# Operating a zero-carbon GB power system: implications for Scotland

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## 1 Executive summary

### Background

In recent history, the British electricity sector landscape has changed as more renewables, particularly solar and wind, are connected to the power system. Since 2004, electricity generated from renewables in the UK has increased tenfold, and in 2019 37.1% of total electricity generated was from renewable sources [1]. These changes have far-reaching implications for the operation of national electricity networks and for ensuring security of supply.

The larger renewable installations are connected to the high voltage transmission network that interconnects the whole of Britain. Smaller ones are connected into the regional lower voltage distribution networks that, typically, transfer power from the transmission network down to each individual electricity users.

The technology used to convert the primary energy source into electricity is very different for renewables such and wind and solar from that used for thermal sources such as fossil fuels and nuclear fission. A common feature of wind and solar generators is the use of power electronic converters. Although the uptake of renewables is in keeping with Britain's emissions reduction and renewable energy targets, it has the side effect of displacing conventional fossil-fuelled generation and the technical characteristics that these synchronous machines[1] provide to power system operation. As a result, the British Electricity System Operator, National Grid ESO (NGESO), frequently needs to pay conventional power plants to come online and deliver key system services to ensure the security of electricity supply.

Ever since the first uses of electricity, demand for it has varied through the day, the week and the year. The services needed to operate Britain's power system are known as Balancing Services, primarily because they allow a correction of any failure by the wholesale electricity market to balance generation with demand minute-by-minute. They

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[1] Synchronous machines are alternating current (AC) motors and generators that are electromagnetically coupled to the rest of the power system. They are called synchronous because the rotor – the moving part that, in the case of a generator, is driven by a prime mover such as high pressure steam or falling water – rotates at a speed that is synchronised with the frequency of the AC voltage on stator that is connected to the power system.

include arrangements to remunerate owners of equipment connected to the transmission network, in particular generators, for contributions made to helping keep system frequency and voltages within acceptable limits. Other physical behaviours are not paid for directly. These include the high currents injected into the network by synchronous generators as an inherent part of their behaviour when short circuit faults occur on the network. These can cause problems when they exceed the capability of circuit breakers to interrupt the flow of current and isolate faults. However, some minimum level is also necessary to enable network protection equipment to identify where and when faults have occurred and to quickly and safely isolate them and preserve stability of the system as a whole.

Going forward, in April 2019 NGESO announced a target of being able to operate a GB electricity system with zero-carbon generation by 2025. In practice, this means that NGESO aims to operate the system without needing to take actions that would restrict the dispatch of zero-carbon generation in favour of providing balancing services using unabated fossil fuel power plants, avoiding the need to "constrain on"[2] such generators in addition to any that the wholesale electricity market might already be using. In order to achieve this, new service specifications and procurement mechanisms will be required to give NGESO the option of accessing services from zero-carbon technologies rather than coal and gas plants.

Current and emerging system operability concerns in GB cover a broad range of topics. Work recently completed at the University of Strathclyde, outlined in this report, has reviewed: how NGESO currently uses balancing services to manage the power system; possibilities for the future provision of frequency response and reserve; prospects for short circuit current support from power electronic converters; and market changes required to avoid the need for NGESO to constrain on fossil-fuelled generation to support system operability in 2025.

## Key findings

1. Largely as a result of the operation of smaller scale generators connected within the regional distribution networks, the minimum levels of demand for electricity experienced by the GB transmission system are lower than they have been for many decades. This means there is a need for new system services under lightly loaded system conditions.
2. £1.2bn was spent on balancing services in 2018/19, higher than any other year since 2011/12, with £615m of this due to the challenge of maintaining power system operability in the changing power landscape.
3. There has been a notable increase in participation of wind plant operators in the frequency response market. However, in the context of total volume of response, the increase is marginal.
4. NGESO has designed new 'end-state' frequency response services that will completely replace existing services by the last quarter of 2021/22. Their most significant feature for future system operability is the requirement for faster responses to system deviations than provided by present day services.
5. NGESO's 'end-state' frequency response services:

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[2] In the British wholesale electricity market, generators 'self-dispatch'; that is, their owners decide what their outputs should be in order to satisfy contracts for production of energy. However, the ESO may find that the full set of dispatches determined by the market fails to satisfy the system's physical limits. The ESO needs to carry out re-dispatch actions. These may include forcing certain generators to operate when originally they had not been scheduled – constraining them to come onto the system at the critical time – or forcing others not to, i.e. constraining them off.

   a. contrary to what NGESO has claimed, are not technology agnostic, seemingly favouring batteries over wind, solar, and some demand response;
   b. will be procured via a market that will include closer to real-time trading, and pay-as-clear (or uniform pricing) auctions;
   c. have a requirement to provide low frequency response (a higher production of power in response to a low system frequency) and a high frequency response (a lower production of power in response to a high system frequency). This is a barrier to some providers, and appears to be contrary to the EU Electricity Markets regulation of 2019;
   d. place a restriction on providers' portfolio provision from a single grid supply point where the distribution network is connected to the transmission system; and
   e. require technology upgrades to provide the required frequency response characteristics. This may be onerous for some providers.
6. Existing frequency response services are inadequate for a future GB power system. Although NGESO's new services are a viable replacement, as more fossil fuelled plants are displaced, the need for even faster-acting frequency response products will increase.
7. A lower boundary has been identified below which NGESO's new end state services perform with an increased risk to security of electricity supply. Rough estimates suggest that the increased risk exists for about 1% of the year in 2025, about 22% of the year in 2030 and even more with increased penetration of renewables.
8. The uptake of renewables in the power dispatch of any given day is also limited by the minimum baseload power supply from nuclear power plants which cannot be deloaded, constrained off, or used to provide frequency response.
9. Fast Reserve provides the ability to adjust power production close to real-time as errors in forecasts of demand or outputs from renewables become apparent resulting in an overall system imbalance. The need for Fast Reserve is expected to increase in the future, and there is an increasing need for downward regulation within Fast Reserve timescales.
10. At present, NGESO signs contracts with providers of Fast Reserve a month ahead of when it might be needed. This involves the agreement of terms for how much reserve will be available and what NGESO will pay for it. EU regulation may require the Fast Reserve service to move towards day-ahead procurement, but NGESO has requested a derogation for procurement to remain month-ahead. Because of the impossibility of knowing, with any degree of confidence, how much power would be available from non-schedulable resources such as wind and solar so far ahead of time, this would continue to prevent such providers from participating in this market even though, on sunny or windy days, they would reduce the possible need to constrain fossil fuelled plant on.
11. There is no existing market for short circuit current capabilities in GB, and such services are currently provided "free of charge" by synchronous generators.
12. The use of power electronic converters for short circuit current provision is limited by safety margins designed to protect the converter. Improving this capability would require increasing the size of the converter and therefore the cost which is linearly proportional to the size of the converter.

13. Although the finding is sensitive to assumptions made in the assessment, it is estimated that short circuit current from synchronous machines is cheaper than oversizing wind turbine power converters by a factor of 2 to 3.

## Recommendations

1. There is a need for the assessment of:
    a. the impact of closure of fossil-fuelled plants on short circuit current and of the procurement of frequency management services from a widening of diversity of technologies;
    b. definition of permissible and required performance envelopes for technology agnostic fast-acting frequency response services; and
    c. the impact on converter lifetime and reliability of providing large amounts of reactive power for regulation of system voltage.
2. Further action is required in market development for frequency management services including:
    a. industry engagement in the creation of a route-map for frequency response and Fast Reserve services;
    b. publication of detailed market data;
    c. unbundling of upwards and downwards frequency response and Fast Reserve products;
    d. closer to real-time procurement of Fast Reserve;
    e. procurement of even faster-acting frequency response in the near future;
    f. enabling distributed resources to form a portfolio provision from more than just a single grid supply point where the distribution network is connected to the transmission system; and
    g. enabling additional market platforms, e.g. futures and intraday.
3. Further work on determining the feasibility of oversizing converters to provide high currents during faults should be done alongside wind plant original equipment manufacturers (OEMs).
4. Future work on a short circuit current market is required including:
    a. investigation of the functionality of protection devices in low short circuit current conditions;
    b. the publication of minimum short circuit level requirements across the GB power system; and
    c. technology-agnostic future stability tenders with short circuit current provision separated from other services to allow alternative types of providers to participate.
5. Improved forecasting and the use of probabilistic forecasts would benefit operation of a low-carbon electricity system. There is also a need to review loss of infeed risks and frequency stability limits.
6. Finally, this study recommends the introduction of carbon accounting for all NGESO actions.

# Contents

# 2 Introduction

In recent history, there has been a change in the electricity sector landscape as more renewables, particularly solar and wind in Britain, are connected to the power system. Although this is in keeping with emissions reduction targets and the target for renewable energy in Scotland, it has the side effect of displacing synchronous generation. This results in a power system that is tending not only towards lower inertia, but also the loss of the inherent characteristics of synchronous machines and the services that the generators have provided around frequency and voltage stability, fault management, balancing and flexibility, system restoration, management of network thermal constraints and resilience to adverse weather conditions.

At the moment, the British Electricity System Operator, National Grid ESO (NGESO), frequently needs to bring conventional plant online to provide key system services. This means that the synchronous generators, which are offline, must be paid to come online and deliver the required services. However, going forward, NGESO announced in April 2019, a target to operate a GB electricity system with zero-carbon generation by 2025 [1]. In practice, this means that NGESO aims to operate the system without needing to take corrective actions that would restrict the dispatch of zero-carbon generation in favour of providing system services from thermal synchronous plants powered by unabated burning of fossil fuels. To achieve this, new service specifications and procurement mechanisms will be required to give NGESO the option of accessing services from zero-carbon technologies, rather than coal and gas plant. The uncertainty over the future of GB generation mix is a challenge for system planners and operators; the issues include conventional plant – such as nuclear – approaching end of life; scheduled new nuclear builds; significant new interconnection plans with mainland Europe; increasing volumes of embedded generation; and growth in wind generation, in particular offshore and in Scotland.

The current and emerging system operability concerns in GB cover a broad range of topics including: inertia and Rate of Change of Frequency (RoCoF); system frequency; system strength; voltage; balancing and flexibility; system restoration; and thermal constraints. Present work at Strathclyde investigates how we currently use balancing services to manage the power system, the future provision of frequency response, fault current support from power electronic converters, and market changes needed to achieve zero carbon from 2025. The investigation builds on previous work, e.g. [2], [3], [4] and the issues raised in NGESO System Operability Framework reports [5]. This report provides a high-level summary of the work undertaken, highlighting key outputs and avenues for future work. The details behind the summaries presented are available separately[3]. The work summarised in this report, and detailed in the Annex considers the GB power system. However, some aspects have particular relevance to Scotland. As a result, this report concludes with a discussion on security of supply in Scotland, and identifies the next steps of work in the Fellowship supported through ClimateXChange.

# 3 Review of system and network issues

Today, NGESO depends on gas and coal plants for a range of essential ancillary services and takes actions to ensure they are online and able to provide them. To enable zero-carbon operation, such services must be provided via non-generation assets, or zero-carbon

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[3] Detailed reports available at https://doi.org/10.17868/74793.

technologies must be given routes to market. In many cases, either the current technical specifications or procurement mechanisms prevent zero-carbon generators from participating. Using the Monthly Balancing Services Summary (MBSS) reports [6], we have reviewed the current suite of balancing services, as well as emerging system needs that may require new ancillary services in the future. However, it should be noted that, from the NGESO's reports, it is difficult for a third party to analyse the reasons behind various actions in the balancing mechanism (BM) – indeed, a single action could serve more than one purpose.

**Key outputs:**

1. In 2018/19, £1.2bn was spent on balancing services, higher than any other year since 2011/12, with £615m attributed to constraints, i.e. voltage, RoCoF and transmission network constraints.
2. It is noted that from April 2018, the MBSS reporting starts to distinguish between different constraints. In 2018/19, the majority of the balancing services spend is on transmission network constraints at £448.2m, followed by RoCoF at £143.6m and voltage constraints at £23.4m. The largest volume of service can be attributed to transmission constraints at 5.15 TWh, followed by RoCoF constraints at 3.29 TWh and voltage constraints at 1.82 TWh.
3. The spending on Black Start (the procedure used to restore power in the event of a total or partial system shutdown) has increased significantly from £19.2m in 2015/16 to £81.9m in 2016/17, and decreased to £48.9m in 2018/19.
4. NGESO doubled Fast Reserve[4] procurement to 600 MW from January 2020, indicating an increased need for flexible energy to manage forecasting errors.
5. NGESO has designed a new suite of dynamic frequency response services, Dynamic Regulation, Dynamic Moderation, and Dynamic Containment; the last two services are fast frequency response services, comparable to Enhanced Frequency Response (EFR). These new dynamic services are intended to replace existing dynamic services, along with a planned phase out of the Firm Frequency Response (FFR) market by the last quarter of 2021/22.
6. At the time of writing, NGESO stated an aim to procure a total of 1 GW of Dynamic Containment reserve, with an initial procurement of 500 MW this year.
7. In the frequency response market there is an increasing share of response volume from the commercial FFR market, at a utilisation price that makes it comparable to the cost of services in the Mandatory Frequency Response (MFR) market: £8.6/MWh for FFR and £4.2/MWh for MFR in 2018/19. A marginal increase of wind participation in the MFR market is also noted.
8. GB is experiencing increasing periods of low transmission demand, and there is an increase in demand for reactive power absorption due to high voltages under lightly loaded system conditions.
9. It is noted that power electronic converter-based generation, like wind plants, can produce reactive power support even when there is no wind. In addition, the BM mandatory reactive market does not transparently signal the requirement as it relies on dispatching MW to bring synchronous generators online and access reactive power capability.

This review also highlighted avenues for further work including: the assessment of the impact of plant closure on fault current; widening diversity of the technologies behind the

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[4] Fast Reserve is a service that is procured monthly. Providers of Fast Reserve deliver active power response within 2 minutes of electronic instruction at a delivery rate of 25 MW/minute, sustained for at least 15 minutes.

provision of Fast Reserve; the likelihood of angular stability issues due to rapid injection of active power following a network fault in an accelerating region; and the impact of providing large amounts of reactive power on converter lifetime and reliability.

# 4 Frequency management

One of the challenges associated with zero-carbon operation is frequency stability, particularly in scenarios with low inertia and/or demand on the transmission network. Frequency stability in the GB power system is managed in terms of both the RoCoF (dependent on inertia and the maximum loss risk) and frequency limits. Plans are underway to update the RoCoF settings of loss of mains (LoM) protection devices, and it is expected that by 2022 the GB power system will be compliant with Engineering Recommendation G99. However, since a significant[5] power imbalance at extremely low inertia could result in a RoCoF of 1 Hz/s, it is worth investigating the suitability of using the proposed frequency response services to contain such an event within frequency stability limits. Using models and tools designed for frequency studies, we considered existing, proposed and alternative frequency response services in a range of scenarios. We also investigated the impact that proposed frequency response services would have on the maximum penetration of non-synchronous generation, e.g. wind. Lastly, we considered the potential technologies for delivering frequency response in a 2025 zero carbon GB power system.

**Key outputs:**

1. Existing services are adequate for containing normal and infrequent loss events at levels of system inertia that lead to a RoCoF of 0.125 Hz/s, but they are inadequate for normal loss events at levels of system inertia that lead to a RoCoF of 0.5 Hz/s, and any loss event at levels of system inertia that lead to a RoCoF of 1 Hz/s.
2. At extremely low inertia values where a power imbalance results in a RoCoF greater than 0.5 Hz/s and tending towards 1 Hz/s, there is an increased value in the need for fast-acting frequency response services that are faster than the proposed definitions but can be slower than synchronous inertia.
3. The ESO’s proposed frequency response products, as they are defined, are adequate for containing normal and infrequent loss events at levels of system inertia that lead to a RoCoF of both 0.125 Hz/s and 0.5 Hz/s, but inadequate for normal loss events at levels of system inertia that lead to a RoCoF of 1 Hz/s; at this low inertia there is also an increased risk of frequency instabilities that depends on the specific control design deployed and how much faster the service activates compared to the delay defined in the requirements.
4. System inertia thresholds of 79 GVAs and 60 GVAs were identified as a boundary beyond which the risk of instability increases for containing 1.32 GW and 1 GW normal loss risks. Inertia data from the ESO suggests that this boundary occurs up to about 1% of the year in 2025, but in a 44% average penetration of non-synchronous generation in 2030 the boundary can be reached or breached up to 22% of the year. This risk can be remedied by introducing a definition for a fast-acting service(s) that activates within 250 milliseconds (ms) of

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[5] E.g. a normal loss of 1 GW of power supply or demand, as defined by the Security and Quality of Supply Standard (SQSS) [11], at 25 GVAs of inertia, or the maximum infrequent loss risk 1.8 GW at 45 GVAs of inertia. See Table II in [2] for loss risk definitions and frequency conditions.

the event, such as the Improved Frequency Containment (IFC) service or Synthetic Inertia.

5. The IFC service can be deployed in tandem with the ESO's proposed services, and can tolerate deactivation after the initial response period; however, it is shown that in some instances deactivation of the service would require an additional secondary service to keep frequency within acceptable limits.
6. Synthetic inertia[6] can also provide benefits to frequency containment, but the service definitions will need to include specifications to any recovery period.
7. The system non-synchronous penetration limit (SNSP) is mostly restricted by the RoCoF limit. Once the changes to the RoCoF settings of LoM protection take place, the RoCoF limit increases; however, with a relaxed RoCoF limit of 0.5 Hz/s or 1 Hz/s there is minimal difference between the SNSP trends produced by either existing frequency response services and proposed frequency response services. This is primarily due to the limiting constraint of baseload power supply from nuclear power plants and it being assumed that the nuclear units cannot be deloaded, constrained off, or used to provide frequency containment reserve[7].
8. It is noted that the SNSP is specific to the assumptions used in the simulations, i.e. the persistence of static response reserve at 250 MW for both Primary and Secondary response services across all scenarios, the fixed constraint of minimum baseload power provided by nuclear power, the size of the loss, and the amount and types of available energy response. Alternative approaches for investigating penetration limits such as the critical inertia and containment component metrics [3], can improve the understanding of penetration/containment limits while accounting for scenario variations.
9. It is likely that synchronous generators will continue to participate in the frequency response market after the ESO replaces existing services with the proposed services, with the most likely product being Dynamic Regulation.
10. Non-synchronous technologies are uniquely suited to fast response services such as Dynamic Moderation and Dynamic Containment. Variable resource technologies like wind can meet some of the compliance requirements for Dynamic Moderation and Dynamic Containment, but the inclusion of storage can improve the certainty of power availability and compliance with service definitions, while also offering a route to surpass limitations if VSM is also deployed.

The studies conducted while completing this work also highlighted avenues for further work including: an assessment and definition of permissible/required activation and deactivation behaviours or performance envelopes for fast-acting frequency response services; an analysis to understand the viability of an interplay between a deactivation frequency containment service and an activating frequency restoration service; and the use of models of provider technologies to further assess their benefits and limitations, particularly when considered in a multi-node model of the power system.

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[6] See Appendix 1 for definition of synthetic inertia and distinction from fast frequency response.

[7] In practice, the output of the pressurised water reactor at Sizewell B can be turned down, albeit at a cost to the ESO and payers of Balancing Service Use of System (BSUoS) charges. The original contract to turn down the output from Sizewell was for the 7th May to 19th June 2020 but this contract has been extended to 10th August 2020. Although the contract is commercially sensitive NGESO have stated a total cost in the range £34 to £46 million depending in market power prices [12, 13].

# 5 Fault current support from power electronic devices

Power electronics play a key role in the integration of renewable power into the power system as the major part of renewable resources have different voltage and frequency requirements and cannot be directly connected. A power converter acts as an interface allowing and optimising the power extracted from the renewable energy source (RES), while also providing grid support and grid code compliance. Power electronic converters, compared to synchronous machines, present very different dynamic characteristics, as they cannot be overloaded even for periods of less than a second if the converters are using IGBT semiconductor devices, as all commercial ‘voltage source converters’ (VSCs) do[8]. If more current is required from the converter, the power converter should be oversized, and this will have a definite impact on the cost. This section considers the power converter limitations and behaviour during the fault, as well as an economic assessment of the different converter technologies for the provision of overcurrent capabilities.

**Key outputs:**

1. There are different VSC power converter solutions (topologies) for grid-tied applications, depending on the energy sources and/or grid requirements. Two-level power converters are used in low power and voltage applications and multilevel converters are used in medium to high voltage and high-power applications.
2. Power semiconductors have to operate within their safe operating area (SOA), where the voltage, current and power capabilities are defined. If the converter’s current, voltage or power exceeds the SOA, the power switch can be destroyed.
3. The converters’ SOA is further limited by the systematic safe operating area (SSOA). As large current and voltage transients exist in the converter, the SOA is further limited to allow room for the current and voltage transients.
4. Optimal electromagnetic and thermal design could be helpful for the maximum utilisation of the semiconductor power capability. However, converter optimisation aiming at enlarging the semiconductor capability is quite limited due to the fast nature of the transients.
5. With the implementation of current control, the power converters have the capability to control the current on its alternating current (AC) side, limiting the current in case of a fault and allowing the converter to continue operating during a fault. Converter control could help in the development of solutions to meet the grid code requirements.
6. Power converters and other related components for grid-tied applications have a cost of around $0.04-0.1k/kW (equivalent[9] to 3% of the turbine cost for onshore or 5% for offshore), which are proportional to the power ratings. Thus, increasing the current capability of the power converter generally implies increasing the cost linearly.

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[8] Older power electronic installations in Britain such as the interconnector to France and most existing SVCs use ‘line commutated converters’ that make use of thyristors as the switching devices. Newer converters such as more recent HVDC connections and wind turbines and solar PV equipment use ‘voltage source converters’ that use IGBTs as the switching device.

[9] According to the International Renewable Energy Agency in [15, 16].

7. Further work on determining the feasibility of oversizing converters to provide overcurrent during faults should be done alongside wind plant original equipment manufacturers (OEMs).

# 6 Market needs

NGESO is reviewing frequency response and it has proposed “end-state” frequency response services including: Dynamic Regulation (DR), Moderation (DM) and Containment (DC). Although NGESO is also reviewing its reserve services, the direction of future reserve services is unclear. Fault current performs key roles in contributing to a voltage waveform, which is essential for other connected equipment to function, especially converters’ “Phase-Locked Loop” control systems under fault conditions. A high fault current is also necessary for protection to detect and discriminate a fault.

Although there is an established and evolving market for frequency management services, there has not been, to date, a market for fault current, because it is provided “for free” by synchronous generators. However, with changing generation patterns, system strength, measured by short circuit levels, is falling in some parts of the country. Actions taken by NGESO to address this and other stability concerns led to the Stability Pathfinder Phase 1 tender, which procured inertia, along with a defined minimum fault current delivery. Although the tender was only open to synchronous technologies, data from the tender provides an insight into pricing, based on tender participants’ MVA ratings and tendered prices, and can give an indication of a future fault current market. This market data has been used to estimate possible capital costs of fault current provision from synchronous plant, in £ per MVA rating (based on assumptions detailed in the full report of the study). The Market Needs: Fault Current report goes on to compare estimated capital costs of synchronous plant with those of oversizing power electronic converters to deliver fault current.

**Key outputs:**

1. Most (and until November 2019, all) existing commercial frequency response services are accessible to schedulable[10] providers only.
2. The proposed end-state frequency response services:
    - have positive features including, closer to real-time trading, potential unbundling of upwards and downwards regulation in Dynamic Containment, and pay-as-clear auctions;
    - are not altogether technology agnostic, seemingly favouring batteries over wind, solar and some demand response;
    - have a requirement for symmetrical, rather than separate upward and downward, frequency response provision, which is a barrier to some providers and appears to be contrary to the EU Electricity Markets (recast) regulation of 2019;
    - place a restriction in geographical area of a frequency response providers’ portfolio which will be detrimental to some, and require controller/software updates to provide the required frequency response characteristics which may be onerous for some providers.
3. The need for Fast Reserve is expected to rise in the future, and there is an increasing need for downward regulation within the Fast Reserve timescales.

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[10] Schedulable providers being a source of power for which a non-zero output can be planned for any time of the day with a high degree of confidence some days ahead. In this case, commercial frequency repose services are procured in month-ahead tenders for delivery periods up to two years.

4. EU regulation may require Firm Fast Reserve to move towards day-ahead procurement, but NGESO has requested a derogation for procurement to remain month-ahead, which would continue to prevent non-schedulable providers from participating in this market.
5. Based on prices that were awarded to successful new-build stability phase 1 tender applicants and assuming usual synchronous plant performance of 3-5 per unit MVA under fault conditions, fault current provision could be judged to have been acquired at prices from around 30 pence to £1 per rated MVA per settlement period, for contracts around five years in length. (Prices would be proportionately higher if providers deliver only the minimum requirement of 1.5 per unit.) Some existing thermal plant offered fault current at lower prices.
6. Equivalent fault current from synchronous plant appears to cost less than oversizing power electronic converters, probably by a factor of 2 or 3[11], measured in capital cost per unit of fault current. Cost ranges are broad and overlap, and these estimates are sensitive to assumptions about the tender participants' business models.
7. The power system of the island of Ireland is in the process of introducing two products: Fast Post Fault Active Power Recovery, to be delivered within 250ms of a voltage perturbation; and Dynamic Reactive Response, to be delivered during voltage dips.
8. Like GB, the Australian power system does not have a fault current market. However, there are suggestions around modifying protection components.

Our investigation identified further actions required in market development for frequency management including: unbundling upwards and downwards frequency response products while moving towards a day-ahead market; procurement of even faster activation times in the near future; enabling portfolio provision beyond a single grid supply point; and enabling additional market platforms, e.g. futures and intraday. Similarly, in terms of Fast Reserve, further actions required in the market development were identified, including: industry engagement in the creation of a route-map for end state services that includes unbundled upwards and downwards regulation; closer to real-time procurement; and publication of detailed market data. In addition, the investigation identified future work within fault current market needs including: the publication of minimum fault level requirement across the GB power system; investigation of the functionality of protection devices in low fault current conditions; and technology agnostic future stability tenders with fault current provision separated from other services to allow alternative types of provider to participate. Furthermore, improved forecasting and the use of probabilistic forecasts would benefit operation of a low carbon electricity system, and there is a need to review loss of infeed risks, RoCoF settings on LoM protection, and frequency limits. Finally, this study recommends the introduction of carbon accounting for all NGESO actions.

# 7 Security of electricity supply in Scotland

Questions are raised regarding the security of electricity supply in Scotland, particularly in light of the ambitions for zero-carbon operation of the GB power system, and renewables targets that foresee substantial growth in wind generation. Furthermore, the closure of Cockenzie and Longannet power stations and the expected closure of Hunterston and

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[11] Details are available in the Annex.

Torness nuclear power stations leaves Peterhead as the sole large synchronous generator in Scotland capable of sustaining a maximum output for a number of days[12].

With this changing landscape, along with an expected growth in peak demand, it is likely that the flows across the transmission network in and out of Scotland would vary from large amount of exports in windy weather to large amounts of imports when conditions are calm. NGESO's 2019 Electricity Ten Year Statement (ETYS) [7] indicates an expectation that Scotland would generate between 18 and 30 GW of power by 2035[13], with gross[14] demand not expected to exceed 6 GW by 2040, significantly less than generating capacity and leading to increasing exports to England. Network reinforcements would be needed to accommodate the thermal loading of network branches under such high export conditions. However, with such high transfers and with plant in Scotland, as currently envisaged, adding up to very little inertia once Torness has closed, it is not known what impact a short circuit fault on an export boundary would have on angular stability within Scotland. Furthermore, a point made in the ETYS is the necessity "… for conventional synchronous generation to remain in service in Scotland to maintain year-round secure system operation" due to the possibility of high south to north flows under high demand, low wind conditions).

Enough schedulable plant to meet demand within Scotland might also be judged to be prudent for scenarios under which loss of the connection to England is thought to be likely or a Black Start of the whole GB system is being undertaken, although such scenarios should be very rare. The System Operability Framework (SOF) report on regional trends and insights[15] in [8] further draws attention to concerns around short circuit current, and the need for dynamic reactive power sources to deal with rapid changes in power flows arising from variability of wind farm output combined with variation in demand. In addition, the declining penetration of synchronous generation in Scotland could give rise to other issues such as converter instability, mal-operation of protection devices, voltage unbalance, voltage dip, harmonics and flickers. There is also the need to have resources available to manage forecast errors. Along with the use of energy storage and demand side flexibility, changes such as NGESO's new suite of frequency response products, the power available signal from wind, and improvements to Fast Reserve could be deployed to address at least some of these challenges.

There are some suggestions of steps worth considering to address the volatility of regional flows, including: dispatching more flexible resources such as energy storage and demand side flexibility; automated dynamic reactive power support; and improved wind and demand forecasts. NGESO has a number of initiatives designed to mitigate the challenge including the power available signal from wind plants, which improves certainty of the assets' capability and could increase wind participation in balancing services. The 1st stability framework tender procured inertia and reactive power capability via 12 contracts for synchronous machines, three of which are planned for Scotland[16]. Virtual synchronous machines have been trialled at wind farms[17] and show promise in being able to emulate the behaviour of synchronous machines. However, capabilities are limited both by the rating of

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[12] The next largest synchronous units in Scotland after Peterhead are Foyers (150 MW each) and Cruachan (110 MW each) pumped storage hydro plants.

[13] Interconnectors and storage account for up to 5 GW.

[14] Note that this is not peak demand. Gross demand is the volume of active import with no adjustment made for active export.

[15] The report also comments on variability and susceptibility of GB to rapid changes to regional flows due to variable interconnector operations that are driven by pan-European market signals.

[16] Cruachan pumped storage hydro plant and two new builds in Keith. It may also be noted that SP Transmission has a number of synchronous compensators in its RIIO-T2 business plan.

[17] E.g. the trail at the 60 MW Dersalloch wind park, details of which are available in the Annex. See also an earlier Siemens trail in [14].

the power electronic converter and, such as in the case of use at a wind farm, variability of the source of energy. While promising, it is worthwhile testing these and other solutions in the context of the challenges posed to Scotland by the changing power landscape using a multi-node model of the power system that focuses on Scotland.

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# 9 Appendix

Synthetic inertia as defined by the European Network of Transmission System Operators for Electricity (ENTSO-E) is “… the facility provided by a power park module or HVDC system to replace the effect of inertia of a synchronous power generating module to a prescribed level of performance” [9]. Eriksson, Modig and Elkington in [10] define synthetic inertial response as “… the controlled response from a generating unit to mimic the exchange of rotational energy from a synchronous machine with the power system. (…) [It is] the controlled contribution of electrical torque from a unit that is proportional to the RoCoF at the terminals of the unit. (…) The constant of synthetic inertia $H_{syn,i}$ for a generator *i* is defined by the relationship between the terminal frequency $\omega_t$ and $\Delta P_{e,i}$” as shown in equation (1). On the other hand, fast frequency response is defined by Eriksson et al. as “… the controlled contribution of electrical torque from a unit which responds quickly to changes in frequency in order to counteract the effects of reduced inertial response”. That is, according to them, while synthetic inertial response is proportional to RoCoF, fast frequency response is proportional to frequency [10].

$$\Delta P_{e,i} = -2H_{syn,i}\frac{d\omega_t}{dt}\omega_t \tag{1}$$

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