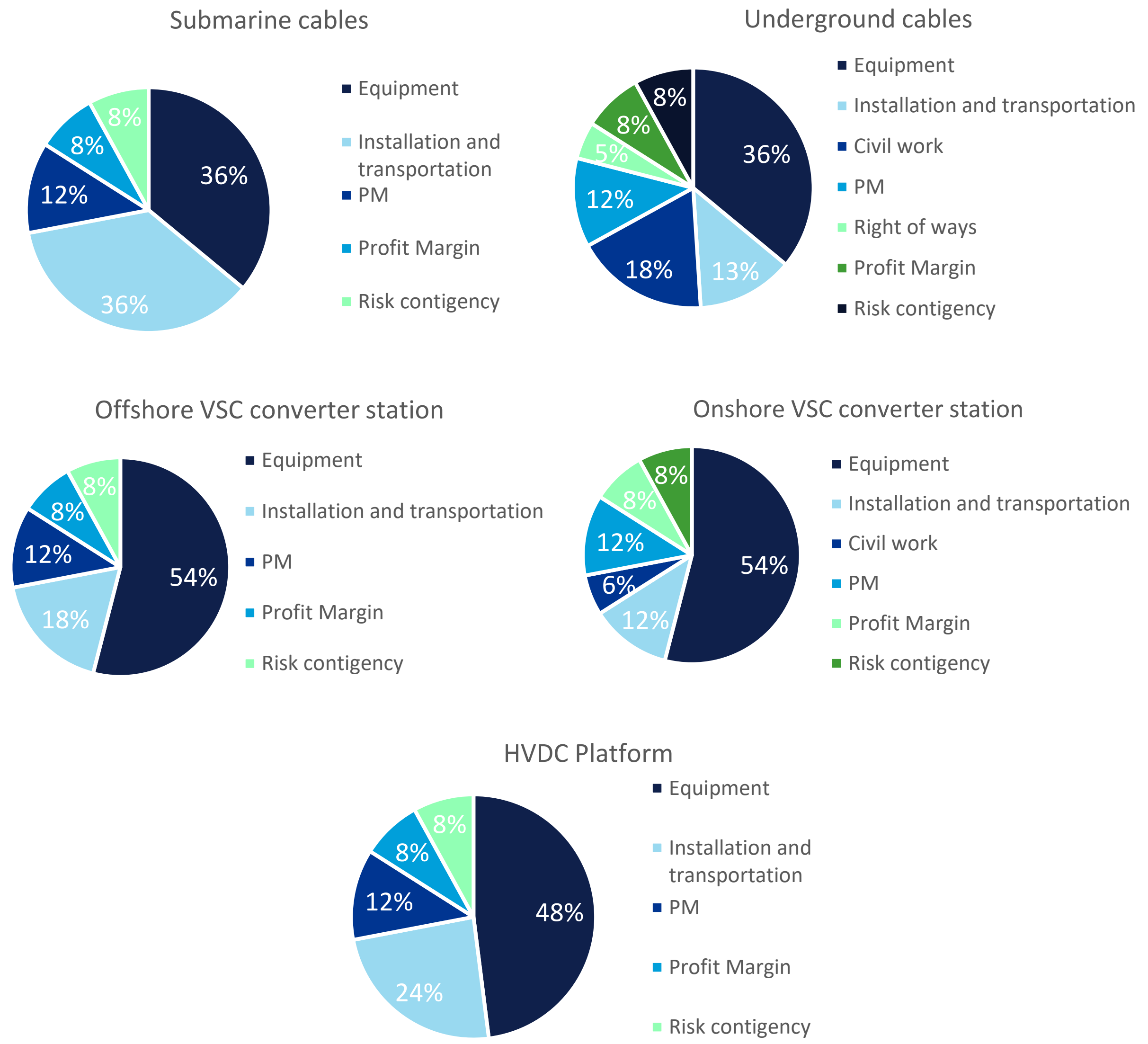

**Figure D-1 CAPEX breakdown for primary components**

### 3. Factors contributing to OPEX

OPEX cost for AC and DC systems include periodic maintenance of equipment which typically includes the following tasks:

- Scheduled maintenance of the foundation and structure
- Scheduled maintenance of the topside and electrical equipment
- Scheduled maintenance of the electrical equipment at the onshore substation
- Scheduled maintenance of cables

Costs included in OPEX are labour, spare parts, consumables, supply and accommodation vessels, crew transfer vessels or helicopter costs if applicable, travel expenses for staff and overnight accommodation, waste disposal and management.

Replacement costs are not included in the OPEX, since all major transmission equipment is designed at least for the lifetime equal to that of an offshore wind farm. The only subsystem which may need replacement is control and communication systems. Typically to be designed for 15-year lifetime. OPEX costs for the transmission equipment are defined as an annual percentage of CAPEX.

## 8.2 Data tables for the main results

### 8.2.1 CAPEX assessment

Table 8-1 Asset count for CAPEX assessment (for cables the distance in km is given, for all other equipment their number is given)

| Bill of Materials | | | | 2030 | | | 2040 Counterfactual | 2040 | | | 2050 Counterfactual | 2050 min | | | 2050 max | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | IE-GB | IE-FR | IE-ES | IE-GB | IE-GB | IE-FR | IE-ES | IE-GB | IE-GB | IE-FR | IE-ES | IE-GB | IE-FR | IE-ES |
| | MW | configuration | voltage | | | | | | | | | | | | | | |
| **HVDC Converter onshore** | 500 | monopole | 320 | 2 | | | 2 | 2 | | | 2 | 2 | | | 2 | | |
| | 750 | monopole | 320 | 2 | | | 2 | | | | 2 | | | | 2 | | |
| | 800 | monopole | 400 | | | | | 2 | | | | 2 | | | | | |
| | 900 | monopole | 400 | | | | | | | | | | | | | | 2 |
| | 1,000 | monopole | 400 | | | | | | | 2 | | | | | | 2 | 2 |
| | 1,050 | monopole | 525 | | | | | | 2 | | | | 4 | | 2 | 4 | |
| | 1,500 | bipole | 525 | | | | | | | | | | | 2 | | | |
| | 1,600 | bipole | 400 | | | | 1 | | | | 1 | | | | 1 | | |
| | 2,100 | bipole | 525 | | | | | | | | 1 | 1 | | | | | |
| **HVDC Converter offshore** | 1,600 | monopole | 400 | | | | 1 | 1 | | | 1 | 1 | | | 1 | | |
| | 2,100 | monopole | 525 | | | | | | | | 1 | 1 | | | 1 | | |
| **HVDC Platform** | 1,600 | | | | | | 1 | 1 | | | 1 | 1 | | | 1 | | |
| | 2,100 | | | | | | | | | | 1 | 1 | | | 1 | | |
| **HVDC cable (undersea pair)** | 500 | | 320 | 135 | | | 135 | 135 | | | 135 | 135 | | | 135 | | |
| | 750 | | 320 | 200 | | | 200 | | | | 200 | | | | 200 | | |
| | 800 | | 400 | | | | | 215 | | | | 215 | | | | | |
| | 900 | | 400 | | | | | | | | | | | | | | 950 |
| | 1,000 | | 400 | | | | | | | 950 | | | | | | 520 | 950 |
| | 1,050 | | 525 | | | | | | 520 | | | | 1,040 | | 215 | 1,040 | |
| | 1,500 | with DMR | 525 | | | | | | | | | | | 950 | | | |
| | 1,600 | with DMR | 400 | | | | 75 | | | | 75 | | | | 75 | | |
| | 2,100 | with DMR | 525 | | | | | | | | 75 | 75 | | | | | |

**Table 8-2 CAPEX estimates for all study cases**

| | | 2030 | 2040 | | | 2050 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *mlnEUR* | | Factual | Counterfactual | IC GB | IC FR | IC ES | Counterfactual | IC min GB | IC max GB | IC min FR | IC max FR | IC min ES | IC max ES | All min IC | All max IC |
| SEM-GB | Onshore converter | 470 | 470 | 220 | | | 470 | 220 | 470 | | | | | 220 | 470 |
| | Cable | 217 | 217 | 69 | | | 217 | 69 | 217 | | | | | 69 | 217 |
| SEM OWF | Onshore converter | - | 320 | - | | | 660 | 340 | 320 | | | | | 340 | 320 |
| | Cable | - | 113 | - | | | 240 | 127 | 113 | | | | | 127 | 113 |
| | Offshore converter | - | 317 | - | | | 788 | 471 | 317 | | | | | 471 | 317 |
| | Platform | - | 350 | - | | | 867 | 517 | 350 | | | | | 517 | 350 |
| Hybrid SEM-GB | Onshore converter | - | - | 280 | | | | 280 | 362 | | | | | 280 | 362 |
| | Cable | - | - | 133 | | | | 133 | 170 | | | | | 133 | 170 |
| | Offshore converter | - | - | 317 | | | | 317 | 471 | | | | | 317 | 471 |
| | Platform | - | - | 350 | | | | 350 | 517 | | | | | 350 | 517 |
| SEM-FR | Onshore converter | - | - | | 362 | | | | | 724 | 1,038 | | | 724 | 1,038 |
| | Cable | - | - | | 411 | | | | | 822 | 1,180 | | | 822 | 1,180 |
| SEM-ES | Onshore converter | - | - | | | 314 | | | | | | 440 | 614 | 440 | 614 |
| | Cable | - | - | | | 656 | | | | | | 1,406 | 1,283 | 1,406 | 1,283 |

**Table 8-3 CAPEX difference between factuals and counterfactual (in mlnEUR)**

| | 2030 | 2040 | | | 2050 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *mlnEUR* | Factual | IC GB | IC FR | IC ES | IC min GB | IC max GB | IC min FR | IC max FR | IC min ES | IC max ES | All min IC | All max IC |
| Onshore converter | 470 | - 290 | 362 | 314 | - 290 | 22 | 724 | 1,038 | 440 | 614 | 874 | 1,674 |
| Cable | 217 | - 128 | 411 | 656 | - 128 | 43 | 822 | 1,180 | 1,406 | 1,283 | 2,100 | 2,767 |

### 8.2.2 SEW assessment

**Table 8-4 SEW outputs for all study cases, per absolute value (CTF: counterfactual; F: factual).**

| | 2030 | | 2040 | | | | | 2050 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***mlnEUR/yr*** | **CTF** | **F** | **CTF** | **IC GB** | **IC FR** | **IC ES** | **IC All** | **CTF** | **IC min GB** | **IC max GB** | **IC min FR** | **IC max FR** | **IC min ES** | **IC max ES** | **IC min All** | **IC max All** |
| **IE** | 423 | 373 | 202 | 208 | 207 | 184 | 205 | 154 | 158 | 133 | 105 | 96 | 115 | 101 | 83 | 76 |
| **NI** | 60 | 54 | 174 | 176 | 179 | 167 | 177 | 138 | 140 | 131 | 111 | 108 | 111 | 104 | 94 | 97 |
| **GB** | 2,036 | 2,001 | 2,134 | 2,139 | 2,120 | 2,123 | 2,091 | 2,788 | 2,803 | 2,726 | 2,733 | 2,668 | 2,745 | 2,746 | 2,703 | 2,516 |
| **FR** | 3,407 | 3,397 | 5,564 | 5,550 | 5,344 | 5,441 | 5,264 | 3,854 | 3,832 | 3,811 | 3,681 | 3,631 | 3,687 | 3,685 | 3,522 | 3,424 |
| **ES** | 838 | 837 | 1,065 | 1,061 | 1,038 | 971 | 938 | 619 | 603 | 611 | 588 | 596 | 575 | 571 | 569 | 551 |
| **SEM** | **483** | **427** | **376** | **384** | **387** | **351** | **382** | **292** | **299** | **265** | **216** | **203** | **226** | **206** | **177** | **173** |
| **TOTAL** | **6,765** | **6,662** | **9,139** | **9,134** | **8,888** | **8,885** | **8,675** | **7,554** | **7,536** | **7,412** | **7,218** | **7,098** | **7,232** | **7,208** | **6,971** | **6,663** |

#### 8.2.2.1 Benefits attributed to $CO_2$ reduction assessment

**Table 8-5 Benefits attributed to $CO_2$ reduction outputs for all study cases, per absolute value (CTF: counterfactual; F: factual).**

| | 2030 | | 2040 | | | | | 2050 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***mlnEUR/yr*** | **CTF** | **F** | **CTF** | **IC GB** | **IC FR** | **IC ES** | **IC All** | **CTF** | **IC min GB** | **IC max GB** | **IC min FR** | **IC max FR** | **IC min ES** | **IC max ES** | **IC min All** | **IC max All** |
| **IE** | - | 19 | - | -2 | -2 | 6 | -3 | - | -2 | 7 | 15 | 19 | 14 | 19 | 23 | 25 |
| **NI** | - | 2 | - | 0 | -1 | 0 | -2 | - | 0 | 1 | 5 | 5 | 3 | 5 | 6 | 6 |
| **GB** | - | 8 | - | -2 | 6 | 4 | 15 | - | -7 | 18 | 14 | 41 | 16 | 17 | 27 | 90 |
| **FR** | - | 3 | - | 5 | 77 | 43 | 105 | - | 7 | 12 | 54 | 67 | 59 | 58 | 110 | 139 |
| **ES** | - | 0 | - | 2 | 11 | 35 | 49 | - | 6 | 2 | 12 | 11 | 27 | 29 | 29 | 39 |
| **SEM** | - | 21 | - | -3 | -3 | 6 | -4 | - | -2 | 9 | 20 | 23 | 16 | 23 | 29 | 31 |
| **TOTAL** | - | 33 | - | 2 | 91 | 89 | 165 | - | 4 | 41 | 101 | 142 | 119 | 127 | 195 | 299 |

#### 8.2.2.2 Benefits attributed to RES integration assessment

**Table 8-6 Benefits attributed to RES integration outputs for all study cases, per absolute value (CTF: counterfactual; F: factual).**

| | 2030 | | 2040 | | | | | 2050 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***mlnEUR/yr*** | **CTF** | **F** | **CTF** | **IC GB** | **IC FR** | **IC ES** | **IC All** | **CTF** | **IC min GB** | **IC max GB** | **IC min FR** | **IC max FR** | **IC min ES** | **IC max ES** | **IC min All** | **IC max All** |
| **IE** | - | 72 | - | 4 | 92 | 45 | 123 | - | -1 | 65 | 107 | 158 | 57 | 67 | 135 | 241 |
| **NI** | - | 16 | - | 0 | 0 | 0 | 0 | - | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **GB** | - | -2 | - | -3 | 0 | -2 | -1 | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **FR** | - | 0 | - | 0 | 0 | 0 | 0 | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **ES** | - | 1 | - | 12 | 13 | 39 | 55 | - | 8 | -1 | 1 | -4 | 18 | 18 | 17 | 26 |
| **SEM** | - | 88 | - | 4 | 92 | 45 | 123 | - | 0 | 65 | 107 | 158 | 58 | 67 | 135 | 241 |
| **TOTAL** | - | 87 | - | 13 | 105 | 82 | 176 | - | 8 | 64 | 108 | 154 | 76 | 85 | 152 | 267 |

## 8.2.3 Congestion rent assessment

**Table 8-7 Congestion rent outputs for all study cases, per absolute value (CTF: counterfactual; F: factual).**

| | 2030 | | 2040 | | | | | 2050 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***mlnEUR/yr*** | **CTF** | **F** | **CTF** | **IC GB** | **IC FR** | **IC ES** | **IC All** | **CTF** | **IC min GB** | **IC max GB** | **IC min FR** | **IC max FR** | **IC min ES** | **IC max ES** | **IC min All** | **IC max All** |
| **IE-GB** | 107 | 56 | 152 | 147 | 140 | 129 | 120 | 207 | 212 | 181 | 179 | 171 | 219 | 215 | 173 | 151 |
| **IE-GB NEW 1** | 0 | 42 | 94 | 0 | 86 | 91 | 0 | 176 | 0 | 154 | 134 | 129 | 147 | 144 | 0 | 115 |
| **NI-GB** | 61 | 32 | 80 | 78 | 74 | 70 | 65 | 128 | 129 | 112 | 97 | 92 | 118 | 116 | 94 | 82 |
| **NI-GB NEW 1** | 0 | 32 | 80 | 78 | 74 | 70 | 65 | 128 | 129 | 112 | 97 | 92 | 118 | 116 | 94 | 82 |
| **GB-IEOW NEW 1** | 0 | 0 | 0 | 75 | 0 | 0 | 69 | 0 | 139 | 0 | 0 | 0 | 0 | 0 | 129 | 0 |
| **GB-IEOW NEW 2** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 171 | 0 | 0 | 0 | 0 | 0 | 154 |
| **IE-IEOW NEW 1** | 0 | 0 | 0 | 38 | 0 | 0 | 24 | 0 | 45 | 0 | 0 | 0 | 0 | 0 | 4 | 0 |
| **IE-IEOW NEW 2** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 0 | 0 | 0 | 0 | 0 | 2 |
| **IE-FR** | 118 | 94 | 245 | 240 | 225 | 228 | 202 | 165 | 167 | 153 | 120 | 113 | 153 | 149 | 114 | 100 |
| **IE-FR NEW 1** | 0 | 0 | 0 | 0 | 328 | 0 | 316 | 0 | 0 | 0 | 185 | 170 | 0 | 0 | 175 | 154 |
| **IE-FR NEW 2** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 178 | 165 | 0 | 0 | 166 | 147 |
| **IE-FR NEW 3** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 161 | 0 | 0 | 0 | 144 |
| **IE-ES NEW 1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 233 | 0 | 174 | 0 |
| **IE-ES NEW 2** | 0 | 0 | 0 | 0 | 0 | 248 | 232 | 0 | 0 | 0 | 0 | 0 | 0 | 146 | 0 | 109 |
| **IE-ES NEW 3** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 133 | 0 | 102 |
| **Hybrid SEM-GB TOTAL** | 0 | 0 | 0 | 113 | 0 | 0 | 93 | 0 | 183 | 183 | 0 | 0 | 0 | 0 | 132 | 156 |
| **SEM-GB TOTAL** | 168 | 162 | 405 | 304 | 374 | 360 | 250 | 638 | 470 | 559 | 506 | 485 | 601 | 591 | 361 | 431 |
| **SEM-FR TOTAL** | 118 | 94 | 245 | 240 | 554 | 228 | 519 | 165 | 167 | 153 | 483 | 609 | 153 | 149 | 455 | 545 |
| **SEM-ES TOTAL** | 0 | 0 | 0 | 0 | 0 | 248 | 232 | 0 | 0 | 0 | 0 | 0 | 233 | 279 | 174 | 210 |
| **TOTAL SEM** | **286** | **256** | **651** | **657** | **928** | **835** | **1,093** | **803** | **820** | **895** | **989** | **1,094** | **987** | **1,018** | **1,122** | **1,342** |

## 8.2.4 RES curtailment assessment

Table 8-8 RES curtailment outputs for all study cases, per absolute value (CTF: counterfactual; F: factual).

| | 2030 | | 2040 | | | | | 2050 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***GWh/yr*** | **CTF** | **F** | **CTF** | **IC GB** | **IC FR** | **IC ES** | **IC All** | **CTF** | **IC min GB** | **IC max GB** | **IC min FR** | **IC max FR** | **IC min ES** | **IC max ES** | **IC min All** | **IC max All** |
| **IE** | 8,050 | 6,218 | 34,159 | 33,974 | 29,857 | 31,430 | 27,248 | 82,286 | 82,359 | 77,518 | 72,200 | 67,540 | 77,693 | 76,895 | 67,884 | 58,475 |
| **NI** | 952 | 548 | 28 | 24 | 30 | 34 | 17 | 58 | 11 | 21 | 24 | 56 | 23 | 59 | 64 | 37 |
| **GB** | 1,236 | 1,277 | 4,674 | 4,775 | 4,682 | 4,753 | 4,709 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **FR** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **ES** | 1,680 | 1,667 | 94,829 | 94,395 | 94,348 | 93,431 | 92,833 | 112,249 | 111,605 | 112,330 | 112,184 | 112,563 | 110,688 | 110,617 | 110,689 | 109,758 |
| **SEM** | 9,003 | 6,766 | 34,187 | 33,998 | 29,887 | 31,464 | 27,266 | 82,344 | 82,370 | 77,539 | 72,225 | 67,596 | 77,716 | 76,954 | 67,947 | 58,512 |
| **TOTAL** | 11,919 | 9,711 | 133,690 | 133,168 | 128,917 | 129,648 | 124,808 | 194,593 | 193,975 | 189,869 | 184,409 | 180,159 | 188,404 | 187,571 | 178,636 | 168,270 |

## 8.2.5 Carbon emission reduction assessment

Table 8-9 Carbon emission outputs for all study cases, per absolute value (CTF: counterfactual; F: factual).

| | 2030 | | 2040 | | | | | 2050 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***ktonne $CO_2$/yr*** | **CTF** | **F** | **CTF** | **IC GB** | **IC FR** | **IC ES** | **IC All** | **CTF** | **IC min GB** | **IC max GB** | **IC min FR** | **IC max FR** | **IC min ES** | **IC max ES** | **IC min All** | **IC max All** |
| **IE** | 1,563 | 1,357 | 538 | 562 | 557 | 480 | 564 | 354 | 368 | 292 | 225 | 197 | 238 | 197 | 160 | 139 |
| **NI** | 171 | 147 | 44 | 48 | 53 | 46 | 60 | 71 | 71 | 60 | 29 | 31 | 48 | 32 | 19 | 23 |
| **GB** | 3,630 | 3,539 | 3,707 | 3,726 | 3,649 | 3,666 | 3,566 | 5,314 | 5,372 | 5,162 | 5,195 | 4,968 | 5,177 | 5,171 | 5,089 | 4,555 |
| **FR** | 1,333 | 1,297 | 13,186 | 13,140 | 12,447 | 12,769 | 12,173 | 6,045 | 5,989 | 5,940 | 5,584 | 5,479 | 5,543 | 5,556 | 5,110 | 4,866 |
| **ES** | 1,651 | 1,646 | 3,437 | 3,415 | 3,331 | 3,100 | 2,962 | 1,276 | 1,229 | 1,255 | 1,172 | 1,180 | 1,048 | 1,028 | 1,030 | 946 |
| **SEM** | 1,734 | 1,504 | 582 | 610 | 610 | 526 | 624 | 425 | 438 | 352 | 254 | 228 | 286 | 229 | 178 | 162 |
| **TOTAL** | 8,349 | 7,986 | 20,912 | 20,890 | 20,038 | 20,061 | 19,325 | 13,060 | 13,029 | 12,709 | 12,205 | 11,856 | 12,053 | 11,983 | 11,408 | 10,529 |

### 8.2.5.1 Additional societal benefit due to $CO_2$ emissions reduction assessment

Table 8-10 Additional societal benefit due to $CO_2$ reduction outputs for all study cases, per absolute value (CTF: counterfactual; F: factual).

| | 2030 | | 2040 | | | | | 2050 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***mlnEUR/yr*** | **CTF** | **F** | **CTF** | **IC GB** | **IC FR** | **IC ES** | **IC All** | **CTF** | **IC min GB** | **IC max GB** | **IC min FR** | **IC max FR** | **IC min ES** | **IC max ES** | **IC min All** | **IC max All** |
| **IE** | - | 2 | | -4 | -3 | 10 | -4 | - | -2 | 9 | 19 | 24 | 17 | 24 | 29 | 32 |
| **NI** | - | 0 | | -1 | -2 | 0 | -3 | - | 0 | 2 | 6 | 6 | 4 | 6 | 8 | 7 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **GB** | - | 1 | | -3 | 10 | 7 | 23 | - | -9 | 23 | 18 | 52 | 21 | 21 | 34 | 115 |
| **FR** | - | 0 | | 8 | 122 | 69 | 167 | - | 8 | 16 | 69 | 85 | 76 | 74 | 141 | 178 |
| **ES** | - | 0 | | 4 | 17 | 56 | 78 | - | 7 | 3 | 16 | 14 | 34 | 37 | 37 | 50 |
| **SEM** | - | 2 | 0 | -5 | -5 | 9 | -7 | - | -2 | 11 | 26 | 30 | 21 | 30 | 37 | 40 |
| **TOTAL** | - | 3 | 0 | 4 | 144 | 140 | 262 | - | 5 | 53 | 129 | 182 | 152 | 162 | 249 | 382 |

## 8.2.6 Interconnector utilization assessment

**Table 8-11 Interconnector utilization outputs for all study cases, per absolute value (CTF: counterfactual; F: factual).**

| | 2030 | | 2040 | | | | | 2050 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **%** | **CTF** | **F** | **CTF** | **IC GB** | **IC FR** | **IC ES** | **IC All** | **CTF** | **IC min GB** | **IC max GB** | **IC min FR** | **IC max FR** | **IC min ES** | **IC max ES** | **IC min All** | **IC max All** |
| **IE-GB** | 67 | 58 | 69 | 70 | 67 | 68 | 68 | 83 | 84 | 82 | 80 | 78 | 82 | 81 | 80 | 78 |
| **IE-GB NEW 1** | | 34 | 69 | | 68 | 69 | | 82 | | 81 | 81 | 79 | 82 | 82 | | 78 |
| **GB-IEOW NEW 1** | | | | 63 | | | 60 | | 77 | | | | | | 77 | |
| **GB-IEOW NEW 2** | | | | | | | | | | 74 | | | | | | 72 |
| **IE-IEOW NEW 1** | | | | 25 | | | 26 | | 22 | | | | | | 19 | |
| **IE-IEOW NEW 2** | | | | | | | | | | 19 | | | | | | 17 |
| **NI-GB** | 74 | 55 | 80 | 81 | 79 | 80 | 80 | 90 | 91 | 89 | 89 | 87 | 91 | 91 | 89 | 86 |
| **NI-GB NEW 1** | | 61 | 80 | 82 | 79 | 80 | 80 | 90 | 91 | 89 | 90 | 88 | 91 | 91 | 90 | 86 |
| **IE-FR** | 75 | 72 | 83 | 84 | 81 | 82 | 80 | 85 | 85 | 84 | 81 | 78 | 84 | 84 | 80 | 77 |
| **IE-FR NEW 1** | | | | | 81 | | 81 | | | | 82 | 79 | | | 81 | 78 |
| **IE-FR NEW 2** | | | | | | | | | | | 80 | 78 | | | 79 | 77 |
| **IE-FR NEW 3** | | | | | | | | | | | | 80 | | | | 79 |
| **IE-ES NEW 1** | | | | | | | | | | | | | 66 | | 67 | |
| **IE-ES NEW 2** | | | | | | 71 | 71 | | | | | | | 65 | | 68 |
| **IE-ES NEW 3** | | | | | | | | | | | | | | 65 | | 67 |
| **AVERAGE SEM** | 71 | 56 | 75 | 65 | 75 | 74 | 67 | 85 | 73 | 70 | 82 | 80 | 79 | 78 | 72 | 70 |
| **AVERAGE** | 72 | 56 | 76 | 67 | 76 | 75 | 68 | 86 | 75 | 74 | 83 | 81 | 83 | 80 | 74 | 72 |

## 8.2.7 Fuel mix assessment

**Table 8-12 Fuel mix outputs for all study cases, per absolute value (CTF: counterfactual; F: factual).**

| | | 2030 | | 2040 | | | | | 2050 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***TWh/yr*** | | **CTF** | **F** | **CTF** | **IC GB** | **IC FR** | **IC ES** | **IC All** | **CTF** | **IC min GB** | **IC max GB** | **IC min FR** | **IC max FR** | **IC min ES** | **IC max ES** | **IC min All** | **IC max All** |
| SEM | Biomass | 1.1 | 1.1 | 7.3 | 7.4 | 7.4 | 7.1 | 7.3 | 5.8 | 5.9 | 5.7 | 5.3 | 5.1 | 4.9 | 4.9 | 4.8 | 4.9 |
| | Natural gas | 5.2 | 4.5 | 1.7 | 1.8 | 1.8 | 1.6 | 1.9 | 1.3 | 1.3 | 1.0 | 0.8 | 0.7 | 0.8 | 0.7 | 0.5 | 0.5 |
| | Solar | 4.7 | 4.9 | 5.9 | 6.0 | 6.1 | 6.0 | 6.2 | 6.6 | 6.6 | 6.8 | 6.9 | 7.1 | 6.7 | 6.6 | 7.0 | 7.3 |
| | Nuclear | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Hydro | 1.5 | 1.6 | 1.3 | 1.3 | 1.4 | 1.3 | 1.4 | 1.1 | 1.1 | 1.1 | 1.1 | 1.2 | 1.1 | 1.1 | 1.1 | 1.1 |
| | Waste | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Marine | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Non-RES | 0.0 | 0.0 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | LFO | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Onshore wind | 25.0 | 25.9 | 22.3 | 23.2 | 23.6 | 23.1 | 26.1 | 20.6 | 21.0 | 21.5 | 21.9 | 22.7 | 21.1 | 21.5 | 23.2 | 25.0 |
| | Offshore wind | 17.1 | 18.2 | 75.3 | 74.5 | 78.1 | 77.2 | 78.1 | 124.4 | 123.9 | 128.2 | 133.0 | 136.6 | 128.5 | 128.9 | 135.8 | 143.2 |
| Total | Biomass | 42.3 | 42.1 | 38.6 | 38.6 | 38.9 | 38.4 | 38.4 | 31.4 | 31.4 | 30.9 | 30.3 | 30.1 | 30.2 | 30.0 | 29.5 | 28.7 |
| | Natural gas | 18.0 | 16.9 | 51.1 | 51.1 | 48.6 | 48.8 | 46.9 | 32.6 | 32.4 | 31.6 | 30.1 | 29.3 | 30.6 | 30.6 | 28.7 | 26.6 |
| | Solar | 162.6 | 162.7 | 423.8 | 424.4 | 424.9 | 425.1 | 425.7 | 573.6 | 574.9 | 574.4 | 574.1 | 574.5 | 574.9 | 574.8 | 575.6 | 576.4 |
| | Nuclear | 412.6 | 412.1 | 254.7 | 254.7 | 254.5 | 254.6 | 254.6 | 326.5 | 326.0 | 324.8 | 323.0 | 321.3 | 325.8 | 325.2 | 322.1 | 319.0 |
| | Hydro | 150.2 | 150.2 | 157.1 | 157.2 | 157.3 | 157.5 | 157.6 | 156.3 | 156.5 | 156.3 | 156.4 | 156.5 | 156.0 | 155.8 | 155.8 | 155.8 |
| | Waste | 10.0 | 10.1 | 17.9 | 17.8 | 17.8 | 17.6 | 17.2 | 10.7 | 10.8 | 10.5 | 10.5 | 10.1 | 9.1 | 8.7 | 9.1 | 8.1 |
| | Marine | 1.7 | 1.7 | 9.1 | 9.1 | 9.1 | 9.1 | 9.1 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 |
| | Non-RES | 0.0 | 0.0 | 5.3 | 5.3 | 5.2 | 5.3 | 5.2 | 2.7 | 2.6 | 2.6 | 2.5 | 2.4 | 2.6 | 2.5 | 2.4 | 2.2 |
| | LFO | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Onshore wind | 275.0 | 276.0 | 330.8 | 331.5 | 331.5 | 331.6 | 335.0 | 391.0 | 390.7 | 391.1 | 392.1 | 392.3 | 391.7 | 392.4 | 393.5 | 395.7 |
| | Offshore wind | 244.7 | 245.8 | 527.6 | 527.0 | 530.6 | 529.6 | 530.5 | 648.7 | 648.3 | 652.5 | 657.3 | 660.9 | 652.9 | 653.2 | 660.2 | 667.6 |

## 8.3 Data tables for the sensitivities

### 8.3.1 SEW assessment

Table 8-13 SEW outputs for all study cases, per absolute value (CTF: counterfactual).

| | 2050 | | | | | |
|---|---|---|---|---|---|---|
| *mlnEUR/yr* | IC CTF lowRES-SEM | IC min All lowRES-SEM | IC max All lowRES-SEM | IC CTF FR LTO | IC min FR LTO | IC max FR LTO |
| **IE** | 259 | 136 | 133 | 152 | 94 | 76 |
| **NI** | 200 | 131 | 130 | 131 | 102 | 92 |
| **GB** | 2,769 | 2,668 | 2,544 | 2,529 | 2,457 | 2,440 |
| **FR** | 3,854 | 3,618 | 3,535 | 3,497 | 3,372 | 3,309 |
| **ES** | 618 | 601 | 597 | 528 | 510 | 497 |
| **SEM** | **459** | **266** | **263** | **283** | **196** | **169** |
| **TOTAL** | **7,700** | **7,154** | **6,939** | **6,837** | **6,535** | **6,415** |

#### 8.3.1.1 Benefits attributed to $CO_2$ reduction assessment

Table 8-14 Benefits attributed to $CO_2$ reduction outputs for all study cases, per absolute value (CTF: counterfactual).

| | 2050 | | | | | |
|---|---|---|---|---|---|---|
| *mlnEUR/yr* | IC CTF lowRES-SEM | IC min All lowRES-SEM | IC max All lowRES-SEM | IC CTF FR LTO | IC min FR LTO | IC max FR LTO |
| **IE** | - | 37 | 38 | - | 18 | 24 |
| **NI** | - | 11 | 10 | - | 5 | 5 |
| **GB** | - | 29 | 67 | - | 25 | 28 |
| **FR** | - | 78 | 101 | - | 36 | 52 |
| **ES** | - | 14 | 16 | - | 7 | 12 |
| **SEM** | - | 48 | 48 | - | 23 | 29 |
| **TOTAL** | - | 169 | 232 | - | 90 | 120 |

#### 8.3.1.2 Benefits attributed to RES integration assessment

Table 8-15 Benefits attributed to RES integration outputs for all study cases, per absolute value (CTF: counterfactual).

| | 2050 | | | | | |
|---|---|---|---|---|---|---|
| *mlnEUR/yr* | IC CTF lowRES-SEM | IC min All lowRES-SEM | IC max All lowRES-SEM | IC CTF FR LTO | IC min FR LTO | IC max FR LTO |
| **IE** | - | 164 | 279 | - | 96 | 134 |
| **NI** | - | 0 | 0 | - | 0 | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **GB** | - | 0 | 0 | - | 0 | 0 |
| **FR** | - | 0 | 0 | - | 0 | 0 |
| **ES** | - | 24 | 42 | - | -2 | 4 |
| **SEM** | - | 164 | 279 | - | 96 | 133 |
| **TOTAL** | - | 188 | 322 | - | 94 | 138 |

## 8.3.2 Congestion rent assessment

**Table 8-16 Congestion rent outputs for all study cases, per absolute value (CTF: counterfactual).**

| | 2050 | | | | | |
|---|---|---|---|---|---|---|
| *mlnEUR/yr* | IC CTF lowRES-SEM | IC min All lowRES-SEM | IC max All lowRES-SEM | IC CTF FR LTO | IC min FR LTO | IC max FR LTO |
| **IE-GB** | 253 | 154 | 120 | 220 | 162 | 148 |
| **IE-GB NEW 1** | 160 | 0 | 91 | 144 | 0 | 114 |
| **NI-GB** | 137 | 84 | 65 | 118 | 88 | 81 |
| **NI-GB NEW 1** | 137 | 84 | 65 | 118 | 88 | 81 |
| **GB-IEOW NEW 1** | 0 | 111 | 0 | 0 | 0 | 0 |
| **GB-IEOW NEW 2** | 0 | 0 | 122 | 0 | 0 | 0 |
| **IE-IEOW NEW 1** | 0 | 11 | 0 | 0 | 0 | 0 |
| **IE-IEOW NEW 2** | 0 | 0 | 7 | 0 | 0 | 0 |
| **IE-FR** | 177 | 103 | 82 | 143 | 102 | 90 |
| **IE-FR NEW 1** | 0 | 158 | 126 | 0 | 155 | 135 |
| **IE-FR NEW 2** | 0 | 152 | 122 | 0 | 149 | 130 |
| **IE-FR NEW 3** | 0 | 0 | 119 | 0 | 0 | 128 |
| **IE-ES NEW 1** | 0 | 200 | 0 | 0 | 0 | 0 |
| **IE-ES NEW 2** | 0 | 0 | 120 | 0 | 0 | 0 |
| **IE-ES NEW 3** | 0 | 0 | 112 | 0 | 0 | 0 |
| **Hybrid SEM-GB TOTAL** | 0 | 122 | 128 | 0 | 0 | 0 |
| **SEM-GB TOTAL** | 686 | 323 | 342 | 600 | 338 | 424 |
| **SEM-FR TOTAL** | 177 | 413 | 448 | 143 | 406 | 483 |
| **SEM-ES TOTAL** | 0 | 200 | 232 | 0 | 0 | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **TOTAL SEM** | **863** | **1,058** | **1,151** | **742** | **744** | **906** |

## 8.3.3 RES curtailment assessment

**Table 8-17 RES curtailment outputs for all study cases, per absolute value (CTF: counterfactual).**

| | 2050 | | | | | |
|---|---|---|---|---|---|---|
| ***GWh/yr*** | **IC CTF lowRES-SEM** | **IC min All lowRES-SEM** | **IC max All lowRES-SEM** | **IC CTF FR LTO** | **IC min FR LTO** | **IC max FR LTO** |
| **IE** | 43,661 | 32,110 | 25,290 | 82,383 | 72,215 | 67,536 |
| **NI** | 0 | 0 | 0 | 43 | 22 | 59 |
| **GB** | 0 | 0 | 0 | 0 | 0 | 0 |
| **FR** | 0 | 0 | 0 | 0 | 0 | 0 |
| **ES** | 112,045 | 109,971 | 108,260 | 112,058 | 112,247 | 111,623 |
| **SEM** | 43,662 | 32,110 | 25,290 | 82,426 | 72,237 | 67,595 |
| **TOTAL** | 155,707 | 142,081 | 133,550 | 194,484 | 184,484 | 179,218 |

## 8.3.4 Carbon emission reduction assessment

**Table 8-18 Carbon emission outputs for all study cases, per absolute value (CTF: counterfactual).**

| | 2050 | | | | | |
|---|---|---|---|---|---|---|
| ***ktonne$CO_2$/yr*** | **IC CTF lowRES-SEM** | **IC min All lowRES-SEM** | **IC max All lowRES-SEM** | **IC CTF FR LTO** | **IC min FR LTO** | **IC max FR LTO** |
| **IE** | 636 | 322 | 314 | 349 | 197 | 142 |
| **NI** | 142 | 50 | 53 | 65 | 26 | 25 |
| **GB** | 5,232 | 4,988 | 4,665 | 4,521 | 4,306 | 4,285 |
| **FR** | 5,999 | 5,342 | 5,143 | 4,141 | 3,839 | 3,704 |
| **ES** | 1,276 | 1,155 | 1,143 | 889 | 830 | 788 |
| **SEM** | 778 | 372 | 367 | 414 | 223 | 168 |
| **TOTAL** | 13,285 | 11,857 | 11,318 | 9,964 | 9,199 | 8,945 |

### 8.3.4.1 Additional societal benefit due to $CO_2$ emissions reduction assessment

**Table 8-19 Additional societal benefit due to $CO_2$ reduction outputs for all study cases, per absolute value (CTF: counterfactual).**

| | 2050 | | | | | |
|---|---|---|---|---|---|---|
| ***mlnEUR/yr*** | **IC CTF lowRES-SEM** | **IC min All lowRES-SEM** | **IC max All lowRES-SEM** | **IC CTF FR LTO** | **IC min FR LTO** | **IC max FR LTO** |
| **IE** | - | 47 | 49 | - | 23 | 31 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **NI** | - | 14 | 13 | - | 6 | 6 |
| **GB** | - | 37 | 86 | - | 32 | 36 |
| **FR** | - | 99 | 129 | - | 46 | 66 |
| **ES** | - | 18 | 20 | - | 9 | 15 |
| **SEM** | - | 61 | 62 | - | 29 | 37 |
| **TOTAL** | - | 215 | 297 | - | 116 | 154 |

## 8.3.5 Interconnector utilization assessment

**Table 8-20 Interconnector utilization outputs for all study cases, per absolute value (CTF: counterfactual).**

| | 2050 | | | | | |
|---|---|---|---|---|---|---|
| **%** | **IC CTF lowRES-SEM** | **IC min All lowRES-SEM** | **IC max All lowRES-SEM** | **IC CTF FR LTO** | **IC min FR LTO** | **IC max FR LTO** |
| **IE-GB** | 80 | 78 | 74 | 82 | 80 | 80 |
| **IE-GB NEW 1** | 82 | | 74 | 83 | | 81 |
| **GB-IEOW NEW 1** | | 73 | | | | |
| **GB-IEOW NEW 2** | | | 68 | | | |
| **IE-IEOW NEW 1** | | 25 | | | | |
| **IE-IEOW NEW 2** | | | 21 | | | |
| **NI-GB** | 88 | 86 | 81 | 91 | 90 | 87 |
| **NI-GB NEW 1** | 88 | 87 | 81 | 91 | 90 | 88 |
| **IE-FR** | 83 | 77 | 74 | 85 | 81 | 79 |
| **IE-FR NEW 1** | | 78 | 75 | | 82 | 79 |
| **IE-FR NEW 2** | | 77 | 74 | | 80 | 78 |
| **IE-FR NEW 3** | | | 76 | | | 80 |
| **IE-ES NEW 1** | | 70 | | | | |
| **IE-ES NEW 2** | | | 71 | | | |
| **IE-ES NEW 3** | | | 71 | | | |
| **AVERAGE SEM** | 83 | 71 | 69 | 86 | 83 | 81 |
| **AVERAGE** | 84 | 72 | 70 | 87 | 84 | 81 |

## 8.3.6 Fuel mix assessment

**Table 8-21 Fuel mix outputs for all study cases, per absolute value (CTF: counterfactual).**

| | | 2050 | | | | | |
|---|---|---|---|---|---|---|---|
| *TWh/yr* | | IC CTF lowRES-SEM | IC min All lowRES-SEM | IC max All lowRES-SEM | IC CTF FR LTO | IC min FR LTO | IC max FR LTO |
| SEM | Biomass | 7.5 | 6.0 | 5.9 | 5.6 | 4.9 | 4.6 |
| | Natural gas | 2.3 | 1.1 | 1.1 | 1.2 | 0.7 | 0.5 |
| | Solar | 6.1 | 6.4 | 6.7 | 6.6 | 6.9 | 7.1 |
| | Nuclear | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Hydro | 1.2 | 1.2 | 1.3 | 1.1 | 1.1 | 1.2 |
| | Waste | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Marine | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Non-RES | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 |
| | LFO | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Onshore wind | 20.6 | 24.5 | 28.0 | 20.6 | 21.9 | 22.6 |
| | Offshore wind | 116.8 | 124.1 | 127.1 | 124.3 | 132.9 | 136.6 |
| Total | Biomass | 33.9 | 31.1 | 30.2 | 29.4 | 28.4 | 27.5 |
| | Natural gas | 32.9 | 29.6 | 28.3 | 25.0 | 23.0 | 22.3 |
| | Solar | 573.1 | 575.2 | 577.4 | 573.8 | 574.0 | 576.0 |
| | Nuclear | 328.9 | 324.9 | 321.5 | 359.9 | 355.8 | 353.6 |
| | Hydro | 156.1 | 155.0 | 155.0 | 156.4 | 156.3 | 156.2 |
| | Waste | 11.2 | 9.7 | 9.3 | 7.8 | 7.4 | 7.4 |
| | Marine | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 |
| | Non-RES | 2.8 | 2.5 | 2.4 | 1.8 | 1.7 | 1.6 |
| | LFO | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Onshore wind | 391.1 | 395.4 | 398.7 | 390.9 | 392.2 | 391.8 |
| | Offshore wind | 641.1 | 648.4 | 651.5 | 648.6 | 657.2 | 660.9 |

## About DNV

DNV is the independent expert in risk management and assurance, operating in more than 100 countries. Through its broad experience and deep expertise DNV advances safety and sustainable performance, sets industry benchmarks, and inspires and invents solutions.

Whether assessing a new ship design, optimizing the performance of a wind farm, analyzing sensor data from a gas pipeline or certifying a food company’s supply chain, DNV enables its customers and their stakeholders to make critical decisions with confidence.

Driven by its purpose, to safeguard life, property, and the environment, DNV helps tackle the challenges and global transformations facing its customers and the world today and is a trusted voice for many of the world’s most successful and forward-thinking companies.