# ESO analysis to support Ofgem's Third Cap and Floor Window and MPI Pilot Regulatory Framework

August 2022

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# Executive Summary

Ahead of the third interconnector investment round, Ofgem requested that the ESO provide future-facing analysis on the system need for, and potential impact of, future interconnection, from a system operability perspective, in different geographical regions. Ofgem have additionally asked the ESO to consider where additional interconnection might reduce the need for system reinforcement and which technologies might enable more interconnection. This report details the findings of our analysis, and, where possible, the findings are summarised in red, amber, green status (RAG).

## Interconnector geographic location and import/export flow mixture are critical to the impact on constraint costs

The economic modelling undertaken for this report has examined system, thermal, voltage and stability constraints. The modelling also tested substation/entry point locations around GB whilst not making assumptions for the connecting country. Broadly, under the existing market regime, the results show:

- The geographic location of the interconnector is critical to determining whether it will increase or decrease constraint costs on the GB system
- The import and export flow across the interconnector is also critical to determining whether it will increase or decrease constraint costs on the GB system
- When the interconnector is located in the Midlands and the South of England, except for export levels greater than 80%, constraint costs relative to the counterfactual (no additional interconnector) are reduced, as the interconnector is supplying to areas of high demand and less electricity is required to flow from North to South, leading to reduced balancing actions
- When the interconnector is connected in Scotland and North Wales, except for export levels greater than 80% of the time, constraint costs relative to the counterfactual are increased, as additional flows drive more balancing actions in regions of the network with limited available capacity
- When the interconnector is connected in Scotland, for cases with export levels greater than 80%, the interconnector is reducing constraints by exporting high levels of renewable generation

The ESO's Future Energy Scenarios (FES) show an increase in exports from GB to connecting countries in the future.  This reflects the shift from import to export as increasing levels of renewable generation is connected to the GB market. At this point in time we are unable to say whether export levels on future interconnectors connecting in Scotland or North Wales will be sufficiently high or low to result in lower or higher national constraint costs respectively. In addition, future changes to the wholesale electricity price, brought about by the implementation of locational market pricing, could change the import-export balance.

An analysis of short circuit level (SCL) on the network shows that the highest capacity available for HVDC interconnector connection is at substations in Northwest England, North Wales and Southeast England. The lowest availability of capacity for HVDC interconnector connection is in the Southwest Scotland and Northeast Scotland.

In addition to new modelling, this report summarises the potential benefits and challenges of additional interconnectors from an operational perspective and highlights some of the other work that the ESO is undertaking with respect to interconnectors. For example the ESO is working on an interconnector policy review entitled *Future of Interconnectors* which will cover many of the topics covered in this report in more detail.

## Operational challenges will increase as more interconnectors connect, but these may be mitigated by potential market and regulatory changes

As the number of interconnectors connecting to the network has increased, this has brought about new operational challenges for the ESO. Although regulations are in place aiming to harmonise cross border trade, there are gaps that can complicate operations, for example where interconnectors do not or are unable to offer a within day capacity trading platform from the start of operations. Also, commercial arrangements are negotiated between NGESO, the interconnector and the relevant EUTSO on an individual basis meaning that the lack of mandatory code requirements and differences in regulation across borders can lead to some interconnectors being more flexible than others. This has an impact on local balancing and system constraints.

Interconnectors will play an important supporting role in achieving net zero by 2050, contributing to security of supply and providing flexibility. To achieve this, the levels of interconnection capacity on the GB network will increase considerably, from 8GW currently (with ElecLink having commenced operations in late May 2022) to potentially 28GW as found in the FES21 Leading the Way scenario. This is in line with the commitment BEIS made in 2020 to work with Ofgem and developers to realise at least 18GW of interconnector capacity by 2030.

As the level of interconnection capacity increases in the future, the challenges in operating the system will increase. It is important that the ESO has the right suite of market and operational tools, cross border arrangements and supporting systems in place to ensure the ESO can balance the system efficiently.

New interconnection can increase or decrease operational balancing costs, but potential increases may be mitigated by a range of market and regulatory changes, such as:

- additional obligations on interconnectors to provide within-day trading platforms on commencement of operations. The range of market tools interconnectors currently used varies from one interconnector to another. Increased standardisation of tools will enable the ESO to minimise balancing costs
- work currently ongoing to develop market based and transparent cross border trading tools. The ESO’s ability to reliably trade capacity over interconnectors requires established, liquid and competitive commercial markets to enable it to trade at market reflective prices and to ensure trades are not easily unwound by other market participants
- changes to the wholesale market, such as a move from national pricing to zonal or nodal pricing, which are discussed in the Department for Business, Energy and Industrial Strategy's (BEIS) Review of Electricity Market Arrangement (REMA) consultation[1]. Nodal or zonal pricing has the potential to resolve operational issues and to deliver significant consumer benefits through facilitating efficient dispatch of generation, demand and flexible assets, and optimising siting decisions across the whole electricity system

## Interconnectors can be a key component in maintaining system operability

Interconnectors are technically a flexible and capable asset with significant potential for consumer benefit. Interconnectors are increasingly becoming a key source of flexibility on the electricity system and in the future will constitute a significant portion of the overall supply and demand mix. Accessing flexibility and ancillary services on interconnectors will become key for maintaining system operability. Work is underway within the ESO to maximise the potential benefits that interconnectors can provide. This will ensure future interconnectors are incentivised to participate in ancillary service markets.

Interconnectors could make material contributions to system services, system operability and markets if appropriate design decisions are made and implemented with respect to DC conversion equipment and control systems. The Grid Forming Capability modification (Grid Code GC0137) aims to enhance the capability of conventional power electronic converter plant (e.g. wind farms, HVDC interconnectors and solar parks), so that the plant responds more like a traditional synchronous plant and is able to offer an additional grid stability service,

## Looking ahead

The ESO has a range of ongoing projects to ensure it has the right tools and systems in place to ensure we can continue to balance the system effectively and efficiently as we transition to a zero-carbon electricity system. These projects will cover future interconnector technology, evolution of markets, development of ancillary services, cross-border balancing tools and new balancing systems

[1] https://www.gov.uk/government/consultations/review-of-electricity-market-arrangements

and architecture, as well as many other areas. The work that the ESO is undertaking in these workstreams is likely to feed into future cap and floor windows.

## Scope of Report

This report focuses on new locational modelling as well as considering operational challenges and opportunities. Several ongoing workstreams are briefly mentioned, which may shape the development of subsequent future windows.

The following section shows Ofgem’s requirements for the report (black text) and our response (orange text).

Future-facing analysis on the system need for, and potential impact of, future interconnectors, from a system operability perspective, in different geographical regions.

**We have** obtained input from all relevant parts of the ESO to ensure a broad consensus view on near-term interconnector developments

**We have** carried out regional analysis examining the economic impact of additional interconnection over that assumed in FES2021

**We have** reviewed the findings and discussed operational experiences with ESO control room experts

**We have not** assessed the potential impact of the recent announcements on the UK Energy Strategy or the increased probability of changes in the direction of European energy policy

**We have not included** the potential impact of the delivery of the Holistic Network Design (HND) that NGESO are undertaking as part of the Department for Business, Energy and Industrial Strategy's (BEIS) Offshore Transmission Network Review (OTNR)

**We have not** discussed system charging in this report due to ongoing workstreams and the complex nature of this topic

Consideration of where additional interconnection might reduce the need for system reinforcement

**We have** assessed system reinforcement needs through economic analysis and discussion of these results with ESO experts

**We have not** carried out a full and detailed analysis of every possible permutation of interconnector timing, technical specification and location. We would expect this to be undertaken as part of the Needs Case Assessment for individual interconnector projects

# Background

Additional interconnection to GB can provide economic and environmental benefit for GB and Europe and is a critical component to achieving net zero by 2050. Interconnectors will have a key role to play in balancing the GB system as increasing levels of variable renewable generation such as offshore wind are connected. Interconnectors provide greater security of supply as both connected markets can access diverse sources of generation to secure their energy needs. They can provide greater access to renewable energy – such as surplus intermittent generation from other countries. They also can maximise competition-related benefits – giving more consumers access to more generation and allowing participants in both markets to benefit financially by transferring electricity when at its cheapest.

Interconnectors are increasingly becoming a key source of flexibility on the electricity system and in the future will constitute a significant portion of the overall generation mix. Interconnectors are already able to participate in ancillary services and other commercial services if they choose to do so. Accessing flexibility and ancillary services on interconnectors will become key for maintaining system operability and also as an important pillar in the ESO's ambition for increased competition.

In August 2020, Ofgem launched a review of its regulatory policy and approach to new electricity interconnectors. As the energy system evolves and interconnector capacity increases, the role interconnectors play in the energy system is changing. Ofgem, therefore, want to ensure that their application framework brings forward the right projects, in the right locations, at the right time for consumers when thinking about the GB energy system.

The four key messages from Ofgem's interconnector policy review (ICPR) decision report, published in December 2021 were:

- The cap and floor regime has been successful in delivering its objectives to date
- Further interconnection is likely to be in consumers' interest. This is also consistent with the Government's ambition for at least 18GW of interconnection by 2030
- The principles of the cap and floor regime remain appropriate to incentivise further interconnector capacity development
- The cap and floor regime is, in principle, a suitable mechanism to support the development of multiple purpose interconnectors (MPIs)

Following Ofgem's review of the consultation feedback and additional evidence they have decided upon the following approach to future interconnector regulation:

- In the near-term Ofgem will open a third cap and floor application window in mid-2022. This will be a locationally targeted window for interconnectors that are able to connect within the next decade, by 2032
- In the long term Ofgem will integrate interconnector planning within more strategic network planning processes, with regular outputs informing cyclical investment windows

Ahead of the third cap and floor window (W3), Ofgem have requested the ESO provide future-facing analysis on the system need for, and potential impact of, future interconnectors, from a system operability perspective, in different geographical regions. This analysis helps inform Ofgem's decision making on how to target W3.

The ESO is uniquely placed to examine the impact of additional interconnection on constraint costs and system operability. This report consists of new analysis to quantify the potential impact of new interconnection on the system, focusing on locational impacts on constraint costs and system operability.

In addition to new modelling, this report summarises the potential benefits and challenges of additional interconnectors from an operational perspective and highlights some of the other work that the ESO is undertaking with respect to interconnectors.

# Impact of interconnectors on Thermal, Voltage and Stability Constraints

## Modelling approach

Previously as part of the Network Options Assessment process, NOA for Interconnectors (NOA IC) has identified how much interconnection would benefit consumers and other interested parties. It highlights the potential benefits of efficient levels of interconnection capacity between GB and other markets. The analysis outlines the socio-economic benefits of interconnection for consumers, generators and interconnector developers under a range of scenarios. Rather than assessing proposed projects it evaluates the benefit from hypothetical interconnections.

For the purpose of this report, we have developed a new methodology. The approach enables a geographic focus, on the potential impact of new interconnection on constraint costs.

Key elements of the methodology are:

- The modelling uses the most recent system and data available at the time of modelling: FES2021 scenarios and NOA 2021/22[2] optimal reinforcement paths
- Our pan-European market model BID3 was used to calculate the impact of additional interconnection on GB constraint costs
- At each BID3 zone on the GB system, in turn, a new theoretical interconnector was added, of 1GW. 37 GB zones are modelled, resulting in 37 separate results
- At each of the BID3 zones:
    - the interconnector is initially set to 100% import for all hours in each year of the study period
    - the simulation is rerun with the interconnector set to 100% export, for all hours in each year
    - The impact on constraint costs (thermal, stability, voltage) is captured for each run separately
- The interconnector is assumed to have a 25-year operational life, connecting in 2025
- Alternate years were modelled in the study period between 2025 and 2041 (i.e. every other year)
- Constraint costs are discounted to calculate the Present Value and compared to the counterfactual, where no additional interconnector is connected
- The resultant net constraint costs allow each GB zone geographic location to be ranked

Variations were also run on this approach by varying the percentage split of import and export flows. Settlement periods in the year were ranked in price order, then a percentage split was applied. For example, for the 50% import and 50% export case, the interconnector GB prices for each period were then ranked highest to lowest. The interconnector was assumed to be importing in the top 50% of the GB price periods in the year and exporting in the bottom 50% of GB price periods in the year. Other import/export percentage splits were also studied.

This approach builds upon the tools developed for NOA IC 2021/22. The modelling does not take into account the latest round of Government announcements on energy strategy, such as the ambition for 50GW of offshore wind by 2030: these will be incorporated into subsequent FES and NOA iterations. In addition, the analysis does not factor in the potential impact of the delivery of the Holistic Network Design (HND) that the ESO are undertaking as part of the Department for Business, Energy and Industrial Strategy's (BEIS) Offshore Transmission Network Review (OTNR). The *NOA 2021/22 Refresh*, which is an update to the *NOA 2021/22,* integrates the HND's offshore network and confirms the wider onshore network requirement.  The NOA 2021/22 Refresh is one of a suite of documents

[2] https://www.nationalgrideso.com/research-publications/network-options-assessment-noa

that sit under the Pathway to 2030 Holistic Network Design[3]. The analysis in this report was undertaken before the *NOA 2021/22 Refresh* was completed.

The approach does not try to quantify the optimal level of interconnection capacity at any particular GB zone. It provides an indication of the impact on constraint costs over the lifetime of an additional 1GW interconnector at that particular location, and the results show this relative to all other GB zones. It should also be noted that the analysis uses the levels of interconnection within the FES 2021 scenarios as a starting point.

The modelling approach undertaken is deliberately independent of connecting country. In reality however, the flow across an interconnector is a function of the market spread between the two connected countries.

[3] The Pathway to 2030 Holistic Network Design | National Grid ESO

## Results: Regional impact of constraints

The results are shown primarily in the form of heat maps. The heat maps show the effect on GB constraint costs of an additional 1GW interconnector connecting in turn in each of the 37 GB zones modelled. **It is important to note that the heat map is not showing regional variations in constraint costs: it is showing the impact on total nationwide constraint costs of an interconnector connecting in that particular zone.** Red represents an increase in national constraint costs, relative to the counterfactual over the lifetime of the interconnector (25 years) and green represents a reduction in national constraint costs relative to the counterfactual**.** The yellow regions do not represent an absence of change relative to the counterfactual: they represent the median values within the data set, which may be higher or lower than the counterfactual, depending on the spread of results.

Note that care should be taken when interpreting the heat maps: each heat map should be considered individually, rather than drawing conclusions across multiple heat maps at once.

The results show that whether the interconnector is importing or exporting is critical to the impact the additional interconnector has on GB constraint costs.

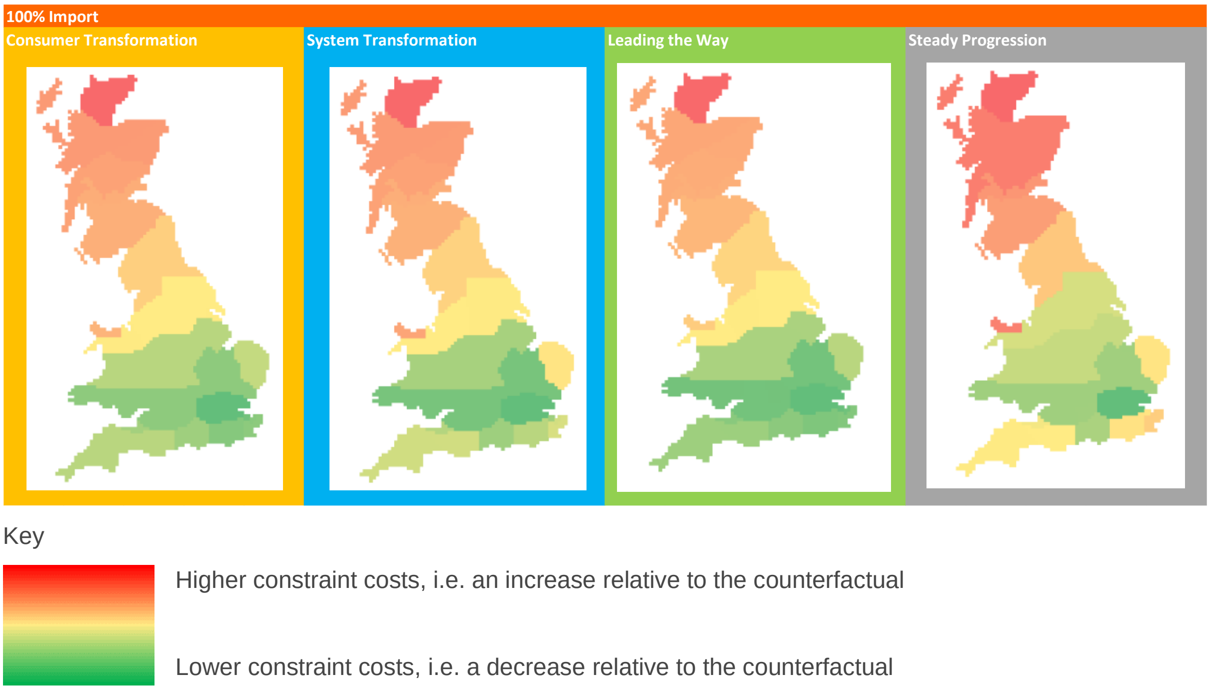



*Figure 1: RAG for constraint costs for interconnector with 100% imports.*

Figure 1 shows the change in constraint costs due to the addition of a 1GW interconnector that imports for 100% of each year. The interconnector is added to each zone in turn, and the colour of the zone represents the change in total constraint costs relative to the counterfactual, over the lifetime of the interconnector. A separate heat map is shown for each FES. In broad terms the charts show the additional importing interconnector reduces constraints when connecting in the South of England because the interconnector is supplying electricity to areas of high demand. Lower levels of electricity are required to flow from North to South, hence constraint costs are reduced as the number of balancing actions decreases. Conversely, when the additional interconnector connects in Scotland, Northern England and in Northern Wales, the constraint costs are increased because the additional interconnector is trying to import additional supplies into areas with low demand and limited transmission capacity, leading to increased balancing actions. There is some variation across the four FES, due to the differing underlying supply and demand assumptions, as well as differences in the future network capabilities.

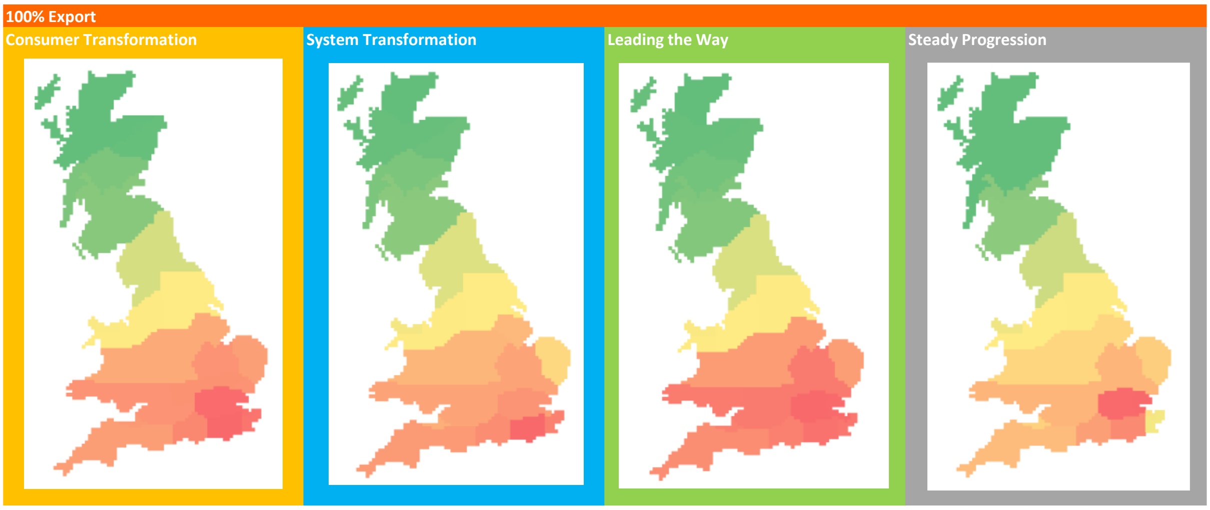



*Figure 2: Heat map for constraint costs for interconnector with 100% exports.*

Figure 2 shows the change in constraint costs due to the addition of a 1GW interconnector that exports for 100% of the time each year over the lifetime of the interconnector. In broad terms the charts show that the additional exporting interconnector increases constraints when connecting in the South of England because the export flows across the interconnector lead to increased network flows in the South, where electricity demand is already high, leading to increased balancing actions and higher constraint costs. Conversely, when the additional interconnector connects in Scotland, the constraints are decreased because the interconnector is exporting supplies from areas of low demand and increasing levels of renewable generation, resulting in less flows across the network from North to South, and leading to reduced balancing actions and lower constraint costs.

Figure 3 below gives an indication of the change in constraint costs relative to the counterfactual for 100% import and 100% export for all 37 GB zones modelled.

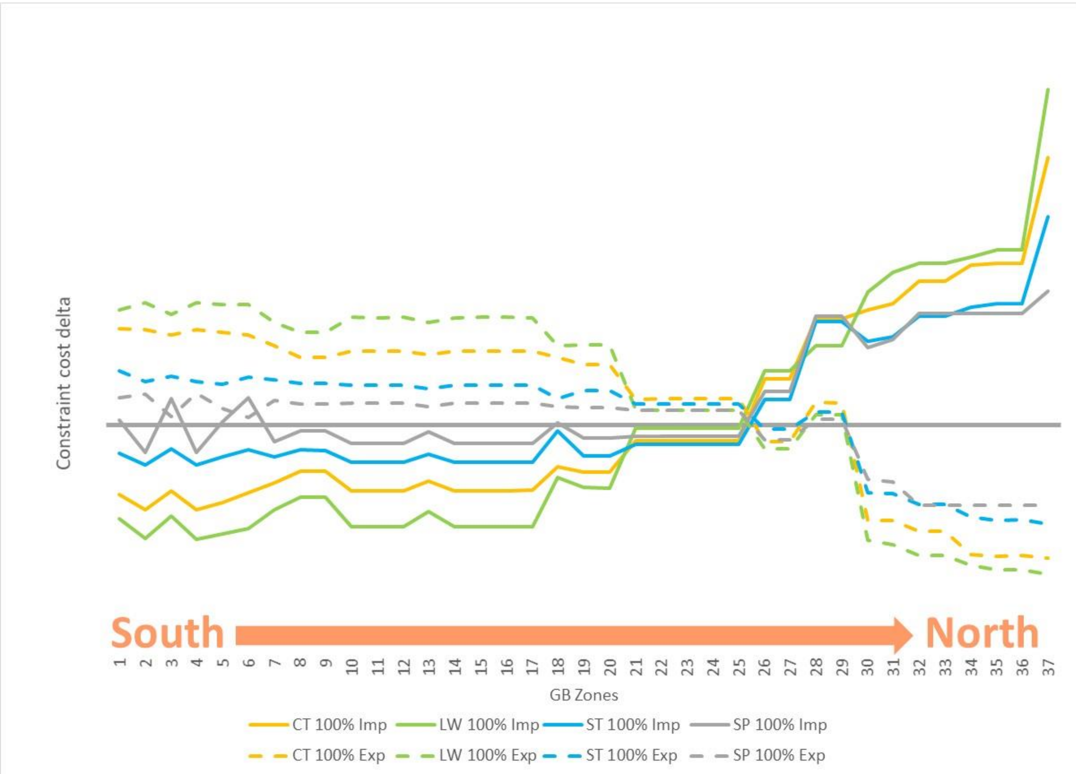



*Figure 3: Constraint costs for 100% import case and 100% export case.*

Figure 3 shows that for the 100% import case, for zones in North of England and Scotland, constraint costs over the life of the interconnector show the highest increases, particularly for Leading the Way and Consumer Transformation. Also, for the 100% import case, for zones in the South of England, constraint costs over the life of the interconnector reduce the most for over 15 of the zones for Leading the Way and Consumer Transformation. The results are reversed for the 100% export case, with Northern England and Scotland seeing constraint costs reduced the most, and many regions of the South of England seeing constraint costs increased for Leading the Way and Consumer Transformation. The level of the constraint costs is driven by a range of factors, including the generation mix, in particular the levels of renewable generation, system demand and the transmission network capability. Leading the Way and Consumer Transformation have the highest levels of intermittent wind capacity of the four FES2021.[4]

Figure 3 highlights the difference in constraint costs between interconnector import and export flows. It shows that for Leading the Way, for many of the zones, the difference in constraint costs over the life of the interconnector, comparing 100% imports to 100% exports, is significant. These strong differences may require the ESO to intervene and change the direction of interconnector flows to reduce constraint costs or facilitate efficient system operability.

To understand the impact of additional interconnection with different import/export splits, a range of different import/export combinations were considered.

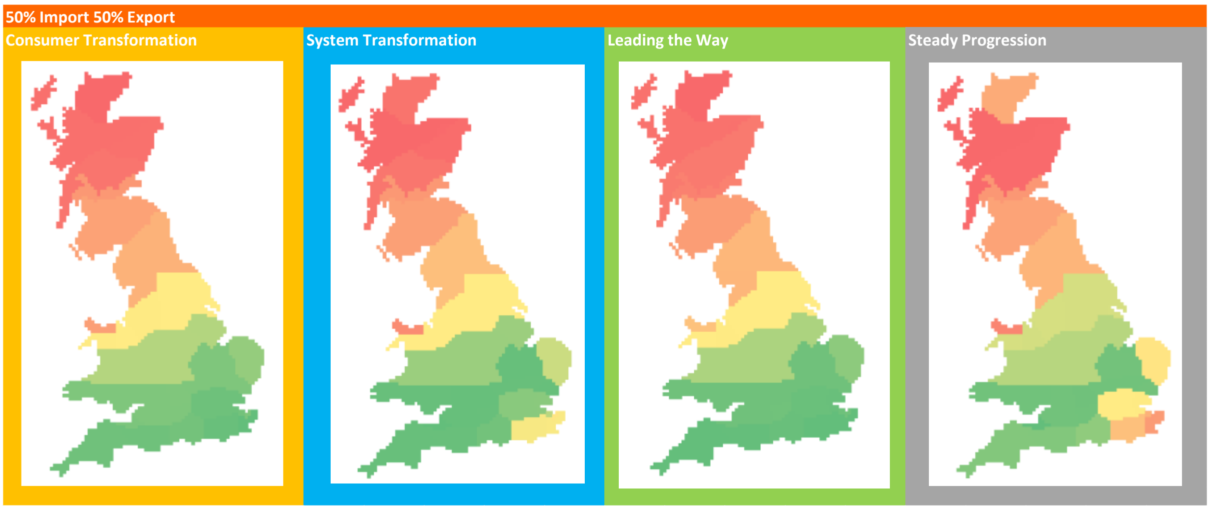



*Figure 4: Heat map for constraint costs for interconnector with 50% imports and 50% exports*

Figure 4 shows that for when the interconnector is importing for 50% of the time and exporting for the other 50% of the time within the year, the heat maps are broadly similar to those for the 100% import case, that is the additional interconnector increases constraints when the interconnector connects in the North of England and Scotland and reduces constraints when the interconnector connects in the South of England. Figure 5 gives a more detailed breakdown of the impact on constraint costs of the 50% import / 50% export split.

[4] For a high-level overview of FES2021, visit: https://www.nationalgrideso.com/electricity-transmission/document/199926/download

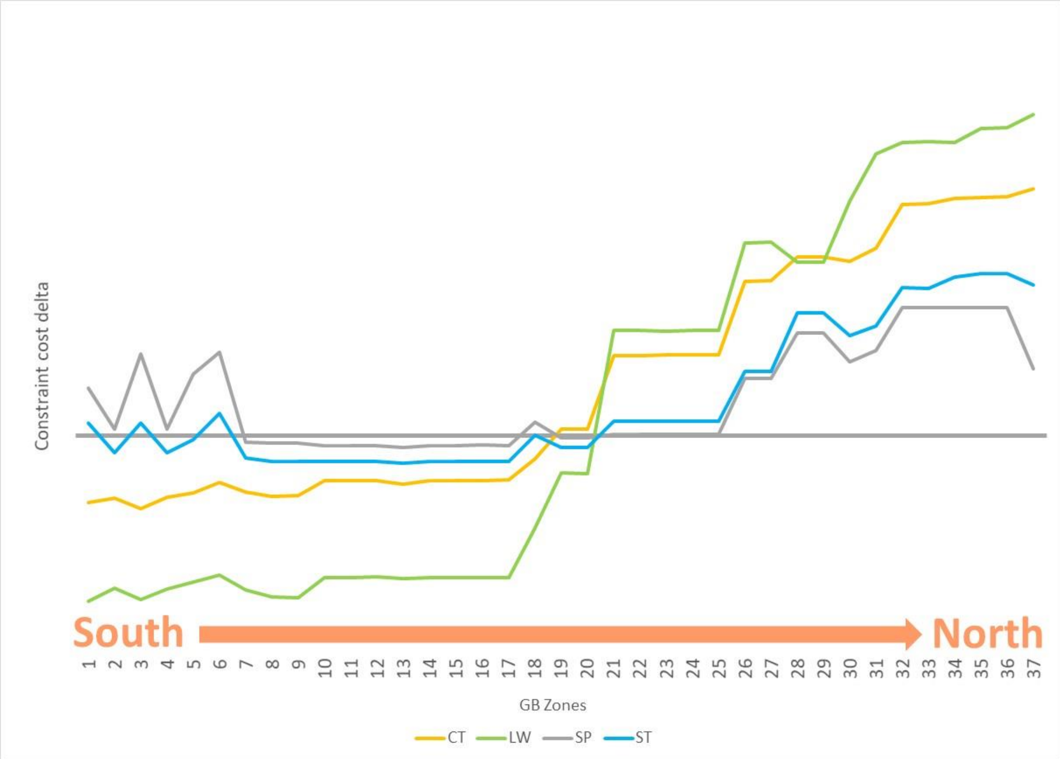



*Figure 5: Constraint costs for 50% import and 50% export case.*

Figure 5 shows that for the case where the interconnector is importing for 50% of the time and exporting for the other 50% of the time, the additional constraint profile is similar to that for 100% imports, that is increased constraints in Scotland and the North of England and reduced constraints in the South of England, particularly for Leading the Way and Consumer Transformation.

In order to understand the potential impact of a worst-case combination of 100% imports or 100% exports, the worst-case change in constraint costs for each GB zone was considered, i.e. the highest constraint cost for each zone from the 100% import and 100% export was selected. Figure 6 shows the resultant heat maps.

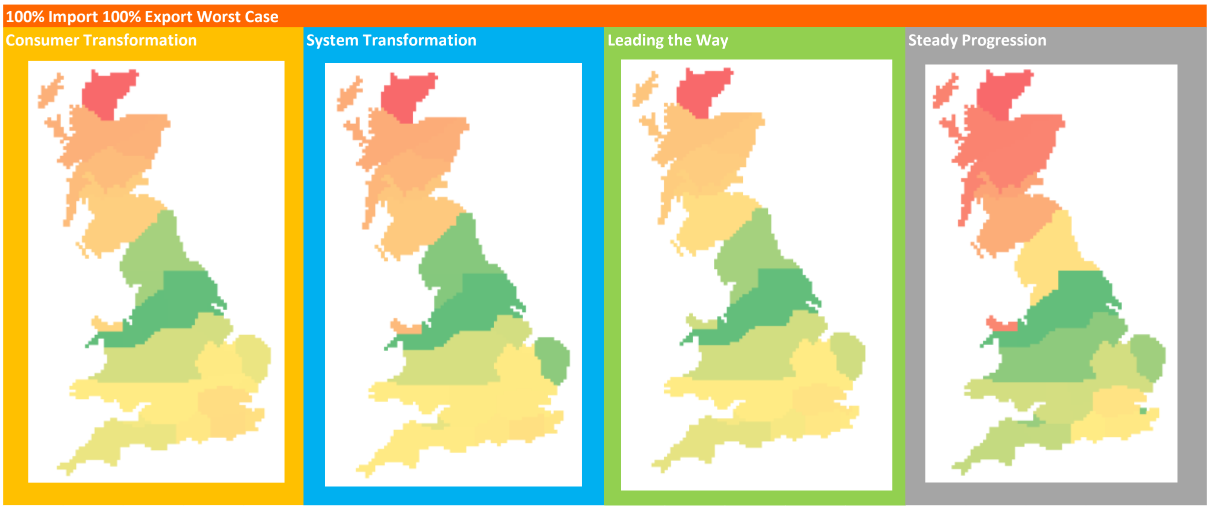



*Figure 6: Heat map for constraint costs for worst case of 100% Import and 100% Export*

Figure 6 shows that the combination of the worst case of 100% import and 100% export produces a heat map where broadly speaking, the lowest increase in constraint costs tend to be in the Midlands. This is to be expected as the 100% import case has additional constraint costs rising from south to north, and the 100% export case shows the additional constraint costs rising from north to south. Figure 7 shows the results numerically.

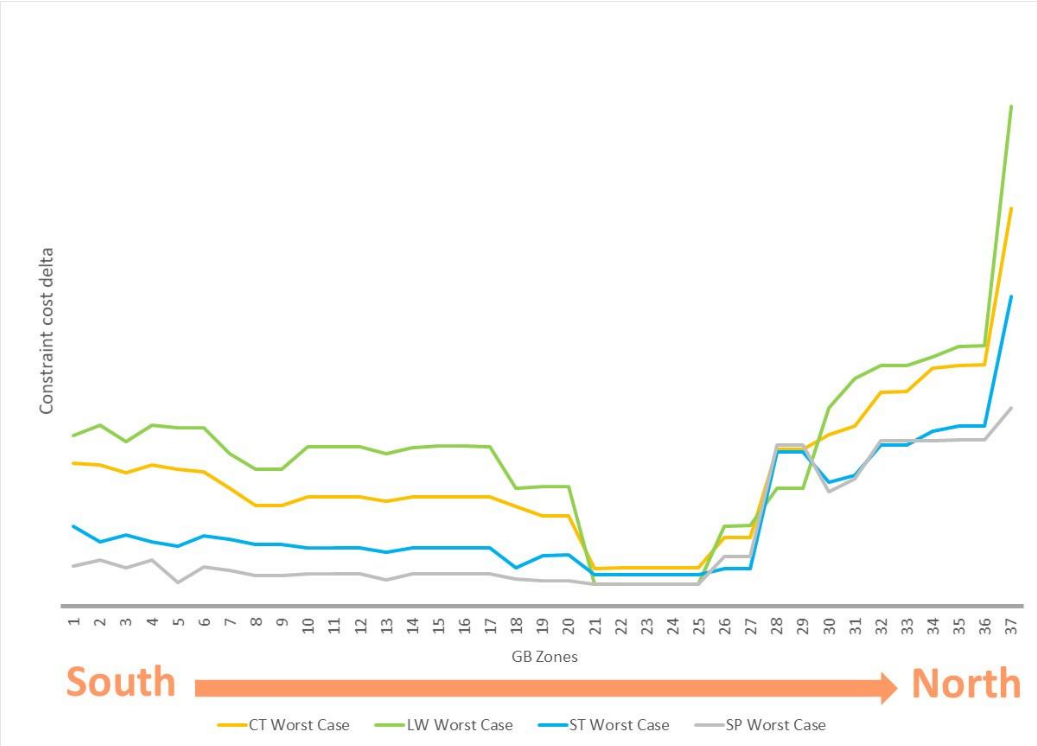



*Figure 7: Additional constraint costs for worst case of 100% Imports and 100% Exports.*

Figure 6 and Figure 7 only consider the worst case of 100% imports or exports for an interconnector connecting at each of the GB zones. A more valuable approach is to consider a wider range of potential import and exports splits. Figure 8 explores the impact of constraint costs of a range of import and export combinations for all four FES2021 scenarios.

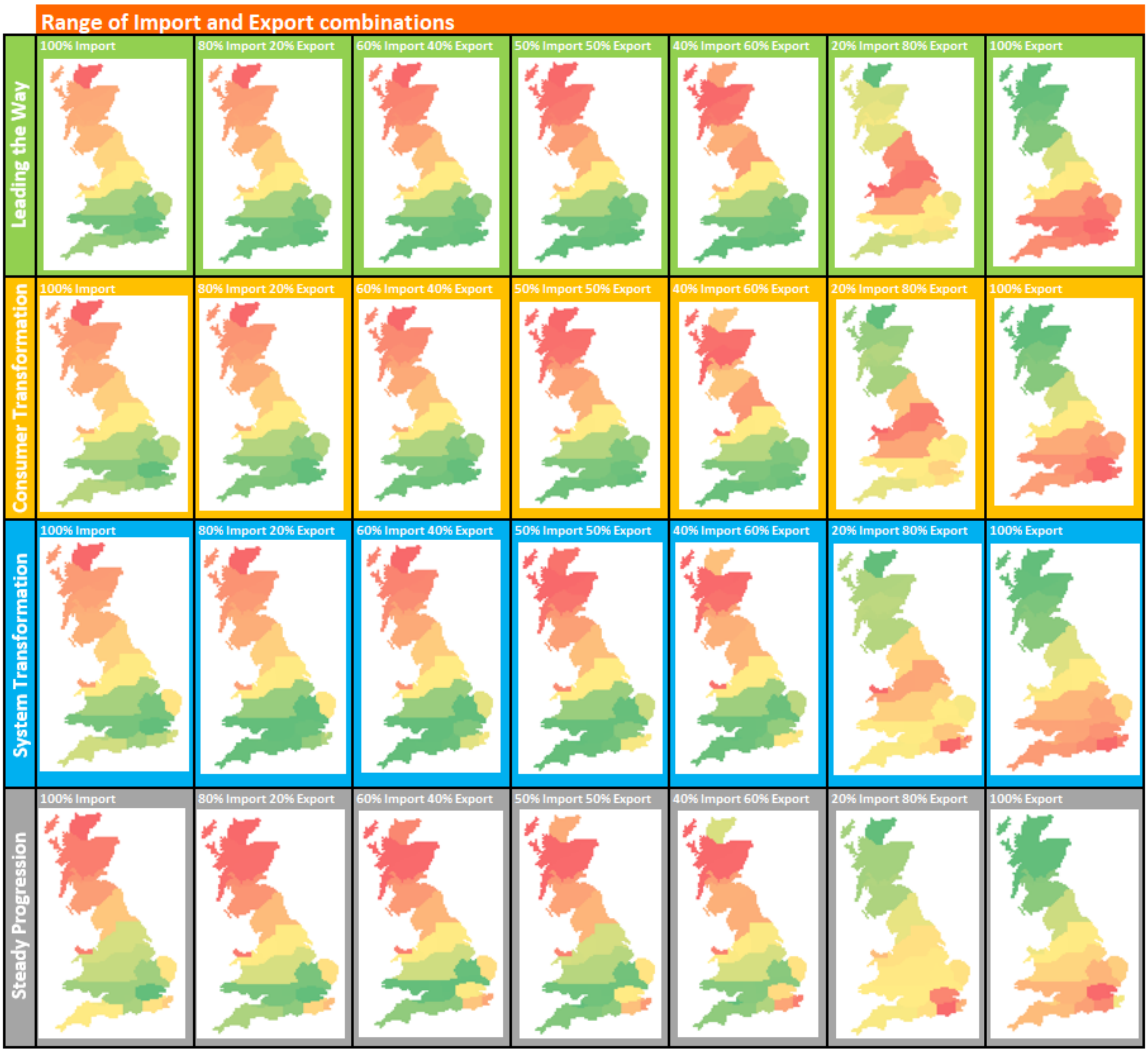



*Figure 8: Heat maps of additional constraint costs for a range of import/export splits for the four FES2021 scenarios.*

Figure 8 shows a broad similarity between the first five heat maps for each of the four scenarios, which cover 100% import through to 40% import and 60% export. For these combinations of import/export split, additional constraint costs increase from southern England to the North of Scotland. The 20% import / 80% export case shows highest constraint costs in Northern England, the Midlands and mid / North Wales for Leading the Way, Consumer Transformation and System Transformation. It is only the final heat map, for 100% exports, that shows additional constraint costs increasing from the North of Scotland to the South of England for all four scenarios. These results are confirmed by considering Figure 9, which shows the numeric values for the additional constraint costs for the import/export combinations shown in Figure 8 for Leading the Way.

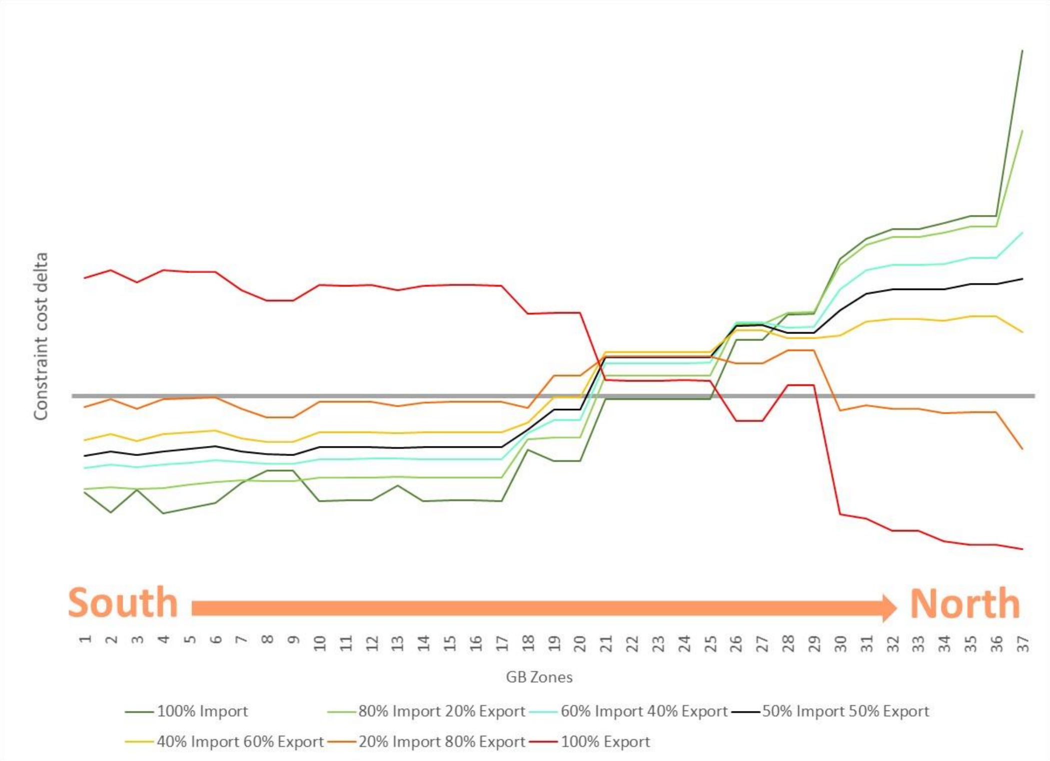



*Figure 9: Additional constraint costs for a range of import/export splits for Leading the Way.*

Figure 9 shows that it is only the 100% Export case that shows a decline in additional constraint costs from the South of England to Scotland. This suggests that only interconnectors that export for more than 80% of the time would reduce constraint costs in Scotland: lower levels of exports would result in an increase in constraint costs over the lifetime of the interconnector.

Figure 1 to Figure 9 show the importance of interconnector imports and exports on future constraint costs.

The following section highlights the interconnector import and export flows seen within FES2021.

## FES2021 interconnector flows

Figure 10 below shows annual interconnector flows for FES2021. Note that these are unconstrained flows, that is they represents a market-based solution, and not a network-based solution that conforms to any network constraints. It shows that in all four scenarios, exports are expected to increase significantly over the next two decades, with exports in Leading the Way decreasing between 2040 and 2050.

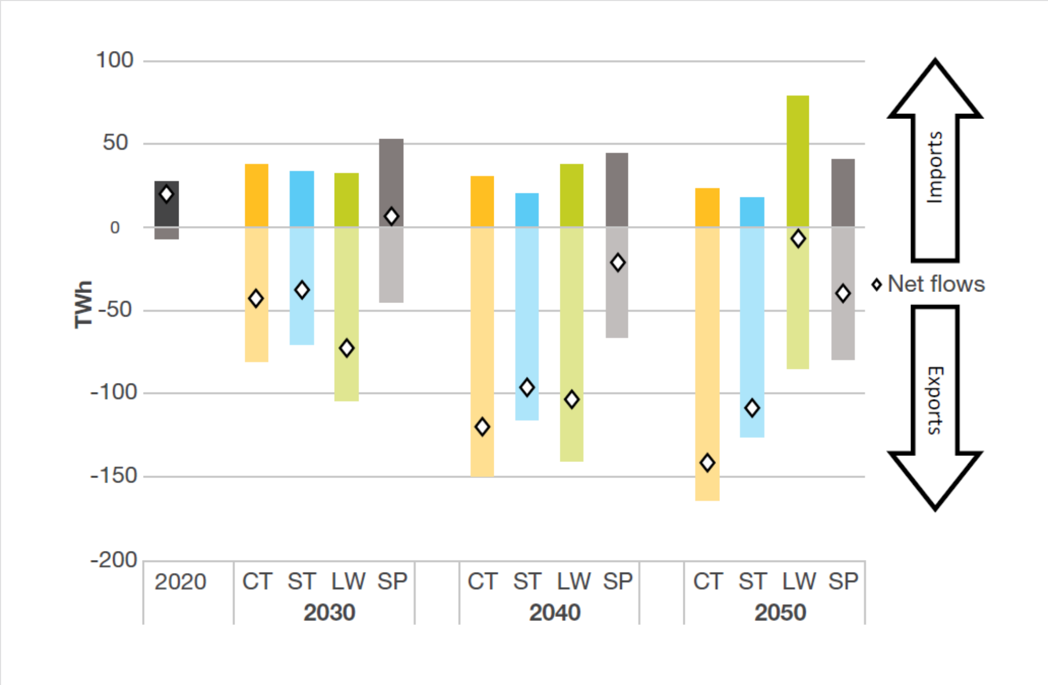



*Figure 10: FES2021 unconstrained annual interconnector flows*

Figure 10 shows that in all four scenarios, exports are expected to increase significantly over the next two decades.

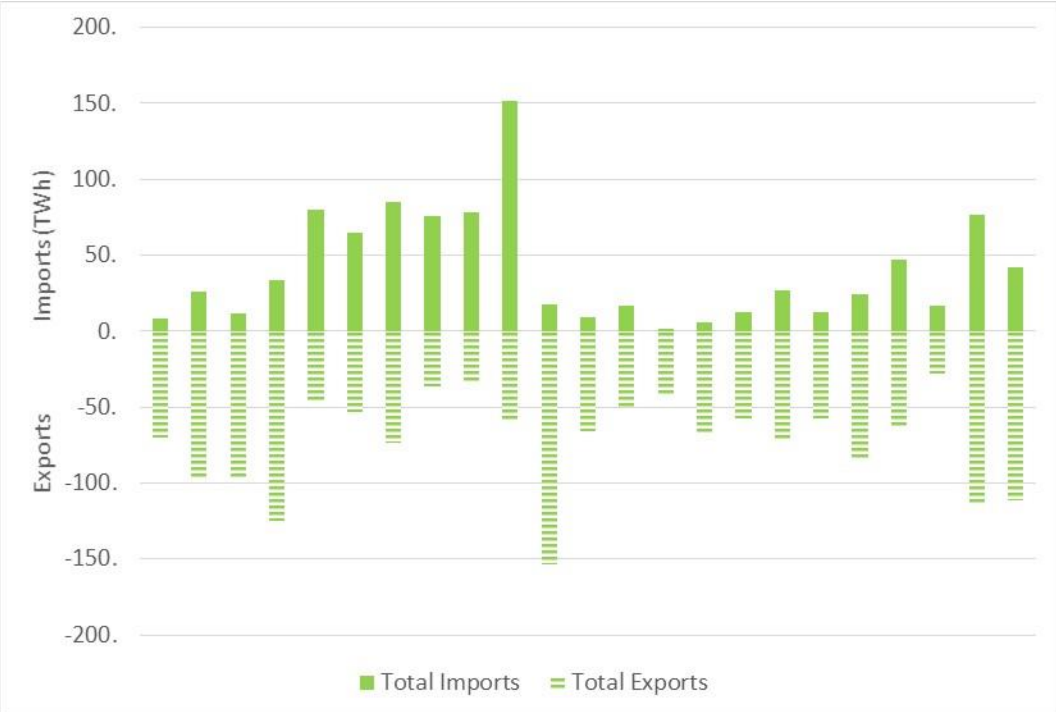



*Figure 11: Imports and exports for each interconnector in Leading the Way for 2022 to 2041*

Figure 11 shows that the ratio of imports to exports varies substantially across the individual interconnectors in Leading the Way. However, interconnectors connected to the same country will have similar import/export splits. This is due to the different arbitrage opportunities driven by the range of wholesale electricity prices across European countries. This shows that the connecting country has a significant impact on the import and export split on each interconnector.

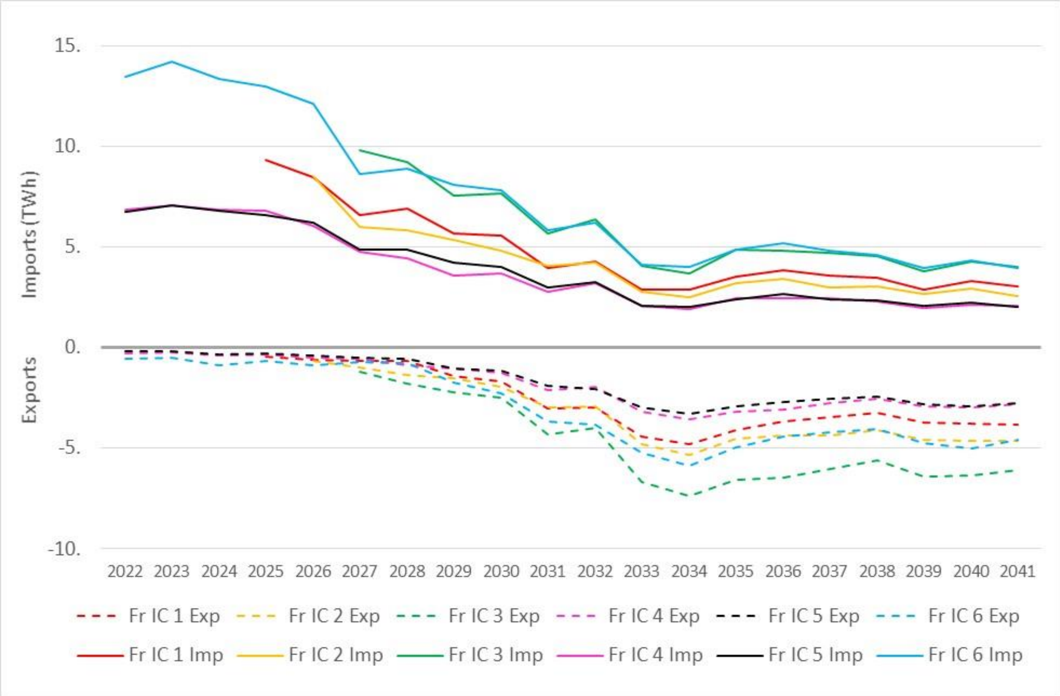



*Figure 12: French interconnector import and export flows for Leading the Way*

The flow patterns across interconnectors will vary from country to country, driven by the market fundamentals in the connected countries. Figure 12 shows the annual import and export flows for each interconnector in Leading the Way that is connected to France. France was selected because there are multiple interconnectors to France: other countries could have been selected as an example. Each coloured line represents a single interconnector, with the solid lines showing annual imports and the dotted lines showing annual exports. Whilst each of the interconnectors to France follow a broadly similar import/export breakdown for a particular year, the split varies considerably across years. For example, flows in 2030 are predominantly imports, driven by the higher wholesale prices in the GB market relative to France, but by 2035 export flows have increased such that they may exceed import flows, as the wholesale price in GB falls as increasing volumes of renewable generation are connected to the GB system.

Figure 10, Figure 11 and Figure 12 highlight some important factors:

- Flows on interconnectors are highly dependent on the underlying energy scenario. The rate of change and make-up of the generation mix and the level of demand in each country will determine the direction and scale of flow across the interconnectors.
- Flows on interconnectors are dependent on the wholesale prices in the two connected markets. As the types and scale of generation in GB and other countries in Europe change, wholesale energy prices will change. Increasing levels of renewable generation in GB, such as offshore wind and solar are forecast to reduce wholesale electricity prices, leading to increased exports.
- Flows on the interconnectors will change from year to year. The rate of change of the generation mix in GB will be different to other countries in Europe, leading to changes in the price differentials in connected countries, which will drive changing import and export flows.
- Flows on the interconnectors will be impacted by other interconnectors, i.e. other interconnectors included within the baseline will have a material impact on the flows on any further interconnectors. As additional interconnectors connect, the price differentials between the two connected markets will be eroded, potentially leading to reduced revenues for any subsequent interconnectors.

- Whilst the geographic location of the GB connection point of the interconnector will have a major impact on whether imports or exports will increase or decrease constraint costs, it will be other factors, such as the underlying energy scenario, connecting country and connection year that will drive how flows on the interconnector will be determined.

## Summary of results for regional impact of constraints

Care should be taken when interpreting the results. The analysis has been undertaken by adding an additional 1GW interconnector to levels of interconnection already within the FES2021 scenarios. Using later FES, which may have different underlying interconnector, supply and demand assumptions may produce different results.

The impact of an interconnector on the absolute levels of constraint costs will be dependent on many factors, including supply and demand assumptions, associated network capabilities, import/export levels and the number and location of other interconnectors in the scenarios. However, there are several high-level themes from this analysis that are to a certain extent independent of those factors:

- The level of increase or decrease in constraint costs is dependent on the geographic location of the GB zone the interconnector connects into and the import/export split on the interconnector, which will be driven by the wholesale price difference between GB and the connecting country.
- Interconnectors that connect to the South of England lead to reduced constraint costs, unless the interconnector is exporting for greater than 80% of the time. The additional importing interconnector reduces constraints when connecting in the South of England because the interconnector is supplying electricity to areas of high demand. Lower levels of electricity are required to flow from North to South, hence constraint costs are reduced as the number of balancing actions decreases.
- When the interconnector connects to the South of England and is exporting for greater than 80% of the time, constraints are increased because the export flows across the interconnector lead to increased network flows in the South, where electricity demand is already high, leading to increased balancing actions and higher constraint costs
- When the interconnector is connected in Scotland and North Wales, except for cases with very high export levels, that is greater than 80% of the time, constraint costs relative to the counterfactual (no additional interconnector) are increased, as additional flows drive more balancing actions in regions of the network with limited available capacity.
- When the interconnector is connected in Scotland, for cases with very high export levels, the interconnector is reducing constraints by exporting supplies from areas of low demand and increasing levels of renewable generation, resulting in less flows across the network from North to South and reduced balancing actions
- Interconnectors connecting in the Midlands and Northern England are likely to have the lowest impact on constraints: they are unlikely to cause significant increases or decreases in constraint costs.

The analysis in this report is based on the FES2021 scenarios. Our updated FES released in 2022 also show an increase in exports from GB to connecting countries in the future. This reflects the shift from import to export as increasing levels of renewable generation is connected to the GB market. At this point in time we are unable to say whether export levels on future interconnectors connecting in Scotland or North Wales will be sufficiently high or low to result in lower or higher national constraint costs respectively. In addition, future changes to the wholesale electricity price, brought about by the implementation of locational market pricing could change the import export balance.

## Results: Breakdown of impact by constraint type

The previous analysis focused on total constraint costs. The constraint cost data from BID3 can also be broken down by type.

For example, in one scenario the constraint cause breakdown over the study period was as follows:

- Thermal Constraint: 93%
- Voltage Constraint: 7%
- Stability Constraint: 0.5%

The above example shows that it is thermal constraints that constitute the majority of the constraint costs, as reflected in previous modelling work and observed operationally.

# Regional stability: Short Circuit Level

## Background

Short circuit level (SCL) is an important parameter for an electricity system. When there is a short circuit, a fault current flows, which must be disconnected and isolated from the system as soon as possible to avoid plant damage and wider system disturbances.

The size of the fault current is determined by the type and size of the generation, how far away this generation is electrically (this being the impedance of the grid system) from the point of the fault and the topology of the network. SCL or MVA infeed is a measure of system strength and its behaviour under fault conditions.

A high system strength is characterised by a high short circuit fault level (i.e. a high current infeed) and thus low system impedance.

A low system strength is characterised by a low short circuit infeed and hence a high system impedance. This is important as it means that where a fault is applied at a point on the system where there is a high system strength, the resulting voltage depression and effect across the wider system is more contained, whereas in the case of a low system strength, the higher system impedance results in lower retained voltages and a greater disturbance seen across the wider system.

This has important implications for characteristics such as fault ride through and the robustness of the system to disturbances. In the transition from synchronous plant to converter-based plants, which naturally have lower fault currents, there is a general decline in system short circuit level which needs to be managed going forward. The ESO together with wider industry are aware of these issues which are being managed through wider initiatives such as the Stability Pathfinder work and Industry Code (e.g. Grid Code) working groups.

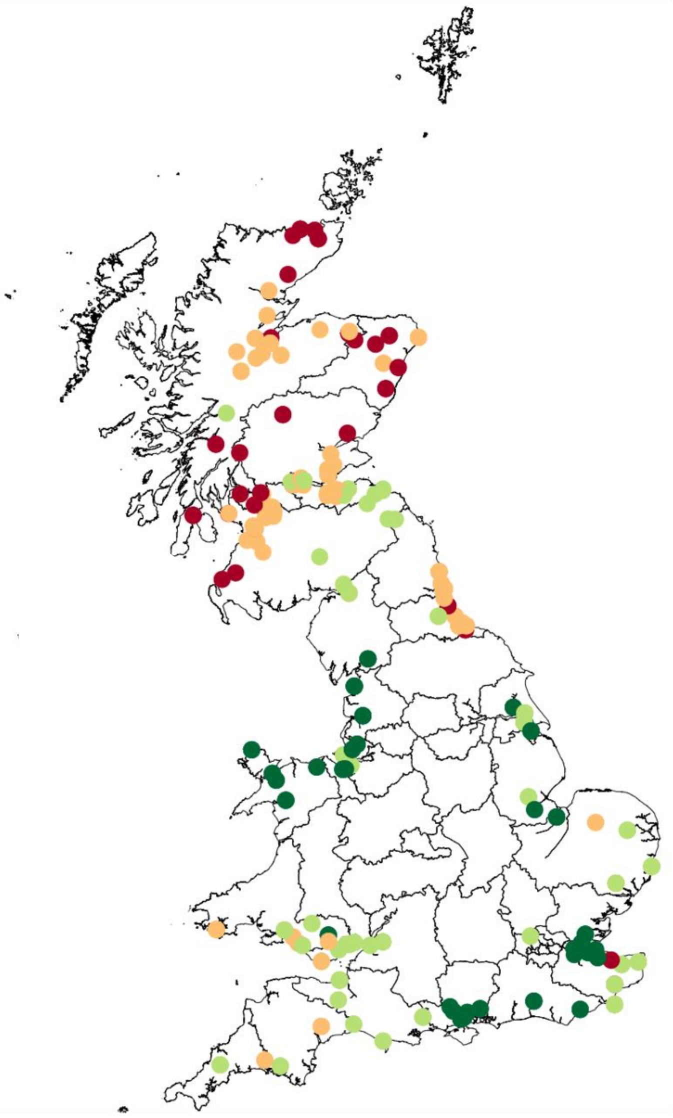
## Methodology

We examined existing interconnectors and their distances from transmission operator substations, both within GB and in the counterpart country. This was done to identify how far away from the shore interconnectors might connect and therefore allow targeted analysis for this report.

It was identified that the deepest current connection was around 60 km inland, and we used this to identify which substations to illustrate for this report.

We then calculated how much additional interconnection could be connected at each substation before there was an unacceptable reduction in SCL.

## Results



Key

| | | |
|---|---|---|
| | Cannot connect a 1 GW HVDC | Likely to need reinforcement for stability |
| | Can connect 1GW HVDC | Likely to allow small amount of HVDC before reinforcement |
| | Can connect 2-3, 1GW HVDC | Likely to allow medium amount of HVDC before reinforcement |
| | Can connect 4+, 1GW HVDC | Likely to allow large amount of HVDC before reinforcement |

*Figure 13: Short Circuit Level analysis results*

Figure 13 shows that the highest capacity available for HVDC interconnector connection is at substations in Northwest England, North Wales and Southeast England, as shown by the dark green circles. The lowest availability of capacity for HVDC interconnector connection is in Southwest Scotland and Northeast Scotland. For potential new interconnection connecting in Southwest Scotland or Northeast Scotland there may be a need for additional investment in the network or the deployment of balancing services on a long-term basis.

# Operational challenges and benefits from interconnectors

## Summary

Operational challenges will increase as more interconnectors connect, but these may be mitigated by potential market and regulatory changes.

Over the last decade, more interconnectors have connected to the GB system and have contributed to an increase in balancing costs. As more interconnectors connect, resulting in increased flows across the network, the ESO will need the right operational tools to manage flows on the interconnectors, otherwise the ESO will be exposed to increasing balancing costs.

Many existing interconnectors have different commercial arrangements in place due to a lack of mandatory code requirements, differences in regulation across borders, and optionality on whether to provide within-day capacity trading platforms (for example, on which the ESO could use to trade with individual capacity holders on a within-day, real-time basis). As a result, some interconnectors are more flexible than others which has a direct impact on local balancing and system constraints.

It would be highly desirable for all future interconnectors that connect to the GB system to be able to provide an intraday trading platform at the earliest opportunity.

## Market challenges

Interconnectors connecting to the GB National Electricity System (NETS) currently do not participate in the Balancing Mechanism. As interconnectors do not participate in the Balancing Mechanism, the ESO is unable to issue BOAs (Bid Offer Acceptances) on interconnectors post gate closure, hence the ESO is reliant on capacity trading or emergency instructions to control interconnector flows.

The range of market tools interconnectors use varies from one interconnector to another: some have day ahead capacity auctions or are implicitly coupled with day-ahead energy auctions: some participate in no day-ahead market at all. Similarly, some have a form of intraday market and others have none. Some offer SO-SO within-gate trading. All interconnectors offer Emergency Assistance/Emergency Instruction allowing real-time emergency control. This variance between interconnectors can lead to increased balancing costs due to different trading and flow control arrangements.

The ESO's ability to reliably trade capacity over interconnectors requires established, liquid and competitive commercial markets to enable it to trade at market reflective prices and to ensure trades are not easily unwound by other market participants. To date, the main market mechanisms to allow this are the day ahead and intra-day markets. Therefore, any interconnector that operates without a within-day or day-ahead market structure means the ESO is unable to alter the flow across the interconnector. This means the ESO will undertake all possible non-discriminatory market-based solutions to ensure the most cost-effective method to secure system operability.

Changing interconnector flows post gate-closure can be very expensive: managing interconnector flows by trading in capacity markets is considerably cheaper than resorting to balancing actions.

## Securing the largest loss of load

All existing interconnectors are connected via a single circuit breaker, except for IFA. For larger capacity interconnectors this presents an issue when securing the largest system loss as all of the interconnector's flow feeds through the single breaker. This can result in increased balancing costs in securing additional system response.

IFA has the current largest interconnector capacity but does not present a Largest System Loss issue as it is connected via two grid circuit breakers, the simultaneous loss of which is not a fault secured for under the Security and Quality of Supply Standard (SQSS)[5]. Additionally, single circuit connections

[5] https://www.nationalgrideso.com/industry-information/codes/security-and-quality-supply-standards

create challenges when scheduling maintenance. It would be beneficial therefore for any future interconnector that could represent the Largest System Loss to be designed as a bipole.

## System wide stability: A technology overview

In the past, the primary method by which electricity has been supplied to the Grid has been through the use of the synchronous generator, a device that converts rotational kinetic energy into electrical energy. Its design has worked well and has been used for many decades in thermal and hydroelectric power stations, which are generally based on a controllable primary energy source. In addition, the design and operational behaviour of synchronous generators together with their dominance in grid supply applications has a fundamental influence upon the dynamical characteristics of the Electricity Transmission and Distribution System.

Over the last twenty years, there has been a dramatic reduction in thermal plants and a rapid growth in renewable generation. Unlike thermal plants however, renewable generation technologies such as wind, solar, storage and HVDC technologies do not rely on the synchronous generator but other technologies such as induction generators and power electronic converters.

When there is a fault on the system, synchronous generators exhibit a range of features, for example they can supply inertia to the system (the ability to limit the rate of frequency rise or fall following the loss of a generator or load). Unfortunately, many of these features, that are inherent in the synchronous generation design, are not available in the current generation of converter-based designs. It is the deficit of these features, which if left unchecked, could result in either significantly higher operating costs or reduced system security.

There are two traditional solutions to this problem. The first is to constrain on synchronous plants and the second would be to use synchronous compensators. The first would be expensive and may also be dependent upon the use of carbon-based thermal plants, which would make it difficult, if not impossible, to achieve the net-zero ambition. The second does not produce Active Power output, however by varying the magnetic field strength they can contribute to reactive power control and grid voltage control.

A further solution is the approach developed through the Grid Forming Capability modification (Grid Code GC0137) which was approved by Ofgem in late January 2022[6]. The aim here is to enhance the capability of conventional power electronic converter plant so it exhibits similar characteristics to that of synchronous plant.

### Grid Forming vs Grid Following

Grid forming is the ability of a plant to respond instantaneously to system disturbances such as faults. Synchronous generators have an inbuilt inherent capability to provide a grid forming capability. As such, they contribute to qualities such as inertia and fault infeed.

This is very different to the current generation of renewable based/converter-based plant, which are generally classified as “grid following plants”. A grid following plant is one where the plant will see a fault or disturbance on the system, undertake calculations and then provide a response later. As such, grid following plants are not synchronised with each other and do not contribute to attributes such as inertia and short circuit level, which are fundamental to secure system operation.

It is for this reason that grid forming is such a fundamentally important feature. To date we have seen a significant replacement of carbon-based plant (synchronous/grid forming plant) to renewable plant (asynchronous/grid following) on a MW for MW basis but the absence of new renewable plant without a grid forming capability will cause significant operational, security and reliability issues. Therefore, to

[6] https://www.nationalgrideso.com/industry-information/codes/grid-code-old/modifications/gc0137-minimum-specification-required

ensure we replace like with like, grid forming applied to renewable generation will address this issue and put us firmly on the map to achieving zero carbon operation and net zero.

The ESO recognise that the natural capabilities traditionally provided by synchronous generation in contributing to stability will no longer be available and in future will have to be paid for. The aim of the GC0137 work sets out to complement other initiatives such as the stability pathfinder work and provides a minimum GB non-mandatory grid forming specification into the Grid Code. This specification can now be used as the foundation for a full system stability market which will be undertaken as a separate piece of work and would sit alongside the Stability Pathfinder work and other balancing services such as Dynamic Containment.

Grid forming is a fundamental pre-requisite to achieving zero carbon operation and maintaining secure system operation in the most economic manner. It is also seen as one of the key enablers in achieving net zero.

## Interconnector benefits

Interconnectors are increasingly becoming a key source of flexibility on the electricity system and in the future will constitute a significant portion of the overall supply and demand mix. Accessing flexibility and ancillary services on interconnectors will become key for maintaining system operability and as a key element in achieving competition across all market participants. Work is underway within the ESO to maximise the potential benefits that interconnectors can provide. This will ensure future interconnectors are incentivised to participate in ancillary service markets.

Interconnectors are technically a flexible and capable asset with significant potential for consumer benefit. Interconnectors are already able to participate in ancillary services and other commercial services if they choose to do so, but the extent to which this potential can be realised varies significantly across the interconnectors currently connected.

Interconnectors could make material contributions to system services, system operability and markets if appropriate design decisions are made and implemented with respect to DC conversion equipment and control systems.

## Looking ahead

The ESO has a range of ongoing projects to ensure it has the right tools and systems in place to ensure we can continue to balance the system effectively and efficiently as we transition to a zero-carbon system that will take us to net zero 2050. These include:

### ESO Markets Roadmap

In March 2022, the ESO published its latest "Markets Roadmap (to 2035)". This annual document[7] is intended to:

- Give stakeholders confidence that ESO is making the right market reform and design decisions
- Share what strategic decisions are being tackled and explain how industry can work with ESO on these questions
- Provide a clear and transparent view of what market reforms are being introduced, why and when.

The publication provides an overview of developments in priority market areas as well as a forward view of potential developments. It provides a good summary of current market services, their potential development path over the next five years and who currently participates.

[7] https://www.nationalgrideso.com/research-publications/markets-roadmap

We want to encourage a greater range of providers, including interconnectors, to participate in a wide range of markets.

### Balancing Capability Strategic Review

We are undertaking a strategic review[8] of our plans in this area and to reconsider our overall approach to planning. Transformational change to our existing or new balancing systems and architecture is necessary to facilitate the significant changes expected in the energy industry. We are also aware that, due to the rate of change across the industry, it is not in the best interest of customers to maintain the existing legacy balancing systems.

The challenges our strategic review will address include:

- Assessing the ongoing costs and the viability of maintaining existing systems
- Determining the correct balance of investment between maintaining existing balancing capability and developing future capability
- Understanding the transition between existing and future balancing tools
- Scoping the requirements and timescales for integrating future balancing tools into IT systems and Control Centre processes
- Prioritising the integration of new data feeds and features to deliver benefits from other RIIO-2 deliverables
- Scheduling the releases of new balancing capabilities to align with other RIIO-2 plans.

### Future of Interconnectors

The Futures of Interconnectors (FIC) project will explore how interconnectors can best be utilised to facilitate a GB net zero system, with a goal to maximise benefits for the consumer while minimising risks and costs.

The project will focus on the 2025-2035 period, with the following key objectives:

- Analyse how interconnector behaviour might change under different circumstances such as the introduction of locational pricing in GB or the development of Multi-Purpose Interconnectors (MPI) models
- Identify potential barriers to and risks of provision of system services by interconnectors in a net zero system
- Identify possible tools, levers or mechanisms that the ESO and the wider industry could consider, ensuring interconnectors benefit the GB system more optimally.

The findings of the project will be published in February 2023.

### Net Zero Market Reform

Another important workstream is the ESO's Net Zero Market Reform project[9]. This was established in early 2021 to examine holistically the changes to current GB electricity market design that will be required to achieve net zero.

Phase 3 of the project concluded that the current market was not designed for net zero and left unchanged will impose excessive costs on consumers.

Nodal pricing with central dispatch and with self-commitment was identified as the optimal solution for resolving the critical operational issues identified. Nodal pricing would dramatically impact the magnitude and volatility of price differentials between interconnected countries and the relevant interconnected GB locations. As such, it has the potential to significantly alter probabilistic

[8] https://www.nationalgrideso.com/industry-information/balancing-services/balancing-programme/strategic-capability-review
[9] https://www.nationalgrideso.com/future-energy/projects/net-zero-market-reform

assessments of arbitrage opportunities for interconnector users, and therefore could have a material impact on the value of access rights. It is prudent for this to be taken into consideration in future interconnector cap and floor regimes.

### Review of Electricity Market Arrangements

On 18 July 2022, BEIS launched the first step in their Review of Electricity Market Arrangements[10] (REMA) – a public consultation seeking views on a broad range of options for updating GB electricity market arrangements. The REMA programme and consultation covers a range of options for improving the accuracy of locational signals, including with zonal and nodal pricing. To support the REMA programme, Ofgem has initiated a project to assess alternative wholesale market designs that send more granular locational signals through the wholesale price.

Zonal and nodal pricing are amongst the high-level options and will be subject to extensive industry consultation and detailed assessment by BEIS prior to any formal implementation decision. We believe that it is credible that nodal pricing could be implemented within five years following such a decision.

[10] https://www.gov.uk/government/consultations/review-of-electricity-market-arrangements