System Operability
Framework

Regional Trends and Insights

Over the next decade, the peak flows across the transmission network remain high in all seasons. The regional flows will be increasingly volatile and there will be regions with no synchronous generation. To operate the system securely and sustainably, we will require more flexible resources and voltage support.

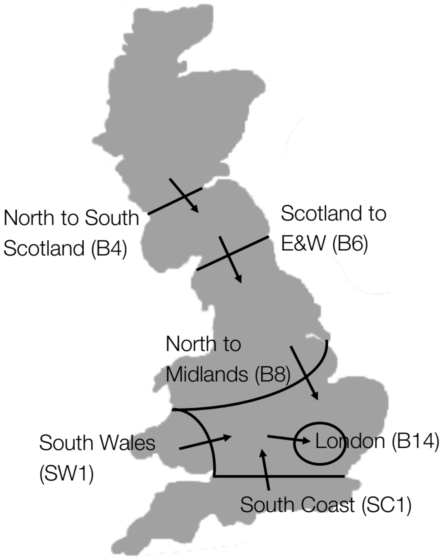
Executive Summary

The way that electricity generation, demand and flows change throughout the day affects how we operate the electricity network. We have analysed the hourly electricity flows across the network boundaries shown in Figure 1. Similarly on a regional basis we have assessed the hourly regional capacities of synchronous generation over next ten years.

Our results indicate periods of high electricity flows between regions for all seasons over the next decade. The regional electricity flows become more volatile due to the increasing contribution of renewable generation and interconnectors. As a consequence we will need to secure more flexible resources and voltage support in order to run the system.

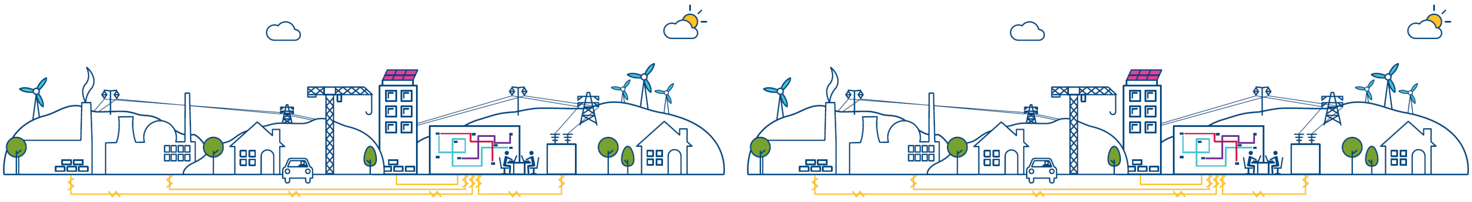
The amount of transmission connected synchronous generation capacity is decreasing. At the same time the unequal distribution of regional synchronous generation is increasing. Some regions would have a low level of synchronous generation running and this situation would become more frequent in the future. These regions could be vulnerable to mal-operation of protection systems, power quality issues and converter instabilities. Failure to manage these can lead to equipment damage, loss of supply and disruption to generator or interconnector operation.

Figure 1: Selected network boundaries for electricity flow analysis



We have already started to address these operability challenges in collaboration with transmission owners, distribution network operators and manufacturers/developers. There are known technological and commercial solutions to the issues we've highlighted here and known risks and benefits to using them. Please read our Network Development [2] and Product roadmaps [8] for information on how we plan to bring these forward.

We hope that you find this document, along with our other system operator publications, useful as a catalyst for wider debate. For more information please contact us: sof@nationalgrid.com



Regional power flows

Traditionally we have observed the active power in GB transmission system to be predominantly flowing from north to south. This has been mainly due to the historic geographical concentration of demand in the south and generation in the north. However, over the past few years, fossil fuel power stations have been closing. The connection of renewables such as wind and solar, interconnectors and other distributed energy resources has rapidly been increasing. These lead to a differing geographic distribution and differing availability of generation. We see these changes continue within the Future Energy Scenario [1] over the next ten years. We analysed the flows across the six boundaries shown in Figure 1. The detailed methodology is shown in appendix A.1.

Seasonal peak flows

- **Regional peak flows in the transmission network across all seasons remain high over the next decade**
- **Winter peak is no longer the only time the network is heavily used**
- **Regional peak flows have trends of either increasing or staying at the same level across all years.**

High power flows occur across the selected boundaries in all four seasons. Figure 2 and Figure 3 show seasonal peak flows as a percentage of 2018 winter peak flow for each boundary in Consumer Power and Two Degrees scenarios respectively. The peak power flows mostly happen in the direction as indicated by the arrows in Figure 1. While the peak flow via South Coast boundary (SC1) happens in reverse direction from 2018 to 2022 in the Consumer Power scenario.

The maximum peak flow does not always happen in winter. In both scenarios, we can see SC1 has higher flows in spring and autumn than winter in multiple years. During spring, summer and autumn, the thermal ratings for the lines will be lower than winter, and during these months, more outages will be expected to be taken on the network. The network would have a reduction in capacity in other seasons than winter. This may lead to boundary reinforcement being driven by time periods other than winter peak.

In both scenarios, we also observe that most flows are greater than 50% of 2018 winter peak flow of the respective boundary. All boundaries have trends of either increasing or staying at the same level across all years. SC1 has increasing flows from year 2021 to 2025 with new interconnectors being connected. North to South Scotland (B4) and Scotland to E&W (B6) boundaries have increased flows from 2024 onwards

Figure 2: Seasonal peak flows as % of 2018 winter peak in Consumer Power scenario

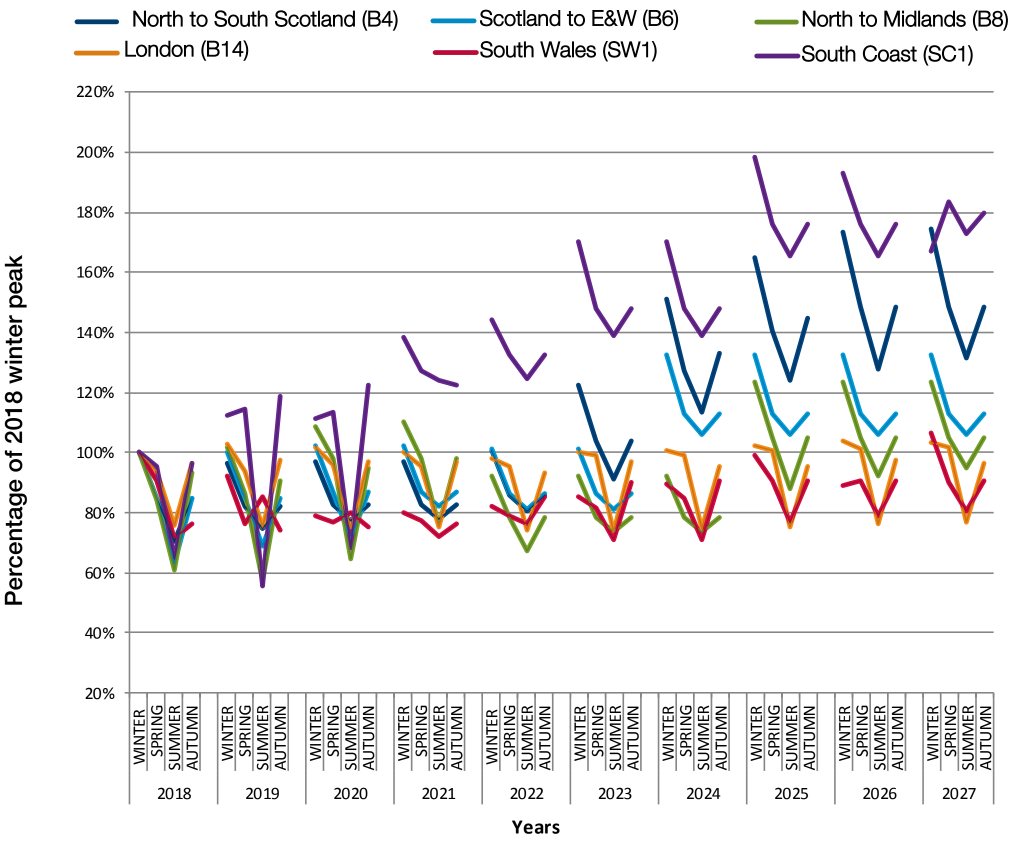
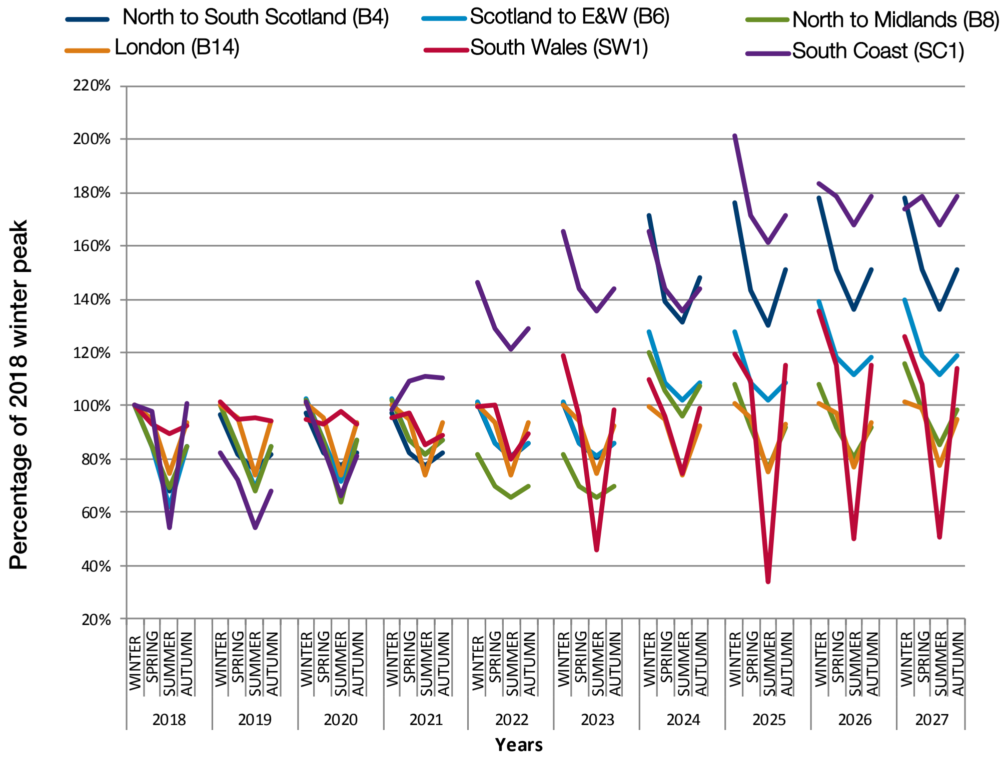


Figure 3: Seasonal peak flows as % of 2018 winter peak in Two Degrees Scenario



enabled by reinforcement of the network, details are provided in Network Options Assessment [2]. In Two Degrees scenario, South Wales boundary (SW1) is seen to have very low flow in summer compared to other seasons from 2023 onwards.

Rate of change of power flows

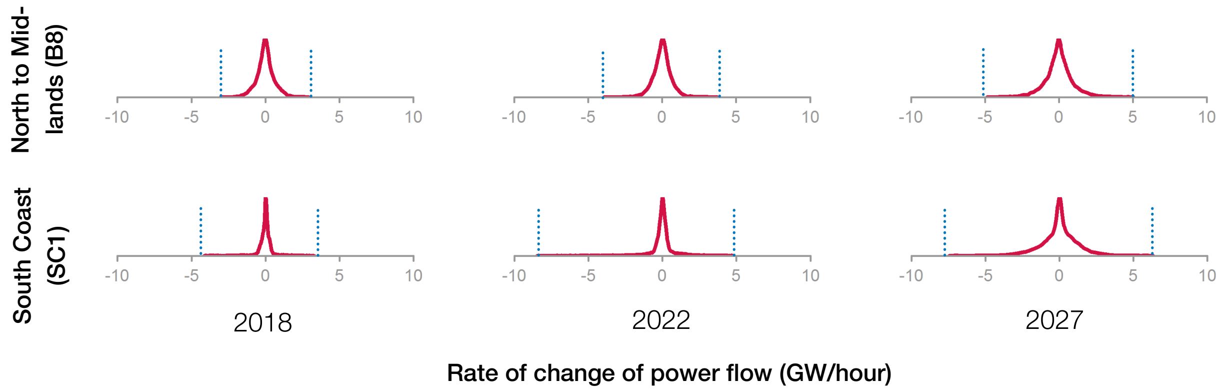
- **There is an increasing volatility of power flows from one region to another**
- **More flexible resources and voltage support need to be secured to operate the network**
- **Accurate regional demand forecasting will become increasingly important.**

We analysed how regional flows are varying from one hour to the next one by calculating rate of change of flows in GW/hour. Figure 4 shows density plots[1] of the change rate of power flows across the North to Midlands boundary (B8) and SC1 in 2018, 2022, and 2027 in the Consumer Power scenario[2].

The regional power flow volatility is increasing. The rate of change of flow increases for future years as shown by the curves becoming wider and covering a larger range of x-axis. The peaks of all those plots occur at zero GW/hour; this indicates the flows mostly stay at a low rate of change. SC1 sees a range of –8 to 5 GW/hour in 2020 and a range of -7 to 6 GW/hour in 2027. This is due to large volumes of new interconnectors in the south coast area.

The rate of change of regional power flow could rise up to 8GW/hour in 2020 and 7GW/hour in 2027, equivalent to 133MW/min and 117MW/min respectively. These

Figure 4: Rate of change of power flow (GW/hour) in Consumer Power Scenario



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[1] Further explanation for understanding density plots is in Appendix B.1.

[2] The density plot of rate of change of flows across other boundaries are shown in Appendix B.2.

significantly exceed the current maximum level of individual generator permitted ramping within the Grid Code: 50MW/min for a change between 300MW and 1000MW, and 40MW/min for a change of 1000MW or more [3]. Flexible resources which could respond faster would be needed to respond to this.

The increasingly volatile regional flows drive a requirement for further dynamic voltage support. Reactive power required to maintain the voltage level within an acceptable range is directly related to the level of flows in a transmission line or cable. The rapid active power flows can lead to a rapidly changing requirement for reactive power which can not be provided by traditionally switching the static devices. Automated dynamic reactive power support is needed to facilitate such rapid changes in flow. In System Operability Framework 2016, we have illustrated a national requirement for dynamic reactive power support about 3 GVAr/hour is necessary to maintain the voltage level in a typical day in 2016, while this requirement increases to 8GVAr/hour in 2024.

How is reactive power requirement affected by flow change?

When the power flow is low, the transmission line/cable is capacitive, generating extra reactive power and lifting the voltage level. This needs the System Operator to facilitate absorption of the extra reactive power, e.g. switching on a shunt reactor. When the power flow is high, the transmission line/cable becomes inductive, absorbing reactive power from the network and reducing the voltage level. This needs the System Operator to facilitate generation of reactive power, such as switching on a capacitor bank.

Demand forecasting will become more important at a regional level in future years since accurate prediction of the regional flows would be critical to quantify the required flexibility and voltage support. Uncertainty in the demand forecasting will require extra flexible resources and voltage support. Improving accuracy of the demand forecasting will lead to the correct level of flexibility being held which will help control costs.

Please see the Network Development Roadmap[3] for further details of how these challenges are being met.

Case studies

- **Most regional flows follow the traditional north to south direction when there is high wind generation**
- **Reverse flow from south to north could happen when there is high solar output**
- **Increasingly connected intermittent renewable generation, like wind and solar, contributes to the increasing volatility of regional flows**
- **Variable interconnector operations driven by pan-European market signals could cause rapid changes to regional flows.**

We compared the regional flows across selected boundaries in a high wind day, a high solar day, and a high interconnector flow day in 2027 to a low wind, low solar and low interconnector flow day in 2018 as shown in Figure 5[4].

The high wind output drives the power flows from north to south across most boundaries as most windfarms are concentrated in Scotland and northern England as illustrated in Figure 5(b). Most regional flows become more volatile as there is more wind generation 2027 compared to 2018. The varying output from windfarms contribute to this increasing volatility.

The selected high solar day in 2027 has a low national transmission demand. There are still high power flows, which are volatile, across the selected boundaries as shown in Figure 5(c). The high solar output drives the power flows from south to north as most solar farms are located in the south in the distribution network. Northern system boundaries such as B4, B6 and B8 are seeing net flows of zero or negative (south to north direction) during the daytime.

Variable interconnector flows cause rapid change of regional flows as shown in Figure 5(d). In this modelling, the interconnector behaves to compensate for the drop of wind output. The flows across B4, B6, B8 follow the wind profile; they drop rapidly during the night and then increase to a high level during the daylight. The flow via SC1 behaves in the reverse way due to the influence of interconnectors in south coast area.

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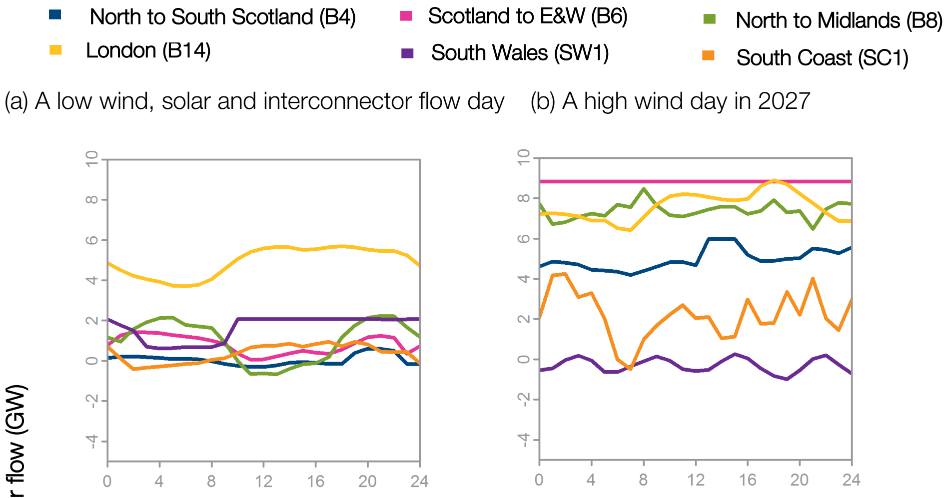
[3] Network Development Roadmap was published in May 2018. To drive greater value for consumers, we will be considering year round network needs and regional voltage challenges. We will be comparing network and non-network solutions across the transmission and distribution networks. This roadmap is available at https://www.nationalgrid.com/uk/publications/network-options-assessment-noa. We welcome your views on the proposals and you can contact us about them via transmission.etys@nationalgrid.com.

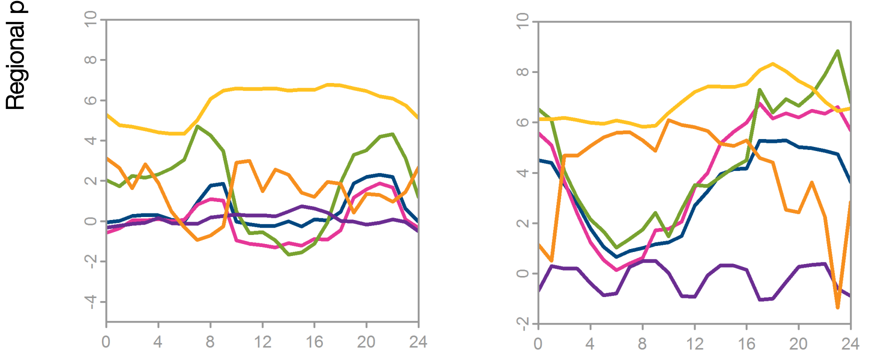
[4] More detailed case study results are included in Appendix C.

Figure 5: Flows in different cases



(a) A low wind, solar and interconnector flow day (b) A high wind day in 2027

(c) A high solar day in 2027 (d) A high interconnector flow day in 2027



The increasing volume of interconnectors in future would increase the volatility of regional flows. Rapid variation of regional flows could happen when multiple interconnectors simultaneously respond to the same market signal. This is explained in detail in SOF 2016 [9]. This results in the need for more flexible resources and dynamic voltage support.

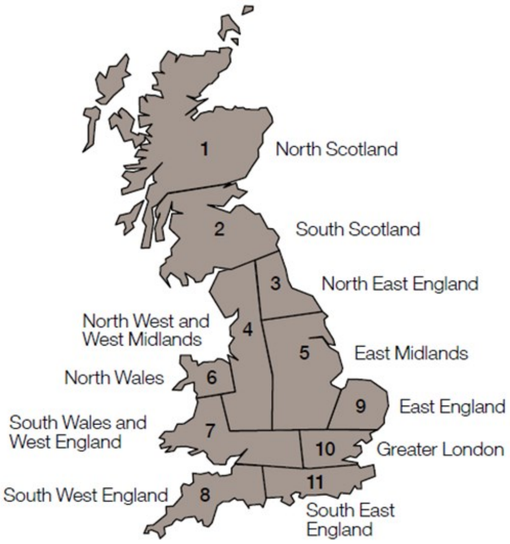
Our modelled interconnector behaviour assumes that market can foresee wind and solar output with appropriate accuracy and that market players can respond to effective price signals. In practice, different behaviour could happen. In either case, our modelling highlights an increasing dependency on understanding the effect of pan-European market arrangements and the potential need for tools to deal with the way they make flows across the networks vary within a given day.

Regional synchronous generation

- **There is a trend of increasing unequal distribution of synchronous generation across the GB transmission network**
- **There is an increase in the occurrence of no synchronous generation running in some regions**
- **Regions with low synchronous generation running are more vulnerable to operability challenges related to low system strength**
- **Dynamic reactive power sources are needed to deal with rapid changes in active power flows in regions with low synchronous generation running.**

The national synchronous generation capacity is decreasing. Transmission connected large synchronous generators are the main providers of system strength in our network. We divided Great Britain (GB) into eleven regions as shown in Figure 6. Based on these regions, we analysed the development of the regional synchronous generation[5]. The detailed methodology is described in Appendix A.2.

Figure 6: Regions used in this study



We used the Gini coefficient analyse and represent the unequal distribution of regional synchronous generation in the eleven regions. Boxplots have been drawn to show the distribution of Gini coefficients over the next decade in Consumer Power scenario as shown in Figure 7[6]. The horizontal line in the middle of the rectangle represents the median value of the Gini coefficient throughout the year, while the box range is from the first quartile of the Gini coefficient to the third quartile (25-75%). The top whisker represents the maximum value reached and the bottom whisker represents the minimum value.

> ***What is Gini Coefficient?***
> Gini coefficient is a term mostly used in economics to express the inequality of the wealth distribution of a nation's residents. A Gini coefficient of one represents maximal inequality, e.g. one person owns all the wealth of a nation. In this report a Gini coefficient of one means that all the synchronous generations come from one region alone. A Gini coefficient of zero represents minimal inequality, e.g. everyone has equal wealth in a nation. In this report, it means that the synchronous generation is spread evenly across all regions.

There is a trend of increasing disparity of regional synchronous generation as indicated by the increase in Gini Coefficient from 2018 to 2027 as shown in Figure 7. This is the result of closure and less frequent running of large synchronous generators. There is an apparent increase from 2022 to 2024. This period is aligned with the gap between the de-commissioning of major existing synchronous generators and commissioning of new synchronous generators.

Figure 7: Boxplot of Gini Coefficient of regional synchronous generation in Consumer Power scenario

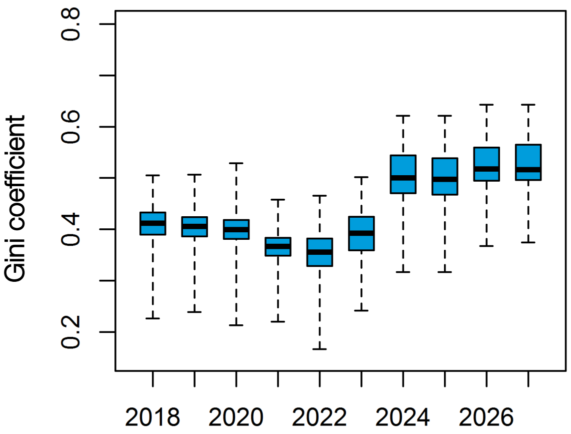


Figure 8 shows the maximum inequality of regional synchronous generation in year 2018, 2022 and 2027 in the Steady State scenario. The corresponding Gini coefficient values at these moments are 0.539, 0.544, and 0.776 respectively. In 2018 over 30% of the synchronous generation comes from East Midlands, while in 2027 over 50% come from East Midlands and North West & West Midlands areas. In year 2027 we see the most unequal distribution of synchronous generation. In East Midlands there is over 50% of the total synchronous generation.

The increased unequal distribution of synchronous generation means that most synchronous generation in the GB network tends to concentrate in some regions and the rest of the system would have very low or even no synchronous generation.

Load duration curves of the percentage of regional synchronous generation in the national synchronous generation in four selected regions in Two Degrees Scenario are shown in Figure 9[7]. We can observe that the percentages in North Scotland and East Midlands areas are increasing due to the commissioning of new synchronous generation in future combined with the decreasing national trend. In South Wales and West England area, there is a significant decrease as a result of the closure of synchronous plants in this region. The

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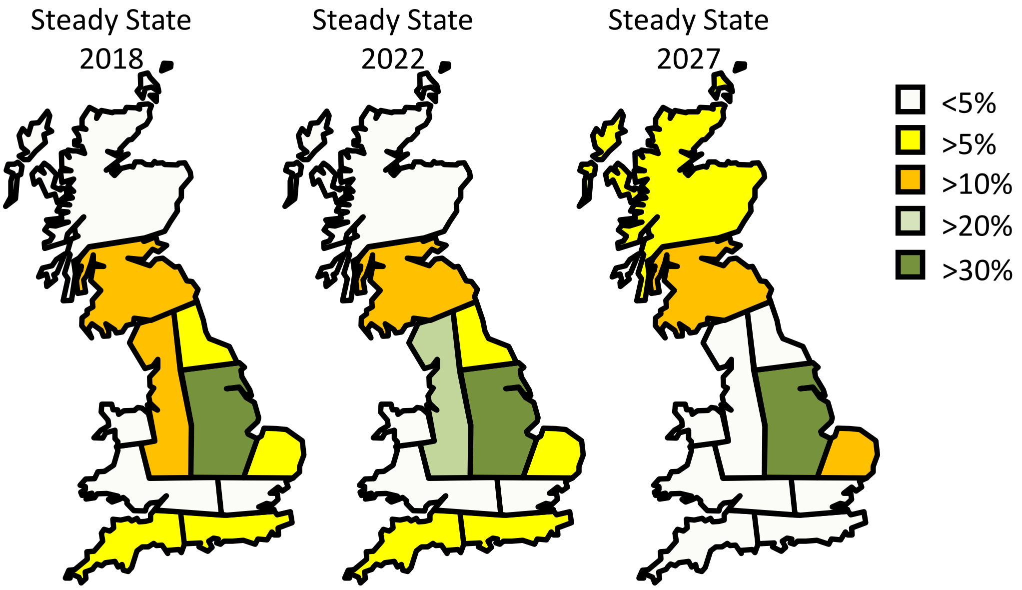
[5] Synchronous generation in 'Regional synchronous generation' section only refers to the synchronous generation connected to the transmission network and supplying power to the network

[6] Boxplots of Gini coefficient in all the four scenarios are illustrated in Appendix D.

[7] Further explanation of load duration curve is provided in Appendix E.1. Load duration curves in all four scenarios are provided in Appendix E.2.

Figure 8: Distribution of synchronous generation at the maximal inequality moment in Steady State Scenario



Greater London area holds a higher percentage, since the generation keeps almost constant, but will run less frequently.

The synchronous generation will run less frequently in some regions in future. This will cause declining fault levels and reducing sources of reactive power. The declining fault level would affect the operation of protection systems and induce power quality issues e.g. voltage unbalance, voltage dip, harmonics and flickers [9]. The reduction in sources of reactive power would affect the ability of maintaining the system voltage; this might cause converter instability [10]. All these operability issues would be dominant in the regions with no synchronous generator running.

As discussed in the 'regional power flow' section, the volatile regional flows drive additional dynamic voltage support. This is very likely to happen in regions where there is high penetration of intermittent renewable generation but limited synchronous generation. In these regions, alternative sources of dynamic reactive power are required to be able to operate the network.

Conclusions

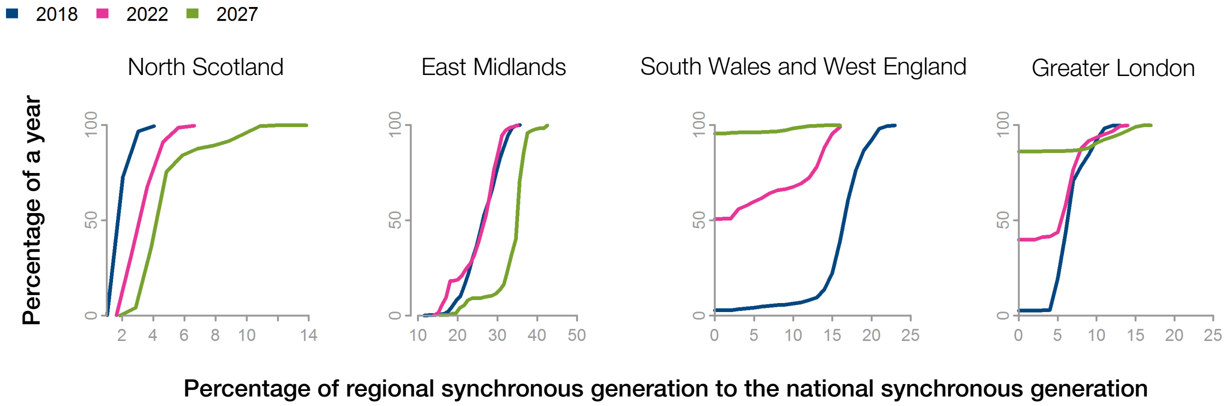
We conclude from our report the following trends:

- High peak flows for all seasons in the transmission network across the next decade
- Increasing in volatility of regional power flows across the GB transmission system in future
- Increasing in the occurrence of low or no synchronous generator running in some regions.

Increasing volatility of regional power flow drives the following operability considerations:

- Volatile regional flows have the potential to require more flexible resources
- The rapid active power flows potentially drive more automated dynamic reactive power support to maintain the regional voltage levels
- Improved regional forecast of demand, wind

Figure 9: Percentage of regional synchronous generation to the national synchronous generation in Two Degrees Scenario



output and solar output would support the network operation with volatile power flows.

Increasing disparity of regional synchronous generation drives the following areas of operability in some regions:

- Low fault level could cause mal-operation of protection systems and power quality issues
- Low system strength could cause converter instability
- Dynamic reactive power sources are needed to deal with the rapid active power flows.

National Grid together with the wider industry has been active in addressing these operability challenges. Our Enhanced Frequency Control Capability project aims to develop new source of flexibility [4]. The Power Potential project aims to obtain voltage support from distributed energy resources [5]. Virtual synchronous machine technique has been investigated to obtain flexibility from converter based resources [6]. National Grid is also a partner in Phoenix project [7], which aims to provide flexibility and dynamic support from synchronous compensator technology.

There are known technological and commercial solutions to the issues we've highlighted here and known risks and benefits to using them. Please read our Network Development [2] and Product roadmaps [8] for information on how we plan to bring these forward. We will collaborate with transmission network owners and distribution network operators to explore the change of system strength in both transmission and distribution networks. We also plan to collaborate with manufacturers/developers to further understand the risk of converter instability.

References

1. Future Energy Scenarios - https://www.nationalgrid.com/uk/publications/future-energy-scenarios-fes
2. Network Options Assessment -https://www.nationalgrid.com/uk/publications/network-options-assessment-noa
3. Grid Code - https://www.nationalgrid.com/uk/electricity/codes/grid-code?overview
4. Enhanced Frequency Control Capability - https://www.nationalgrid.com/uk/investment-and-innovation/innovation/system-operator-innovation/enhanced-frequency-control
5. Power Potential - https://www.nationalgrid.com/uk/investment-and-innovation/innovation/system-operator-innovation/power-potential
6. Virtual Synchronous Machine (VSM) Demonstrator - http://www.smarternetworks.org/project/nia_ngso0004
7. Phoenix project- https://www.ofgem.gov.uk/publications-and-updates/electricity-nic-year-four-screening-submission-phoenix-system-security-and-synchronous-compensators-scottish-power-transmission
8. Future of balancing services - https://www.nationalgrid.com/uk/electricity/balancing-services/future-balancing-services
9. System Operability Framework - https://www.nationalgrid.com/uk/publications/system-operability-framework-sof
10. Performance of Phase-Locked Loop Based Converters - https://www.nationalgrid.com/sites/default/files/documents/Phase%20locked%20loop%20FINAL.pdf

Appendix A

A.1 Methodology for ‘Regional power flow’ study

In the ‘Regional power flow’ assessment, we have focused on six transmission boundaries from National Grid’s Electricity Ten Year Statement (ETYS) and explored the power flows across them. Figure 1 shows the selected boundaries which are: North to south Scotland (Boundary B4), Scotland to England & Wales (Boundary B6), North to midlands (Boundary B8), London (Boundary B14), South Wales (Boundary SW1), and South Coast (Boundary SC1).

We have used the BID 3 model and FES 2017 data to calculate the hourly values for the active power flows across the ETYS transmission boundaries over the next decade. BID3 is an economic dispatch model used by National Grid. Details are provided in the Network Options Assessment [2]. The thermal constraints of transmission network are considered in the calculation. The power flows across the selected six boundaries have been analysed. We have compared the peak power flows in each season of every year to illustrate the variation of the peak regional power flows. The rate of change of the power flows have also been analysed to show the volatility of regional flows and the factors which influence that volatility. Moreover, we also analyse the power flows across the selected boundaries in detail in three sample cases: a windy day, a solar day and a high interconnector flow day.

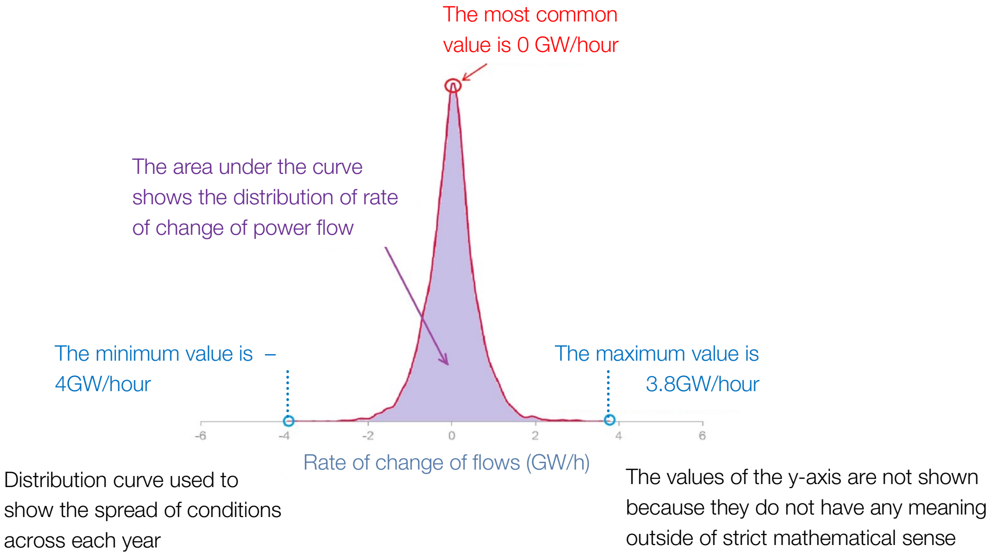
A.2 Methodology for ‘Regional synchronous generation’ study

We analysed the capacities of synchronous generation in 11 regions as shown in Figure. 6. This is consistent with the regions for system strength analysis in SOF 2016. BID3 model and the FES data sets are used to produce hourly values of synchronous generation capacity in each region.

Appendix B

B.1 Detailed description of density plot

Figure B1: Detailed description of density plot



The most common value is 0 GW/hour

The area under the curve shows the distribution of rate of change of power flow

The minimum value is –4GW/hour

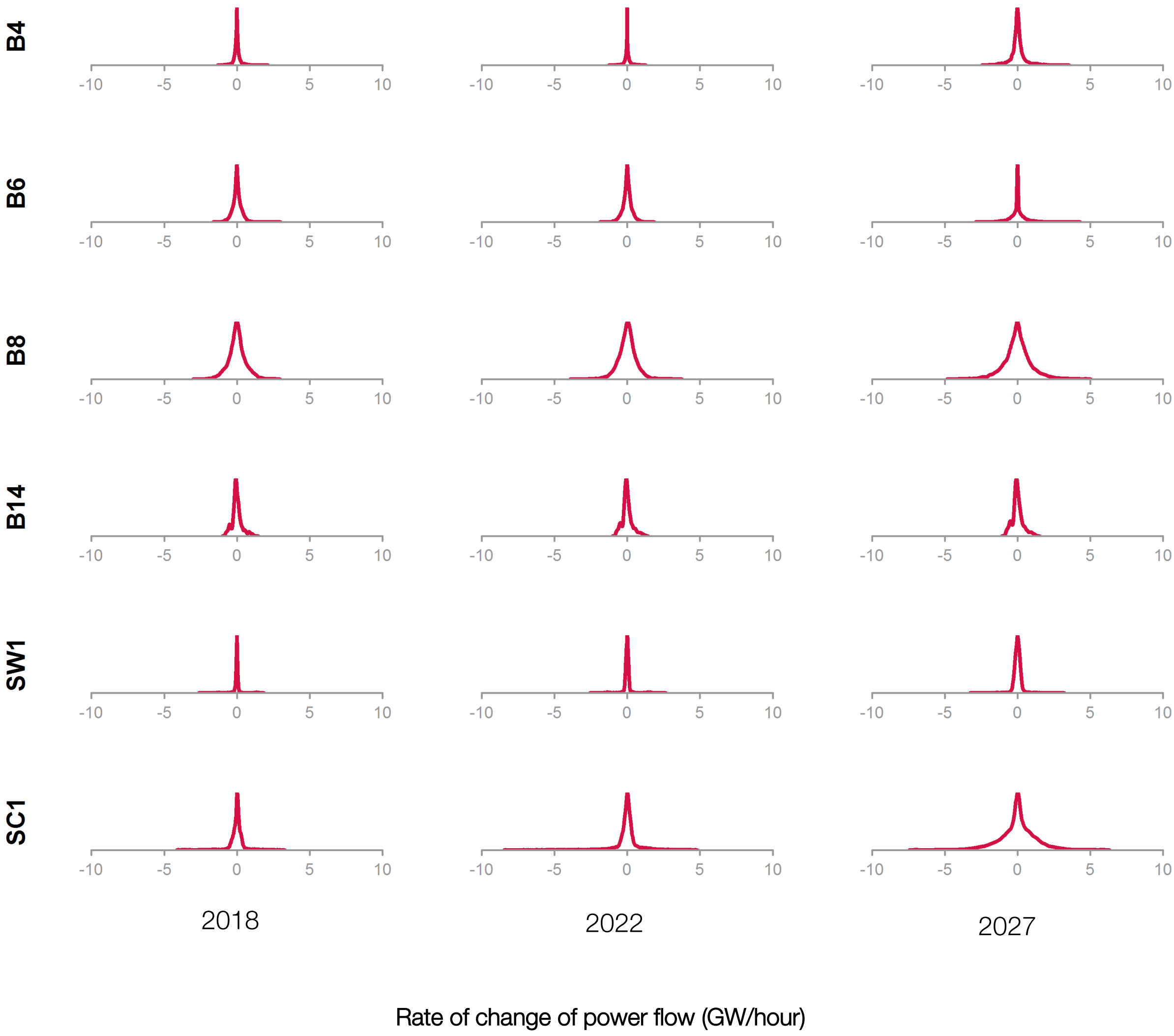
The maximum value is 3.8GW/hour

Distribution curve used to show the spread of conditions across each year

The values of the y-axis are not shown because they do not have any meaning outside of strict mathematical sense

B.2 Density plots of rate of change of flow via all the selected boundaries

Figure B.2: Rate of change of power flow (GW/hour) in Consumer Power Scenario



Appendix C

C.1 A high wind day

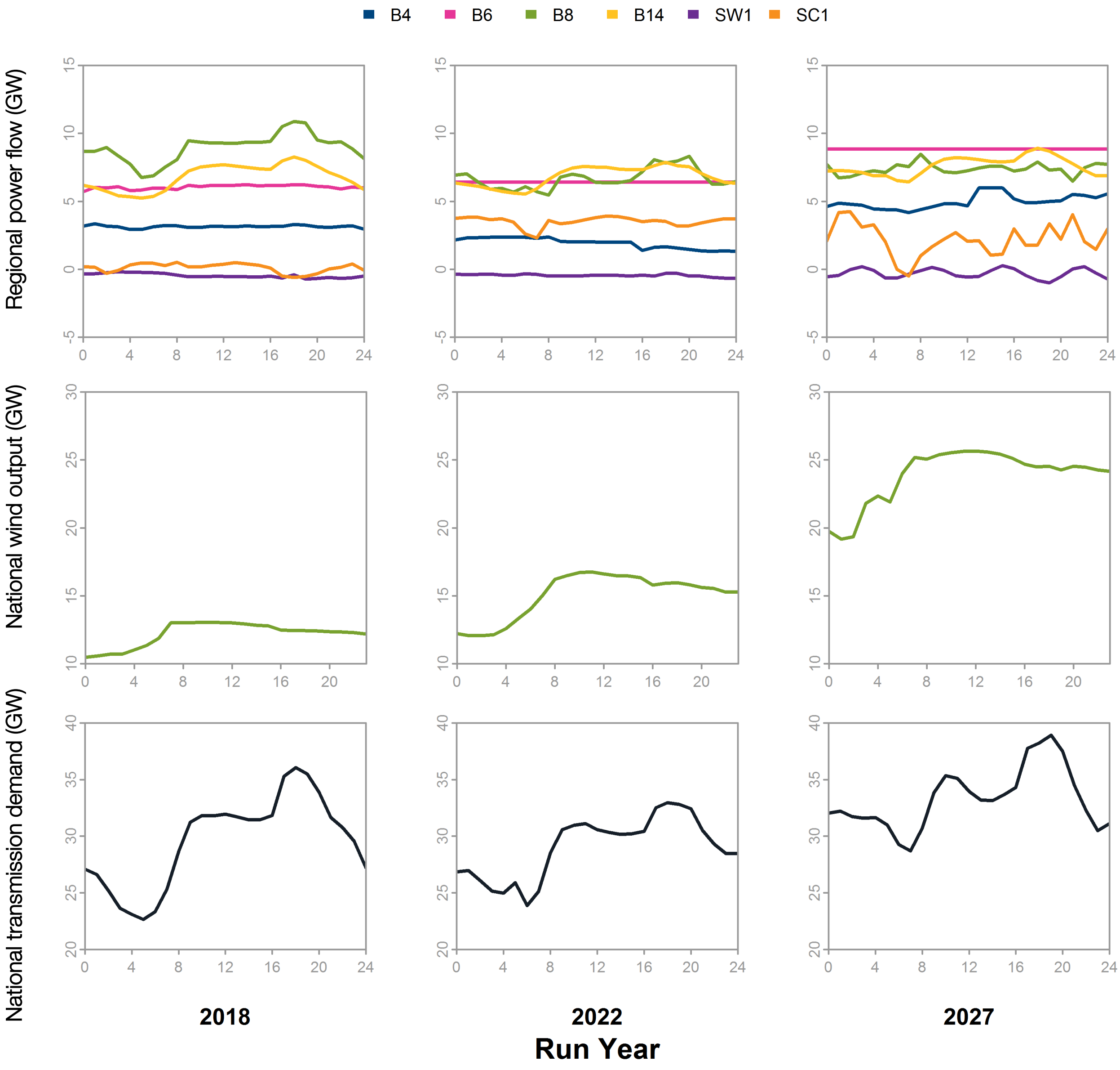
For the Two Degrees scenario, the regional flow profiles in a high wind day in 2018, 2022 and 2027 are illustrated in Figure C.1. The dispatch of transmission connected wind and transmission demand in these three days are also included.

The three selected high wind days are occurring in winter with low solar output. As most windfarms are concentrated in Scotland and northern England, the high wind output drives the power flows from north to south across most boundaries.

For all three years, we observe the flows across B14 (London area) to be broadly following the national demand profile as the London area is predominantly driven by demand. The power flows across B4 and B6 are all close to or at its boundary limits due to the high wind output. The positive flows across B8, SW1 and SC1 supply the central areas of England; therefore they are complementing each other to maintain a relatively constant summation. The SW1 flows keep constant near zero in 2018 and 2022, and it becomes variable in 2027 but within a small range around zero. In 2027, the mirror of B8 flows and SC1 flows are apparent; the B8 power flow from north to south and the SC1 flow supply power to central England area.

Most regional flows become more variable as time goes on, especially the flow across SC1; this is mainly driven by the variable flows through the interconnectors and intermittent output from windfarms. More sources of flexibility and dynamic reactive power support needs to be hold as discussed before. Accurate forecast of regional demand and regional wind output would be very important to quantify the required flexibility resources and reactive power support.

Figure C.1: Flows during high wind periods



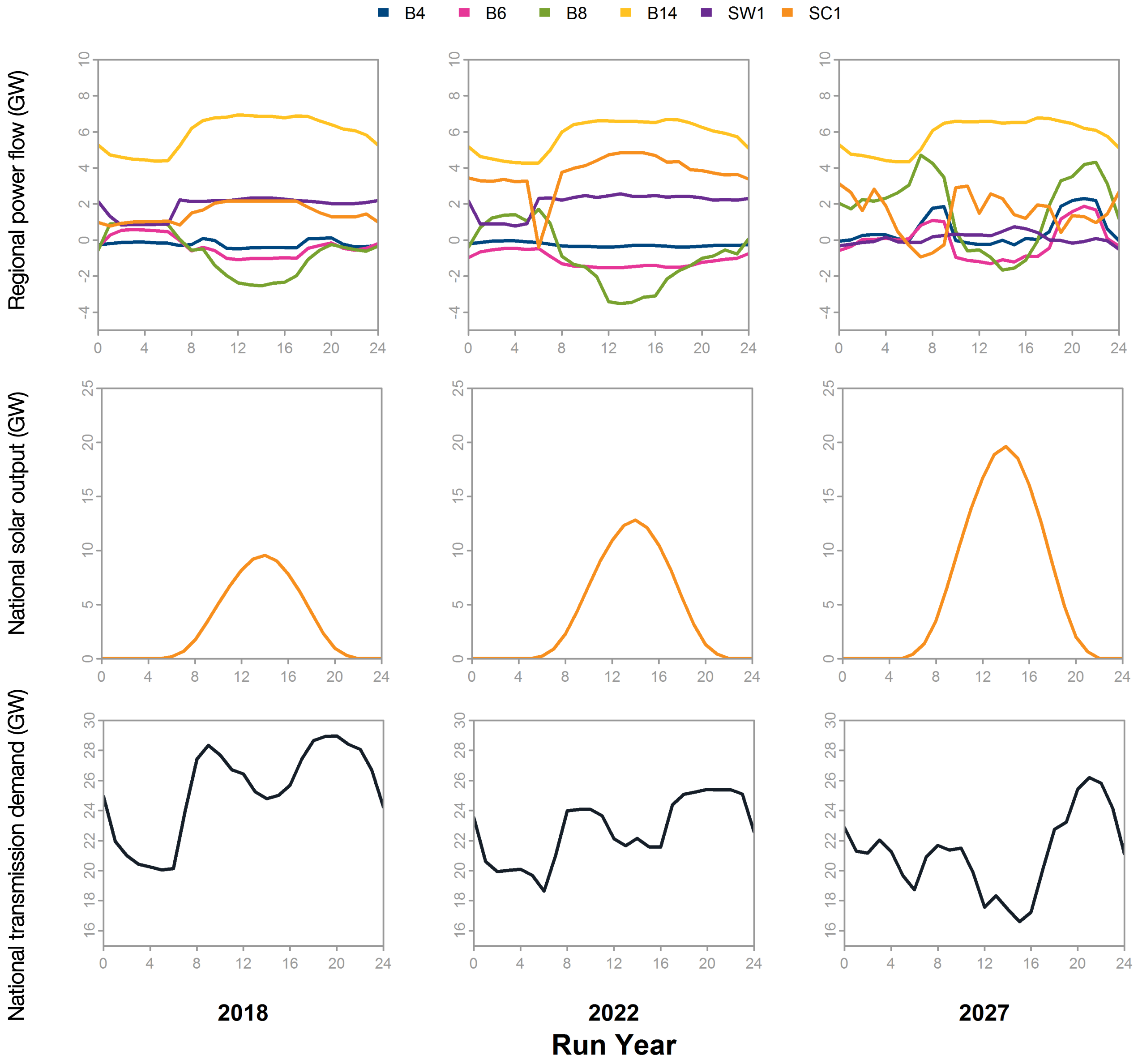
C.2 A high solar day

The regional flow profiles in a sunny day in 2018, 2022 and 2027 are illustrated in Figure C.2 for the Consumer Power scenario. Besides the regional flow profiles, the solar output profiles and the national transmission demand profiles are also included. In all these three days, there is a low wind output and low transmission demand. Although the national transmission demand is very low, there is still high power flows across the selected boundaries.

The flow profiles become more variable as time goes on, similar to the windy day. With decrease in transmission demand and increase in solar PVs in south of the system, northern system boundaries such as B4, B6 and B8 are seeing net flows of zero or negative during the daytime when there is solar generation. This reflects the increased variability of the region power flows. When there is low solar generation, the power mainly flows from north to south; while with high solar generation concentrated in south could drive the power flow from south to north. The solar generation has the effect of increasing the volatility of regional the power flows.

The solar generation plants are mostly connected to the distribution network in the GB. If the solar generation together with other types of distributed generation with in a regional distribution network is higher than the demand, the extra power would flow from the distribution network to the transmission network. This is in contrast to the traditional active power flow direction from transmission to distribution network. We have observed that the reactive power flows from distribution network into transmission network during low demand period. The reverse flow of active power indicates a larger scale and more rapid changes of flows in our network. This would increase the speed and scale of reactive power flow from distribution network to transmission network; if not well managed, the excessive reactive power in transmission system could cause high voltage issues. More reactive power absorbing devices would be necessary to accommodate the extra reactive power.

Figure C.2 : Flows during high solar periods

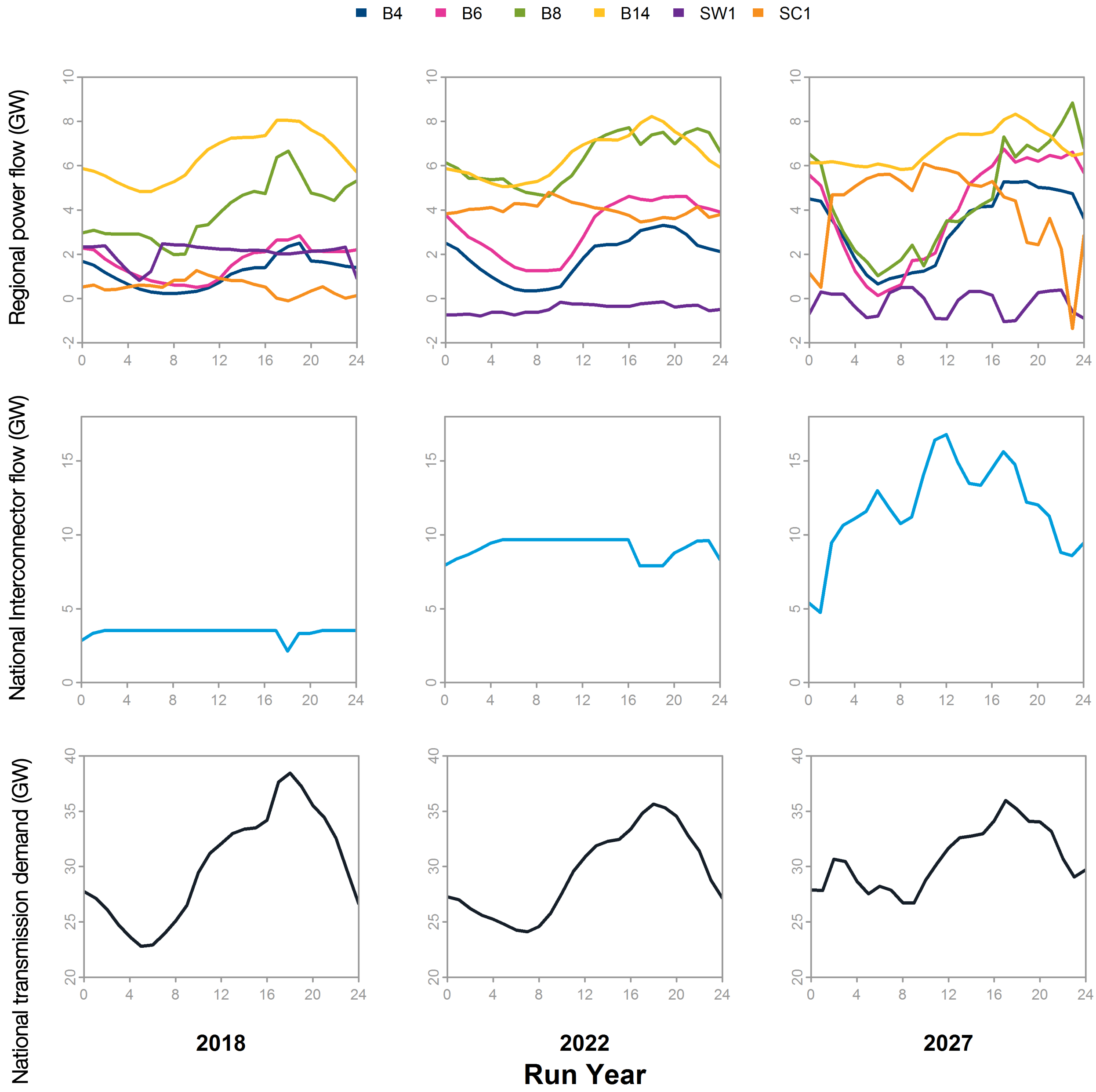


C.3 A high interconnector day

The regional flow profiles in a high interconnector flow day in 2018, 2022 and 2027 are illustrated in Figure C.3 for the Two Degrees scenario. Besides the national interconnector flow profiles and the national transmission demand profiles are also included.

In all these three days, there is a low wind output and low solar output. We could observe the interconnector flow is relatively stable in 2018. However as the volume of interconnector increases, the flow via interconnector becomes more volatile in 2022 and 2027. The change of flow via interconnector is mainly driven by the price signals in both the UK and European electricity market. This change would contribute to the change of power flows within the UK transmission network. We could observe the regional power flows are becoming more volatile from 2018 to 2027.

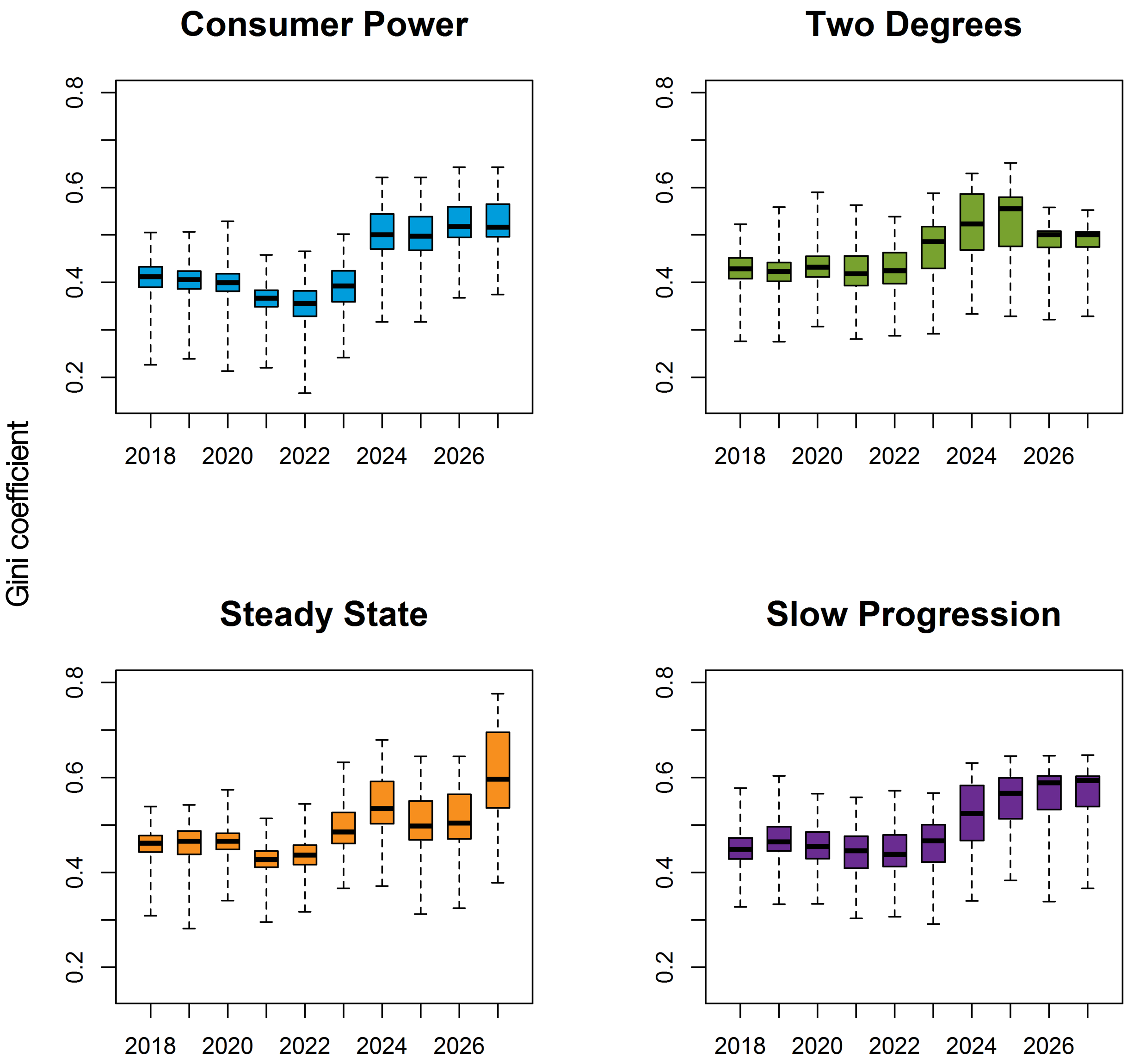
Figure C.3: Flows during high interconnector flow period in Two Degrees scenarios



Appendix D

Boxplots of Gini coefficients in all four scenarios

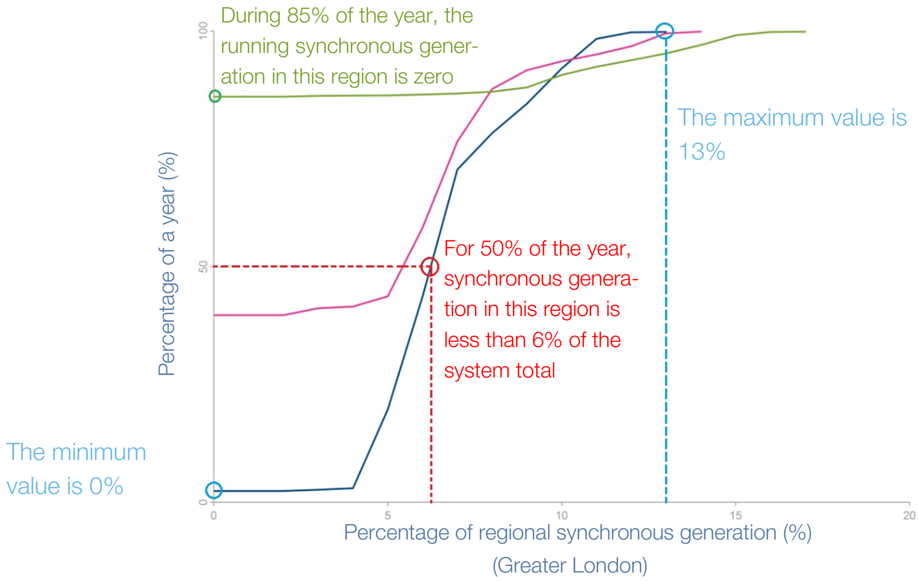
Figure D.1: Boxplot of Gini Coefficient of regional synchronous generation



Appendix E

E.1 Detailed description of load duration curve

Figure E.1: Detailed description of load duration curve



During 85% of the year, the running synchronous generation in this region is zero

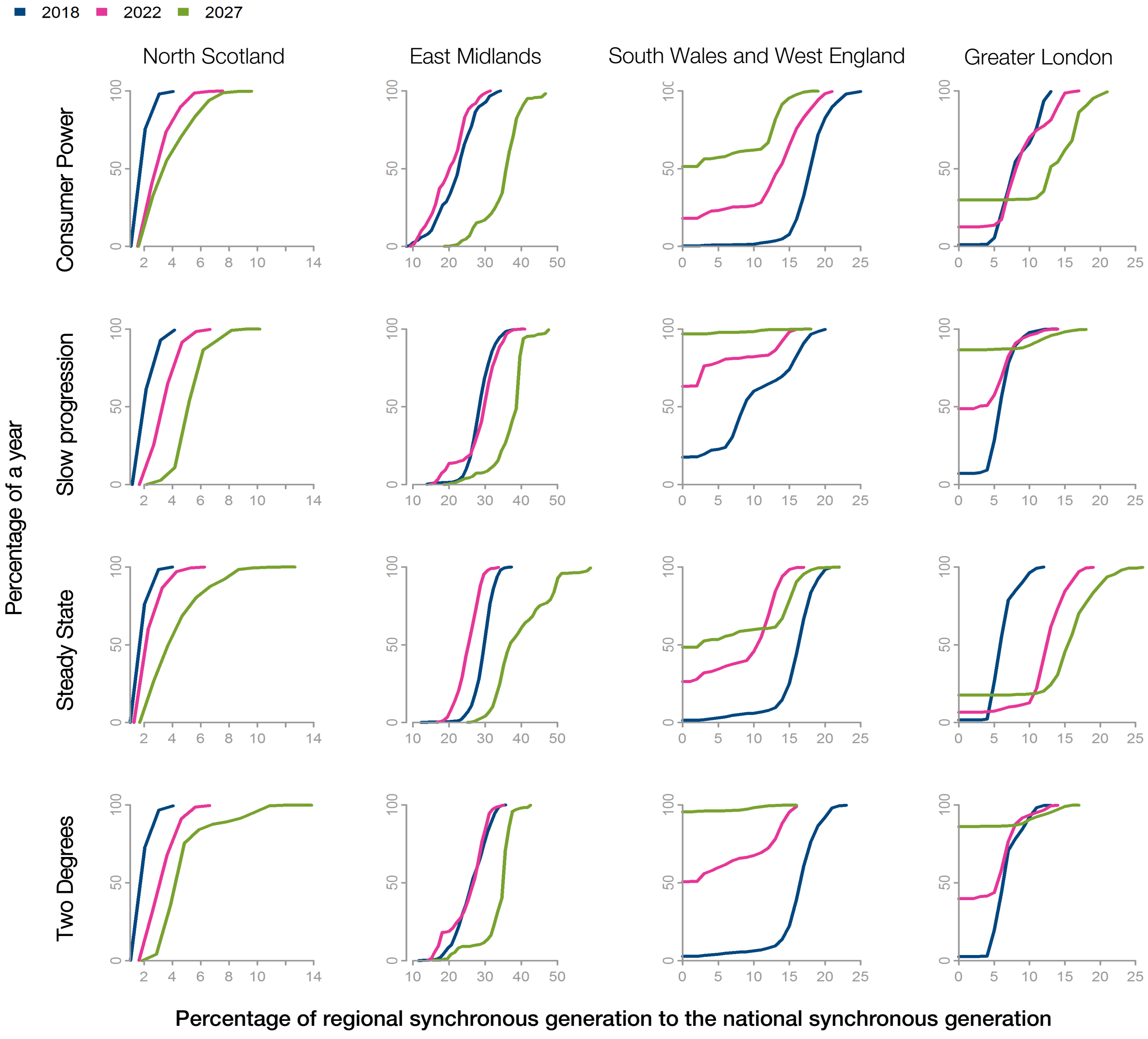
The maximum value is 13%

For 50% of the year, synchronous generation in this region is less than 6% of the system total

The minimum value is 0%

E.2 Load duration curve in all four scenarios

Figure E.2 Percentage of regional synchronous generation to the national synchronous generation



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