climate change

Scotland's centre of expertise connecting climate change research and policy

Security of Scottish electricity supply: gauging the perceptions of industry stakeholders

Marcel Nedd and Keith Bell, University of Strathclyde
September 2021

DOI: http://dx.doi.org/10.7488/era/1776

Executive summary

Efforts to reduce greenhouse gas (GHG) emissions together with the increase in electricity generated from renewable energy are dramatically changing the electricity supply landscape. Among other things, this has involved the closure of large, fossil-fuelled thermal power stations. Such changes introduce challenges associated with security of electricity supply including: having access to enough dependable sources of electricity to meet all of the demand for power sufficiently often; and preventing, containing and recovering from interruptions to supply arising from disturbances. The latter includes the capability to restore supplies following a blackout of the whole country.

This document reports and reviews the opinions of industry experts and stakeholders regarding security of electricity supply in Scotland, collected in May 2021 via an online survey and subsequent discussions in a roundtable event (conducted under 'Chatham House rules') in July 2021. The survey elicited responses from 42 individuals from across the electricity sector while the roundtable was attended by 27 individuals including sector representatives. As well as perceptions of the status of security of electricity supply today and in the future, this report presents the consulted stakeholders' views as to the most significant challenges and the steps needed to ensure security of electricity supply as the energy transition proceeds.

The electricity system in Scotland is privately owned and regulated by the Office of Gas and Electricity Markets – Ofgem. As well as energy users, it has a large number of stakeholders:

- producers, traders and retailers of energy;
- facilitators of transfer of energy between producers and users, i.e. the network owners and the Electricity System Operator (ESO), collectively identified as the 'network licensees';

- providers of services that facilitate operation of the system and balancing of generation and demand in real-time, e.g. 'aggregators' and owners of generation or energy storage;
- consultants and researchers who provide services to other stakeholders; and
- policy makers.

All these stakeholders – including policy makers from both the UK and Scottish Governments – were represented in the survey and in the roundtable, together with representatives of energy users.

A high-level overview summarising the consulted stakeholders' perception of the status of the security of Scottish electricity supply is shown in Figure 1, based on the results of the online survey. The responses have been translated into a red, amber, green (RAG) scale and related to either confidence in, or significance of, different aspects of security of electricity supply. In assessing the status of the security of electricity supply, five aspects of security of electricity supply were considered along with two other aspects related to environmental sustainability.

Security of electricity supply aspects

1. **Electricity imports:** If there is not enough power available from power plant within a particular area at any one time to match demand in the area, demand could still be served by importing power from neighbouring areas with which there is an interconnection. The volume of imports of electrical energy is considered in the context of the GB power system and Scottish power system within it.
2. **Meeting Scottish power demand:** Central to electricity security of supply is the capability to meet the consumer's power demand with a sufficient level of reliability. Considering the transitioning power system, it is important to be confident that demand for electrical energy can be met reliably both now and in the future.
3. **Power system operability:** Operability of the power system concerns the ability to operate a stable system in which its physical limits and those of its various elements are respected. This aspect is considered both in the context of the GB power system and Scottish power system within it.
4. **Scottish power system resilience:** A resilient power system is one that can prevent, contain and recover from interruptions to electricity supply arising from disturbances to the system.
5. **Power system restoration:** In the event of a widespread disruption the power system must be able to quickly[1] restore critical supplies, and thereby minimise the impact of the disruption to electricity supply. Although the question posed to the participants gives an example in the Scottish context, the discussion is broadened to include both Scotland and GB.

Environmental sustainability aspects

1. **Meeting Scottish greenhouse gas emissions targets:** This aspect provides insights as to the perceptions of power industry experts and stakeholders on the likelihood of achieving Scottish 2030 and 2045 emissions reduction targets.

[1] 'Quickly' is subjective but in the context of this work it refers to the timeliness defined in the proposed Restoration Standard [31] (see section 8).

2. **Meeting Scottish offshore wind ambitions:** This aspect provides insights on the perceptions of power industry experts and stakeholders on the likelihood of achieving 11 GW offshore wind capacity by 2030.

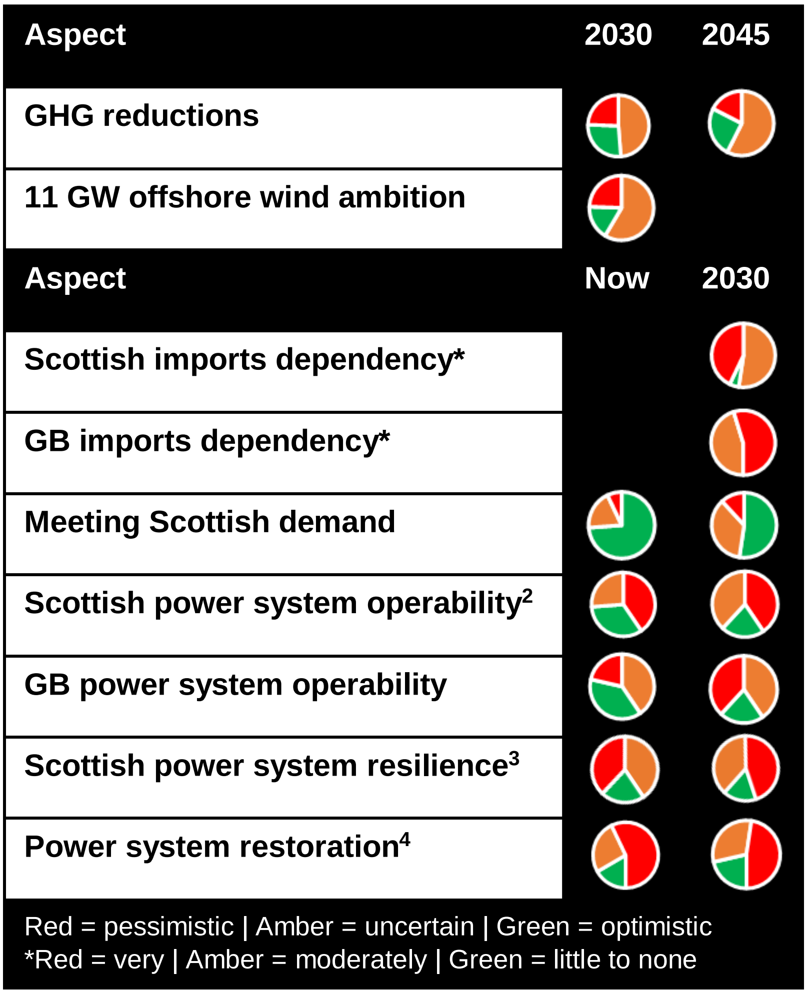


Figure 1: High-level overview of consulted stakeholders' perceptions of the status of Scottish security of electricity supply.

Key messages

A number of key messages emerged from the survey and roundtable, highlighting stakeholders' perceptions around:

- greenhouse gas reductions and renewables targets;
- reliably meeting Scottish electricity demand;
- operability of the electricity system in Scotland, i.e. for it to be continuously operated in a stable manner; and
- resilience and restoration.

[2] The operation of a stable system in which its physical limits and those of its various elements are respected.
[3] To prevent, contain and recover from interruptions to supply arising from disturbances.
[4] Re-starting a power system – "black start" after "the lights have gone out" – and supplies are restored.

The coloured boxes relate to optimistic (green), uncertain (amber) or pessimistic (red) views expressed via the survey and roundtable. The boxes also highlight some specific observations made by the stakeholders.

Greenhouse Gas Reduction and Renewables Targets
The consulted industry experts and stakeholders strongly support the reduction of greenhouse gas emissions to net zero.
There is uncertainty among industry experts and key stakeholders around Scotland's ability to achieve its 2030 and 2045 greenhouse gas (GHG) emissions reduction targets.
There are more pessimists than optimists in respect of the likelihood of meeting the Scottish Government's ambition for 11 GW of offshore wind generation capacity by 2030
There is some concern about the ability to meeting electricity demand during long periods of low wind and solar production – wind 'droughts' with low levels of light, known as "dunkelflaute". These concerns are argued by some stakeholders to mean that there is a case for additional 'schedulable'[5] generation or storage capacity within Scotland instead of allowing interconnectors to mean that less capacity is built locally.
There is general agreement that decarbonisation of electricity needs to be pursued in the context of the wider energy system and to consider how the interconnected elements of the energy system interact, including due consideration given to cybersecurity and consumer protection.

Security of Electricity Supply – System Operability
There are doubts about current and future power system operability for both the British system and the Scottish power system within it, with operability expected to become more challenging between now and 2030.

Security of Electricity Supply – Reliably Meeting Scottish Demand
Industry experts and stakeholders have considerable confidence in the current capability of reliably meeting Scottish electricity demand.
There is an expectation of flexible demand playing a more active role, with an increasing proportion of demand becoming a controllable element rather than a passive one. Caution is raised around a number of commercial, regulatory and engineering factors associated with such a transition, including management of such a complex system with numerous controllable demand elements.

[5] These are plants with highly predictable availability of power such that production can be scheduled a number of days in advance with high confidence.

There was a general view that a balance is needed between dependence on imports for security of electricity supply and locally sourced power capacity, and that the mix of resources can be determined by least-cost options and/or political will.

Security of Electricity Supply – Resilience and Restoration
There is a feeling of concern around the trend of the Scottish power system's ability to prevent, contain and recover from interruptions to supply arising from disturbances, i.e. its resilience.
There are concerns among some stakeholders around existing markets which are perceived to present barriers, particularly to renewables developers, in deploying novel solutions because there is currently no incentive to proceed with their development
There is a prominent role for governments to play, to drive change forward so that deployment of solutions can catch up with policies and the need for solutions.

Recommendations

The observations made by survey respondents and by roundtable participants allow a number of recommendations to be made to the key electricity sector stakeholders. The authors of this report have used their own judgement in ascribing the different recommendations to particular parties.

The Scottish Government is recommended to:	**The electricity system operator (NGESO) is recommended to:**
Provide a clearer communication of greenhouse gas (GHG) emissions reduction targets and clarity on whether targets are territorial within Scotland or within the UK.	Develop and agree with the rest of the industry a clearer set of definitions of Balancing Services markets and encourage the participation of renewables, especially since these technologies are displacing large thermal power stations.

The electricity supply industry, in particular the network licensees and Ofgem, is recommended to:

Bring forward a vision for managing an increasingly complex electricity system, with numerous controllable demand elements, while also ensuring consumer protection and cyber security.	Revise existing sector standards to ensure that equitable and well-regulated system and network services can be efficiently and effectively delivered and coordinated.	Address concerns that deployment of engineering solutions is lagging need and investigate and resolve perceived market barriers.	Explore ways in which local electricity networks and 'resilience as a service'[6] can contribute to security of supply.

The UK and Scottish Governments are recommended to:

Forge closer cooperation between both governments to drive change so that deployment of solutions can catch up to with emissions reduction policies, the needs of citizens, public bodies and businesses for resilient electricity supplies, and the opportunity for new solutions. A united front between UK and Scottish governments would be a strong basis for a wider partnership with the regulator, private companies and consumer.

Give close consideration to the costs and benefits of facilitating new pumped storage hydropower projects, as these technologies could help with many of the security of electricity supply challenges associated with a net-zero electricity system, as well as wider issues associated with the integration of renewables.	Ensure vulnerable groups and regions are not disadvantaged in the prioritisation required in the process of restoring the electricity system following a national black out, as laid out in the new system restoration standard.	Consider the introduction of a regional capacity market or a similar mechanism that might, for example, stipulate the type, power and energy capacities of production or import capability.

[6] There is an innovation project called Resilience as a Service (RaaS) that is funded through Ofgem's Network Innovation Competition. This project aims to develop a new market-based solution aimed at helping maintain supply in the event of a loss of power from the main network.

Contents

1 Introduction

Scotland's electricity system – its power system – has been interconnected with that of England and Wales and operated as a single 'synchronous area[7]' since before the Second World War. Since 2005, there has been a single, GB-wide wholesale market for electricity with a single system operator; the latter is the responsibility of the National Grid Electricity System Operator (NGESO). The electricity transmission network assets in Scotland are operated at nominal voltages of 132 kilovolt (kV) and above. They are owned by Scottish Power Transmission in the south of Scotland and Scottish Hydro Electric Transmission in the north. The lower voltage networks in Scotland – the distribution networks – are owned and operated by Scottish Power Distribution in the south and Scottish Hydro Electric Power Distribution in the north. A large network of licensed power producers, i.e. generators, and retailers, operate across Scotland. The sector across Great Britain (GB) is regulated by the Office of Gas and Electricity Markets (Ofgem).

There are questions over the security of supply in Scotland for several reasons. Scotland has ambitious targets to reduce greenhouse gas (GHG) emissions 75% by 2030 (relative to 1990 levels) and to achieve net zero by 2045. The Scottish Government is also aiming for 11 gigawatts (GW) of offshore wind capacity by 2030 [1, 2]. The Cockenzie and Longannet power stations have already ceased operations and it is expected that the Hunterston[8] and Torness nuclear power stations will also be closed. In this changing power system landscape, Peterhead will be the sole large synchronous[9] generator in Scotland capable of sustaining a maximum output for a number of days[10]. Instead of from large 'thermal[11]' power stations, much of Scotland's electrical energy is already coming from wind farms and, to a lesser extent, solar PV arrays. These both make use of power electronic converters[12] to interface with the grid.

Synchronous generators provide 'inertia'[13] which provides stability to the system in the first few seconds after a fault. Inertia is the engineering term for the kinetic energy associated with the rotation of the electrical generators which, in synchronous machines is in effect 'locked in' to the frequency of the system by fundamental laws of physics. When short circuit faults happen on the network, protection equipment can detect them. A large short circuit current[14] – driven by the behaviour of synchronous machines –

---

[7] Meaning that all regions are connected and operate under the same frequency.

[8] Expected decommissioning date of January 2022 [50].

[9] 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 the stator that is connected to the power system.

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

[11] Power stations that make use of high-pressure steam to drive synchronous generators.

[12] Power electronic converters comprise particular configurations of many individual, high power, high voltage semiconductor switches and are used to convert between DC power and AC power at the desired frequency and voltage.

[13] The energy stored in large rotation generators and motors.

[14] This is the amount of current that flows on the system during a short circuit fault, i.e. when a current path is made that is shorter than the system is designed to operate with. It can be caused by, for example, a lightning strike or

requires appropriate equipment to safely break the current and isolate the affected section of network. However, that large current also makes it possible to detect the fault and to work out where it is. Asynchronous generation, such as wind farms, uses power electronics to form an interface to the network. The software to control the power electronics can be written very flexibly so that interaction with the rest of the power system can be done in a variety of different ways, e.g. to help to control voltages in a similar manner to that of conventional generation, but the amount of current that can be carried by the power electronic devices is strictly limited. This means that the currents flowing in the event of short circuits on the network are much lower than they would be with synchronous machines, potentially presenting challenges for detection of faults and stability of the system.

> *"The magnitude of the south to north power flows is low compared to those in the opposite direction so network capability should be sufficient to support those conditions. While the south to north transfer capability is enough to meet demand in Scotland, it is still necessary for conventional synchronous generation to remain in service in Scotland to maintain year-round secure system operation." – [3]*

A growth in peak demand is expected as a result of the electrification of heat and transport. In future, it is likely that the flows across the transmission network, in and out of Scotland, will vary from large amounts of exports in windy weather to large amounts of imports when conditions are calm. NGESO states in the 2020 Electricity Ten Year Statement (ETYS) [3] that the secure capability[15] for transfers across the Anglo-Scottish (B6[16]) boundary remains at 5.7 GW, with the limiting factor being the post-fault rating[17] of transformers at Harker. The ETYS adds that gross demand in Scotland is not expected to exceed 6 GW by 2040 but electricity generation capacity in Scotland is expected to reach between 18 and 38 GW by 2035[18], and therefore north-to-south[19] transfers "[…] could be more than double compared to what they are today in some scenarios." [3] Increased exports of power from Scotland to the rest of GB would need network reinforcements to accommodate the high loading of network branches under

high wind causing the electrical insulation between two conductors to break down allowing current to flow between them. If not identified and isolated, it can cause the system to be unstable. It also represents a potential threat to human life in the vicinity of the short circuit.

[15] This is the boundary capability that was expected for 2020/21 winter peak.

[16] At the time of writing, power is transferred across two 400 kV double circuits, two 132 kV circuits, and the Western HVDC link.

[17] When current flows through a conductor, heat is generated. The magnitude of current that can be carried by any conductor on the system – an overhead line, transformer, underground cable, generator or load – is limited by how hot it might get. When a fault happens somewhere on the network and it is detected and isolated, the current carried by other branches of the network increases, and the temperature of the components of that branch will increase. The "post-fault" rating is the maximum amount of power that can be carried under such circumstances without breaching temperature limits.

[18] Note that in a highly decentralised scenario like Leading the Way, distribution connected generation in Scotland could reach over 13 GW by 2040.

[19] Used here to refer to transfers across the Anglo-Scottish (B6) boundary. North-to-south means transfers from Scotland to England, while south-to-north is the reverse.

such high export conditions. NGESO's power transfer projections, based on different Future Energy Scenarios [4], show a mostly exporting north-to-south picture.

However, with such high transfers and plant in Scotland, as currently envisaged, adding up to very little inertia once Torness has closed, there is no published information on the impact to stability of the system when there is a fault on an exporting boundary. The System Operability Framework (SOF) report on regional trends and insights[20] produced by National Grid ESO [5] further draws attention to the need for resources to address operability challenges arising from variability of wind farm output combined with variation in demand. Therefore, deploying enough schedulable[21] plant to meet demand within Scotland would be useful:

- for scenarios under which loss of the connection to England is thought to be likely or a Black Start[22] of the whole GB system is being undertaken (although such scenarios should be very rare); and
- to maintain secure operation in Scotland due to the possibility of high south-to-north flows under high-demand, low-wind conditions [3].

The power system's transition to zero carbon or even, via a combination of bioenergy and carbon capture and storage, a net-negative emitter is an essential part of meeting the UK's emissions reduction targets and global action to arrest climate change. The challenge of managing the changing nature of a transitioning power system is complex and urgent, and with it comes the question: what is the status of the security of electricity supply, and how might that change in the future?

This report addresses security of electricity supply in a Scottish context by engaging with experts who either work in the power industry or are involved as key external stakeholders, and relaying their opinions.

The electricity system in Scotland is privately owned and regulated by Ofgem. In addition to energy users, it has a large number of stakeholders:

- producers, traders and retailers of energy;
- facilitators of transfer of energy between producers and users, i.e. the network owners and the Electricity System Operator (ESO), collectively identified as the 'network licensees';
- providers of services that facilitate operation of the system and balancing of generation and demand in real-time, e.g. 'aggregators' and owners of generation or energy storage;
- consultants and researchers who provide services to other stakeholders; and
- policy makers.

These different types of stakeholders were all represented in a survey conducted by the authors of this report. This was built on in a stakeholder roundtable (conducted under 'Chatham House rules') which aimed to leverage the participants' expertise and

[20] 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.
[21] These are those plants with highly predictable availability of power such that production can be scheduled a number of days in advance with high confidence.
[22] Restoration of power supplies following a widespread disruption.

knowledge of the state of the power system, its innovations, challenges and opportunities.

For the electricity system in Scotland, the UK Government Department of Business, Energy and Industrial Strategy (BEIS) is a key stakeholder. However, although the setting of energy policy is reserved to UK Government, the Scottish Government is also an extremely significant electricity sector stakeholder. For example, it has powers over planning consents and many of the policies that affect the demand for electricity such as in transport or standards for buildings. It also has important responsibilities towards essential services to society, such as health and social care and access to clean water, which depend on resilient supplies of electricity. As already noted, the Scottish Parliament has passed legislation committing Scotland to specific GHG emission-reduction targets while Scottish Government has expressed ambitions to further develop wind generation and renewable energy use.

The details of the methodology applied for the survey underpinning this report are described in the next section. Then, Sections 3 to 9 provide details of the survey results and roundtable engagement, organised around key themes. Section 10 provides a summary of the results; Section 11 discusses these further. The key messages and recommendations are presented in Section 12.

2 Methodology

Gathering information about the perception of industry experts and stakeholders on the status of the security of Scottish power followed a two-step approach comprising an online survey and a roundtable where results were presented and discussed. The survey consisted of questions (see Table 1 and Table 2) grouped in terms of the topic being covered; each question was crafted to illicit a considered response from the participant. The full questionnaire is available in Appendix A and the style of the questions is discussed below. In assessing the status of the security of electricity supply, five aspects of security of electricity supply were considered along with two other aspects related to environmental sustainability.

2.1 Security of electricity supply aspects

1. **Electricity imports:** If there is not enough power available from a power plant within a particular area at any one time to match demand in the area[23], demand could still be served by importing power from neighbouring areas with which there is an interconnection. The volume of imports of electrical energy is considered in the context of the GB power system and Scottish power system within it.
2. **Meeting Scottish power demand:** Central to electricity security of supply is the capability to meet the consumer's power demand with a sufficient level of reliability.

[23] Power might be unavailable because of breakdown or maintenance of power plant, lack of fuel for thermal plant that uses to fuel to make heat and then steam to turn turbines, or lack of wind or sun. There might also be a simple shortage of installed generation capacity, e.g. due to closures. In general, a given amount of wind and solar generation capacity does not provide the same confidence in having power available as the same capacity 'schedulable' power plant such as thermal or hydro power stations.

Considering the transitioning power system, it is important to be confident that demand for electrical energy can be met reliably both now and in the future.

3. **Power system operability:** Operability of the power system concerns the ability to operate a stable system in which its physical limits and those of its various elements are respected. This aspect is considered both in the context of the GB power system and Scottish power system within it.
4. **Scottish power system resilience:** A resilient power system is one that can prevent, contain and recover from interruptions to electricity supply arising from disturbances to the system.
5. **Power system restoration:** In the event of a widespread disruption the power system must be able to quickly[24] restore critical supplies, and thereby minimise the impact of the disruption to electricity supply. Although the question posed to the participants gives an example in the Scottish context, the discussion is broadened to include both Scotland and GB.

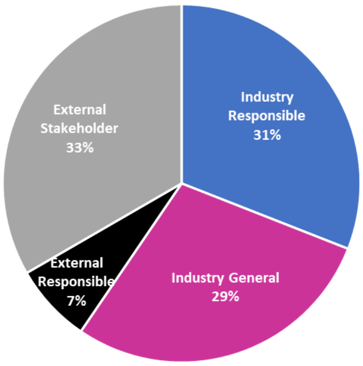
2.2 Environmental sustainability aspects

1. **Meeting Scottish greenhouse gas emissions targets:** This aspect provides insights as to the perceptions of power industry experts and stakeholders on the likelihood of achieving Scottish 2030 and 2045 emissions reduction targets.
2. **Meeting Scottish offshore wind ambitions:** This aspect provides insights on the perceptions of power industry experts and stakeholders on the likelihood of achieving 11 GW offshore wind capacity by 2030 [6].

2.3 Participants

Invitations were sent to experts who conduct activities in, or related to, Scotland's power industry. The survey was completely anonymous and no personal identification data was collected. The subsequent roundtable was conducted under 'Chatham House rules' – observations made by the participants were collected but no personal identification records were kept. The survey was accessible for a month and a total of 47 individuals responded, while the roundtable included 27 individuals. The survey respondents are grouped as shown in Figure 2, based on responses to questions about whether the respondent identifies as working within the electricity supply industry and/or have a responsibility for security of supply as part of their job.

[24] 'Quickly' is subjective but in the context of this work it refers to the timeliness defined in the proposed Restoration Standard [31] (see section 8)



Group name	Works in electricity supply industry	Responsible for security of supply	Number of respondents
Industry responsible	Yes	Yes	13
Industry general	Yes	No	12
External responsible	No	Yes	3
External stakeholder	No	No	14

Figure 2: Survey respondent groups

The roundtable included participants from the same four stakeholder groups in Figure 2. The set of experts included senior employees from the network companies active in Scotland, the system operator, generators, an aggregator, Government, Ofgem, academics, consultants and individuals who work on behalf of customer groups.

2.4 Multiple choice questions

The survey included multiple choice questions with the respondents choosing one out of five options. As shown in Table 1, these questions are grouped into topics, based on the aspects presented in sections 2.1 and 2.2. Each group included a question asking the participant to indicate their own confidence in their response by choosing one of the percentages.

Table 1**:** Questions on the topic of 'Reliably Meeting Scottish Electricity Demand' from the online survey showing the style of multiple-choice questions within a topic

1. Electricity demand in Scotland is met sufficiently reliably now.				
a) Strongly agree	b) Somewhat agree	c) Neither agree nor disagree	d) Somewhat disagree	e) Strongly disagree
2. Electricity demand in Scotland can be met reliably in 2030.				
a) Strongly agree	b) Somewhat agree	c) Neither agree nor disagree	d) Somewhat disagree	e) Strongly disagree
3. How confident are you in your responses?				
a) 95%	b) 75%	c) 50%	d) 25%	e) 5%

2.5 'Rank item' questions

There were also questions that asked the survey participants to rank items on a scale, so that the results could be resolved into a ranking order of those items that is reflective of the overall view of the survey's respondents. An example of a ranking question in the survey is shown in Table 2.

Table 2: A question in the survey that requires participants to rank items on a scale

Q. On a scale of 1 to 5, with 1 being "Unimportant" and 5 being "Extremely important", how important do you think each of the following are in ensuring a reliable, resilient supply of electricity, in the medium to long term?

Via clearly defined standards and obligations on parties in the energy sector	*1 to 5 Scale*
Via centrally administered market mechanisms such as the capacity market	*1 to 5 Scale*
Via a market mechanism that reveals the value that different energy users attach to security of supply	*1 to 5 Scale*
Via explicit government decision to commission new facilities	*1 to 5 Scale*
Via direction from an authority such as Ofgem to commission new facilities	*1 to 5 Scale*
Other (Please Specify)	*1 to 5 Scale*

In addition, there were some additional text fields for the respondents to provide further information that they felt could not be captured by the survey questions, including responses for items marked as 'Other'. Lastly, respondents were given the option to provide comments on how any similar future survey can be improved.

2.6 Analysing responses

The raw data of the multiple-choice responses were converted to numerical values based on Table 3 and weighted by the degree of confidence provided by the respondent. For example, a choice of 'Highly likely' receives a score of 5, which is then multiplied by the degree of confidence '50%', so that the weighted score is 2.5, as indicated by the expression in (1).

$$Weighted\ Score\ (S_w) = Score \times Confidence \tag{1}$$

Table 3: Scoring multiple choice answers

Choice Type 1	**Choice Type 2**	**Choice Type 3**	**Score**	**Weighted Score (S_W)**	**Colour**
Highly likely	Strongly agree	Not at all	5	$4 < S_W \leq 5$	**Green**
Likely	Somewhat agree	A little	4	$3 < S_W \leq 4$	
Moderately	Neither agree nor disagree	A moderate amount	3	$2 < S_W \leq 3$	**Amber**
Unlikely	Somewhat disagree	A lot	2	$1 < S_W \leq 2$	**Red**
Highly unlikely	Strongly disagree	A very great deal	1	$S_W \leq 1$	

The weighted scores are referenced back to the 'Choice Type', based on Table 3. The result for each set of questions are presented in a bar chart that shows the weighted responses of the entire participant population and the variation within groups. An example of the bar chart is presented in Figure 3. Also included in these plots is a pie chart at the top right that shows size of each group in relation to the total population of respondents.

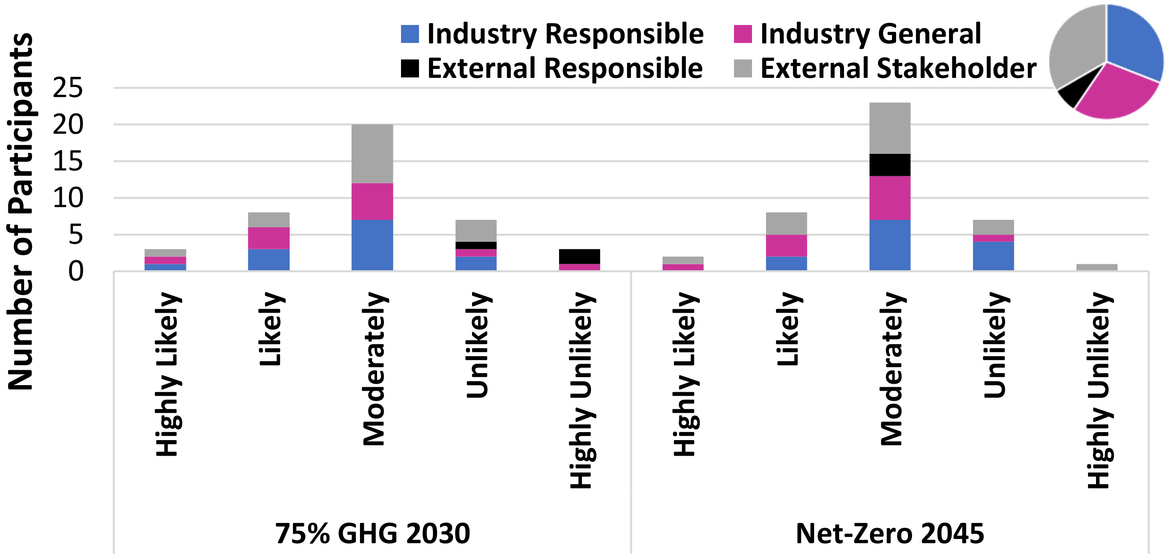


Figure 3: Spread of the weighted responses to questions around achieving Scottish greenhouse gas emissions targets, showing differences between survey groups

The five level 'Choice Type' is reduced to a Red-Amber-Green (RAG) scale, based on Table 3, to produce a pie-chart (e.g. Figure 4) that is used to give a summary of views on the individual topics and a visually representative summary of industry perception of the status of the security of Scottish electricity supply that is presented in section 12. An alternative, numerically representative high-level overview of industry perception of the status of the security of Scottish electricity supply is also presented in section 12[25], with the mean and standard deviation values derived from the weighted scores of each question, colour-coded on a continuous scale from Red (0) to Green (5).

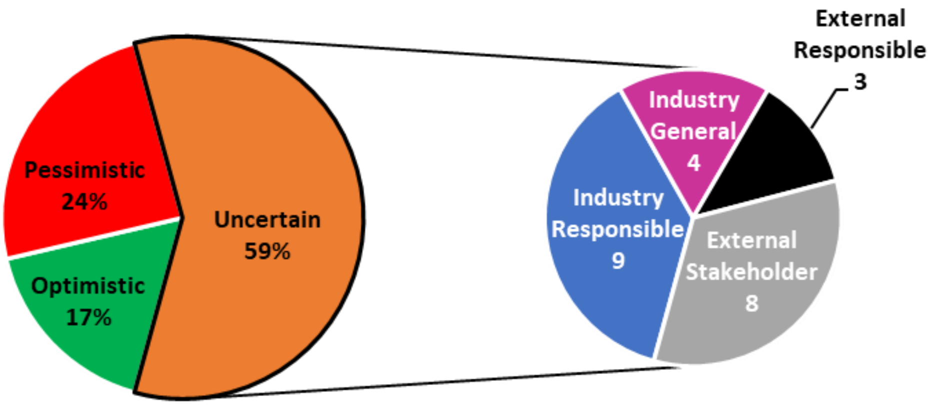


Figure 4: Overall response to offshore renewables ambitions, showing the number of individuals from each group that contributed to the majority rating.

The mean and mode of scores given to 'rank item' questions are derived, and the items are ranked based on the mode score of each item; where there are multiple modes, the mean score is used as a differentiator. Following the analysis, the results of the survey

[25] See also Appendix C for similar data broken down by aspects and respondent groups.

were presented and the perceptions on the status of the security of Scottish electricity supply was discussed at an online roundtable forum with a wide range of experts that conduct activities in, or related to, the Scottish power industry. Both the survey and the roundtable gave participants the opportunity to make particular observations. The most pertinent of these are reported but not attributed in the following sections.

3 Offshore wind and reducing greenhouse gas emissions

The Scottish government has a target of achieving a 75% reduction of GHG emissions in Scotland by 2030 when compared with 1990, and a target for net-zero GHG emissions in Scotland by 2045. For context, the UK targets are 68% reduction of GHG emissions by 2030 and 78% by 2035, and net-zero GHG emissions by 2050 [7]. Furthermore, the Scottish Government has expressed an ambition of increasing offshore wind capacity to 11 GW by 2030 [6]. The question that arises is whether Scotland will achieve its emissions targets and offshore wind ambitions.

The questions posed:

1. How likely are we to meet the target of a 75% reduction of greenhouse gas emissions in Scotland by 2030 when compared with 1990?
2. How likely are we to meet the target of net-zero greenhouse gas emissions in Scotland by 2045?
3. The Scottish Government has set a new ambition to increase offshore wind capacity to 11 GW by 2030. How likely are we to achieve this goal?

The survey participants responded to these questions and the results indicate a degree of uncertainty about Scotland achieving both targets and about the likelihood of achieving the current Scottish offshore wind ambition, as indicated by the results shown in Figure 5 and Figure 6.

It can also be inferred that:

- most of the pessimism[26] about the 2030 target comes from those with a responsibility for security of electricity supply but do not work in the power industry (External Responsible) and those that do not work in the industry and are not responsible for security of electricity supply (External Stakeholder);
- most of the optimism[27] about the 2030 target comes from those that work in the power industry (Industry Responsible and Industry General); and
- those that work in the power industry and are responsible for security of electricity supply (Industry Responsible) are more doubtful about achieving the 2045 target in comparison to the 2030 target, with the weighted scores leaning more towards the ‘Unlikely’ range for 2045 than in 2030.

[26] Based on contribution to number of participants that gave the rating ‘Unlikely’ and ‘Highly unlikely’.
[27] Based on contribution to number of participants that gave the rating ‘Likely’ and ‘Highly likely’.

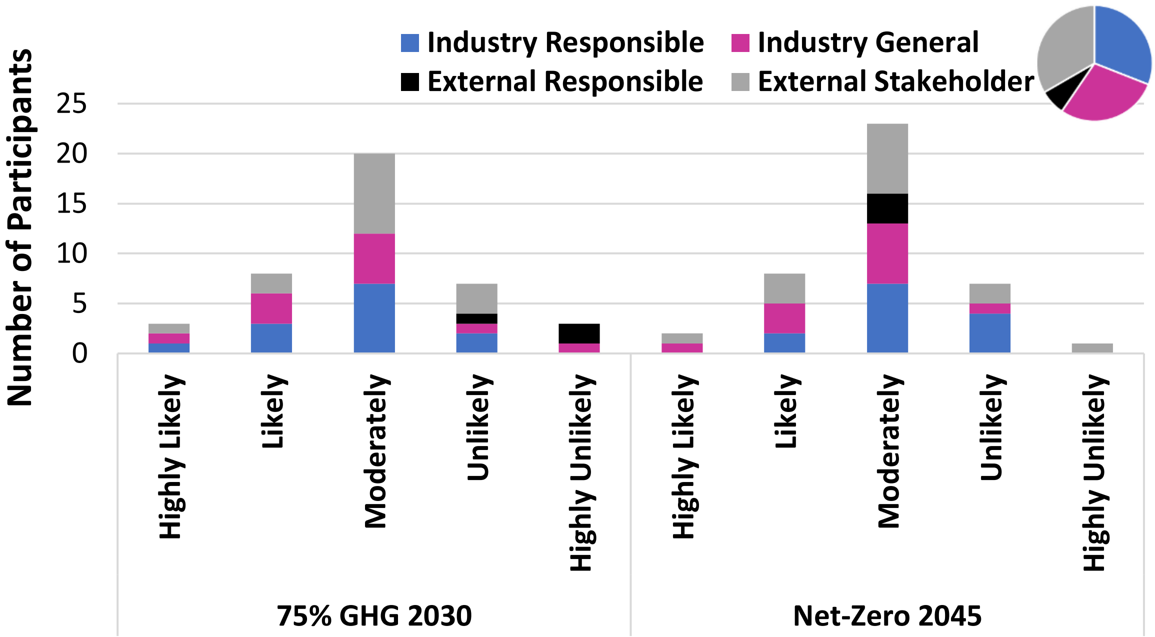


Figure 5: Spread of the weighted responses to questions around achieving Scottish GHG emissions targets, showing differences between survey groups

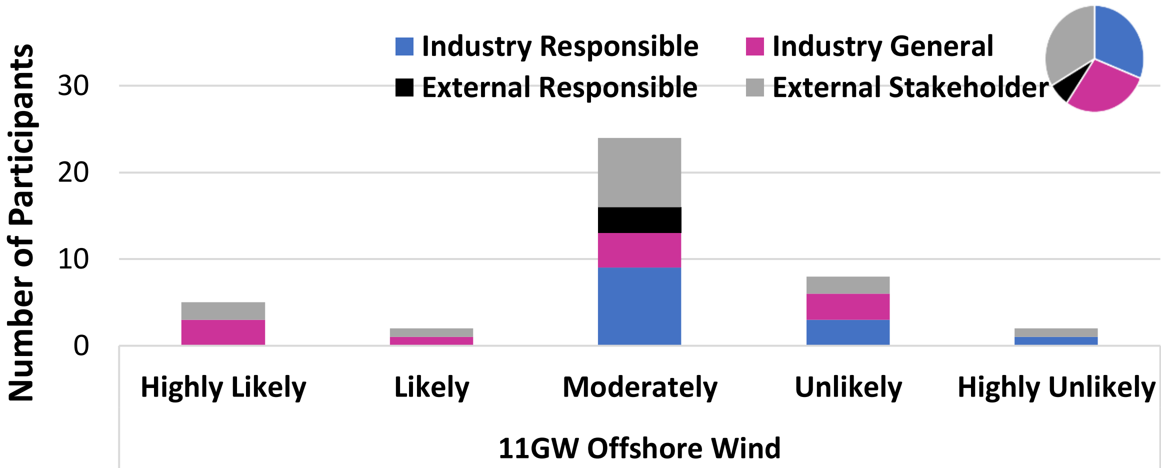


Figure 6: Spread of the weighted responses to questions around achieving Scottish offshore wind ambition, showing differences between survey groups

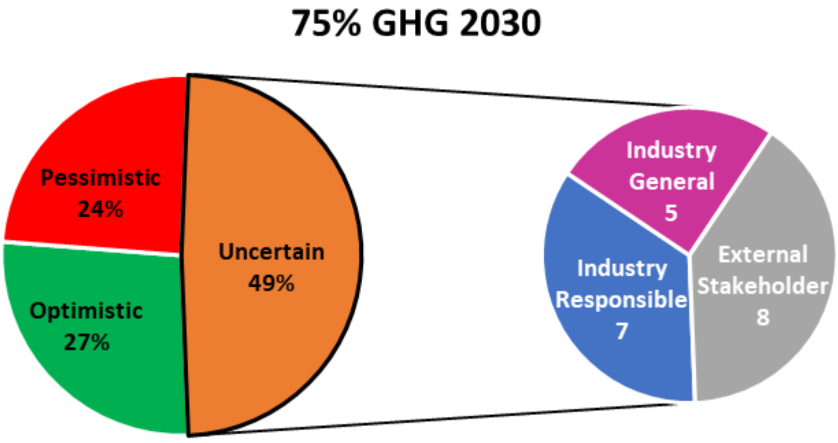


Figure 7: Overall response to questions around the target of a 75% reduction of greenhouse gas emissions in Scotland by 2030 when compared with 1990, showing the number of individuals from each group that contributed to the majority rating

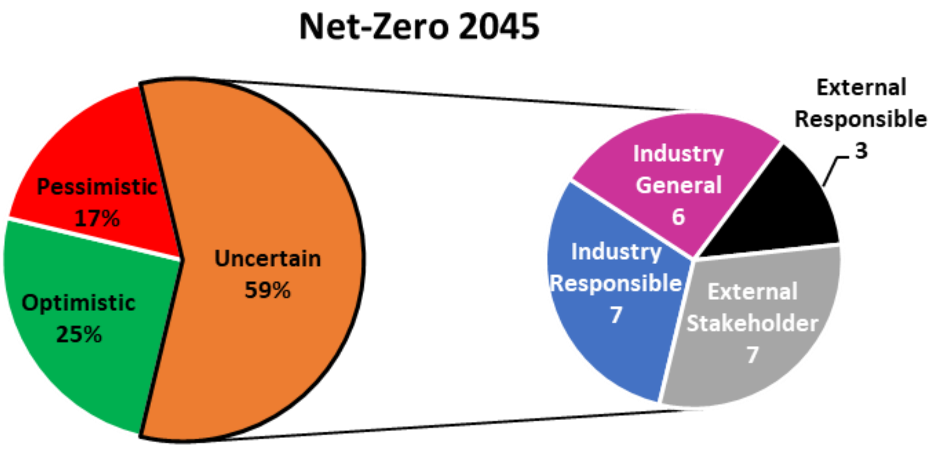


Figure 8: Overall response to questions around the target of net-zero greenhouse gas emissions in Scotland by 2045, showing the number of individuals from each group that contributed to the majority rating

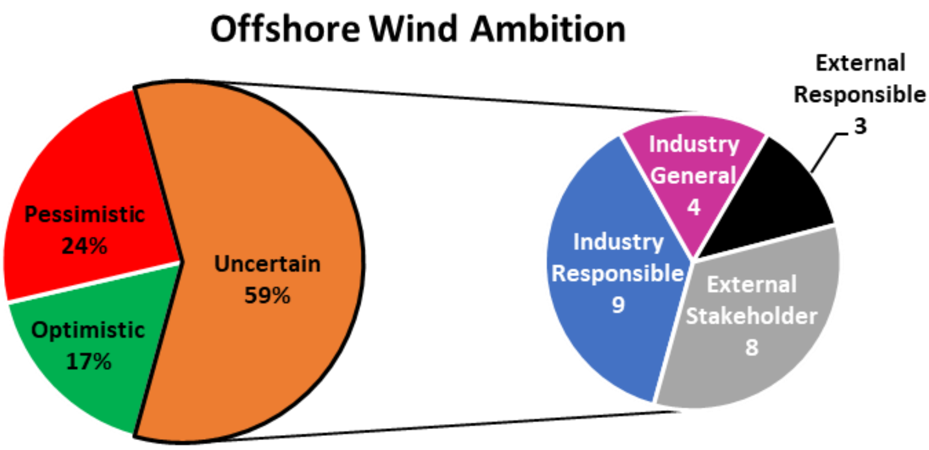


Figure 9: Overall response to questions around 11 GW by 2030 offshore renewables ambitions, showing the number of individuals from each group that contributed to the majority rating.

Figure 9 indicates considerable uncertainty around Scottish GHG emissions targets and offshore renewables ambitions, with an increase in uncertainty regarding GHG emissions target for 2045 targets relative to 2030 targets. There is more optimism than pessimism in respect of both the 2030 and 2045 GHG targets but there is more pessimism than optimism in respect of the offshore wind ambition. Those that work in the power industry but are not responsible for security of electricity supply (Industry General) contributed to most of the weighted scores in the 'Highly likely' range.

There is, however, the view that, compared to other sectors, the electricity sector has so far made relatively good progress in decarbonisation. Data from National Statistics in [8] indicate a 60% reduction of fuels[28] used in electricity generation in 2020 when compared to 1998. This includes reductions in the generation of electricity via the use of coal, oil and gas of 95%, 81% and 13% respectively. Overall, electricity generation from fossil[29] fuels has reduced from 68% of electricity generated in 1998 to 38% of electricity generated in 2020, while electricity generated from renewables[30] has increased from 3% of electricity generated in 1998 to 44% of electricity generated in 2020 [8]. However, further renewables growth is required to achieve net-zero targets, with Aunedi et al of [9] suggesting much more renewables deployment than accounted for in UK-wide targets.

There is the perception among the consulted stakeholders that clearer communication is needed on the meaning of 2030 GHG emissions reduction target and its implications for electricity production in Scotland, which some currently take to mean 0g/kWh emissions intensity for all electricity produced in Scotland. In addition, clarity was requested on whether Scotland's emissions targets are territorial and do not take into account GHG emissions associated with energy produced outside Scottish borders, even if it is used in Scotland. There are also concerns around maintaining reliability and security of electricity supply, especially given the expected greater reliance on electricity for other things such as heating and transportation (see later sections for further discussion).

The move away from fossil-fuelled plants is welcomed by industry stakeholders. However, there is a widely accepted view that the transition is not without implications, i.e. keeping the lights on, restoring the power system in the case of a widespread blackout, resilience to disturbances, and the nature of the complexity involved in bringing together solutions to overcome these challenges in a timely, safe, secure, and cost-effective manner. Consequently, there is the perception that these challenges may impede efforts towards achieving Scottish targets, and indeed those of the UK. Lastly, some stakeholders are of the opinion that work done around the larger topic of decarbonisation, e.g. of transportation and heating, is being done in silos, instead of interconnecting related aspects and including them as part of the same discussion.

Summary

- There is uncertainty among industry experts and key stakeholders around Scotland's ability to achieve its 2030 and 2045 GHG emissions targets although those believing the targets will be met outnumber those who do not.
- In respect of the Scottish Government's ambition for 11 GW of offshore wind generation capacity by 2030, the pessimists outnumber the optimists.

[28] Fuel here is measure in millions of tonnes of oil equivalent (Mtoe).
[29] Considering coal, oil and gas.
[30] Considering hydro (natural flow and pumped storage), wind, wave, tidal, solar, and bioenergy.

- Although there has been much progress in reducing the emissions intensity of electricity production, more is needed to achieve net-zero ambitions, especially if there will be much more reliance on electricity for energy for transportation and heating.
- Some industry experts and stakeholders feel the need for clearer communication of the meaning of the 2030 emissions reduction target, as well as clarity on whether Scotland's GHG emissions targets are territorial within Scotland or within the UK.

Concerns were raised by the consulted stakeholders about the complexities and challenges associated with a net-zero power system that must be addressed to mitigate any potential barriers to implementation, alongside the need to consider decarbonisation in the context of the bigger picture of energy systems in general, and whether the challenge of maintaining resilient supplies of electricity might impede efforts toward decarbonisation.

4 Dependency on imports of electricity

Interconnectors, such as the High Voltage Direct Current (HVDC) link between England and France, enable surplus power to be exported to another market or country, or imported from it. That is, an interconnector facilitates cross border electricity trades [10]. In Scotland there is the 500 MW Moyle HVDC interconnector between Scotland and Northern Ireland, and future interconnectors to Europe have been proposed, including the 1 GW NorthConnnect between Scotland and Norway that is planned to come online in the Autumn of 2027 [11]. In addition, there is an alternating current (AC) connection between Scotland and the rest of GB, transferring power[31] between the Scottish Power Transmission (SPT) area of the south of Scotland and the National Grid Electricity Transmission (NGET) area of England and Wales. Prior to the merger of the wholesale electricity market in Scotland with that in England and Wales in 2005, this would have been seen as an interconnector. Since 2018, there has been a large embedded[32] HVDC interconnector between Scotland and the rest of GB[33], and the Electricity Ten Year Statement (ETYS) shows that other embedded interconnectors are planned to be built between 2024 and 2029 [12].

In a Scottish power system with high renewables penetration, during periods of high production such that power supply exceeds demand, Scotland can export power to other regions instead of curtailing the energy generated. Conversely, during periods of low production such that power demand exceeds supply, Scotland would need to import power to meet its electricity demand. Consequently, the questions posed to the participants in the survey concerns the extent to which Scotland and GB will be dependent on imports of electricity to reliably meet electricity demand in 2030.

1. To what extent will the reliable meeting of electricity demand in Scotland in 2030 depend on imports of electricity?

[31] Across the Anglo-Scottish (B6) boundary.
[32] Embedded HVDC interconnectors refers to those HVDC interconnectors that transfer power within the same synchronous area of a given power system, e.g. the Western HVDC link that transfers power between one part of the GB system and another.
[33] The Western HVDC link is between Hunterston and Deeside with a continuous thermal rating of 2.25 GW [55].

2. To what extent will the reliable meeting of electricity demand in GB in 2030 depend on imports of electricity?

The views of industry experts and stakeholders provided in the survey are summarised in Figure 11, and the perception is that GB and Scotland are both dependent on imports of power, more so with GB than with Scotland. As a follow up, during the discussions at the online roundtable, the participants were asked whether the high dependency indicated by the survey's result in Figure 10 is a bad thing.

In recent history, Scotland has been a net exporter of electricity [3, 13]. Although GB has been net importer, some studies, including that reported in [10], show that changes to the generation background and commissioning of new interconnectors would allow it to become a net exporter in 2030. Industry experts and stakeholders are of the view that dependence on imports has implications for energy security and striking the balance between imports and local generation capacity could get very expensive if done incorrectly, adding that if interconnectors are regarded as contributing towards GB security of supply, less generation plant will end up being built in Britain. It is also suggested that Scotland, once the remaining thermal power stations close, will lack schedulable generation within its borders. However, 'dunkelflaute'[34], which would affect a bigger area than Scotland, could mean that generation elsewhere in GB or at the exporting end of the HVDC interconnection might not be available.

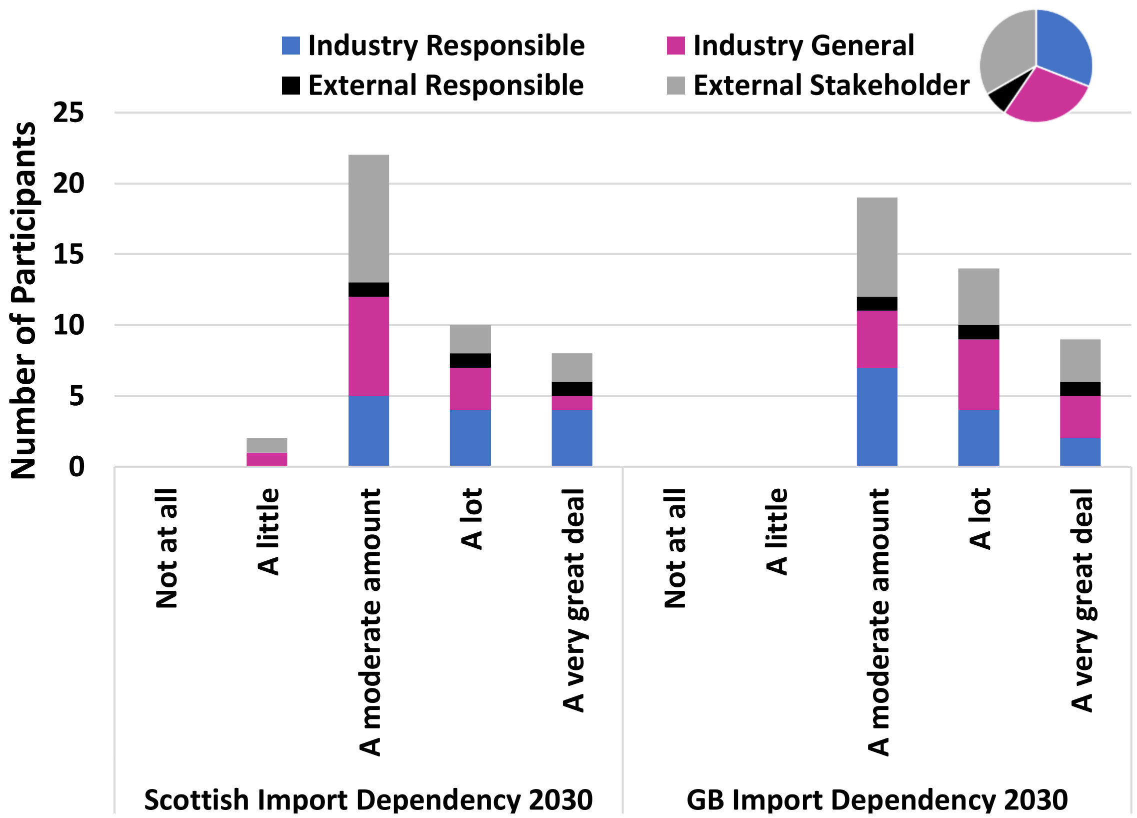


Figure 10: Spread of the weighted responses to questions around imports of electricity to Scotland and GB, showing differences between survey groups

[34] This is a term used in the energy sector to describe a period of time in which little to no energy can be generated with the use of wind and solar power.

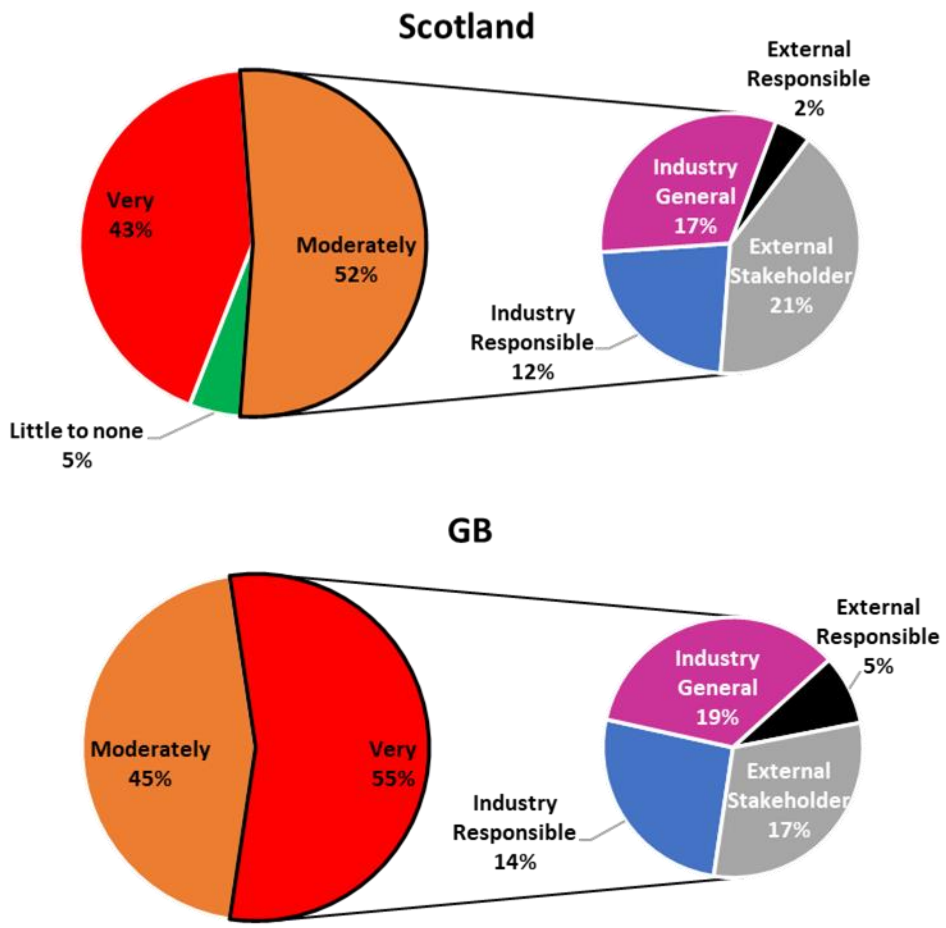


Figure 11: Overall response to questions around dependency on imports of electricity, showing the number of individuals from each group that contributed to the majority rating

Interconnection plays an important role in facilitating a net zero power system and it provides an avenue to both import power to balance demand and export power that would have otherwise been curtailed. Furthermore, recent work by the UK Energy Research Centre and Chatham House in [14] reports that *"It is impossible to unplug the UK from the EU's energy market"*, while some experts note that the GB power system and the regions within it are interdependent, regardless of politics and political boundaries. As far as dependence on imports of power as it relates to energy security is concerned, the consulted stakeholders' preference is to have as much security in the future as we have today. In this context, there is concern raised by some stakeholders on the reliance on interconnectors in emergency situations since the interconnectors react to markets and prices that may not 'point' in the right direction when needed if markets are not aligned correctly. Although some experts suggest revisiting the market practices associated with HVDC interconnectors, there are also suggestions that there is the opportunity to deploy solutions such as pumped hydro storage and hydrogen as alternatives and/or additions to Scotland's or Britain's energy system that can be used to increase reliability and reduce reliance on interconnector imports. However, this is not without additional costs. Consequently, it depends on how reliant a given region is willing to be on imports from other regions, versus how much the importing region is willing to invest to reduce any perceived risks due to dependency, particularly during emergency situations.

Summary

- The level of demand for electricity and production from wind farms varies. Scotland is therefore sometimes dependent on imports of power. GB, as a whole, is a net importer of electrical energy.
- Interconnections, between both Scotland and the rest of GB and between GB and other parts of Europe, enable such imports and provide an avenue to trade (buy and sell) power with other regions. Interconnection also offers access to renewable resources that may be abundant in other regions, or alternatively, a route for export of power during periods of high renewable electricity production within GB.
- Long periods of low wind and solar production – periods becoming known as 'dunkelflaute' – pose some concern, and are argued by some stakeholders to mean that there is a case for additional 'schedulable' generation capacity within Scotland instead of allowing interconnectors to mean that less capacity is built locally.
- There will need to be a balance between dependence on imports for security of electricity supply and locally sourced power capacity. The mix of resources can be determined by least-cost options and/or political will.

5 Reliably meeting Scottish electricity demand

Electricity demand is expected to change in the future with the electrification of heat and transport, and the increasing presence of prosumers[35]. The preceding section has discussed where the required energy will come from and the level of dependency on imports. The question that now arises is whether Scottish electricity demand can be reliably met at all times now and in the future, with survey respondents asked to what extent they agree with the following statements:

1. Electricity demand in Scotland is met sufficiently reliably now.
2. Electricity demand in Scotland can be met reliably in 2030.

From the results shown in Figure 12, there is strong agreement among industry experts and stakeholders that demand for electricity in Scotland can be reliably met now. However, there is an increase in uncertainty for 2030, particularly among external stakeholders, i.e. those who do not work in the power industry and are not responsible for security of electricity supply. Despite some uncertainty, the overall outlook is also optimistic for reliably meeting Scottish electricity demand in 2030.

[35] Those that both consume and produce electricity.

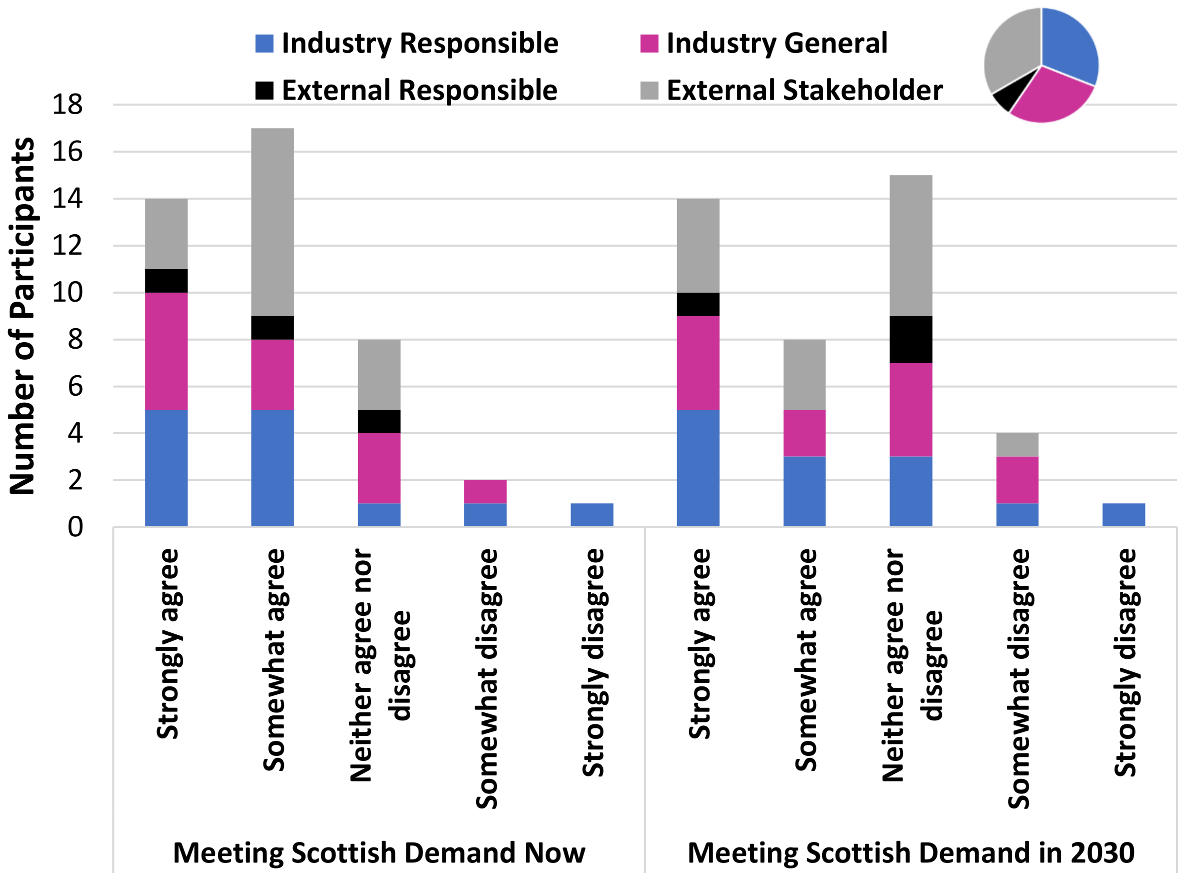


Figure 12: Spread of the weighted responses to questions around reliably meeting Scottish electricity demand, showing differences between survey groups

The perceptions of industry experts and stakeholders provided in the survey are summarised in Figure 13. It can be seen that there is a trend of reducing optimism for reliably meeting Scottish electricity demand between now and 2030. The proportion of respondents that are optimistic about the current status of meeting Scottish electricity demand dropped from 74% to 52%, with the 22% reduction in optimism mostly moving to uncertainty for 2030 relative to the current status.

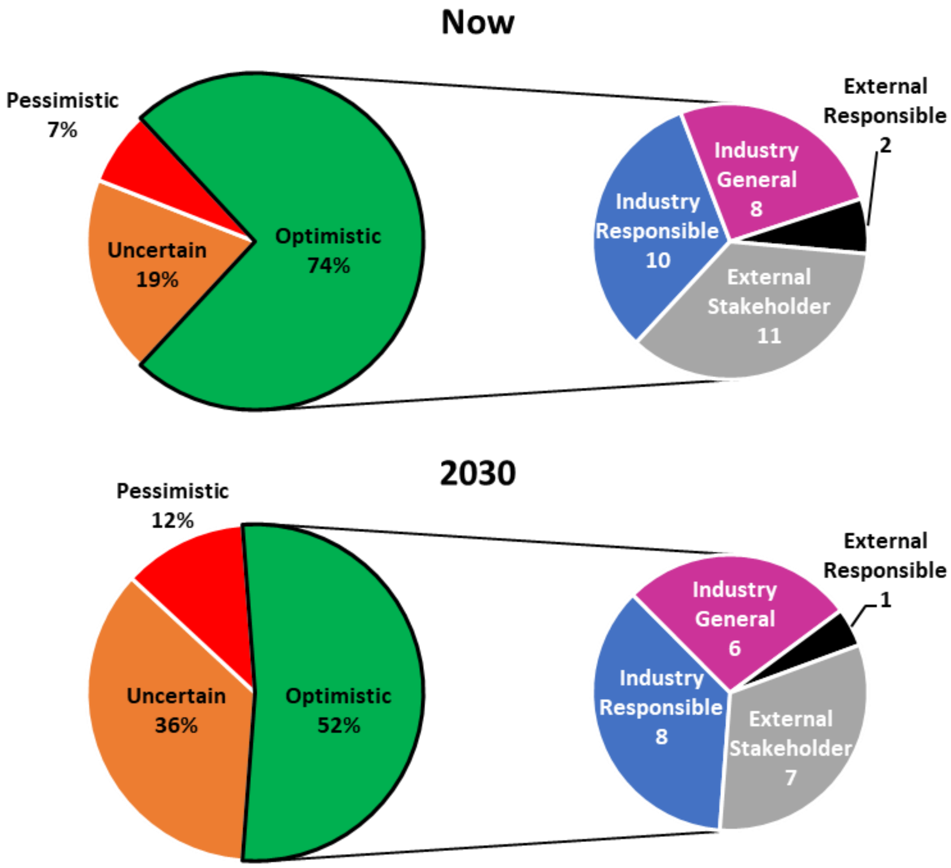


Figure 13: Overall response to questions around reliably meeting Scottish demand, showing the number of individuals from each group that contributed to the majority rating

During the roundtable with experts after the survey, one participant noted that, in their opinion, *"[…] the vast majority of people have no plans to change their heating systems and no plans to engage very much in low carbon technologies […]"*. However, it was also noted that there is already noticeable engagement from consumers that participate in aggregated services delivered to the system via aggregators, and a significant number of actors that export power to the system via connections to the distribution networks which have the effect of reducing the demand for power from the transmission network [15]. Coupled with the rollout of charging networks for electric vehicles [16, 17], the nature of demand on the power system is changing.

"The way we dispatch demand and generation on the system will need to change. Currently we dispatch generation to meet demand because generation is the controllable element but as we look to the future when we have smart devices and storage at different network levels, then demand becomes the controllable element and generation is determined by [wind and solar]. At some point in the next 8 – 10 years [the] control room will start to dispatch more on the demand side to meet the periods of high renewable generation […]"

Roundtable participant, July 2021

This changing nature of demand is a view shared by many industry experts and stakeholders and, as stated by ScottishPower Energy Networks in [18], under the net zero ambitions, electricity demand, generation, and consumer behaviour will all change. The expectation is that demand (and distribution networks) will be much less passive than they have been historically, but the degree or extent of this change is uncertain and somewhat dependent on the uptake of relevant technologies by the public. These changes raise additional layers to the original question, including how to:

- effectively manage and coordinate the large number of devices in such a complex system;
- assign responsibilities, and appropriately license and regulate actors providing services on the distribution network;
- ensure ease of use and "consumer protection";
- manage vulnerabilities in what would likely involve significant digitalisation[36]; and
- equitably do all of the above, with minimal impact to the customer's bill.

Despite the challenges there is significant optimism in the industry and indeed the perception seems to be one that welcomes the changes.

> *"More dispersed resources and more flexibility from storage and [demand side management] create the opportunity for an increase in reliability, so with careful planning and understanding we'll shift towards a more reliable and resilient system than we have today."*
>
> *Roundtable participant, July 2021*

There is some concern about public engagement particularly around the ease of use and access to the tools needed to participate in demand-side services, *"It would be unrealistic to expect consumers to sit on their devices to participate […]"*. That said, using thresholds acceptable to the consumer would facilitate demand side tools that manage the consumer's loads within these thresholds and provide service to the grid when possible. However, there is a view that the value chains and markets that could facilitate something like this are broken. In concert with this, reference was also made to developments outside the UK, like managing load through remotely controlled thermostats in Texas, US [19], where there is some regret from consumers that signed up to participate but did not fully understand their agreement. Some industry experts and stakeholders also expressed the view that the UK's smart meter rollout has been disastrous for public opinion of centrally managed change that impacts the customer's energy experience, and perhaps there are lessons to be learned (and from similar undertakings overseas) in any future deployment to facilitate increased consumer participation in their energy use and in a more controllable demand.

[36] A concern towards the future power system in general.

Summary

- Industry experts and stakeholders have considerable confidence in the current capability of reliably meeting Scottish electricity demand, but there is an increased uncertainty with respect to meeting it in 2030.
- There is an expectation of a shift towards flexible demand playing a more active role, with an increasing proportion of demand becoming a controllable element rather than a passive one. This is especially the case when considering that a power system dominated by renewables would be more dependent on weather and a matching of the timing of use of electricity to when power is available from renewables would help with system balancing.
- Caution is raised around factors associated with such a transition, including management of such a complex system with numerous controllable demand elements, along with issues around: the assignment of responsibilities; regulation; “consumer protection”; ease of use and clarity of the terms of contractual agreements; digital security and vulnerabilities; and equitability.

6 Power system operability

A power system that has adequate resources or mechanisms to ensure stable operation is central to reliably meeting demand. This topic has received increased attention following the severe interruptions to electricity supply experienced on the 9th of August 2019 as detailed in [20]. Survey participants were asked about Scottish and British power system operability now and in 2030 and asked to express the degree to which they agreed with the following statements:

1. At the moment, the electricity system in Scotland has adequate resources or mechanisms to ensure operational stability and protection.
2. In 2030, the electricity system in Scotland will have adequate resources or mechanisms to ensure operational stability and protection.

As shown in Figure 14, the results indicate uncertainty and doubt.

- Most of the pessimism[37] about Scottish power system operability now and in 2030, comes from those who work in the power industry and have a responsibility for security of electricity supply (Industry Responsible).
- Most of the optimism[38] about Scottish power system operability now, comes from those that do not work in the power industry and are not responsible for security of electricity supply (External Stakeholder). Although this group is somewhat uncertain with a tendency towards an optimistic outlook on Scottish power system operability now, the tendency shifted towards a pessimistic outlook for 2030.
- Most of the optimism about Scottish power system operability in 2030, comes from those that work in the power industry but are not responsible for security of

[37] Based on contribution to number of participants that gave the rating ‘Somewhat disagree’ and ‘Strongly disagree’.
[38] Based on contribution to number of participants that gave the rating ‘Somewhat agree’ and ‘Strongly agree’.

electricity supply (Industry General). However, the views of this group were quite widely spread, and the same can be said for the three individuals who identify as being responsible for security of electricity supply but do not work in the power industry (External Responsible).

Survey participants were asked to express the extent to which they agreed with similar statements to those above but with respect to the GB system. The results of the survey on British power system operability, as shown in Figure 15, indicate uncertainty mixed with more optimism for power system operability now versus uncertainty mixed with pessimism in 2030.

- Most of the optimism about British power system operability now, comes from those who do not work in the power industry and are not responsible for security of electricity supply (External Stakeholder), while most of the pessimism comes from those who work in the power industry and are not responsible for security of electricity supply (Industry General[39]).
- Most of the pessimism about British power system operability in 2030, comes from those who work in the industry (Industry Responsible and Industry General), while most of the optimism comes from those who work in the electricity supply industry but are not responsible for security of electricity supply[35] (Industry General).
- Those who work in the power industry and are responsible for security of electricity supply (Industry Responsible) tend more towards a pessimistic perception of British power system operability in 2030 relative to now.

The perception of industry experts and stakeholders provided in the survey is summarised in Figure 16 and Figure 17. It can be seen that there is a trend of reducing optimism for both Scottish and British power system operability between now and 2030. The proportion of respondents who are optimistic about the current status of Scottish power system operability dropped from 33% to 21%, replaced by uncertainty for 2030, and there is also a reduction in optimism about the future status of British power system operability relative to its current status.

---

[39] Note that as with Scottish power system operability, the views of this group on British power system operability are quite widely spread, and the same is true for the External Responsible group.

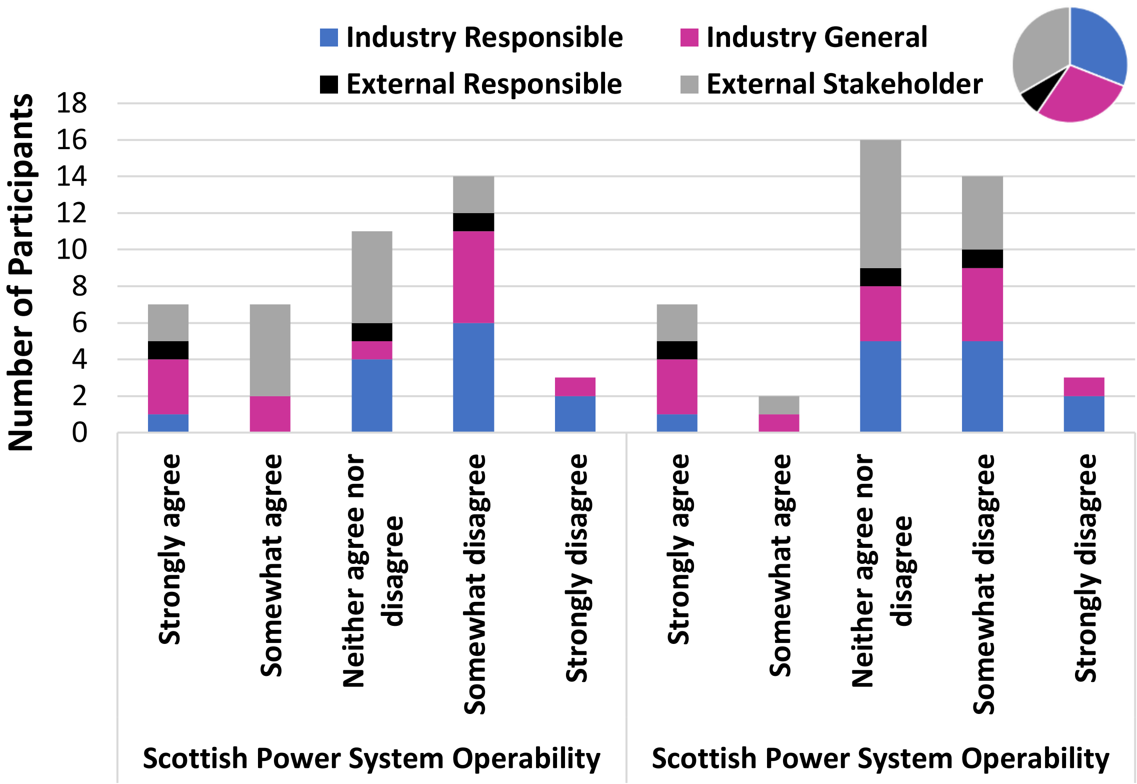


Figure 14: Spread of the weighted responses to questions around Scottish power system operability, showing differences between survey groups.

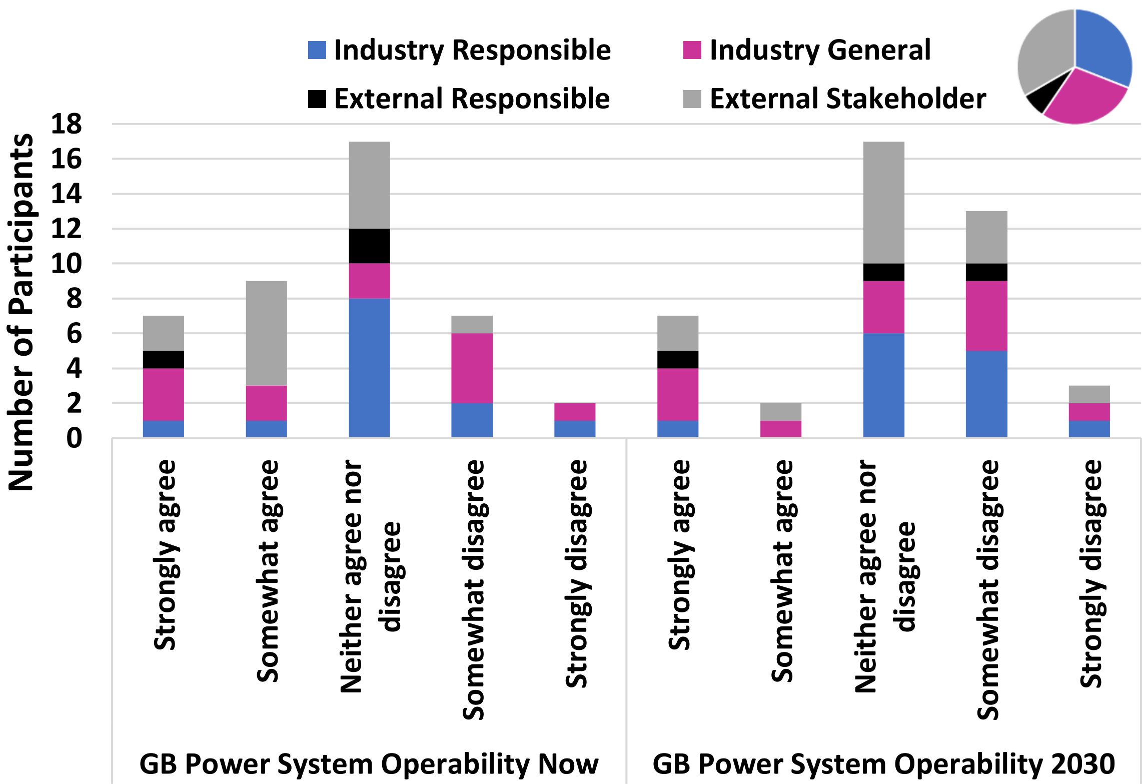


Figure 15: Spread of the weighted responses to questions around British power system operability, showing differences between survey groups.

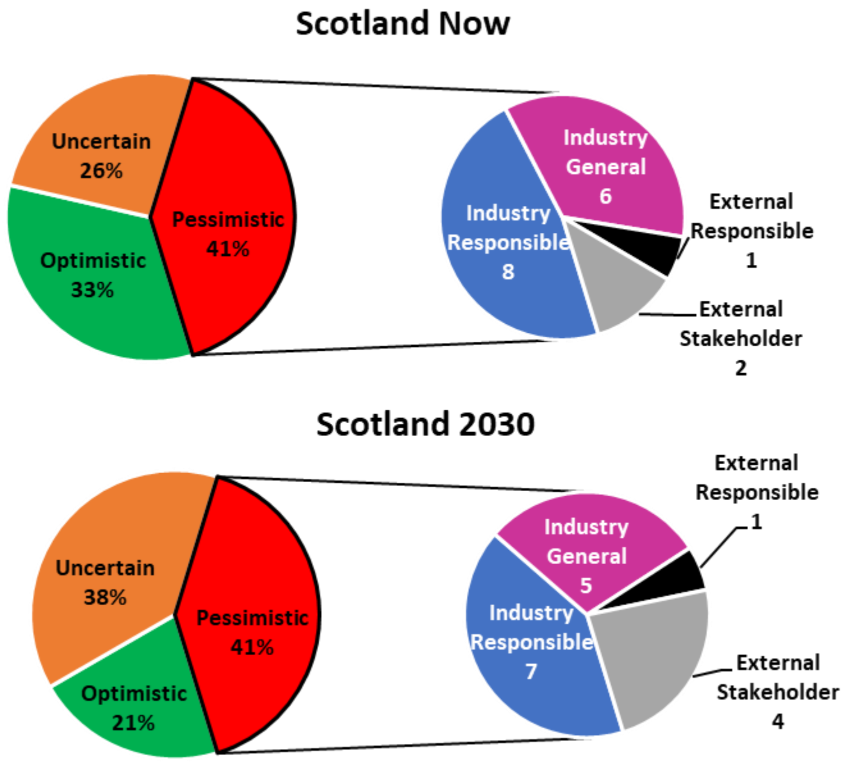


Figure 16: Overall response to questions around Scottish power system operability, showing the number of individuals from each group that contributed to the majority rating

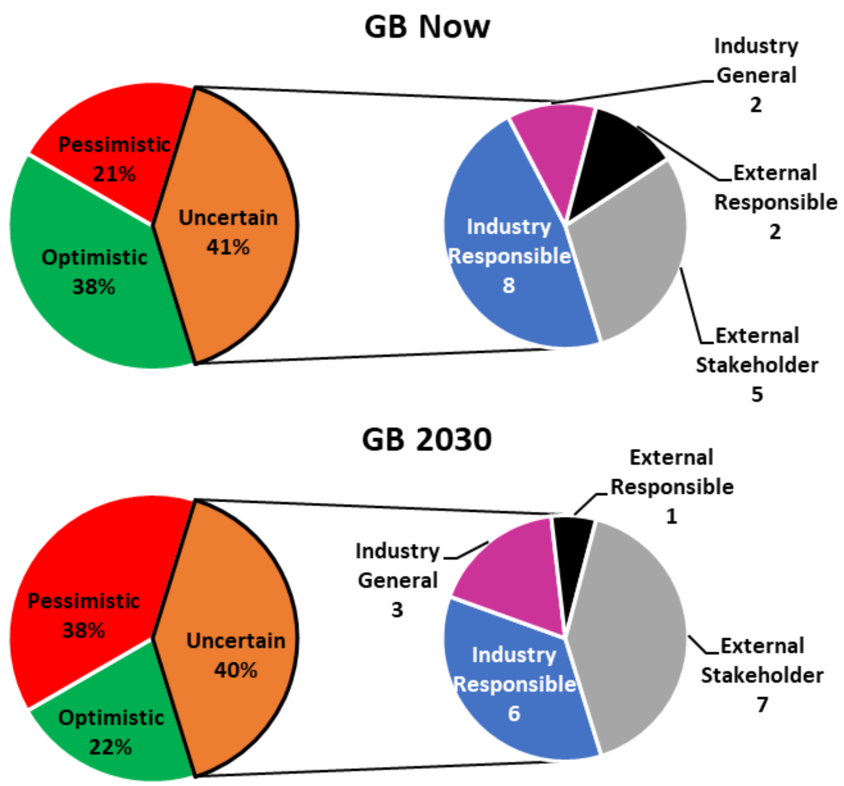


Figure 17: Overall response to questions around GB power system operability, showing the number of individuals from each group that contributed to the majority rating

Some industry experts and stakeholders note the distorted mix of generation in Scotland, which is wind-orientated and leads to concerns such as how the power system deals with extended wind drought in the middle of the winter; and how to manage the power balance at time when it is not windy. However, one fundamental concern industry experts and stakeholders have is the requirement to coordinate different moving parts[40] and digital infrastructure so that the power system continues to work in the event of a fault. Industry experts and stakeholders also say that there is much debate about what to build, in terms of network investments. Some stakeholders are of the opinion that engineers should just get on with building because 2030 is not a long way away, and *"[…] if we don't hit [the] 2030 [target], we don't hit 2045 or 2050 [target]"*, bearing in mind that network assets, once installed, have lifetimes up to 60 years and long lead times build. There is the perception, among the stakeholders, that the deployment of solutions is lagging policy and need. That said, there is also the view among industry experts and stakeholders that the engineering is, or will be, available to solve the challenges including those related to fault level and stability, with some commenting that they felt that NGESO and others have been involved in some impressive work including the Enhanced Frequency Control Capability project [21], the Phoenix project [22], NGESO's stability pathfinders [23] and the Dersalloch trials [24].

The closure of the Cockenzie and Longannet power stations and the expected closure of Hunterston and Torness nuclear power stations raise questions about the security of electricity supply in Scotland and the contributions these stations made to system operability. NGESO has launched the 'pathfinders' and other initiatives to address this and other challenges. The first phase of the stability pathfinder procured inertia and reactive power capability via 12 contracts for synchronous machines, three of which are planned for Scotland[41]. The second phase is focused on increasing short circuit level[42] in Scotland[43]; at the time of writing, feasibility studies were ongoing on the 29 expression of interest (EOI) submissions with 1,575 proposed solutions. The latter included 723 proposals involving grid-forming converters, 514 involving synchronous machines, and 338 involving synchronous condensers and battery storage with grid forming converters [25]. The first phase of the constraint management pathfinder was also ongoing, with EOIs being submitted[44] at the time of writing. This pathfinder focuses on reducing the impact of network constraints on the B6 boundary [26] between Scotland and England. Other initiatives introduced by NGESO include the voltage pathfinders [27], and changes to balancing services and their markets [28]. The view from many stakeholders is that the solutions to many of the operability challenges are known technically but there were concerns raised about waiting for the market to address the challenges. Instead, many stakeholders are of the opinion that engineers should be engaged to enact what is needed on the electricity system now.

---

[40] With particular reference to the transition to less passive demand and an increase in the number of actors in power system operation, the subsequent provision of future electricity system services, and the deployment and management of assets.

[41] 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.

[42] Short circuit level refers to the amount of current that flows at a particular location on the system when a short circuit fault occurs there. Note that NGESO's evaluation of tenders in the 2nd phase also includes inertia [25].

[43] NGESO defines a total requirement for 8.4 GVA across 8 areas in Scotland, including Spittal, Blackhillock, Peterhead, Longannet area, Hunterston, Coylton area, Elvanfoot area, and Eccles area.

[44] See also Energy Storage Technical Feasibility Assessment [54].

Summary

- Operability of the power system concerns the ability to operate a stable system in which its physical limits and those of its various elements are respected.
- There are doubts about current and future power system operability for both the British system and the Scottish power system within it. The survey results indicate a deteriorating view for 2030 relative to now.
- A number of stakeholders expressed frustration because deployment of solutions is seen by them as lagging policy and need.
- Although there have been some innovations there are still challenges involved in operating a future net-zero power system, but there is confidence that the engineering problems can be overcome.

7 Power system resilience

Power system resilience is the capability to prevent, contain and restore the power system following a disturbance [29]. In this context, power system resilience encompasses many of the other topics being discussed in this report. Considering climate change, the incident in Texas in February 2021 [30] where cold weather caused severe interruption to electricity supply, and an increasingly digital power system, it is vital that the power system is protected against, and can contain and recover from, external threats including extreme weather and cyber-attacks. The question posed to participants refers specifically to extreme weather, or physical or cyber-attacks, and the degree to which they agree with the following statements:

1. At the moment, the electricity system in Scotland is resilient against major disturbances such as extreme weather or physical or cyber-attacks.
2. In 2030, the electricity system in Scotland will be resilient against major disturbances such as extreme weather or physical or cyber-attacks.

The results of the survey presented in Figure 18 show that there is considerable uncertainty and pessimism about the resilience of the current and 2030 Scottish power system, with most of the pessimism[45] coming from those who work in the industry (Industry General and Industry Responsible). Furthermore, as shown in Figure 19 the perception of pessimism overtakes uncertainty in industry experts and stakeholders' perception for Scottish power system resilience in 2030.

[45] Based on contribution to number of participants that gave the rating 'Somewhat disagree' and 'Strongly disagree'.

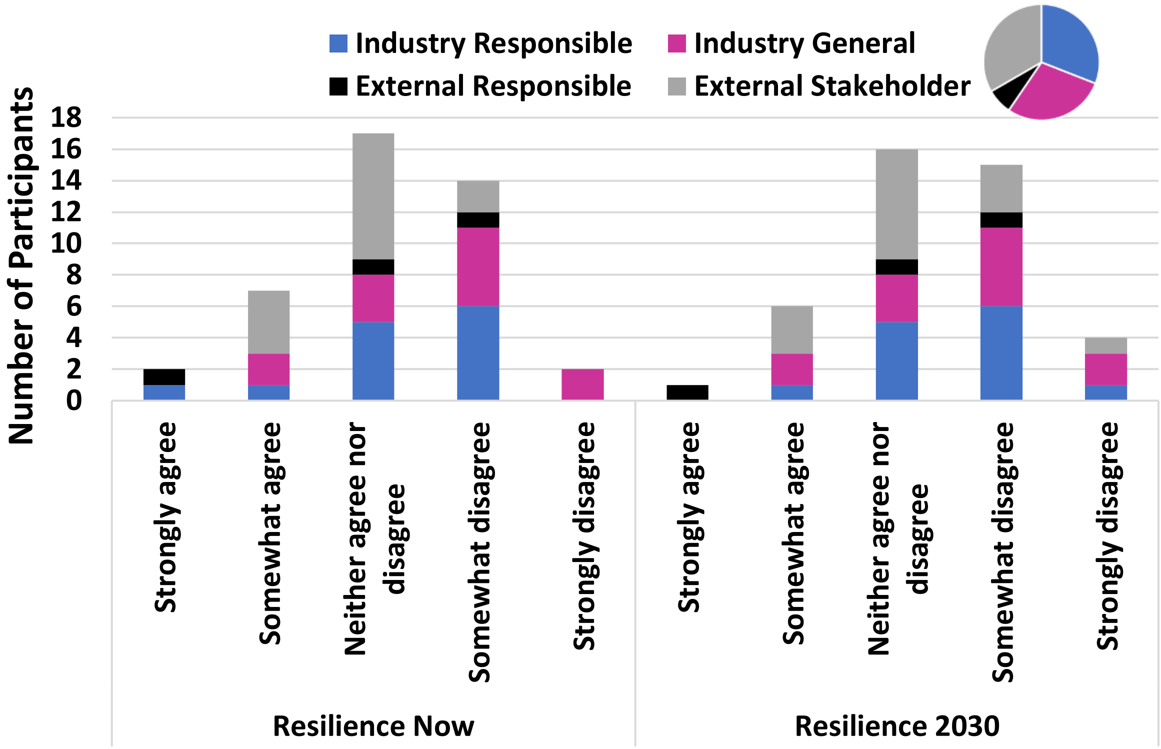


Figure 18: Spread of the weighted responses to questions around Scottish power system resilience, showing differences between survey groups.

The expected closure of Hunterston nuclear power plant next year, the potential closure of Torness by 2030 or earlier, and an ageing Peterhead raise concerns about challenges for Scotland over the next decade, with the suggestion of a local capacity market to incentivise new builds of schedulable plant in Scotland. Some industry experts and stakeholders support a need to return to local systems, with the perception that it is slightly naïve to think that the status of the security of electricity supply will be the same locally, Scotland-wide, or GB-wide. Adding that local networks will need to be sufficiently sized to enable the wider system to access to aggregated resources. There is also the view that Distribution Network Operators (DNOs) should help each other across areas, e.g. restore supplies outside their own areas. There is also the perception that reinforcement of the transmission network would increase and improve interaction between national and local networks, fundamentally increasing resilience. The introduction of 'resilience as a service' was also suggested[46], e.g. if something goes wrong in an area, diesel generators or batteries on a truck can be dispatched to provide relief. Although there was also mention of some sort of warning being given to the public of a risk to continued electricity supply, some industry experts and stakeholders are of the opinion that any such measures may be counterproductive, potentially causing panic actions.

[46] There is an innovation project called Resilience as a Service (RaaS) that is funded through Ofgem's Network Innovation Competition. The project is a partnership between Scottish and Southern Electricity Networks, E.ON and Costain. The aim of the project is to "[…] develop and trial a new market-based solution which uses services provided by a Battery Energy Storage System (BESS) together with local Distributed Energy Resources (DER) to swiftly, automatically, restore power to customers in the event of a fault." [58].

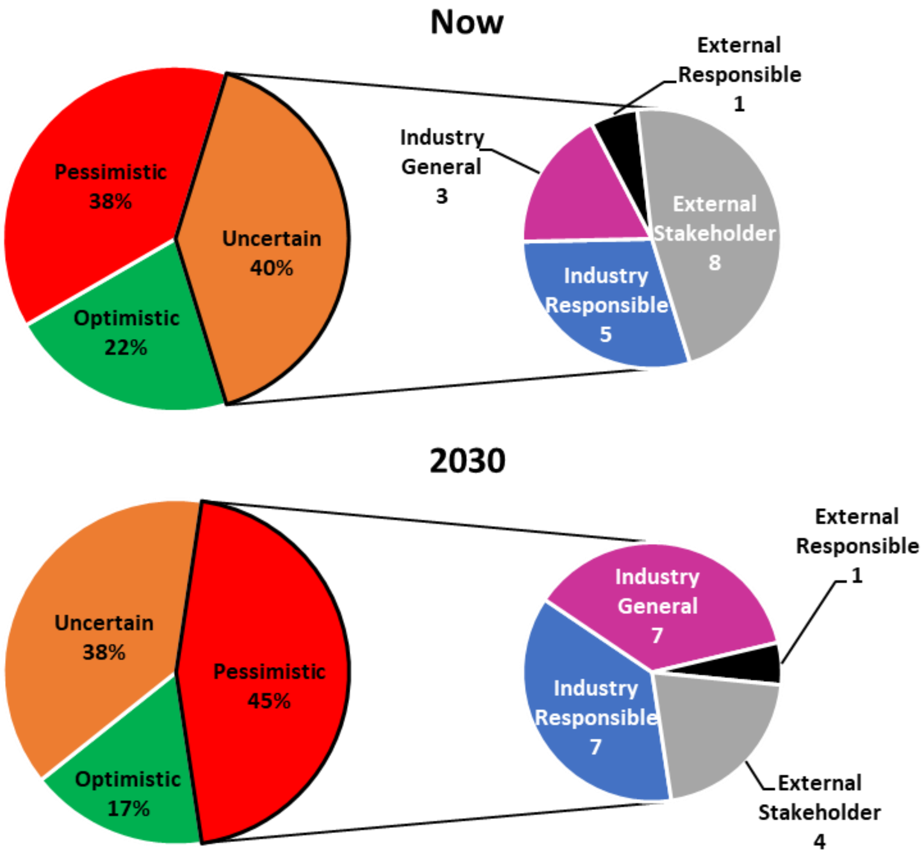


Figure 19: Overall response to questions around Scottish power system resilience, showing the number of individuals from each group that contributed to the majority rating

In a wind-orientated Scottish power system there could be several periods of no productivity from wind farms. Consequently, there are questions on how the power system copes during wind droughts. As part of an interconnected GB system, power could be – and is – imported from England, provided it is available there. Industry experts and stakeholders point to the need for long term storage with an energy capacity roughly around 10 TWh[47], which would essentially replace long duration storage that existed in the form of fossil fuels. How this sort of long-term energy storage will be used and managed is another question, to which there is the perception among some experts of the need for a Strategic Reserve Standard[48] that would ensure reserve availability. Otherwise, the market may incentivise selling energy at a 'good' price now regardless of whether there is a strategic need to hold the reserve of energy for longer. Another alternative of note is using CCGT[49] gas plants with CCS[50], which might make use of long-term storage of gas as well as – provided the plant is designed to have the capability – flexibility for power management and restoration capabilities. Hydrogen is

[47] The authors in [9] suggest the need for grid connected batteries capable of exporting up to 140 GW of power, and for this to be in place by 2035 to achieve net-zero by 2050.

[48] Britain has a 'generation adequacy' standard – of a 'loss of load expectation' (LOLE) of no more than 3 hours per year – which underpins the GB-wide capacity market and a Security and Quality of Supply Standard that governs investment in transmission network capacity and operation of the transmission system. There is also a gas security of supply standard. However, none of these sets a standard for how much energy should be stored for the purpose of producing electricity. A strategic reserve standard might be used to do that.

[49] Combine Cycle Gas Turbine.

[50] Carbon Capture and Storage.

another option, and it can be produced via electrolysis or SMR[51], the latter of which can in theory be done with CCS. However, there are questions about costs, scale, markets and regulation.

Summary

- There is a feeling of concern around the trend of the Scottish power system's ability to prevent, contain and recover from interruptions to supply arising from disturbances, i.e. its resilience, particularly due to the recent and expected closure of large thermal power plants.
- Although reduction in the unabated use of fossil fuels is welcomed along the path to net zero, it is the opinion of industry experts and stakeholders that steps must be taken to address any shortcomings in resilience of the transitioning power system.
- Some suggestions include:
    - a return to more locally oriented systems;
    - the use of adequately sized local networks for aggregated services or creating a regional capacity market to incentivise the construction of new schedulable plants in Scotland;
    - transmission network reinforcement;
    - "resilience as a service", e.g. the use of diesel generators or batteries on a truck that can be dispatched to provide relief;
    - large amounts of long-term storage to manage 'dunkelflaute'; and
    - a Strategic Reserve Standard to ensure the availability of reserves of energy for the production of electricity, e.g. from energy storage.

8 Power system restoration

One of the main challenges associated with the transitioning power system is the availability, management and use of assets to restore electricity supply following a widespread disruption such as a Scotland-wide, or GB-wide blackout, and this question was posed to the survey participants. That is, to what extent do the participants agree with the following statements:

1. At the moment, it would be possible to restore electricity supply quickly were there to be a widespread disruption e.g. a Scotland-wide blackout.
2. In 2030, it would be possible to restore electricity supply quickly were there to be a widespread disruption e.g. a Scotland-wide blackout.

The results of the survey, shown in Figure 20, indicate significant doubt that there is and will be (by 2030) sufficient capability to quickly restore electricity supply in the case of a widespread disruption. Figure 21 shows that while there is an increase in optimism for 2030 relative to current capabilities, there is also an increase in uncertainty and there remains significant doubt around future capabilities.

[51] Steam Methane Reforming is a method for producing hydrogen and carbon monoxide via reaction of hydrocarbons with water.

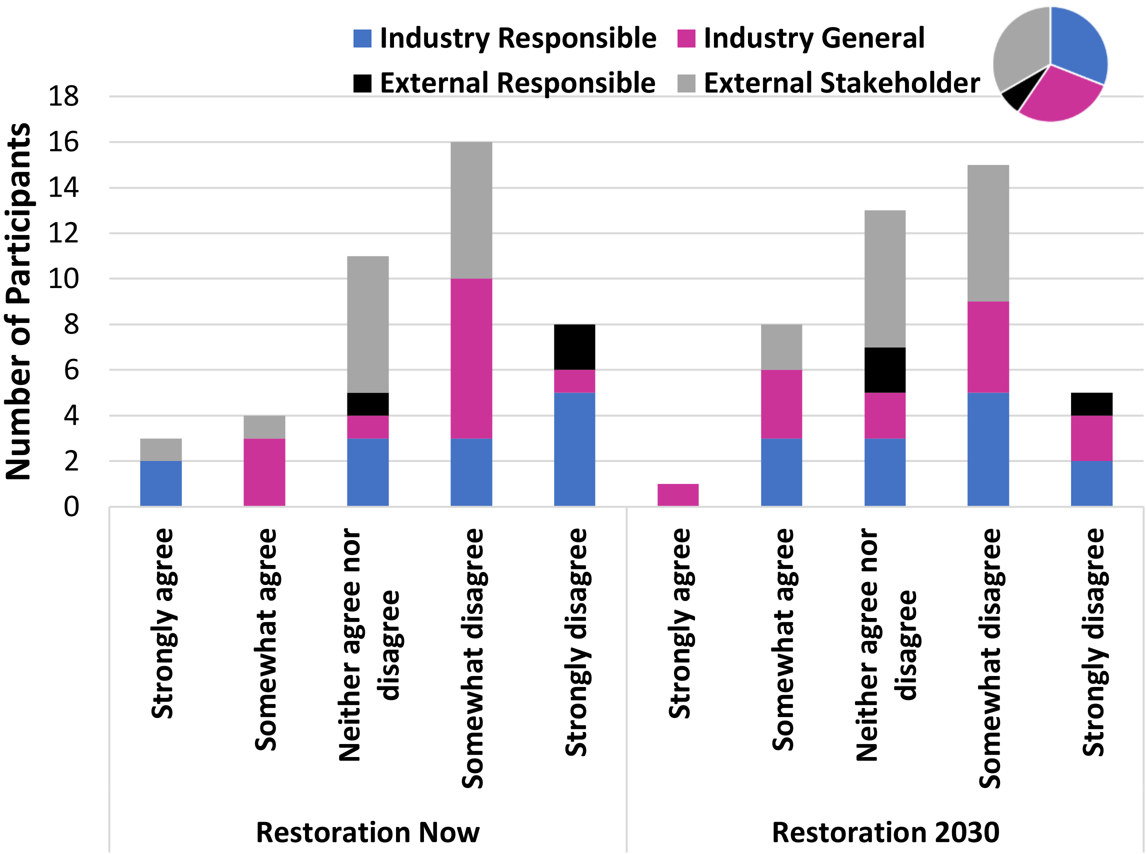


Figure 20: Spread of the weighted responses to questions around power system restoration, showing differences between survey groups.

During discussions with industry experts and stakeholders, points were made on what different groups of energy users might perceive as a ‘quick’ restoration, and reference was made to the new Electricity System Restoration standard announced by BEIS in April 2021 [31]. Quite what might be regarded as timeliness of restoration was questioned by some industry experts and stakeholders, with the view that *“What's important is that the restoration is successful and that critical services are covered in the meantime.”* Others raised caution about customer-centric approaches to define the timeliness of restoration being counterproductive adding that the timeliness should instead be defined by what can be done in terms of the capabilities of the technologies available.

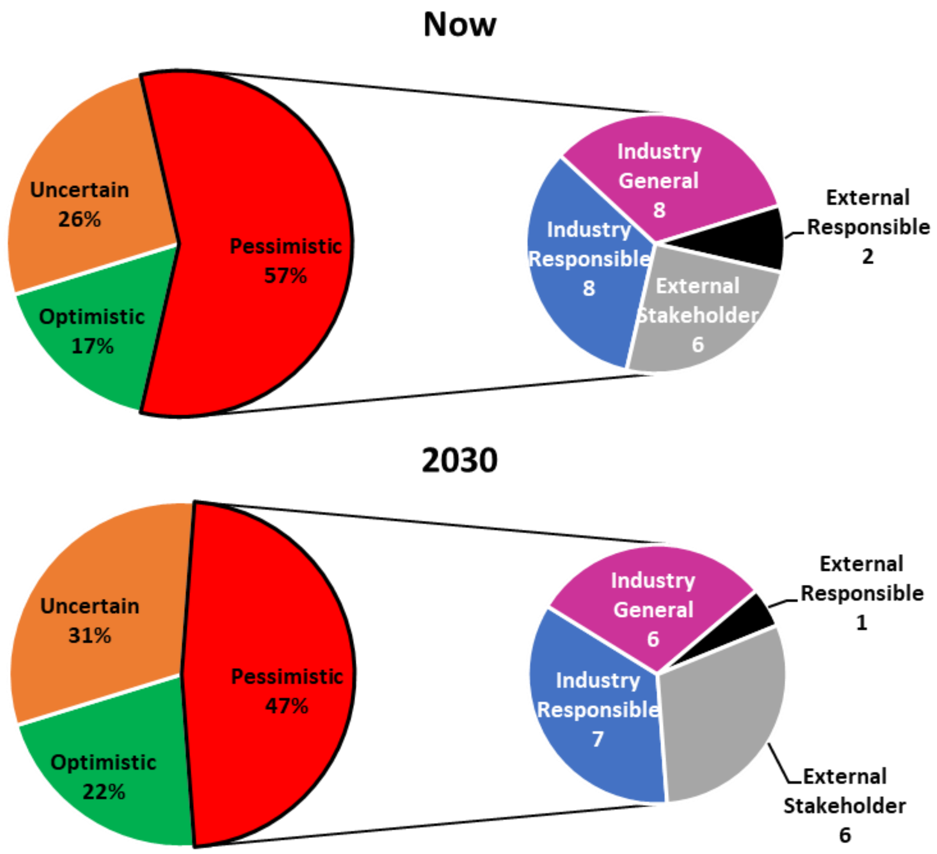


Figure 21: Overall response to questions around power system restoration, showing the number of individuals from each group that contributed to the majority rating.

> *"This new Electricity System Restoration Standard will require NGESO to have sufficient capability and arrangements in place to restore 100% of Great Britain's electricity demand within 5 days. It should be implemented regionally, with an interim target of 60% of regional demand to be restored within 24 hours. The Electricity System Restoration Standard will reduce restoration time across Great Britain and ensure a consistent approach across all regions." – [31]*

In reference to the new restoration standard, some industry experts and stakeholders suggested that the standard aims to maintain current levels of security of supply, whereas the value of electricity derived services will significantly increase, in which case restoration expectations might change. Specific reference was made to impact of loss of electricity on heating and transportation which will be increasingly dependent on electricity, along with increased dependence on broadband and mobile, and managing and coordinating many actors with much more variability.

> *"[We're] going from tens of plants to tens of thousands if not hundreds of thousands of actors in a restoration situation that would need to be coordinated [with] more variability related to weather dependency leading to a more complex problem. It's solvable but complex."*

Roundtable participant, July 21

Another point raised in reference to the standard was which energy user or loads make up the prioritised[52] 60%, and how these would be identified and supplied from an engineering perspective. Industry experts and stakeholders also noted that the most vulnerable energy users should be prioritised for access to energy, adding that evidence from past major events worldwide suggests that it is often neighbourhoods with the highest numbers of vulnerable people that get access last. It was noted that DNOs should have records of vulnerable energy users, or critical or essential loads. Furthermore, by identifying priority and non-priority groups, system operators and network owners could identify resources that could be used in Low Frequency Demand Disconnection (LFDD)[53] or in any necessary rolling blackouts, which would be used to avoid a system-wide blackout. On that note, industry experts and stakeholders point out that LFDD schemes should be more capable of discriminating between different categories of load[54].

"Peterhead remains an extremely important plant to provide 1 GW to get the transmission networks up and running and potential within 30 – 40 hours power from England and Wales would be exported to Scotland potentially one or two units from Drax. However, this means long system restoration in terms of distance."

Roundtable participant, July 2021

Industry experts and stakeholders highlighted that, in Scotland, the transitioning power landscape and plant closures mean that in terms of large schedulable plants there are only two nuclear plants (Hunterston and Torness) and Peterhead, plus smaller run-of-river hydro schemes and the pumped hydro storage stations. The latter are very useful in system restoration but must be managed carefully in view of the limited stores of energy to which they have access, due to the finite sizes of reservoirs. The nuclear power plants are not very useful for black start, for safety reasons and the longer time to restart, meaning that Peterhead is extremely important to the restoration plan in Scotland. With the hydropower fleet in operation it should be possible to get a skeleton network up and going from the north of Scotland, but the Central belt will be more challenging with reliance almost entirely on Cruachan pumped hydro station; it is therefore likely that there would be reliance on support coming from the NGET-owned network region in England. Some of the industry experts and stakeholders in the roundtable highlighted the benefits of pumped storage hydropower, which addresses a range of problems but for which a business case for new capacity is currently very

[52] Industry experts and stakeholders noted that nuclear power stations do not contribute to restoration. Instead, they are among the critical demands to be supplied.
[53] Low Frequency Demand Disconnection is a scheme that is used to automatically disconnect loads from the network to prevent frequency collapse and a blackout.
[54] There is work currently being done by NGESO and WPD to revise and improve the existing LFDD scheme [51].

difficult to make. The perception is that there should be more work being done to try to get some of the pumped storage developments up and running, perhaps with the strategic benefits being identified by the ESO in an exercise similar to the Network Options Assessment (NOA) . It was also noted that steps are being taken to address some of the challenges associated with restoration with attention being given to large scale renewables and Virtual Synchronous Machines (VSMs)[55]. Other work also includes the Distributed Restart project, which aggregates dispersed renewables to facilitate restoration [32].

Summary

- Evidence from around the world, including Europe, shows that complete shutdowns of whole countries' or large regions' power systems can and do happen. Every system should therefore be prepared with facilities to enable the system to be re-started – "black start" after "the lights have gone out" – and supplies restored.
- There is significant pessimism around the restoration capabilities of the Scottish power system – an aspect of resilience – mostly coming from those who work in the electricity supply industry. This is attributed to the transitioning power system and plant closures in Scotland and reliance on support from power sources across the border in England and the network connections to them that make a restoration strategy challenging.
- The value of resources like hydropower is highlighted and there are calls for measures that facilitate the deployment of new pumped storage hydropower projects, which could help with many of the challenges facing the future power system.
- Development work and trials are ongoing and offer the opportunity to alleviate some of the challenges by creating new providers of restoration services and coordinating distributed energy resources[56] in the provision of such services.
- In April 2021 the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) announced an intention to introduce a new system restoration standard requiring that, in the event of a nationwide collapse of the system, the System Operator should have "sufficient capability and arrangements in place to restore 100% of Great Britain's electricity demand within 5 days […] with an interim target of 60% of regional demand to be restored within 24 hours" [31].
- Increased dependency on electricity, for information technology, heating and transport, might mean that security of supply and restoration expectations will change.
- Caution is raised in reference to the prioritisation implied in the new standard, to ensure that essential services and vulnerable groups and regions are prioritised.

---

[55] This work is still considered to be in its early stages with a test conducted in Dersalloch [24].

[56] Relatively small individual generators, storage and flexible demand that are connected to the distribution network. (Larger scale resources tend to be connected to the transmission network. Distributed generation now adds up to a significant proportion of total generation capacity).

9 Secure, reliable and resilient electricity supply

The authors of the survey postulated that a number of different factors might contribute to security, reliability and resilience of electricity supply in Scotland now and in 2030. Survey participants were asked to rank these factors, producing the result shown in Figure 22. Based on the results the following key points can be inferred.

- Reliable supplies of fossil fuels, for the generation of electricity, are considered less important in 2030 than they are now, having moved down 11 places to 15th (last) in 2030.
- Large volumes of flexible demand, i.e. demand side management or demand side response, are considered more important in 2030 than they are now, having moved up 6 places to 4th in 2030.
- Innovative, 'smarter' ways of operating an electricity system, are considered more important in 2030 than they are now, having moved up 5 places to 6th in 2030.

Ranking			Change from 'Now' to '2030'	
2030	Now	Description	Direction	Steps
1	2	A strong electricity network in Scotland	↑	1
2	1	A strong electricity network in Britain	↓	1
3	3	A clear electricity sector mechanism to ensure sufficient 'dispatchable' electricity generation capacity in Britain		
4	10	Large volumes of large-scale energy storage	↑	6
5	6	A clear electricity sector mechanism to ensure sufficient 'dispatchable' electricity generation capacity in Scotland	↑	1
6	11	Innovative, 'smarter' ways of operating an electricity system	↑	5
7	5	A high amount of wind generation capacity in Scotland	↓	2
8	7	A strong electricity network connection between Scotland and other countries	↓	1
9	8	Strong and clear electricity prices to highlight times and locations of scarcity	↓	1
10	13	Large volumes of flexible demand, i.e. demand side management or demand side response	↑	3
11	9	A high amount of wind generation capacity in Britain	↓	2
12	14	Large volumes of localised energy storage	↑	2
13	15	Large volumes of seasonal energy storage	↑	2
14	12	Large volumes of localised back-up generation	↓	2
15	4	Reliable supplies of fossil fuels for the generation of electricity	↓	11

Figure 22: Consulted stakeholders' ranking of factors that contribute to a secure, reliable and resilient electricity supply in Scotland

It is noted that the rankings appear consistent with the comments offered by industry experts and stakeholders when discussing the results of the previous survey questions. In addition to the ranked factors, some survey participants mentioned other factors that, in their opinion, contribute to a secure, reliable, and resilient electricity supply in Scotland.

- Sources of system strength.
- Grid forming converters for system stability services.
- Inertia, baseload power and nuclear generation.
- Extensive backup for large scale deployment of renewables.
- Use of hydrogen for flexibility.
- A competent system operator.
- Operational and planning measures.
- Scottish system resilience versus GB system resilience.

Survey participants were also asked to rate the importance of different means of ensuring a reliable and resilient supply of electricity in the medium to long term. The results are shown in Figure 23.

		Proportion of each group that views the items as "Extremely Important"			
Rank	**ITEM**	**Industry Responsible (13)**	**Industry General (12)**	**External Responsible (3)**	**External Stakeholder (14)**
1	Via clearly defined standards and obligations on parties in the energy sector	77%	42%	33%	43%
2	Via explicit government decision to commission new facilities	31%	42%	0%	7%
3	Via direction from an authority such as Ofgem to commission new facilities	23%	0%	0%	29%
4	Via centrally administered market mechanisms such as the capacity market	23%	8%	33%	29%
5	Via a market mechanism that reveals the value that different energy users attach to security of supply	38%	0%	0%	36%

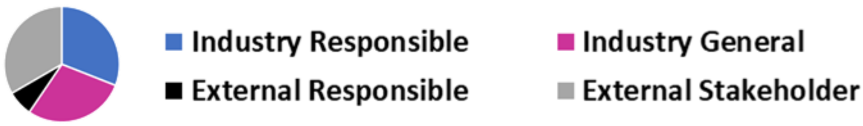


Figure 23: Consulted stakeholders' ranking of how we can ensure a reliable and resilient supply of electricity in the medium to short term. Also showing the number of members of each group that thought a given item was of the highest importance

In addition to the ranked factors shown above, participants specified other factors that, in their opinion, are worth considering.

- Cultivating technical design authorities and other de-risking activities.
- Clear/well-founded generation resource pathways and system architecture that supports security.
- Offshore wind coordination/control.
- Smarter supervisory control across devices.
- Information and control infrastructure for a more dynamic, complex system.
- Incentives and policy to support flexibility (generation, demand, and other).
- Explicit government decision to decommission higher carbon facilities to create space for new facilities.
- Hydrogen as a storage/flexibility mechanism and the use of curtailed renewables.
- Improved understanding [of the] changing technical needs of the system.
- Whole system approach to planning and operation of future electricity system including cybersecurity, climate change impacts, etc.
- A diverse portfolio of generation, by type or geography.

As a final question in the survey, respondents were asked to rate the extent to which the ranking in Figure 23 should be specific to Scotland. The results presented in Figure 24 show a wide spread of views.

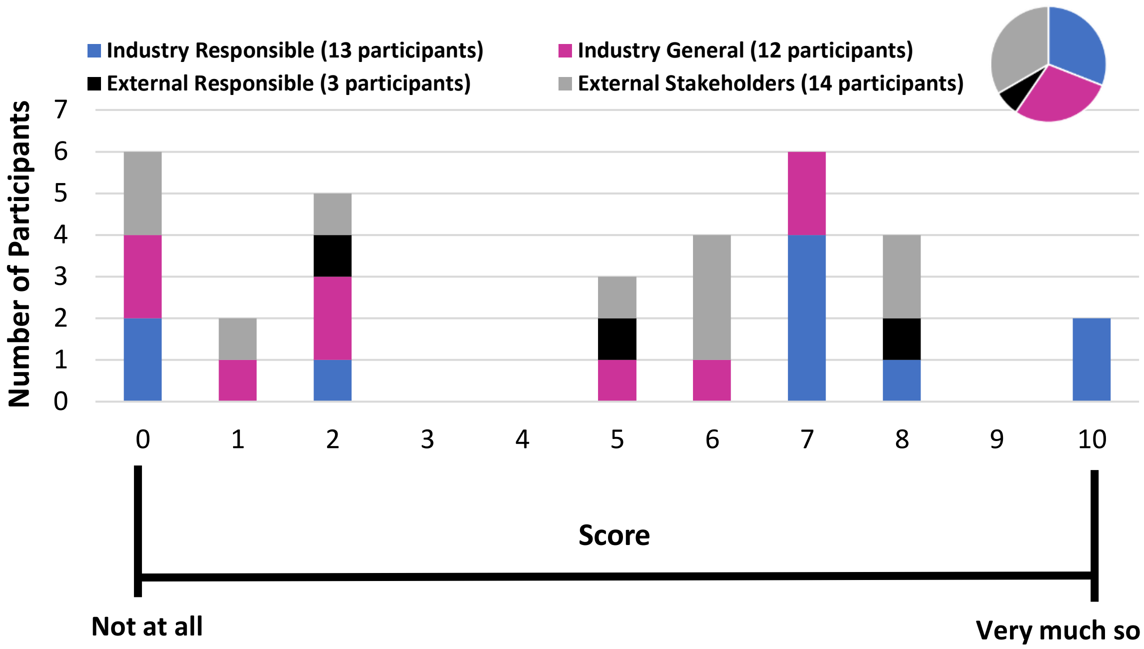


Figure 24: Consulted stakeholders' rating of the extent to which Figure 23 should be specific to Scotland

There is a perception among industry experts and stakeholders that ensuring security, reliability and resilience in a transitioning power system provides an opportunity to rethink the way that the electricity and wider energy system operates. However, in light of the technology that is required or will be available, experts raise questions about whether existing policy, regulations and responsibilities can deliver a much more integrated, complex and digitalised system while maintaining a secure, reliable and resilient power system that remains equitable.

> *"[Given] that renewable power is a very different entity from fossil fuelled power, [we should] take the opportunity now, while there's still a small amount of time left, to rethink the electricity and wider energy system, while maintaining resilience."*
>
> *Roundtable participant, July 2021*

There is also the perception that there is urgency around planning for an uncertain future and, adopting a least regret approach, that network investment should be done ahead of the need. Furthermore, industry experts and stakeholders suggest that the deployment of network upgrades should be coordinated, e.g. if a road needs to be dug up for broadband, then perhaps it is worth considering whether the opportunity should be taken to do any work necessary to provide for Electric Vehicle (EV) chargers as well, so that the number of times the same road is dug up is reduced. Some experts highlighted the need for DNOs that act more like Distribution System Operators (DSOs)[57] given the trend towards a renewable focused distribution system. Furthermore, there was the opinion that the ability to alter generation and demand within local areas is an effective way to provide services and resilience to the power system as whole, something that would benefit from having DNOs behaving more like DSOs. Some experts and stakeholders raised questions about licensing and regulation of the actors providing grid services via the distribution network, noting that any arrangements should be centred around consumer protection and consider social implications.

> *"The technology is there but the commercial arrangements need to be in place, and that would benefit from having the right parties speaking to each other."*
>
> *Roundtable participant, July 2021*

There was some doubt around existing markets with some industry experts and stakeholders of the view that service definitions are unclear. In addition, there was the opinion that solutions like VSMs face a barrier to implementation because there is no payment mechanism to incentivise a renewable developer to incorporate the technology in their assets. Furthermore, some parties view the present situation as one in which short-term markets are designed to cater to specific participants who may have been involved in designing the product – *"[…] it's not really an open market and it's unclear how long it'll last"*. According to a number of industry experts and stakeholders, there is not currently an open market for electricity or other products or services needed in the electricity sector (particularly in reference to the stability pathfinders). The proponents of this view regard the market as artificial because of the subsidies, etc., used to deliver very particular outcomes that a market on its own would not deliver; it is a pseudo-market.

> *"[…] it's important to remember that we don't have an open market for electricity or other products needed in the electricity sector (ancillary services etc.). It's artificial because of the subsidies and other 'adaptations' to the market used to deliver very particular outcomes which a market on its own wouldn't deliver. It's a pseudo-market."*
>
> *Roundtable participant, July 2021*

A number of industry experts and stakeholders highlighted that one of the issues for Scotland is recognising the scale and pace of change expected by 2030, and that it is

[57] In Britain, the term Distribution System Operator has tended to be used to refer to the party responsible for operation of the distribution network taking a more active role in it, e.g. re-dispatching generation or making of use of flexible demand to manage power flows prior to the occurrence of any network fault. This can be contrasted with conventional, historic practice for distribution network operation to be quite passive with action tending to be taken only in response to fault outages.

therefore important to both have markets in place to provide system services from net-zero sources and to bring together different actors to deliver solutions that address the complex challenges. That said, there was a strong opinion among experts that market forces alone will not suffice, with some expressing a preference for government intervention and standards to drive change. However, there is also the perception that existing standards need to be revised and, in some cases, expanded. It is thought by some industry experts and stakeholders that most of the work around standards has been around increasing utilisation on the networks while maintaining security and releasing more capacity to more market participants, *“[…] but there hasn’t been a lot done on setting standards for what we should expect to pay for generation and what should be expected within those contracts”*.

> *“The power system would be inherently more complex and potentially riskier, so standards could be the preference going forward, over markets, since it’s tried and tested.”*
>
> *Roundtable participant, July 2021*

Industry experts and stakeholders consulted in the survey and roundtable are generally of the opinion that there is a prominent role for government to play in driving change, to get agreement on areas of concern between Scottish and UK governments, to push forward required actions and convert pilot experiments into commercial solutions. They added that if the situation and questions are put in a meaningful form for government consideration, so that both UK and Scottish governments understand that there are issues that need a resolution, both parties can work together with the appropriate political will. It is also thought that such a partnership should be extended to include the regulator, private companies and the consumer. Involving the consumer was raised as being of particular importance because these changes to the power system towards achieving net zero will require a change to the way of life of the consumer, e.g. the electrification of heat and transport; and this transition would likely incur additional costs associated with keeping power supplies secure.

Industry experts and stakeholders believe that security of electricity supply is not just the NGESO’s problem, adding that there is a responsibility of various parties to look after their own security of electricity supply and, in particular, provide their own back-up supplies. It was noted that during the frequency incident on the 9th of August 2019 [20], the operators of disrupted trains that were difficult to restart did not seem to know that their supplies could be affected. Some stakeholders added that because major disturbances are so rare, it is easy to forget that they can happen. Therefore, relevant facilities or tests and procedures can be overlooked or not prioritised, and as the aging workforce retires, their replacements do not always appreciate the significance of those tests and procedures. There is the perception that many standby diesel generators are unreliable and not maintained properly, with some owners storing between a day to 4 days’ worth of fuel whereas the new restoration standard says that the restoration of all power supplies may take up to 5 days.

The overall perception from industry stakeholders is that now is the right time to be having these discussions because, even though we might be in a relatively good position now, there are aspects related to the net-zero transition and the whole energy system that need to be addressed, which will take time.

Summary

- The transitioning power system is expected to have significantly less reliance on fossil fuels for generating electricity, while large volumes of flexible demand and 'smarter' ways of operating the grid will have much more importance in a 2030 power system.
- Other factors highlighted as important for a future grid include "a competent system operator", flexibility, "system strength"[58], backup for large scale renewables deployment, schedulable and persistent sources of power, and services for system inertia and stability including provision of such services via power electronic converters[59].
- There is the view that it is important to consider a "whole system approach" to planning and operating the future electricity system to ensure that it is reliable and resilient.
- During the roundtable it was suggested that the power system transition presents an opportunity to rethink how the interconnected elements of the energy system interact, with due consideration given to "consumer protection".
- Standards have a major role to play to ensure responsible, equitable and regulated grid services that can be efficiently and effectively delivered and coordinated. A general view was expressed that existing standards will need to be expanded and revised.
- Some stakeholders called for protocols and technical design authorities that understand the changing technical needs of the system, and can facilitate the de-risking of development activities and coordinate the efficient deployment of assets.
- There are concerns around existing markets which are perceived to present barriers, particularly to renewables developers, in deploying solutions because there is currently no incentive to proceed.
- It is thought by a number of stakeholders that some existing markets are really only pseudo-markets, designed to be short-term, with unclear service definitions and catering to specific participants.
- During the roundtable some participants suggested that there is a prominent role for governments to play. The UK and Scottish governments should form a united front and extend partnership to the regulator, private companies and the consumer, to drive change forward so that deployment of solutions can catch up with policies and the need for solutions.

[58] The term "system strength" relates to how key features of the system, such as voltage, are affected by faults on the system.

[59] Britain's interconnections with other countries and power sources such as solar PV and many wind turbines, make use of power conversion equipment using power electronic devices as the interface between the interconnected AC power system – 'the grid' – and the source of power. There is a great deal of flexibility in how they are controlled, but also strict physical limits due to the nature of the electronic devices.

10 Summary of results

10.1 Greenhouse gas reductions and offshore wind targets

There is uncertainty among industry experts and key stakeholders around Scotland's ability to achieve its 2030 and 2045 GHG emissions targets although those believing the targets will be met outnumber those who do not. In respect of the Scottish Government's ambition for 11 GW of offshore wind generation capacity by 2030, the pessimists outnumber the optimists.

Although there has been much progress in reducing the emissions intensity of electricity production, more is needed to achieve net-zero ambitions, especially if there will be much more reliance on electricity for energy for transportation and heating. Some industry experts and stakeholders feel the need for clearer communication of the meaning of the 2030 emissions reduction target, as well as clarity on whether Scotland's GHG emissions targets are territorial within Scotland or within the UK.

Concerns were raised by the consulted stakeholders about the complexities and challenges associated with a net-zero power system that must be addressed to mitigate any potential barriers to implementation. Alongside this, stakeholders noted the need to consider decarbonisation in the context of the bigger picture of energy systems in general, and whether the challenge of maintaining resilient supplies of electricity might impede efforts toward decarbonisation.

10.2 Dependency on imports of power

The level of demand for electricity and production from wind farms varies. Scotland is, therefore, sometimes dependent on imports of power. GB, as a whole, is a net importer of electrical energy. Interconnections, between both Scotland and the rest of GB and between GB and other parts of Europe, enable such imports and provide an avenue to trade (buy and sell) power with other regions. Interconnection also offers access to renewable resources that may be abundant in other regions, or alternatively, a route for export of power during periods of high renewable electricity production within GB.

Long periods of low wind and solar production – periods becoming known as 'dunkelflaute' – pose some concern, and are argued by some stakeholders to mean that there is a case for additional 'schedulable' generation capacity within Scotland instead of allowing interconnectors to mean that less capacity is built locally. There will need to be a balance between dependence on imports for security of electricity supply and locally sourced power capacity. The mix of resources can be determined by least-cost options and/or political will.

10.3 Reliably meeting Scottish electricity demand

Industry experts and stakeholders have considerable confidence in the current capability of reliably meeting Scottish electricity demand, but there is an increased uncertainty with respect to meeting it in 2030.

There is an expectation of a shift towards flexible demand playing a more active role, with an increasing proportion of demand becoming a controllable element rather than a passive one. This is especially the case when considering that a power system dominated by renewables would be more dependent on weather and a matching of the timing of use of electricity to when power is available from renewables would help with system balancing. However, caution is raised around factors associated with such a transition, including management of such a complex system with numerous controllable demand elements, along with issues around: the assignment of responsibilities; regulation; "consumer protection"; ease of use and clarity of the terms of contractual agreements; digital security and vulnerabilities; and equitability.

10.4 Power system operability

Operability of the power system concerns the ability to operate a stable system in which its physical limits and those of its various elements are respected. There are doubts about current and future power system operability for both the British system and the Scottish power system within it. The survey results indicate a deteriorating view for 2030 relative to now.

A number of stakeholders expressed frustration because deployment of solutions is seen by them as lagging policy and need. Although there have been some innovations there are still challenges involved in operating a future net-zero power system, but there is confidence that the engineering problems can be overcome.

10.5 Power system resilience

There is concern around the trend of the Scottish power system's ability to prevent, contain and recover from interruptions to supply arising from disturbances, i.e. its resilience, particularly due to the recent and expected closure of large thermal power plants.

Although reduction in the unabated use of fossil fuels is welcomed along the path to net zero, it is the opinion of industry experts and stakeholders that steps must be taken to address any shortcomings in resilience of the transitioning power system. Some suggestions include: a return to more locally oriented systems; the use of adequately sized local networks for aggregated services or creating a regional capacity market to incentivise the construction of new schedulable plants in Scotland; transmission network reinforcement; "resilience as a service", e.g. the use of diesel generators or batteries on a truck that can be dispatched to provide relief; large amounts of long-term storage to manage 'dunkelflaute'; and a Strategic Reserve Standard to ensure the availability of reserves of energy for the production of electricity, e.g. from energy storage.

10.6 Power system restoration

Evidence from around the world, including Europe, shows that complete shutdowns of whole countries' or large regions' power systems can and do happen. Every system should therefore be prepared with facilities to enable the system to be re-started – "black start" after "the lights have gone out" – and supplies restored.

There is significant pessimism around the restoration capabilities of the Scottish power system – an aspect of resilience – mostly coming from those who work in the electricity supply industry. This is attributed to the transitioning power system and plant closures in Scotland and reliance on support from power sources across the border in England and the network connections to them that make a restoration strategy challenging.

The value of resources like hydropower is highlighted and there are calls for measures that facilitate the deployment of new pumped storage hydropower projects, which could help with many of the challenges facing the future power system. Development work and trials are ongoing and offer the opportunity to alleviate some of the challenges by creating new providers of restoration services and coordinating distributed energy resources[60] in the provision of such services.

In April 2021 the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) announced an intention to introduce a new system restoration standard. In the event of a nationwide collapse of the system this standard would require that the System Operator has "sufficient capability and arrangements in place to restore 100% of Great Britain's electricity demand within 5 days […] with an interim target of 60% of regional demand to be restored within 24 hours" [31]. Increased dependency on electricity, for information technology, heating and transport, might mean that security of supply and restoration expectations will change. Caution is raised in reference to the prioritisation implied in the new standard, to ensure that essential services and vulnerable groups and regions are prioritised.

10.7 Secure, reliable and resilient electricity supply in 2030

The transitioning power system is expected to have significantly less reliance on fossil fuels for generating electricity, while large volumes of flexible demand and 'smarter' ways of operating the grid will have much more importance in a 2030 power system. Other factors highlighted as important for a future grid include "a competent system operator", flexibility, "system strength"[61], backup for large scale renewables deployment, schedulable and persistent sources of power, and services for system inertia and stability including provision of such services via power electronic converters[62].

There is the view that it is important to consider a "whole system approach" to planning and operating the future electricity system to ensure that it is reliable and resilient. During the roundtable it was suggested that the power system transition presents an opportunity to rethink how the interconnected elements of the energy system interact, with due consideration given to "consumer protection".

Standards have a major role to play to ensure responsible, equitable and well regulated grid services that can be efficiently and effectively delivered and coordinated. A general

---

[60] Relatively small individual generators, storage and flexible demand that are connected to the distribution network. (Larger scale resources tend to be connected to the transmission network. Distributed generation now adds up to a significant proportion of total generation capacity).
[61] The term "system strength" relates to how key features of the system, such as voltage, are affected by faults on the system.
[62] Britain's interconnections with other countries and power sources such as solar PV and many wind turbines, make use of power conversion equipment using power electronic devices as the interface between the interconnected AC power system – 'the grid' – and the source of power. There is a great deal of flexibility in how they are controlled, but also strict physical limits due to the nature of the electronic devices.

view was expressed that existing standards will need to be expanded and revised. Some stakeholders called for protocols and technical design authorities that understand the changing technical needs of the system, and can facilitate the de-risking of development activities and coordinate the efficient deployment of assets.

There are concerns around existing markets which are perceived to present barriers, particularly to renewables developers, in deploying solutions because there is currently no incentive to proceed. In addition, it is thought by a number of stakeholders that some existing markets are really only pseudo-markets, designed to be short-term, with unclear service definitions and catering to specific participants.

During the roundtable some participants suggested that there is a prominent role for governments to play. The UK and Scottish governments should form a united front and extend partnership to the regulator, private companies and the consumer, to drive change forward so that deployment of solutions can catch up with policies and the need for solutions.

11 Discussion

11.1 Interconnectors and dependency on imports of power

Traditionally, security of electricity supply was centred around thermal plants and the fuels used in those plants, some of which were imported [33]. However, towards achieving GHG emissions targets there is shift from burning fuels towards using renewable resources [8], in particular weather dependent renewables with use, in Scotland, of significant and growing volumes of electricity generated from wind. Added to the electrification of heating and transportation, this has implications for security of energy supply and the supply of electricity in particular.

The power system in Scotland is an interconnected part of the British power system, and the British power system is interconnected with power systems in the rest of Europe. This interconnection is useful in efforts to achieve emissions reductions as renewable energy can be exported at times of high production rather than production being curtailed. It also contributes to security of supply as power can be imported when productivity from renewables is low. These exchanges are facilitated via electricity markets and the capacity of interconnectors [34]. The alternative to utilisation of imports is a need for adequate local backups and reserves to be self-sufficient, potentially incurring additional costs. It is in effect a question of striking a balance between dependence on power imports and deploying local generation capacity. How much expenditure would be acceptable to deploy locally additional schedulable capacity to facilitate power security? Put another way, how much self-reliance is sufficient?

11.2 Transitioning towards net zero

The emissions reduction targets set by the Scottish Parliament are understood to be territorial, i.e. the Scottish target of net zero by 2045 refers to GHG emissions generated in Scotland. Clarity on this would be welcomed by a number of the stakeholders who participated in the roundtable discussion which followed the survey described in this report. Although the electricity sector has a key role to play, achievement of the target is not the sole responsibility of the power industry. Any undertakings towards achieving emissions reductions targets should consider the broader picture of the whole energy system, alongside related systems such as digital networks.

Based on the evidence of the stakeholder consultations reported here, the perception of industry experts and stakeholders is one of uncertainty about achieving emissions reductions and renewables deployment targets. The extensive discussion of perceived risk to system operability, absence of anticipatory network development and barriers to deployment of new system services suggest that a lot of this uncertainty is down to unsolved challenges associated with the power system. These could lead to delays in the deployment of renewables. For instance, network capacity will need to be developed to transfer the increased offshore production across the country, with additional assets needed within the onshore network to facilitate continued operability. These and new services that would prepare the grid for renewables dominance are seen by a number of stakeholders as being slow to deploy. Some of the new capacity and services needed are still at the pilot phase and others are facing barriers to entry due to lack of commercial incentives.

The consulted stakeholders believe that a united front from UK and Scottish governments, in concert with private companies, regulators and consumers, can drive change more rapidly than is currently the case. For instance, with respect to management of system frequency, the amount of wind on the power system can be managed using methods such as those described in [35]. However, one key constraining factor is the loss of mains (LoM)[63] protection settings. The standards governing these settings have been changed [36] and the use of vector shift has been deemed by Ofgem to be unacceptable for LoM protection[64], but it took the events of August 9th 2019 to raise pressure to initiate a programme in September 2019 [37] to accelerate the update of LoM protection settings. The August 9th incident also prompted changes to the clauses Security and Quality of Supply Standard (SQSS)[65] relating to frequency management [38]. This links to another point - that owners of electrical equipment should take responsibility to look after their assets, such as the susceptibility of trains to low system frequencies.

11.3 Flexibility and reserve in a renewables-dominant power system

The impact of 'dunkelflaute' and its implications for system operation and meeting power demand cannot be ignored [39, 40]. Although interconnectors have a role to play, long-

---

[63] Distributed generation (DG) is required to disconnect in the event that the section of network to which it is connected becomes isolated from the rest due to a network fault, a link to the main system – the 'mains' – is lost. Different means might be used to effect this, with the settings of some being noted to disconnect DG when 'mains' have not, in fact, been lost [56].

[64] Effective since February 2018 [52, 53].

[65] The SQSS specifies the unplanned events against which the transmission system's operation should be secured and the technical limits within which it should be operated. The SQSS also sets out rules for the development of the transmission network's capacity. Compliance with the SQSS is a condition of the licences of all three GB electricity transmission network owners and NGESO.

term storage[66] can also be used. There is also a case to be made for the provision and availability of reserves via a Strategic Reserve Standard to maintain some level of reliability of electricity supply. Flexible demand can also play a role, perhaps more suitable for shorter timescales, and informed participants could agree to have their loads centrally controlled to provide services to the grid including power balancing in times of need, helping to reduce the magnitudes of peaks of demand. A renewables dominant power system with less schedulable, weather dependent production would greatly benefit from controllable demand. That said, it is crucially important any such scheme provides adequate to safeguards to consumers, e.g. with the provision of a facility to override the exercise of flexibility. It is also equally important to ensure that, given that such a scheme would depend on digitalisation, vulnerabilities are properly managed. The customer must be a fully informed participant to prevent circumstances of regret because they did not know or understand the terms of their agreement(s). Any such scheme must have appropriate incentives, and it must be accessible, equitable and well-regulated, with provisions for responsibilities in the event that something goes wrong. It may also be noted that reduction of electrical load at peak times and shifting of demand to other times might be useful not only in respect of the whole electricity system's balance but also in terms of respecting a regional or local network's capacity to import or export power. The more active management of local, distribution networks to maximise utilisation of network capacity and limit the need for reinforcement would benefit from access to services from flexible demand, generation and storage. It has been argued by many that a 'distribution system operator' would be best placed to utilise such services. It was also argued by a number of the consulted stakeholders that improved visibility of distributed resources is essential and is a pre-requisite for making them controllable, but that the provision of this is lagging far behind need. The potential for interconnection to be made available between neighbouring distribution networks and provide mutual support between areas was mooted as a complement to connections via the transmission network. The concept of 'resilience as a service' was also noted where, for example, portable, local sources of electricity might be used in the event of a connection to the main grid being lost.

11.4 Restoring electricity supplies

Major failures of power systems can, and do, happen. It is therefore important that, aside from ensuring generally reliable supplies, power supplies can be restored quickly following a widespread disruption. Central to this is defining the prioritisation of segments of demand which should include vulnerable groups and critical loads representing essential services to society, such as communications and clean water. The consulted stakeholders generally welcomed the proposal of a new restoration standard that sets an upper limit on the time within which supplies should be restored in the event of a nationwide shutdown. However, one stakeholder noted that the speed with which a certain proportion of demand can be restored will be dependent on the

[66] 'Long-term' is regarded in different ways by different stakeholders. For the purpose of the discussion here, it is taken to mean where the energy is stored for periods of longer than a day. To date, batteries have tended to be discharged within a day of being charged. Other media such as pumped hydro storage, hydrogen or compressed air have been envisaged as having energy capacities and overall costs that are suited to longer-term storage. A generalised comparison of discharge time and power rating for various energy storage technologies is available in [57].

physical facilities available at the time. Another noted that the standard should drive investment such that sufficient facilities will, normally, be in place and usable. In addition, provision might be made, in the detail of a standard, to account for a ‘confidence level’ with which restoration might be achieved or a restoration service delivered, e.g. provider *A* can facilitate the restoration of *x*% of demand in *y* hours with *z*% confidence.

As a whole, the consulted experts expressed considerable scepticism regarding current system restoration capabilities. Conventional system restoration plans depend on schedulable, transmission-connected resources such as fossil-fuelled power stations and hydro power. Work has begun in Britain in the last few years to explore the potential to use other sources in the absence of fossil-fuelled electricity production. This includes the numerous distributed resources installed across Britain – being investigated in the Distributed Restart project – and wind farms with production controlled using the virtual synchronous machine concept. This will involve significant levels of complexity and therefore adequate resources should be made available to ensure that solutions are in place, sooner rather than later.

In this modern digital era, with considerable (and sometimes vital) dependence on electricity for many aspects of daily life, the impact of any widespread disruption will be significant even if it only lasts 24 hours. This will become increasingly so when reliable electricity demand for heating and transport are added to mobile, broadband, etc. Exactly what would be the minimum level of supply for basic requirements and how reliably it should be delivered is debatable and, according to [41], there are regions around the world with significantly less reliable power supplies than others. Nonetheless, even if it delivered significant saving in the total cost of electricity, whether significant reductions in reliability of supply would be politically acceptable is open to debate. However, there may be a case to be made for some owners of electrical equipment, e.g. in the commercial and industrial sectors, to take some responsibility for ensuring their equipment is not overly sensitive to quality of supply variations and have adequate back-up supplies of energy in the event of loss of supplies from the grid. Lastly, means of providing support to expansion of Britain’s pumped storage hydro capacity might be considered that, in addition to system stability and restoration services, can help to manage day-to-day variations in system balance.

11.5 Managing the future power system

A zero-carbon power system with flexible demand and many actors participating in system services will give rise to a more complex system that will require integration of physical, digital and market systems [42]. Innovative ways of managing the system are needed with services coming from new sources such as wind farms and flexible demand. A number of stakeholders consulted in the course of the work reported here expressed disappointment with delays in engaging new service providers and, more specifically, the role of Britain’s electricity system operator, NGESO. At the time of writing, Ofgem is consulting on proposals for the introduction of an independent system operator (ISO) [43]. One model suggested by Ofgem for the ISO includes a broader ‘whole system’ set of responsibilities in respect of energy system planning. It may also present an opportunity to introduce a technical design authority that understands the changing technical needs of the electricity system and would push forward protocols to facilitate security of supply and measures that can help to de-risk future activities and coordinate the proactive deployment of appropriate assets needed to facilitate a net-zero power system.

Although there are many challenges related to the transitioning power system, such as noted in prior work [44], there are also potential solutions. A number of industry actors are being proactive by identifying potential solutions, but some perceive barriers to driving change forward and the sentiment is that these have to do with limitations of existing standards and markets. There is a sense of frustration, with the engineers among the consulted stakeholders just wanting to get on with delivering solutions.

11.6 Standards and markets

The standards governing the operation of the power system were, in the main, written many years ago, based on the technology at the time. Modern power generation technologies have very different characteristics from those in the past with a number of the consulted experts saying that they are out of date. There has been some work reviewing the standards [45], pointing to aspects that require further attention. However, there is a perception among stakeholders that there is still more to be done. One aspect raised is to do with standards that apply to the facilities that we depend on to produce power. Attention was also drawn to what were described as 'pseudo-markets' by one stakeholder with specific reference to ancillary services. Others raised the lack of markets to incentivise the deployment of certain solutions that further a net-zero power system. In the case of the latter, particular reference was made here to VSMs, where there is currently no mechanism, market-based or otherwise, that would incentivise or require a renewables developer to incorporate the technology, despite real-world trials indicating the potential benefits of the technology [46]. The stability pathfinders were cited as examples as pseudo-markets that are short term and, it was suggested, tailored for specific technologies. In addition, markets like the commercial frequency response market that bundles three services into one, procured in month-ahead markets, mean that providers found it difficult to compete when they could only deliver one service or would be able to offer a service with confidence only at a day-ahead stage [47]. That said, the frequency response markets are currently undergoing change, with the inclusion of day-ahead procurement and some unbundled services that can be stacked along with others [48, 49]. Overall, the perception held by stakeholders is some things are happening but, in general, change is too slow, and some moves that are intended to help, e.g. market arrangements, are actually slowing things down.

12 Key messages and recommendations

This section summarises the study with ‘dashboards’ that present high level overviews of the status of the consulted stakeholders’ perceptions of the security of electricity supply in Scotland, and the key messages from the survey and roundtable. It also presents recommendations drawn from the observations made by stakeholders and industry experts in the course of this work.

Figure 25 shows the dashboard as a collection of RAG scale pie charts, while Figure 26 shows the dashboard as a collection colour-coded mean and standard deviation values of the weighted scores.

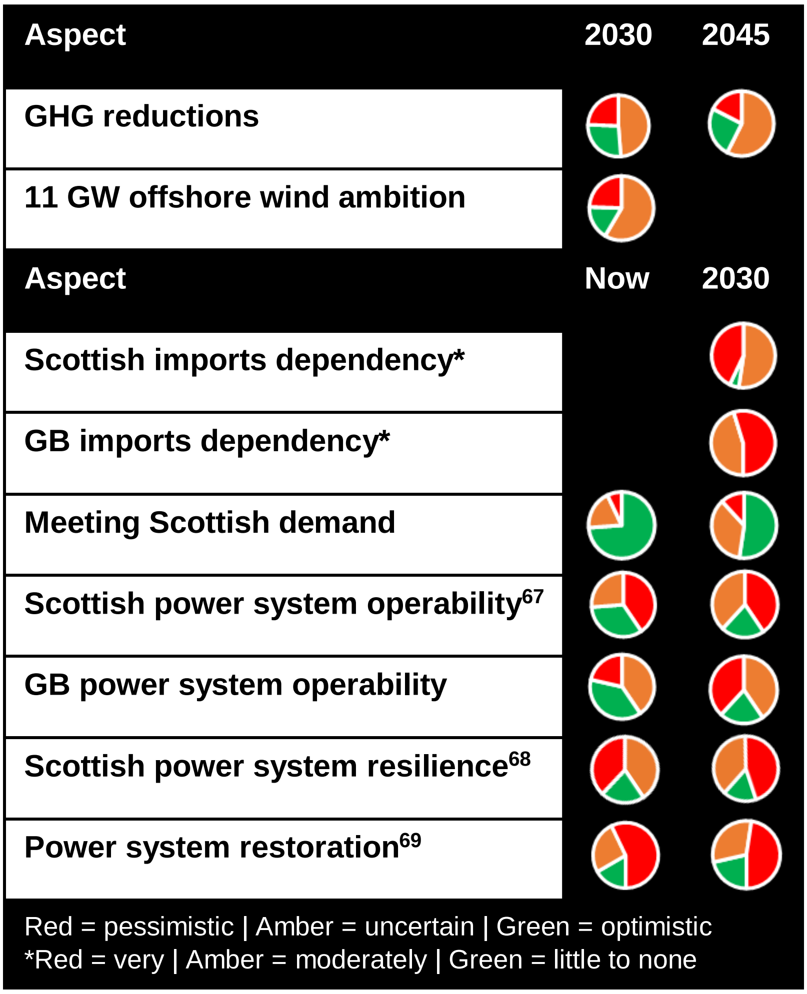


Figure 25: Visually representative high-level overview of consulted stakeholders’ perceptions of the status of Scottish security of electricity supply

---

[67] The operation of a stable system in which its physical limits and those of its various elements are respected.
[68] To prevent, contain and recover from interruptions to supply arising from disturbances.
[69] Re-starting a power system – “black start” after “the lights have gone out” – and supplies are restored.

Aspect	2030	Standard Deviation	2045	Standard Deviation	Change
Scottish GHG Reductions (2030 and 2045)	2.76	1.03	2.83	0.78	0.07
Scottish 11 GW Offshore Wind by 2030 Ambition	2.69	1.03			
Aspect	**Now**	**Standard Deviation**	**2030**	**Standard Deviation**	**Change**
Scottish Electricity Imports			2.13	1.04	
GB Electricity Imports			1.90	0.91	
Meeting Scottish Demand	3.75	0.85	3.47	0.93	-0.27
Scottish Power System Operability	2.79	1.12	2.66	1.07	-0.13
GB Power System Operability	3.08	0.87	2.78	1.00	-0.30
Scottish Power System Resilience	2.60	0.82	2.43	0.95	-0.16
Scottish Power System Restoration	2.28	1.26	2.41	1.09	0.13

0 RAG scale 5

Figure 26: Numerically representative high-level overview of consulted stakeholders' perceptions of the status of Scottish security of electricity supply. The spread of survey responses is available in Appendix D.

We are knowingly driving forward a policy that has the potential to reduce the security of electricity supply. We must ensure that actions are taken in this area to keep the power system reliable, despite the transition towards achieving emissions reductions and renewables targets.

12.1 Key messages

A number of key messages emerged from the survey and roundtable, highlighting stakeholders' perceptions around:

- greenhouse gas reductions and renewables targets;
- reliably meeting Scottish electricity demand;
- operability of the electricity system in Scotland, i.e. for it to be continuously operated in a stable manner; and
- resilience and restoration.

The coloured boxes relate to optimistic (green), uncertain (amber) or pessimistic (red) views expressed via the survey and roundtable, while the 'light bulb' points highlight specific observations made by the stakeholders.

Security of Electricity Supply – System Operability
There are doubts about current and future power system operability for both the British system and the Scottish power system within it, with operability expected to become more challenging between now and 2030.

Security of Electricity Supply – Reliably Meeting Scottish Demand
Industry experts and stakeholders have considerable confidence in the current capability of reliably meeting Scottish electricity demand.
There is an expectation of flexible demand playing a more active role, with an increasing proportion of demand becoming a controllable element rather than a passive one. Caution is raised around a number of commercial, regulatory and engineering factors associated with such a transition, including management of such a complex system with numerous controllable demand elements.
There was a general view that a balance is needed between dependence on imports for security of electricity supply and locally sourced power capacity, and that the mix of resources can be determined by least-cost options and/or political will.

Security of Electricity Supply – Resilience and Restoration
There is a feeling of concern around the trend of the Scottish power system's ability to prevent, contain and recover from interruptions to supply arising from disturbances, i.e. its resilience.
There are concerns among some stakeholders around existing markets which are perceived to present barriers, particularly to renewables developers, in deploying novel solutions because there is currently no incentive to proceed with their development
There is a prominent role for governments to play, to drive change forward so that deployment of solutions can catch up with policies and the need for solutions.

Greenhouse Gas Reduction and Renewables Targets
The consulted industry experts and stakeholders strongly support the reduction of greenhouse gas emissions to net zero.
There is uncertainty among industry experts and key stakeholders around Scotland's ability to achieve its 2030 and 2045 greenhouse gas (GHG) emissions reduction targets.
There are more pessimists than optimists in respect of the likelihood of meeting the Scottish Government's ambition for 11 GW of offshore wind generation capacity by 2030
There is some concern about the ability to meeting electricity demand during long periods of low wind and solar production – wind 'droughts' with low levels of light, known as "dunkelflaute". These concerns are argued by some stakeholders to mean that there is a case for additional 'schedulable'[70] generation or storage capacity within Scotland instead of allowing interconnectors to mean that less capacity is built locally.
There is general agreement that decarbonisation of electricity needs to be pursued in the context of the wider energy system and to consider how the interconnected elements of the energy system interact, including due consideration given to cybersecurity and consumer protection.

12.2 Recommendations

The observations made by survey respondents and by roundtable participants allow a number of recommendations to be made to the key electricity sector stakeholders. The authors of this report have used their own judgement in ascribing the different recommendations to particular parties.

[70] These are plants with highly predictable availability of power such that production can be scheduled a number of days in advance with high confidence.

The Scottish Government is recommended to:	The electricity system operator (NGESO) is recommended to:
Provide a clearer communication of greenhouse gas (GHG) emissions reduction targets and clarity on whether targets are territorial within Scotland or within the UK.	Develop and agree with the rest of the industry a clearer set of definitions of Balancing Services markets and encourage the participation of renewables, especially since these technologies are displacing large thermal power stations.

The electricity supply industry, in particular the network licensees and Ofgem, is recommended to:

Bring forward a vision for managing an increasingly complex electricity system, with numerous controllable demand elements, while also ensuring consumer protection and cyber security.	Revise existing sector standards to ensure that equitable and well-regulated system and network services can be efficiently and effectively delivered and coordinated.	Address concerns that deployment of engineering solutions is lagging need and investigate and resolve perceived market barriers.	Explore ways in which local electricity networks and 'resilience as a service'[71] can contribute to security of supply.

The UK and Scottish Governments are recommended to:

Forge closer cooperation between both governments to drive change so that deployment of solutions can catch up to with emissions reduction policies, the needs of citizens, public bodies and businesses for resilient electricity supplies, and the opportunity for new solutions. A united front between UK and Scottish governments would be a strong basis for a wider partnership with the regulator, private companies and consumer.

Give close consideration to the costs and benefits of facilitating new pumped storage hydropower projects, as these technologies could help with many of the security of electricity supply challenges associated with a net-zero electricity system, as well as wider issues associated with the integration of renewables.	Ensure vulnerable groups and regions are not disadvantaged in the prioritisation required in the process of restoring the electricity system following a national black out, as laid out in the new system restoration standard.	Consider the introduction of a regional capacity market or a similar mechanism that might, for example, stipulate the type, power and energy capacities of production or import capability.

[71] There is an innovation project called Resilience as a Service (RaaS) that is funded through Ofgem's Network Innovation Competition. This project aims to develop a new market-based solution aimed at helping maintain supply in the event of a loss of power from the main network.

13 References

[1] Scottish Government, "Climate Change: Reducing greenhouse gas emissions," 2021. [Online]. Available: https://tinyurl.com/crwcbr7k. [Accessed 07 07 2021].

[2] Scottish Government, "Update to the Climate Change Plan 2018 - 2032: Securing a Green Recovery on a Path to Net Zero," 12 2020. [Online]. Available: https://tinyurl.com/5758u72x. [Accessed 07 07 2021].

[3] National Grid ESO, "Electricity Ten Year Statement (2020)," 11 2020. [Online]. Available: https://tinyurl.com/b5p9tfk. [Accessed 16 07 2021].

[4] National Grid ESO, "Welcome to the ESO Future Energy Scenarios," 2021. [Online]. Available: https://tinyurl.com/xh762nrs. [Accessed 16 07 2021].

[5] National Grid ESO, "System operability framework: Regional trends and insights," 06 2018. [Online]. Available: https://tinyurl.com/y9qzl5wh. [Accessed 09 07 2020].

[6] Scottish Government, "Increased offshore wind ambition by 2030," 28 10 2020. [Online]. Available: https://tinyurl.com/67va5r7k. [Accessed 13 09 2021].

[7] Department for Business, Energy & Industrial Strategy, "UK enshrines new target in law to slash emissions by 78% by 2035," 20 04 2021. [Online]. Available: https://tinyurl.com/exvt9esp. [Accessed 07 07 2021].

[8] National Statistics, "Energy Trends: UK electricity," GOV.UK, 29 06 2021. [Online]. Available: https://tinyurl.com/4ajw3z82. [Accessed 12 07 2021].

[9] M. Aunedi, K. Wills, T. Green and G. Strbac, "Net-zero GB electricity: cost optimal generation and storage mix," 06 2021. [Online]. Available: https://tinyurl.com/94krzvsa. [Accessed 13 07 2021].

[10] C. MacIver, W. Bukhsh and K. R. W. Bell, "The impact of interconnectors on the GB electricity sector and European carbon emissions," *Energy Policy,* vol. 151, no. 112170, 2021.

[11] National Grid ESO, "Connections Register: Latest Interconnector Register," 2021. [Online]. Available: https://tinyurl.com/4syhu66x. [Accessed 13 07 2021].

[12] National Grid ESO, "Electricity Ten Year Statement (ETYS) Archive: Appendix B - System Network Data (2020)," 2021. [Online]. Available: https://tinyurl.com/r2pc8mbk. [Accessed 13 07 2021].

[13] P. Matthews and I. Scherr, "Annual Compendium of Scottish Energy Statistics 2020," 18 12 2020. [Online]. Available: https://tinyurl.com/5auszy82. [Accessed 13 09 2021].

[14] A. Froggatt and C. Kuzemko, "Brexit Implications for UK Decarbonisation Objectives," 06 2021. [Online]. Available: https://tinyurl.com/4y8dznfp. [Accessed 02 07 2021].

[15] S. Gordon, C. McGarry and K. Bell, "The growth of distributed generation in Great Britain and associated challenges," in *IET Renewable Power Generation 2021*, 2021.

[16] D. Hirst, J. Winnett and S. Hinson, “Electric vehicles and infrastructure,” 23 06 2021. [Online]. Available: https://tinyurl.com/pzhc3yy. [Accessed 13 07 2021].

[17] Zap Map, “EV Charging Stats 2021: How many charging points are there in the UK?,” 05 07 2021. [Online]. Available: https://tinyurl.com/583p7yyu. [Accessed 13 07 2021].

[18] ScottishPower Energy Networks, “We've launched our draft RIIO-ED2 business plan,” ScottishPower Energy Networks, 01 07 2021. [Online]. Available: https://tinyurl.com/wvdbub2h. [Accessed 02 07 2021].

[19] Ars Technica, “Texans regret opting in to power plan that remotely raises thermostat temps,” 21 06 2021. [Online]. Available: https://tinyurl.com/2bkkhn7c. [Accessed 13 07 2021].

[20] C. MacIver, K. Bell and M. Nedd, “An analysis of the August 9th 2019 GB transmission system frequency incident,” *Electric Power Systems Research,* vol. 199, no. 107444, 2021.

[21] National Grid ESO, “The Enhanced Frequency Control Capability (EFCC) Project,” 2021. [Online]. Available: https://tinyurl.com/bfvnda8. [Accessed 13 07 2021].

[22] ScottishPower Energy Networks, “Investment and Innovation: Phoenix,” 2021. [Online]. Available: https://tinyurl.com/jw5cds74. [Accessed 13 07 2021].

[23] National Grid ESO, “NOA Stability Pathfinder,” 2021. [Online]. Available: https://tinyurl.com/u9dhkxvy. [Accessed 13 07 2021].

[24] ScottishPower Renewables, “Black-Start Capability - A Global first for ScottishPower Renewables,” 2021. [Online]. Available: https://tinyurl.com/5xttrcm4. [Accessed 13 07 2021].

[25] National Grid ESO, “NOA Stability Pathfinder Phase 2,” 22 02 2021. [Online]. Available: https://tinyurl.com/2p2y7v2y. [Accessed 16 07 2021].

[26] National Grid ESO, “NOA Constraint Management Pathfinder Phase 1 - B6,” 2021. [Online]. Available: https://tinyurl.com/sey5spnn. [Accessed 16 07 2021].

[27] National Grid ESO, “NOA High Voltage Pathfinder,” 2021. [Online]. Available: https://tinyurl.com/2byfshm8. [Accessed 16 07 2021].

[28] National Grid ESO, “Future of balancing services,” 2021. [Online]. Available: https://tinyurl.com/rmxrvb3c. [Accessed 16 07 2021].

[29] CIGRE Working Group C1.17, “Planning to Manage Power Interruption Events,” in *Technical Brochure 433*, Paris, CIGRE, 2010.

[30] J. W. Busby, K. Baker, M. D. Brazilian, A. Q. Gilbert, E. Grubert, V. Rai, J. D. Rhodes, S. Shidore, C. A. Smith and M. E. Webber, “Cascading risks: Understanding the 2021 winter blackout in Texas,” *Energy Research and Social Science,* vol. 77, no. 102106, 2021.

[31] Department for Business, Energy & Industrial Strategy, “Introducing a new ‘Electricity System Restoration Standard’: policy statement,” GOV.UK, 01 04 2021. [Online]. Available: https://tinyurl.com/ypnw57xk. [Accessed 05 07 2021].

[32] National Grid ESO, “Distributed Restart,” 2021. [Online]. Available: https://tinyurl.com/vyfyuhds. [Accessed 14 07 2021].

[33] The Energy and Climate Change Committee, “UK Energy Supply: Security or Independence?,” 10 10 2011. [Online]. Available: https://tinyurl.com/jjba79b7. [Accessed 16 07 2021].

[34] G. C. Gissey, B. Guo, D. Newbery, G. Lipman, L. Montoya, P. Dodds, M. Grubb and P. Ekins, “The value of international electricity trading,” 2019. [Online]. Available: https://tinyurl.com/uxjzzpk4. [Accessed 16 07 2021].

[35] M. Nedd, W. Bukhsh, C. MacIver and K. Bell, “Metrics for determining the frequency stability limits of a power system: A GB case study,” *Electric Power Systems Research,* vol. 190, no. 106553, 2021.

[36] Energy Networks Association, “Engineering Recommendation G99 Issue 1 - Amendment 6,” 09 03 2020. [Online]. Available: https://tinyurl.com/aj3yspmt. [Accessed 14 07 2021].

[37] National Grid ESO, “Accelerated Loss of Mains Change Programme (ALoMCP),” 2021. [Online]. Available: https://tinyurl.com/3pderdtc. [Accessed 14 07 2021].

[38] National Grid ESO, “GSR027: Review of the NETS SQSS Criteria for Frequency Control that drive reserve, response and inertia holding on the GB electricity system,” 17 06 2021. [Online]. Available: https://tinyurl.com/vz5nv75c. [Accessed 14 07 2021].

[39] B. Li, S. Basu, S. J. Watson and H. W. J. Russchenburg, “Mesoscale modeling of a “Dunkelflaute” event,” *Wind Energy,* vol. 24, no. 1, pp. 5 - 23, 2021.

[40] I. Staffell, R. Green, T. Green, M. Jansen and N. Skorupska, “Electricity Insights Quarterly: January to March 2021,” 2021. [Online]. Available: https://tinyurl.com/2ac355c7. [Accessed 22 07 2021].

[41] I. Staffell, M. Jansen, R. Green, R. Gross and T. Green, “Electricity Insights Quarterly: July to September 2019,” 2019. [Online]. Available: https://tinyurl.com/2yue95ke. [Accessed 22 07 2021].

[42] IET, “Future Power Systems Architecture,” 09 09 2019. [Online]. Available: https://tinyurl.com/4vrsdznz. [Accessed 22 07 2021].

[43] Ofgem, “Consultation on proposals for a Future System Operator role,” 21 06 2021. [Online]. Available: https://tinyurl.com/3ybxay2d. [Accessed 14 09 2021].

[44] M. Nedd, J. Browell, A. Egea-Alvarez, K. Bell, R. Hamilton, S. Wang and S. Brush, “Operating a zero-carbon GB power system: implications for Scotland,” 12 2020. [Online]. Available: https://tinyurl.com/yawdejef. [Accessed 16 06 2021].

[45] Department for Business, Energy and Industrial Strategy, “Electrical engineering standards: independent review,” 25 02 2021. [Online]. Available: https://tinyurl.com/nyktpd5a. [Accessed 14 07 2021].

[46] A. Roscoe, P. Brogan, D. Elliott, T. Knueppel, I. Guiterrez, J.-C. P. Campion and R. D. Silva, “Practical experience of operating a grid forming wind park and its response to system events,” in *18th International Wind Integration Workshop*, Dublin, Ireland, 2019.

[47] M. Nedd, J. Browell, K. Bell and C. Booth, “Containing a credible loss to within frequency stability limits in a low inertia GB power system,” *IEEE Transactions on Industry Applications,* vol. 56, no. 2, pp. 1031 - 1039, 2020.

[48] National Grid ESO, “Response and Reserve Roadmap,” 03 12 2019. [Online]. Available: https://tinyurl.com/5avkuzn8. [Accessed 22 07 2021].

[49] National Grid ESO, “Future of balancing services,” 2021. [Online]. Available: https://tinyurl.com/2x5yn3wm. [Accessed 22 07 2021].

[50] EDF, “Hunterston B Power Station,” EDF, 2021. [Online]. Available: https://tinyurl.com/wtmwuehv. [Accessed 05 07 2021].

[51] Energy Networks Association, “SHEDD – System HILP Event Demand Disconnection,” 2021. [Online]. Available: https://tinyurl.com/535dssps. [Accessed 14 07 2021].

[52] Ofgem, “DC0079 - Frequency Changes during Large Disturbances and their impact on the Total System,” 18 12 2017. [Online]. Available: https://tinyurl.com/y7cu94e5. [Accessed 14 07 2021].

[53] Energy Networks Association, “Engineering Recommendation G59 Issue 3 Amendment 7,” 01 09 2019. [Online]. Available: https://tinyurl.com/vj6p2wwj. [Accessed 14 07 2021].

[54] National Grid ESO, “Energy Storage Technical Feasibility Assessment,” 2021. [Online]. Available: https://tinyurl.com/a3j7hjbw. [Accessed 16 07 2021].

[55] A. S. C. Leavy, W. A. Bukhsh and K. R. W. Bell, “Optimal Operation of the Western Link Embedded HVDC Connection,” in *Power Systems Computation Conference (PSCC)*, Dublin, Ireland, 2018.

[56] D. A, D. Tzelepis and C. Booth, “Practical risk assessment of the relaxation of LOM protection settings in NIE Networks' distribution system,” *The Journal of Engineering,* vol. 15, pp. 1335 - 1339, 2018.

[57] T. M. Gur, “Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage,” *Royal Society of Chemistry Energy and Environment Science,* vol. 11, pp. 2696 - 2767, 2018.

[58] Scottish and Southern Electricity Networks, “Raas,” Scottish and Southern Electricity Networks, 2021. [Online]. Available: https://tinyurl.com/5xv3vz37. [Accessed 21 09 2021].

14 Appendices

Appendix A: Questionnaire available at https://doi.org/10.15129/dc0b86e0-f313-417c-9b12-ded9642c4eae.

Appendix B: Survey results available at https://doi.org/10.15129/f5e87e1a-54a2-4455-ae38-2bdaa8b4365b.

Appendix C: Breakdown of mean and standard deviation values of the weighted scores from the online survey showing the population groups.

Reducing Green House Gas Emissions	Mean of Responses				Mode of Responses		Confidence	
	2030	SD	2045	SD	2030	2045	Mean	SD
All Participants	2.76	1.03	2.83	0.78	3.00	3.00	76%	15%
Industry Responsible (13 participants)	2.97	0.73	2.47	0.74	3.00	1.50	72%	14%
Industry General (12 participants)	2.93	0.98	3.18	0.60	3.80	3.00	80%	17%
External Responsible (3 participants)	1.13	0.47	2.95	0.47	0.75	3.00	82%	9%
External Stakeholders (14 participants)	2.79	0.72	2.86	0.88	3.00	3.00	76%	13%

Offshore Wind Ambitions	Mean of Responses		Mode of Responses	Confidence	
	2030	SD	2030	Mean	SD
All Participants	2.69	1.03	2.25	76%	15%
Industry Responsible (13 participants)	2.32	0.73	3.00	72%	14%
Industry General (12 participants)	3.08	0.98	4.75	80%	17%
External Responsible (3 participants)	2.45	0.47	2.25	82%	9%
External Stakeholders (14 participants)	2.78	0.72	3.00	76%	13%

Dependence on Imports 2030	Mean of Responses				Mode of Responses		Confidence	
	Scotland	SD	GB	SD	Scotland	GB	Mean	SD
All Participants	2.13	1.04	1.90	0.91	2.25	1.50	78%	14%
Industry Responsible (13 participants)	1.86	1.07	1.97	0.75	1.83	2.25	82%	13%
Industry General (12 participants)	2.33	0.86	1.74	0.92	2.25	1.50	80%	13%
External Responsible (3 participants)	1.58	0.47	1.58	0.47	1.86	1.97	67%	12%
External Stakeholders (14 participants)	2.32	1.06	2.05	1.03	2.63	2.25	76%	13%

Reliably Meeting Scottish Electricity Demand	Mean of Responses					Mode of Responses			Confidence	
	Now	SD	2030	SD	Change	Now	2030	Change	Mean	SD
All Participants	3.75	0.85	3.47	0.93	-0.27	4.25	4.75	0.50	82%	13%
Industry Responsible (13 participants)	3.69	1.26	3.46	1.30	-0.23	4.75	4.75	0.00	86%	10%
Industry General (12 participants)	3.75	0.62	3.50	0.62	-0.25	4.75	3.88	-0.88	79%	16%
External Responsible (3 participants)	3.83	0.47	3.58	0.47	-0.25	3.69	3.00	-0.69	82%	9%
External Stakeholders (14 participants)	3.78	0.45	3.43	0.77	-0.34	3.75	4.75	1.00	80%	13%

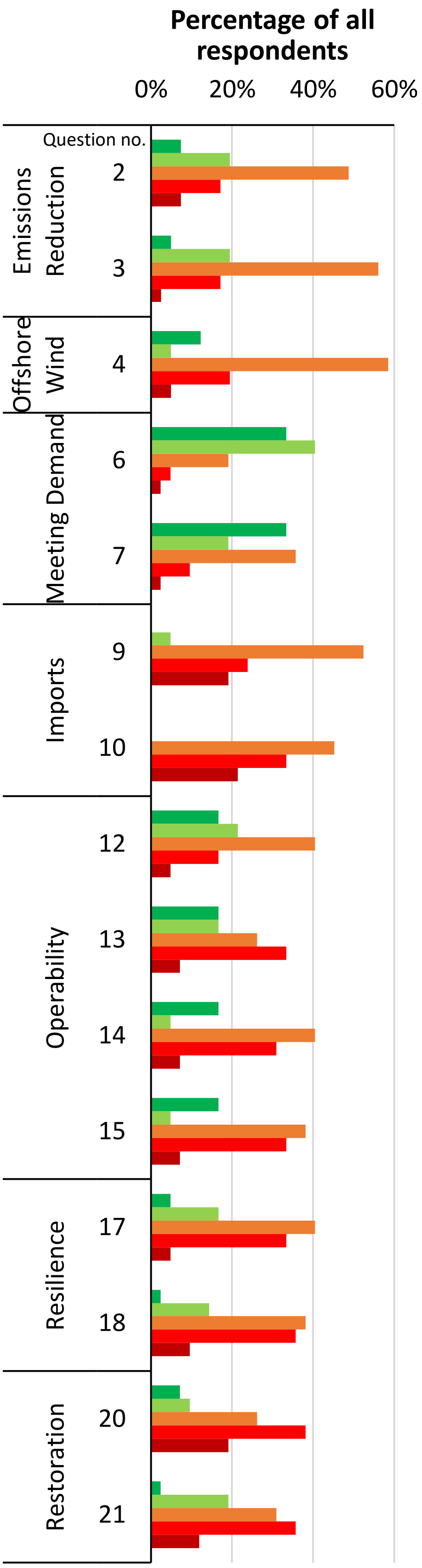
Operability (Scotland)	Mean of Responses					Mode of Responses			Confidence	
	Now	SD	2030	SD	Change	Now	2030	Change	Mean	SD
All Participants	2.79	1.12	2.66	1.07	-0.13	3.08	3.00	-0.08	73%	18%
Industry Responsible (13 participants)	2.11	1.18	2.21	1.23	0.10	1.50	2.50	1.00	70%	15%
Industry General (12 participants)	2.85	1.09	2.81	0.92	-0.04	3.38	4.75	1.38	73%	24%
External Responsible (3 participants)	3.00	0.82	3.25	0.47	0.25	2.11	2.21	0.10	73%	18%
External Stakeholders (14 participants)	3.33	0.70	2.83	0.97	-0.51	3.38	3.00	-0.38	77%	14%

Operability (GB)	Mean of Responses					Mode of Responses			Confidence	
	Now	SD	2030	SD	Change	Now	2030	Change	Mean	SD
All Participants	3.08	0.87	2.78	1.00	-0.30	3.00	3.00	0.00	73%	18%
Industry Responsible (13 participants)	2.72	0.86	2.51	1.08	-0.21	3.00	3.00	0.00	70%	15%
Industry General (12 participants)	2.93	1.00	2.89	0.86	-0.04	4.75	4.75	0.00	73%	24%
External Responsible (3 participants)	3.42	0.47	3.25	0.47	-0.17	2.72	2.51	-0.21	73%	18%
External Stakeholders (14 participants)	3.46	0.63	2.83	1.04	-0.63	3.75	3.00	-0.75	77%	14%

Resilience	Mean of Responses					Mode of Responses			Confidence	
	Now	SD	2030	SD	Change	Now	2030	Change	Mean	SD
All Participants	2.60	0.82	2.43	0.95	-0.16	3.00	3.00	0.00	75%	18%
Industry Responsible (13 participants)	2.60	0.93	2.25	1.00	-0.35	3.00	3.00	0.00	75%	16%
Industry General (12 participants)	2.20	0.80	2.20	0.80	0.00	1.50	1.50	0.00	69%	24%
External Responsible (3 participants)	2.83	0.94	3.08	0.82	0.25	2.60	2.25	-0.35	73%	18%
External Stakeholders (14 participants)	2.88	0.62	2.66	0.97	-0.22	3.40	3.00	-0.40	80%	13%

Restoration	Mean of Responses					Mode of Responses			Confidence	
	Now	SD	2030	SD	Change	Now	2030	Change	Mean	SD
All Participants	2.28	1.26	2.41	1.09	0.13	3.00	3.00	0.00	75%	18%
Industry Responsible (13 participants)	2.13	1.44	2.27	1.10	0.14	2.19	1.50	-0.69	80%	16%
Industry General (12 participants)	2.30	1.07	2.48	1.18	0.18	2.43	2.68	0.25	73%	18%
External Responsible (3 participants)	1.58	1.41	2.08	0.82	0.50	2.13	2.27	0.14	63%	32%
External Stakeholders (14 participants)	2.56	0.98	2.55	0.90	-0.01	3.00	3.00	0.00	73%	14%

Appendix D: Spread of survey responses



Question No.	Topic	Choice Type
2	Scottish 75% GHG 2030	1
3	Scottish Net-Zero 2045	1
4	Scottish 11 GW Offshore Wind 2030	1
6	Meeting Scottish Demand Now	2
7	Meeting Scottish Demand in 2030	2
9	Scottish Import Dependency 2030	3
10	British Import Dependency 2030	3
12	British Power System Operability Now	2
13	Scottish Power System Operability Now	2
14	British Power System Operability 2030	2
15	Scottish Power System Operability 2030	2
17	Scottish Power System Resilience Now	2
18	Scottish Power System Resilience 2030	2
20	Scottish Power System Restoration Now	2
21	Scottish Power System Restoration 2030	2

Choice Type 1	Choice Type 2	Choice Type 3	Colour
Highly likely	Strongly agree	Not at all	
Likely	Somewhat agree	A little	
Moderately	Neither agree nor disagree	A moderate amount	
Unlikely	Somewhat disagree	A lot	
Highly unlikely	Strongly disagree	A very great deal	

climate change

Scotland's centre of expertise connecting climate change research and policy

info@climatexchange.org.uk
+44(0)131 651 4783
@climatexchange_
www.climatexchange.org.uk

ClimateXChange, Edinburgh Climate Change Institute, High School Yard, Edinburgh EH1 1LZ