Black Start from Non-Traditional Generation Technologies

Network Innovation Allowance
June 2019

Technology capability and readiness for distributed restoration

In partnership with:

tnei

nationalgridESO

Contents

Executive summary

TNEI Services Ltd (TNEI) was commissioned by National Grid ESO to investigate the capability of non-traditional technologies in the restoration of the GB power system in the event of a partial or total system shutdown. The project is a Network Innovation Allowance (NIA) project initiated by National Grid ESO, with support from SP Energy Networks. The overall aim of the NIA project was to provide insight into the capability of several prevalent non-traditional technologies: wind, solar, storage, demand side response (DSR) and electric vehicles (EV), to provide ancillary services to National Grid ESO in the event that the GB network requires a Black Start.

Responding to the significant changes in the energy landscape in the past decade, National Grid ESO are seeking to understand how renewable generation and distributed energy resources (DER) could facilitate the restoration of the GB power system with the decline and decommissioning of traditional Black Start providers (larger, synchronous power stations). The creation of smaller, distributed power islands is of particular interest as a result, whereby these would be initiated on distribution networks and grow to energise the transmission network. This project has considered the technical capability of the technologies, the challenges of creating and maintaining small power islands with high penetrations of renewables and DER, and how to better predict the reliability and availability of renewable generation in such a scenario.

The project has three distinct deliverables:

- **Report 1**: Overview of the capability of non-traditional technologies to provide Black Start and restoration services;
- **Report 2**: Investigation of the challenges around power system strength and stability specifically in relation to power islands with high penetrations of renewables and converter-based technology; and
- **Report 3**: A sophisticated planning tool specifically designed to simulate distributions for the reliable output of wind over periods of hours to days, and how these distributions vary on timescales of months and years.

This report is Report 1, one of the three deliverables from the “Black Start from Non-Traditional Technologies” project. The report outlines the existing Black Start technical requirements set out by National Grid ESO and should be reviewed in response to the evolving generation landscape in GB.

An extensive research and stakeholder engagement exercise yielded important insights into the capability of non-traditional technologies, currently deployed extensively across GB, to provide Black Start services. It is recognised that a significant proportion of the non-traditional technology in GB is connected to distribution networks and is much smaller in size than conventional Back Start provider sites i.e. large synchronous power stations.

As such, it is assumed that Black Start providers in future will not have to meet all of the technical requirements and services procured by National Grid ESO, but instead can provide more discrete services along the restoration timeline in accordance with their capabilities and strengths. The capability of the different technologies has been assessed according to their Shutdown Resilience Characteristics, their Black Start Performance and their Restoration Capabilities.

The key findings from the technology capability and readiness review are summarised as:

- With the exception of EVs (which are not yet prolific enough to be considered viable in this context), all non-traditional technologies investigated have characteristics and capabilities that could be utilised by National Grid ESO to support a Black Start and restoration effort.
- Much uncertainty surrounds the resource availability of battery storage (state of charge at the time of shutdown) at the time of a Black Start but this can be improved through providing a route to market for DER such that these sites are incentivised to ensure a minimum level of charge at all times.
- Similar concerns around the uncertainty of wind and solar resource are evident. Some of this uncertainty can be mitigated through better modelling tools (see Report 3) to increase confidence and provide a minimum level of assurance that this resource can or will be available as and when required.

- The ability to self-start is a key attribute of conventional Black Start providers; and it is one that most non-traditional technologies and DER have limited or no capability. Sites can be limited by myriad of factors, including having no back-up generation on site, or insufficient resource at the time of the shutdown (battery storage)/Black Start (solar). Several solutions are readily available to address this issue, but all require a route to market for DER to justify the additional expense.
- The majority of converter-connected DER sites operate with grid-following inverters, rather than grid-forming inverters, which means they cannot generate their own voltage signal for the purposes of network energisation and creating a Power Island. Instead, the grid-following inverters require a voltage signal to latch onto which must first be created by a site with grid-forming capability. Upgrading this capability is straightforward if the necessary incentives are put in place.
- Synchronous DER (e.g. biomass) can provide many of the same services as conventional Black Start providers, however this is typically on a much smaller scale and so this must be considered when setting technical requirements and “levels of service”. This is relevant for all DER sites, which are smaller but more numerous than conventional providers.
- A common issue throughout all DER sites is the resilience of the communications infrastructure which, at present, is typically not adequate to meet the requirements for Black Start. A minimum level of resilience is stipulated in Connection Agreements and rarely are sites incentivised to provide more than this minimum level. A route to market for DER would encourage more sites to incur additional cost to meet the necessary resilience requirements.
- None of the technical barriers which exist are insurmountable, they only require appropriate commercial and regulatory support to ensure these can be addressed to the benefit of all.

1 Introduction – Black Start in Great Britain

1.1 Background

Black Start is the process of restoring the National Electricity Transmission System (NETS) following the highly unlikely, but highly impactful, event of a partial or total shutdown. National Grid Electricity System Operator (ESO) is responsible for ensuring there is an adequate provision for NETS restoration. The current restoration strategy has remained largely unchanged for many years, and is based on a transmission-led approach of starting large synchronous generators, energising a skeleton transmission network, and controlling demand.

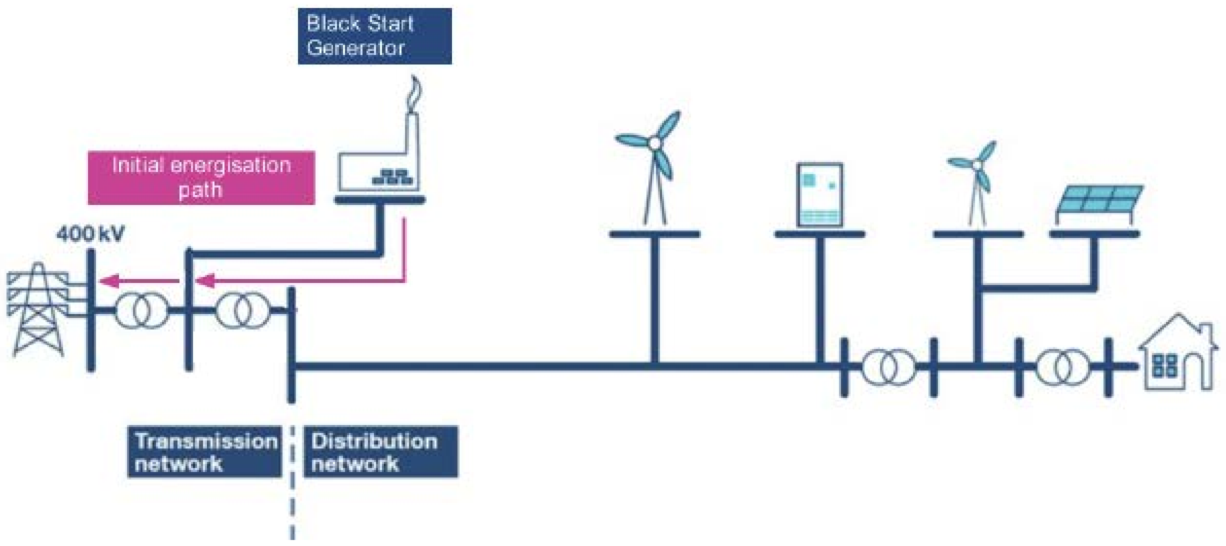
The current restoration strategy procures large power stations and interconnectors as Black Start providers as shown in figure 11. These providers must meet certain technical requirements, including the ability to start up without external power supplies. Once this is achieved, the Black Start provider then energises sections of the transmission system, using local demand to balance its load requirement in a Power Island.

Once this Power Island is established, the priority is to restore electrical supplies to other generators which do not have Black Start capability by energising the transmission network. These generators then join this growing network to progressively restore demand across the country until full restoration is achieved.

Currently there are four groups of organisations involved in restoration: National Grid ESO, Black Start providers, transmission owners (TO), and distribution network operators (DNO). Each organisation receives instructions, and implements these as part of their restoration plans using resilient and secure private telecommunications networks.

Figure 1.1

Traditional Black Start restoration



A more detailed outline of the current Black Start procedures for GB and the requirements of Black Start providers is given in Section 3.

1.2 The evolving energy landscape

Over the past decade, the energy landscape in GB, and indeed in the majority of developed countries, has changed dramatically. Large conventional generation e.g. coal, plants are being phased out of the generation portfolio from a combination of decarbonisation ambitions and ageing assets. Demand is being increasingly met by renewable and non-traditional technologies, and more efficient operational tools and management strategies are supporting this transition.

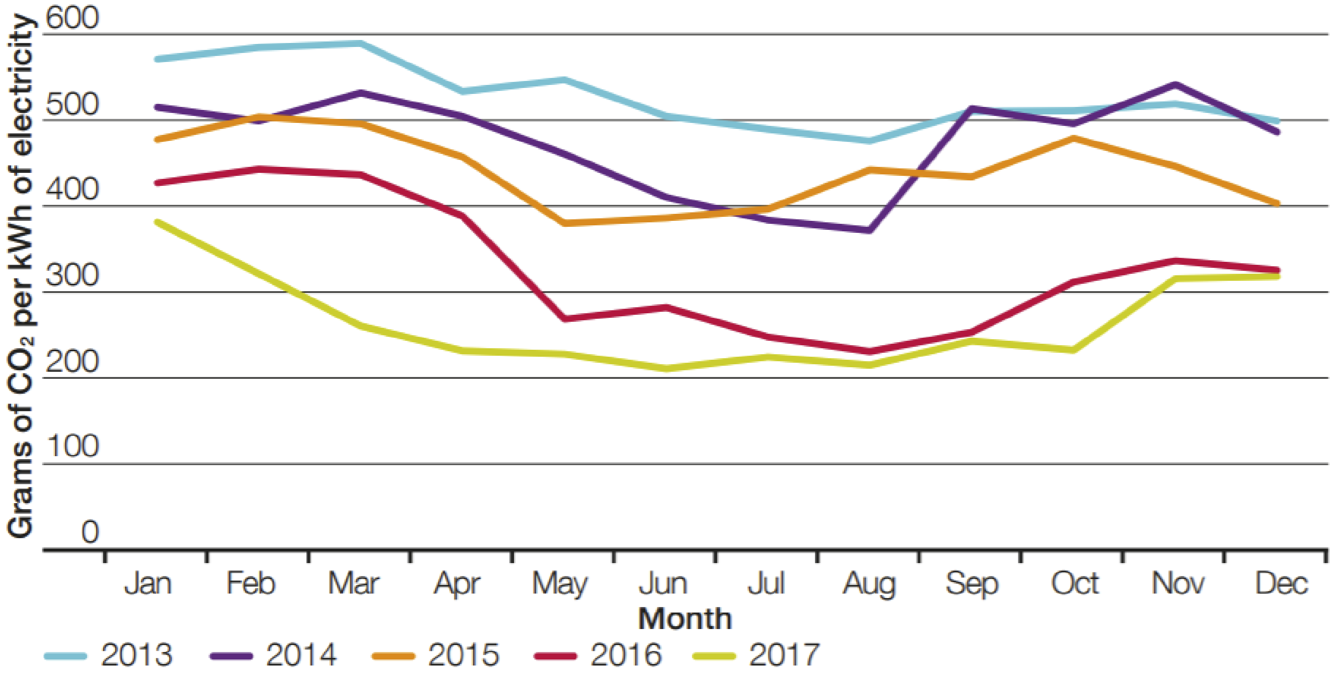
The technical issues that have arisen from the changing energy landscape have been challenging but are not insurmountable. Continued innovation and development have allowed innumerable opportunities to be unlocked and the way in which the electrical power systems in GB operate is evolving. An excellent example of this is the Orkney Isles in the North of Scotland which has been publicly hailed as “leading the way for sustainable energy”.

The islands have an abundance of renewable resource, most prominently wind and wave/tidal, and they are exploiting this to the fullest. The Orkney Isles are now a net exporter of electrical power, a far cry from the previous status quo of reliance on importing fossil fuel generated power from the Scottish mainland. They have also implemented an active network management (ANM) scheme to manage generation and power flows, and more recently added a hydrogen electrolyser to act as a storage mechanism, with plans in future to use the hydrogen as a fuel for ferries, thus decarbonising their transport network.

There are ambitions to follow Orkney’s example across GB and implement non-traditional technologies to generate, store and manage power. And this is already happening on a large scale, so much so that the carbon intensity of the electricity system has decreased year on year since 2013 as shown in the 2018 Future Energy Scenarios[1] (FES), figure 1.2 below. The FES reported that there has been a 49.7 per cent decrease in carbon intensity from 2013–2017.

Figure 1.2

FES 2018 Graph highlighting carbon intensity of GB electricity generation



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[1] http://fes.nationalgrid.com/media/1363/fes-interactive-version-final.pdf

As this trend continues, consideration must be given to such things as network security, safety, reliability etc. And it is under this context that the work presented in this report relating to Black Start has relevance. As described in the previous section, Black Start has traditionally been, and is presently, reliant on a few large conventional power stations providing the necessary shutdown and restoration services. However, as these large power plants are displaced by more and more non-traditional, renewable and distributed energy resources (DER), the strategy for Black Start must adapt to incorporate this and strive to maintain the same level of security and reliability from a vastly different starting point.

The market must also accept Black Start services from non-traditional technologies and DER which will require considerable changes. Maintaining the status quo for restoration is not an option. Black Start costs have been rising steadily in recent years as the costs associated with keeping large generators on standby have risen, with this trend predicted to continue. Creating solutions to allow non-traditional technologies and DER to participate in the Black Start market will bring significant financial benefits to consumers through increased competition and lower costs.

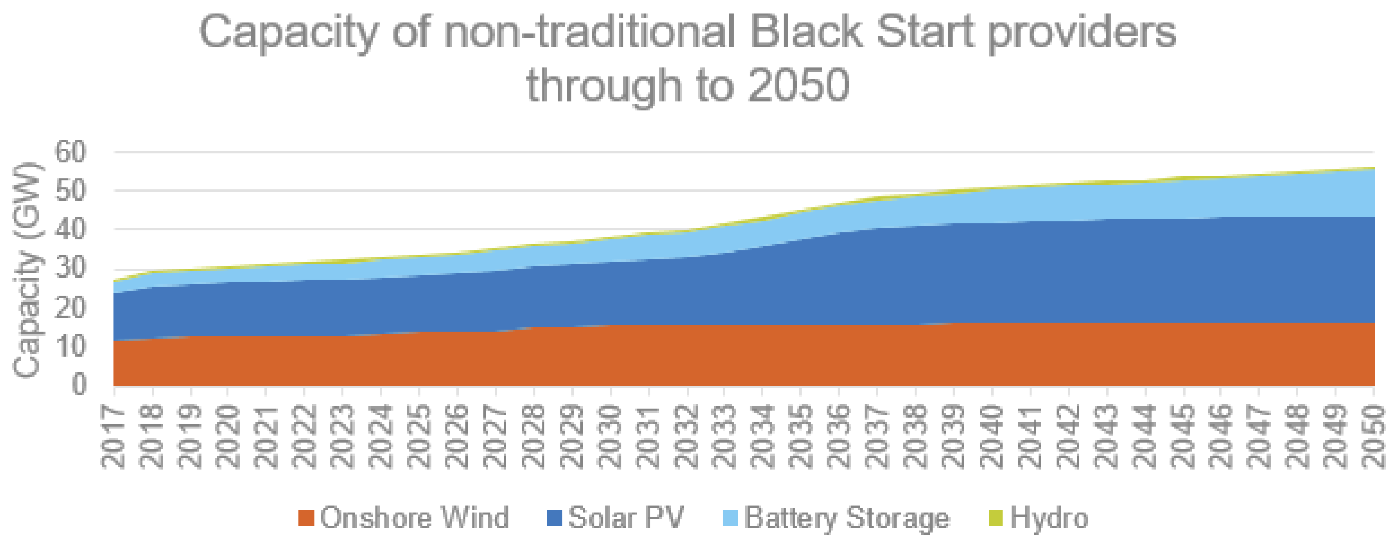
1.3 Opportunities for non-traditional technologies

The Future Energy Scenarios, published annually by National Grid ESO, provide ongoing insight into credible futures for energy in GB. The most conservative scenario is the Steady Progression scenario, which has a lower level of decentralisation and a slower speed of decarbonisation than that required to meet the 2050 targets as set out in the Climate Change Act 2008 and the Paris Agreement.

In the context of Black Start, some key facts and figures can be extracted from the FES which highlight both the necessity to modify the current Black Start strategy, and the opportunity for non-traditional technologies and DER to contribute to this updated strategy.

Figure 1.3 shows the current and projected installed capacity of non-traditional technologies and DER under Steady Progression. This shows that, even in the most conservative of the scenarios, the penetration of DER, including onshore wind, solar and battery storage, is set to grow, most notably with solar and battery storage. As it stands, there is approximately 12 GW of solar in operation in GB, rising to 22 GW by the mid-2030s and 27 GW by 2050 in the Steady Progression FES reported in 2018.

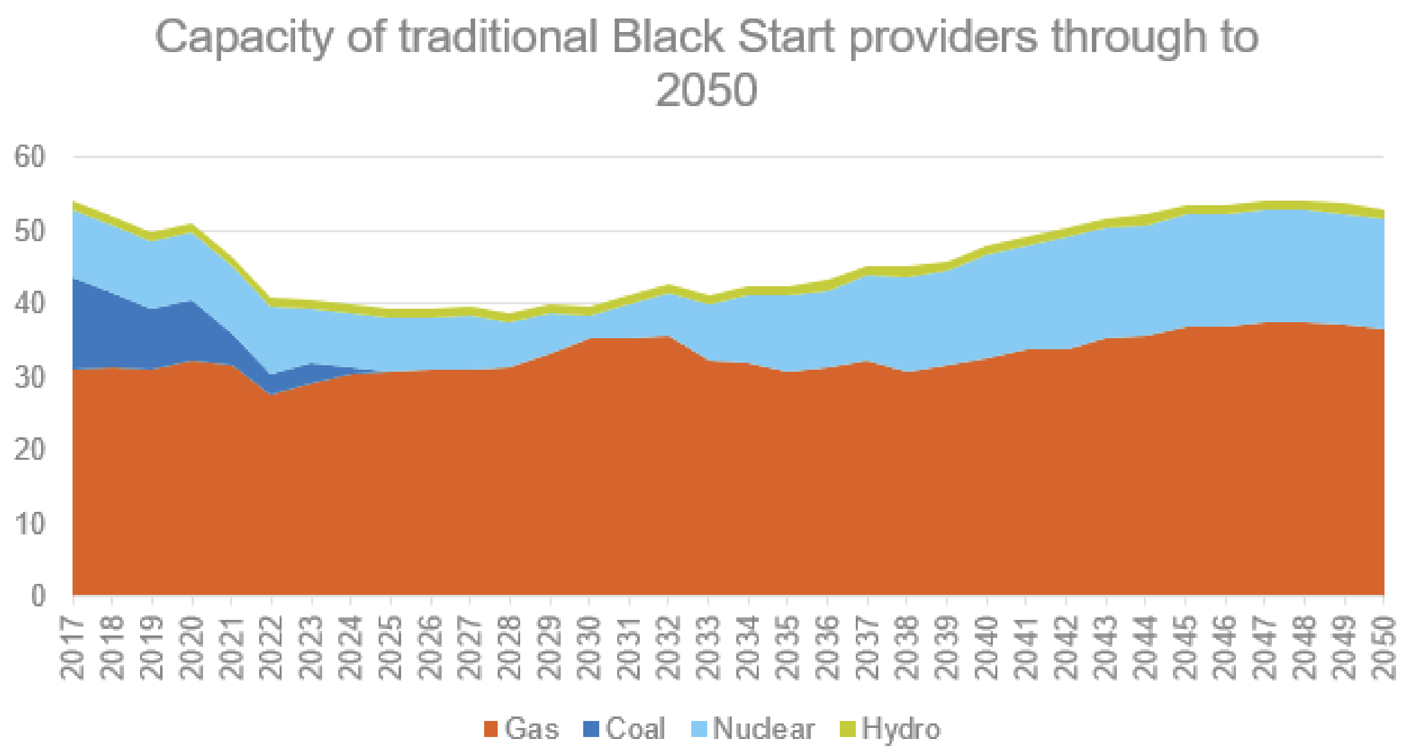
Figure 1.3
Non-traditional Black Start providers by technology type (FES 2018, Steady Progression scenario)



The commercial Black Start market is still currently configured to align with large power station capabilities and therefore, there is a large and increasing volume of DER that cannot compete in this market. This is not solely due to a lack of technical capability, but rather because of network restrictions, technical requirements and the current restoration strategy. VSC interconnector capacity is also forecast to increase but, although technically proven, interconnectors are reliant on neighbouring energy markets.

In contrast to the extensive growth of DER, by 2024 for Steady Progression, it is expected that all of the coal-fired power plants are likely to cease generation as shown in figure 14. Gas-fired capacity, however, is set to remain fairly steady out to 2050, with nuclear increasing slightly and hydro generation remaining constant.

Figure 1.4
Capacity of transmission Black Start provider technology in Steady Progression



With this large a decrease in traditional Black Start providers (more than 15GW in Steady Progression), market operation must adapt accordingly, otherwise this smaller selection of generators that meet the current requirements would drive up the costs of this vital service due to less competition and increasing operational costs to ensure availability i.e. these power stations would have to stay "warm". However, rising fuel and carbon costs, Government policies and the falling cost of alternative technologies have impacted the economics of large thermal generators, and several have made the decision to close permanently.

It is also the case that traditional thermal power stations are now used more and more as peaking plants, where they are used less often specifically to balance generation and demand. Just as this has happened to coal, it is also true for gas plants and this can be seen by examining the average load factor of these technologies. In all FES scenarios through to 2050, the average load factor decreases, with the average found to be nine per cent across all scenarios. Figure 15 clearly shows this decline for gas generation, despite the capacity of gas plants increasing overall (figure 14). The effect this may have on future Black Start provision is significant, as operation at such low load factors could dramatically increase the cost of Black Start, given that National Grid ESO will need to ensure a certain capacity is available at all times for Black Start and therefore needs to dispatch these larger generators more often[2].

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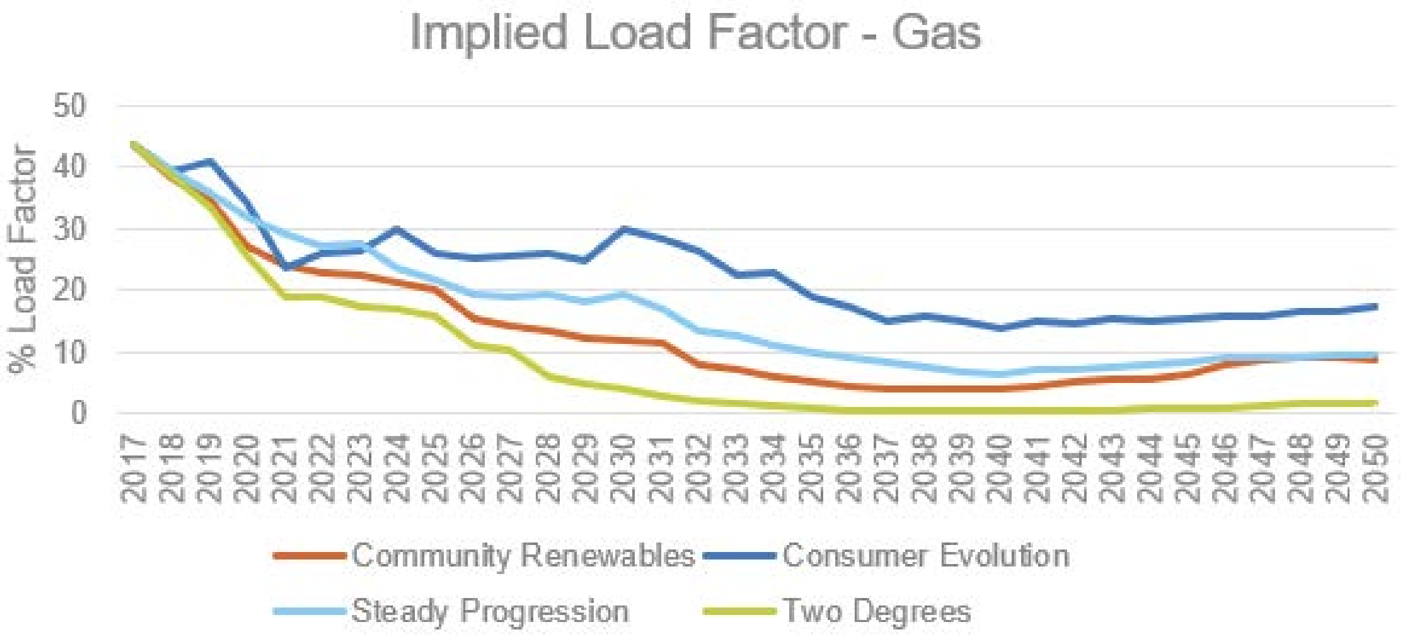
[2] For example, CCGTs and coal generators need to be run once a week.

Figure 1.5
FES Scenarios: Average load factor of transmission connected gas



The traditional service providers are mainly coal- or gas-fired generators, pumped hydro storage and to a lesser extent biomass, due to their capability to meet all technical requirements and provide all of the necessary services, however National Grid ESO has recently confirmed that combined services[3], interconnectors and sites with trip to house load[4] can provide services for Black Start within the existing arrangements. This opens up the market to more technologies and also paves the way for the allowance of DER to offer individual services to contribute to the restoration process. This is the principal focus of this report, which details the capability of a number of prevalent non-traditional technologies and DER, namely onshore wind, solar, battery storage, demand side response (DSR) and electric vehicles (EV), in providing distinct services during a partial or total shutdown. Understanding the capabilities of DER in this context will allow opportunities to be created and built into any new approaches to restoration and into Black Start strategy.

1.4 The future of Black Start

National Grid ESO is fully committed to understanding the future of Black Start in GB, and the outcomes of this technology review and assessment will feed directly into the Network Innovation Competition (NIC) project "Distributed ReStart" which is working towards trialling the restoration of a distribution level Power Island using predominantly DER.

Non-traditional, renewable and DER technologies are already known to be capable of providing certain services that form part of a Black Start and restoration process e.g. frequency control. This project has therefore investigated in more detail the coordination and overall procedures when deploying these technologies for a Black Start, while still paying due attention to the individual characteristics and parameters (inertia, active, reactive power, block loading etc.) that would be required to perform adequately.

To date, the coordination of Black Start from DERs is not known to have been proven anywhere in the world, so there remain commercial, organisational, regulatory and technical unknowns. To overcome these, the NIC project will focus on the challenges outlined in table 11 below.

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[3] A combination of two providers is used for a Black Start service.

[4] After loss of grid supply, a generator continues operating as a Power Island, maintaining supply on its own site, which may include loads associated with the power generation process and on-site industrial processes.

Table 1.1
Challenges in procuring Black Start services from DERs

Organisational	• New approach and more parties involved so existing coordination approach may not be suitable • New roles and responsibilities across the industry – significant impact on resource, skills, systems and equipment • Resilience of communications, control systems and processes needs to be understood, tested and their integration assessed • Impact of more coordination actions on restoration times and risk needs to be captured in a new restoration strategy
Technical	• Current technical requirements are not appropriate for smaller providers and new technologies • Unknown inertia, reactive range and block loading requirements for different types of distribution power island • Impact on distribution assets due to energising from lower voltage networks has not been trialled and needs to be understood • Unknown equipment (network and DERs) investment requirements at each DER site to deliver Black Start
Procurement and Regulatory	• Larger volume of smaller providers so existing procurement approach may not be efficient • Decentralisation of services may require new commercial and regulatory frameworks • Existing SO and DNO funding mechanisms for Black Start currently do not facilitate the method

This NIA project focuses on trying to shed light on some of the technical challenges noted above. Section 3 outlines the current Black Start technical requirements, noting those that would not be suitable for small generation sites and/or non-traditional technologies. Some amendments and changes to these existing requirements are proposed which could provide a more inclusive process in procuring Black Start services in future.

These amendments have been informed by significant research, review and stakeholder engagement which has provided insight on some of the more technical characteristics that different technologies have and how this impacts what and when they can contribute to a restoration effort.

An overall technology readiness level (TRL) has been assigned to the different technologies, in terms of their ability to provide different Black Start services and contribute to network restoration. Discussion around this is provided in Section 7.

1.5 Project approach

This project has been approached through three distinct work packages:

- WP1: Capability and Requirements;
- WP2: Operational Impacts; and
- WP3: Readiness and Next Steps.

WP1: Capability and requirements

Work package 1 comprised a number of activities, brought together to form a view of the current Black Start capabilities of non-traditional technologies. The non-traditional technologies referred to in this report include onshore wind, solar, storage, DSR and EVs. The existing Black Start regulations for GB have been reviewed to understand how the relevant principles could be adapted to reflect the changing generation landscape, while also maintaining the baseline integrity of the requirements.

The capability of the technologies to provide Black Start and restoration services was also evaluated through a combination of research, review and extensive stakeholder engagement. A mapping exercise between the capabilities and the requirements has facilitated the identification of gaps and potential solutions to overcome these.

WP2: Operational impacts

It is intended that the outcomes of this study are fed into the larger Network Innovation Competition (NIC) project "Distributed ReStart". The NIC project is investigating the feasibility of a Power Island being created and/or sustained using DER. This particular work package has investigated some of the operational limitations and constraints of non-traditional technologies, and their contribution to a Power Island as part of a Black Start.

Two key features of the technologies have been the focus of this study:

- asynchronous operation; and
- intermittency.

The impact of asynchronous generation on system strength and stability has been assessed, in particular how this will limit their contribution to a Power Island. A number of microgrid case studies have been reviewed to gain insight into practical experience in this area.

A quantitative assessment of wind intermittency has also been conducted to understand the adequacy and reliability of the technology to provide the necessary services in a Power Island.

The findings of WP2 have been published in two separate stand-alone reports and are not discussed in any detail in this report.

WP3: Readiness and next steps

Work package 3 brings together the outcomes of WP 1, allowing some conclusions to be drawn about the capability of non-traditional technologies to provide Black Start services and how they could potentially contribute to a Power Island. A TRL for the technologies has been assigned per Black Start service, recognising that in future, National Grid ESO will likely have to procure different services from different providers.

Roadmaps have been created which show what and how specific interventions could improve the capabilities of the technologies to provide different Black Start services.

Report structure

The report structure largely follows the flow of the work packages described in the previous section:

- chapter 2 outlines the existing Black Start requirements for GB alongside the scale of the potential for non-traditional technologies and DER;
- chapter 3 presents the capabilities of non-traditional technologies to provide Black Start and restoration services in future, and outlines the form these services could take; and
- chapter 4 summarises the TRL level of the technologies per Black Start service, and indicates on roadmaps the necessary interventions to improve the range and/or level of service they can offer to a restoration effort.

2 Non-traditional technologies

2.1. Non-traditional technologies considered for Black Start

In 2017, renewable sources provided almost 30 per cent of the electricity generated in the UK. At present, the restoration capability of these various technologies is not well understood and will be investigated as part of this project. This report will focus on the following non-traditional technologies and DER that could potentially be used for Black Start restoration, these are outlined in table 2.1.

Table 2.1

Technologies and DER considered for Black Start capability

Technology	Connection	Type
Large Wind (≥ 30 MW) (onshore only)	Transmission/EHV Distribution	Intermittent generation
Small Wind (< 30 MW) (onshore only)	EHV distribution	Intermittent generation
Small Solar	HV and LV distribution	Intermittent generation
Battery Storage	distribution	Flexible DER
EVs and V2G	LV distribution	Flexible DER
Industrial and commercial demand side response (DSR)	Various (including transmission)	Demand

Offshore wind was excluded from this study, mainly because offshore windfarms are typically hundreds of MW in size that connect directly to the transmission grid, and therefore not really relevant to distribution-level power islands. However, it is worth mentioning that the Carbon Trust's Offshore Wind Accelerator (OWA) programme has undertaken a separate study into the Black Start capability of offshore wind farms. The findings of this programme may be relevant to the "Distributed ReStart" NIC project and will be considered as appropriate.

2.2. Growth of DER technologies

In 2018, roughly a third (29 per cent) of all energy resources in GB was connected to the distribution grid while 71 per cent was connected directly to the transmission grid [2] (excluding DSR, which was not considered in the calculations).

According to the different future energy scenarios, the ratio of DERs to transmission-connected generation will change over time. The most conservative forecast scenario, Steady Progression, projects that the share of DERs will increase to 37 per cent by 2050, while the Community Renewables scenario forecasts that DERs will increase to 65 per cent, meaning that the share of transmission-connected resources will decrease to 35 per cent.

The exact share of DERs in 2050 will probably lie somewhere in between these two values, but in all the FES it is clear that the contribution of energy from DERs will increase, while the share of transmission-connected generation will decrease. By inference, Black Start services, traditionally sourced from large transmission connected generators, will reduce, thus creating the opportunity for DERs to play a bigger role with respect to Black Start and restoration.

The DERs that are expected to show the most growth across all the different FES are:

- solar;
- onshore wind;
- energy storage; and
- V2G.

In the sections to follow, the growth of each of the DER technology is examined in more detail to provide an overview of the prevalence of each technology and how it will change over time.

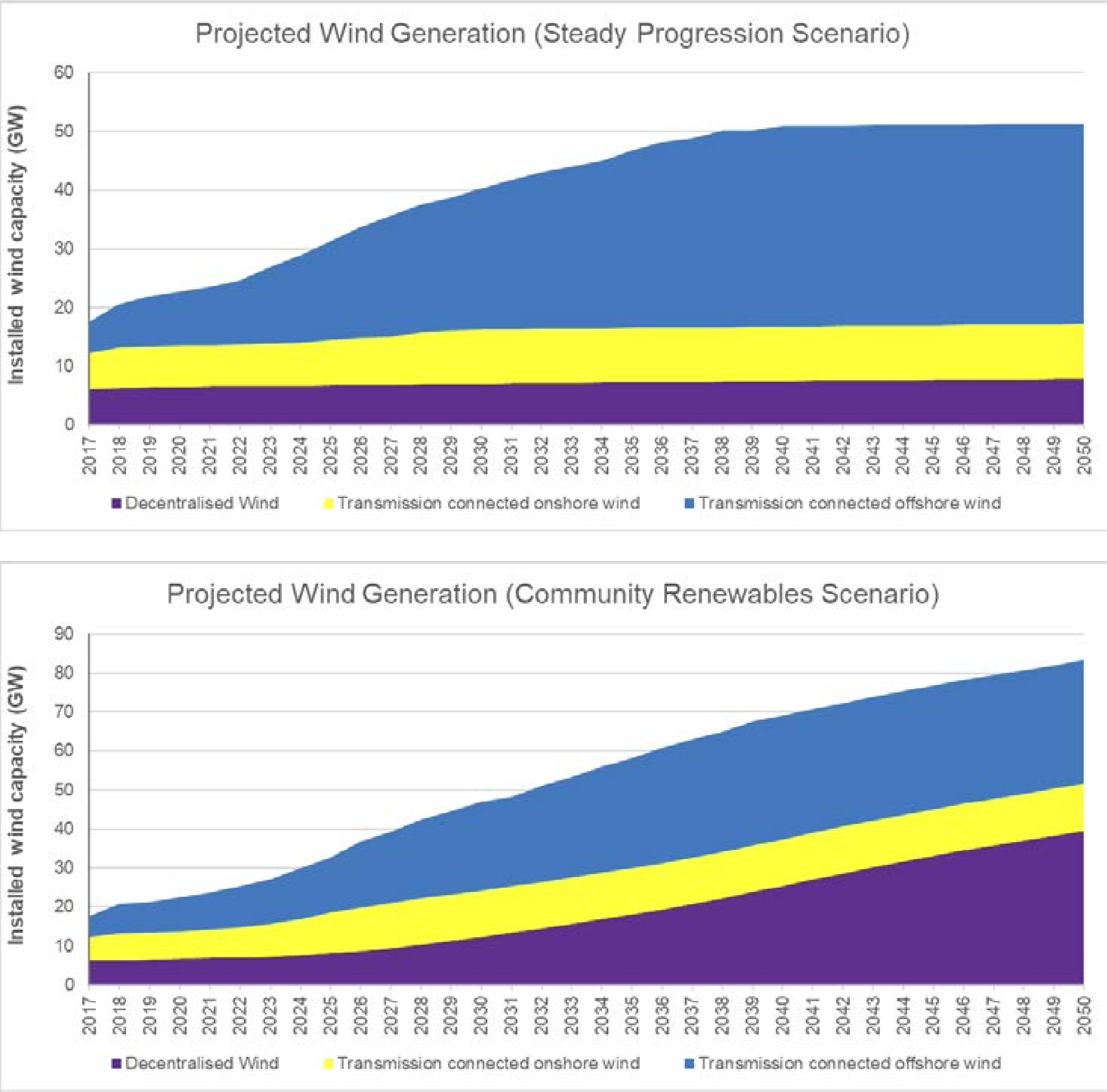
2.2.1 Wind

Within GB, wind power is the largest source of renewable electricity and the second largest source of renewable energy after biomass.

Figure 6 provides the Steady Progression scenario projection of wind generation between 2017 and 2050. Although wind generation is set to more than double over this period, almost all the growth is expected from offshore transmission connected wind farms. Decentralised wind is only projected to increase from 6.2 GW–7.9 GW, or 27 per cent, over the 33 years, suggesting that the growth market for onshore wind connected at 11kV and 33kV is very minimal. This is in stark contrast with the Community Renewables growth scenario which forecasts that small wind could grow to 39 GW by 2050, representing a 530 per cent increase.

Figure 2.1

Projected wind generation: Steady Progression vs Community Renewables scenario [2]



2.2.2 Solar

Solar PV is the dominant solar technology used in GB with an installed capacity of 12.9 GW in 2018. The majority of the GB photovoltaic installations are located in the South of England in order to access the relatively higher solar irradiation density. All solar PV installations are connected to the distribution network and are therefore regarded as DER.

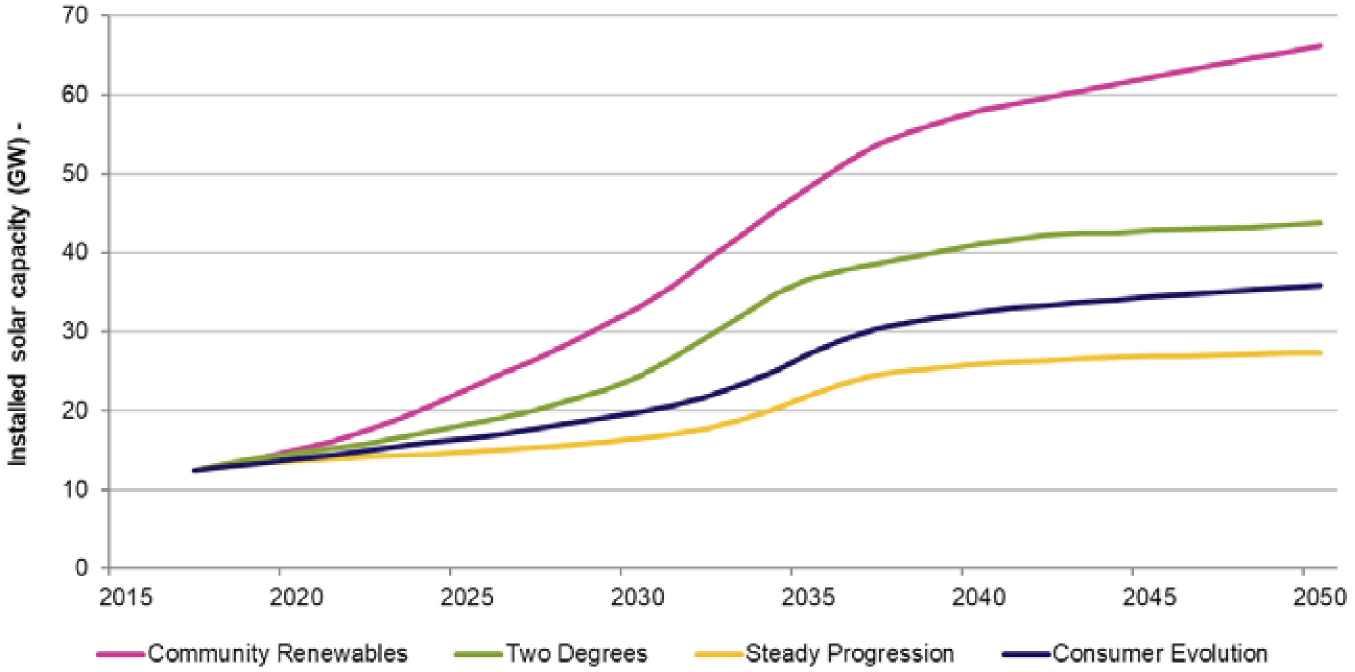
From a sizing perspective, PV facilities can be categorised as follows:

- domestic/small scale e.g. rooftop PV – up to 10 kW
- commercial/medium scale – 10 kW–10,000 kW
- utility/large scale – multi MW e.g. 1 MW–40+ MW

The forecast for solar PV growth is shown in figure 2.2. In the Steady Progression scenario, solar DER generation will increase by 111 per cent from 2018–2050, while the Community Renewables scenario projects a growth of 400 per cent over the same period.

Figure 2.2

Energy scenario forecast for solar PV [2]

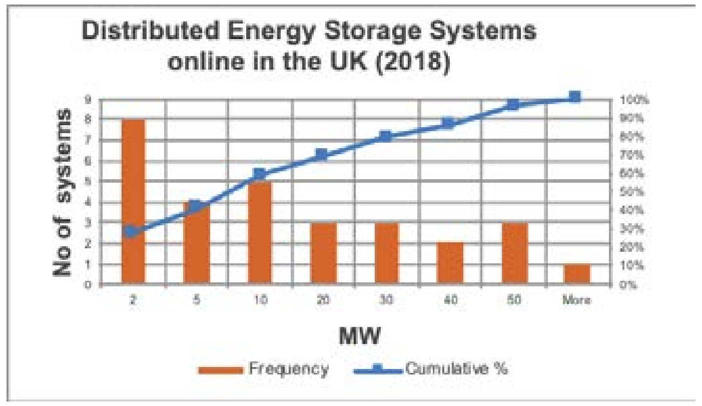


2.2.3 Energy storage

By the end of 2018, 460 MW of distributed energy storage was online in GB, compared to 146 MW connected to the transmission system. This consisted of 99 per cent lithium-ion battery systems, and one 5 WM liquid air storage system.

Figure 2.3

Distributed energy storage online in 2018 [31]



As shown in figure 2.3, approximately 60 per cent of the distributed storage systems are 10 MW or smaller, of which just less than half are smaller than 2 MW. Only four energy storage systems are sized at 50 MW and above, one such system is shown in figure 2.4.

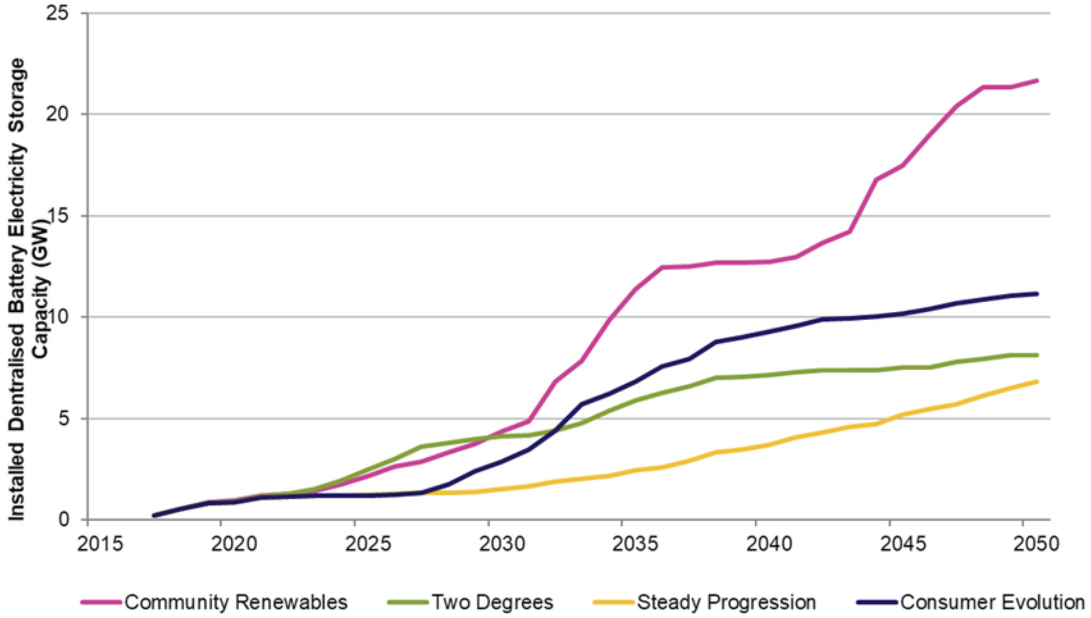
Figure 2.4

Stratera Energy's 50 MW Pelham BESS in Hertfordshire (www.strateraenegy.co.uk)

The projected growth of decentralised energy storage systems is shown in figure 2.5 for all FES. The pipeline for distributed storage systems suggests that in 2019, systems in the range of 10 MW–30 MW will be the most prevalent size. By 2021, 56 per cent of new storage systems will be larger than 10 MW [31].

Figure 2.5

Projected installed decentralised battery storage capacity (excluding V2G) [2]



2.2.4 Industrial and commercial DSR

Demand Side Response (DSR) is the turning up or down of electrical consumption in response to an external signal or incentive from the network operator. This normally occurs at times of peak demand to help balance supply and demand on the grid to avoid the use of additional generation. Users could also be incentivised to increase consumption when there is excess energy on the grid, for example on a windy day.

Systems and processes that are typically turned off under a DSR scheme include lighting, air conditioning, electric heating, pumps and other non-essential services which do not impact materially on day to day operations or comfort. Participants include industrial manufacturers, commercial and public buildings, hospitals and universities.

According to the Association for Decentralised Energy (ADE)[5] the smallest economical demand response is commonly regarded as 200 kW of flexibility which can be provided up to 200 hours per year. Most services are automated. Some site equipment can respond with the full demand response within one second, while other sites may take up to 15 minutes. DSR events usually last between 30 minutes and four hours. Generally, the faster the response time, the shorter the time the site will be asked to deliver the service. Demand response customers have the ability to manually override and suspend the demand response at any time.

Providers usually have to supply a minimum volume of balancing services to National Grid ESO. Small service providers usually contract through a third party, typically an aggregator. The following sections outline the demand response services that are currently contracted by National Grid ESO.

Frequency response

Four types of frequency response services are currently procured by National Grid ESO[6]:

- **Firm Frequency Response (FFR)**
  FFR services are tendered on a monthly basis for a combination of primary responses (i.e. demand reduction within ten seconds), secondary response (i.e. demand reduction within 30 seconds), high responses (i.e. demand increase within ten seconds) on a static or dynamic basis. The minimum size to tender for FFR services is 10 MW.
- **Firm Frequency Response Bridging**
  FFR bridging contracts are for providers with a minimum of 1 MW up to 10 MW and involve one- or two-year contracts with a fixed price per MW. New contracts are no longer available.
- **Firm Frequency Control Demand Management (FFCDM)**
  Contracts with customers with more than 3 MW of flexible demand to reduce demand within two seconds and up to 30 minutes if the frequency drops below 49.7 Hz. No new contracts are being signed as this has been replaced by static FFR contracts.
- **Mandatory Frequency Response**
  All large generators (i.e. types C and D, > 10 MW in accordance with ENTSO-E Requirement for Generators (RfG)[7]) must provide mandatory dynamic frequency response as part of the RfG, and by extension, the GB Grid Code requirements, found in Clause CC.A.3.

Short term operating reserve

Short term operating reserve (STOR) is needed, either in the form of generation or demand reduction, to be able to meet actual demand when overall system demand exceeds the forecast, or because generation plant becomes unavailable. National Grid ESO may issue a call for STOR when frequency response alone cannot provide the required power.

The service is usually required during the morning and evening peak windows, but may be required at any time. The minimum size contracted is 3 MW. The capacity must ideally be provided within 20 minutes (maximum 240 minutes) for at least two hours. The maximum recovery period must not be more than 1,200 minutes[8].

Fast reserve

Fast reserve is used to respond quickly to sudden or unpredictable changes in generation or demand. The requirement is that DSR providers must provide the required energy at 25 MW or more per minute and maintain this for at least 15 minutes. The minimum volume is 50 MW.

DSR market growth

The volumes of DSR services held by National Grid ESO between 1 April 2017 and 30 September 2017 are shown in table 2.2.

Table 2.2

DSR service volumes contracted by National Grid ESO (non-balancing mechanism participants)[9]

DSR service	Volume contracted
Frequency Response	617 MW
STOR	1,369 MW
DSBR	0 MW
Fast Reserve	300 MW
Total	2,286 MW

National Grid ESO has set an aspiration to meet 30 per cent–50 per cent of balancing capability from demand response by 2020. The ADE calculates that 16 per cent of the UK's peak electricity requirement i.e. 9.8 GW, could be provided by businesses implementing flexibility in their energy demand, resulting in a saving of £600 million by 2020 and £2.3bn by 2035 for UK consumers[10].

The growth of DSR and the flexibility it provides is crucial in supporting the GB transition to lower-carbon generation. Large customers could save up to ten per cent of their annual energy bills by participating in DSR and avoiding peak charges.

The FES report [2] makes the forecasts shown in figure 2.6 and figure 2.7 for DSR services out to 2050.

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[5] https://www.theade.co.uk/

[6] https://www.nationalgrideso.com/balancing-services/frequency-response-services

[7] https://www.entsoe.eu/network_codes/rfg/

[8] https://www.nationalgrideso.com/balancing-services/reserve-services/short-term-operating-reserve-stor

[9] https://www.nationalgrideso.com/document/107511/download

[10] https://www.energy-reporters.com/industry/industry-body-aims-to-boost-smart-energy-system/

Figure 2.6

I&C Demand response available

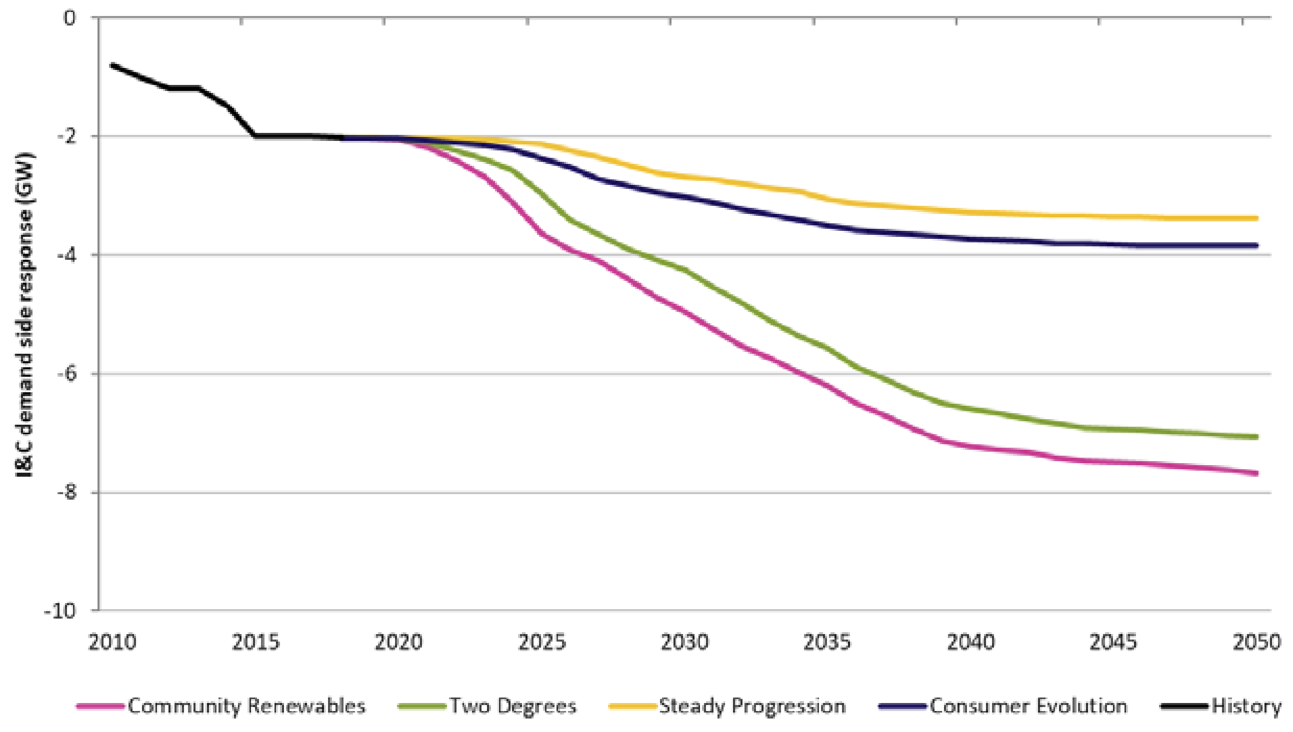
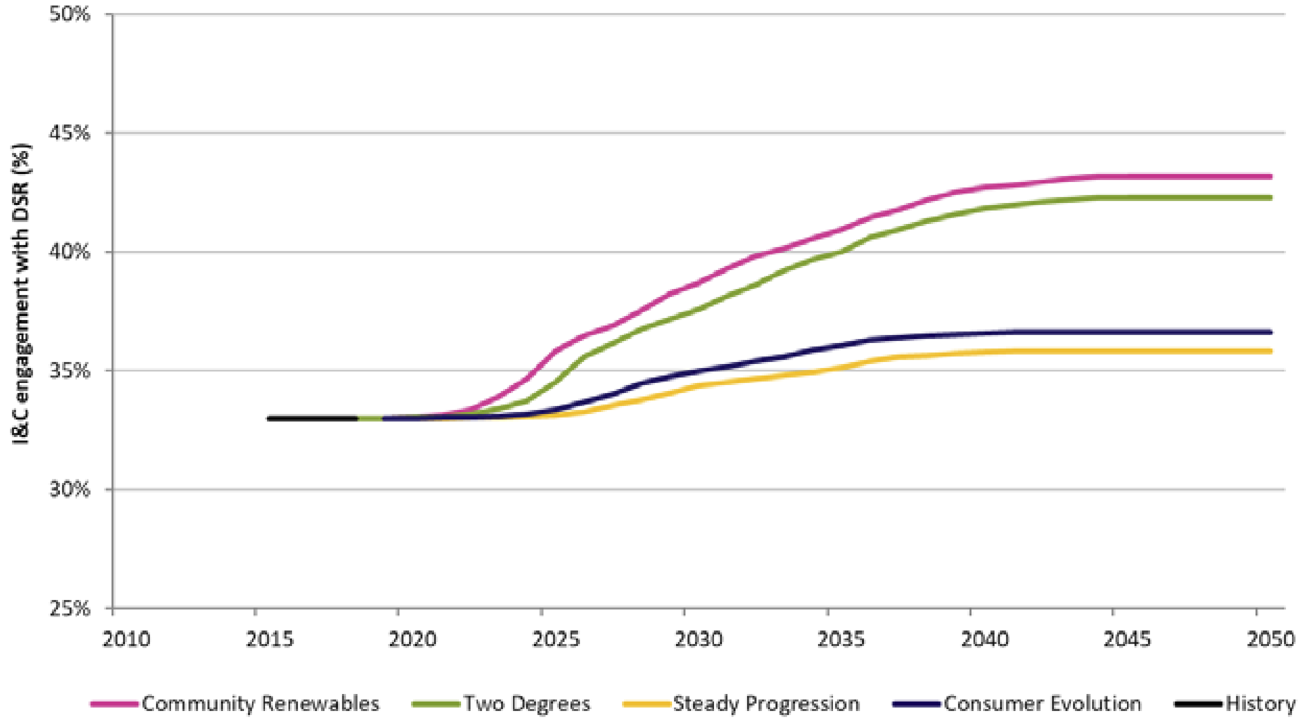


Figure 2.7

I&C engagement with DSR



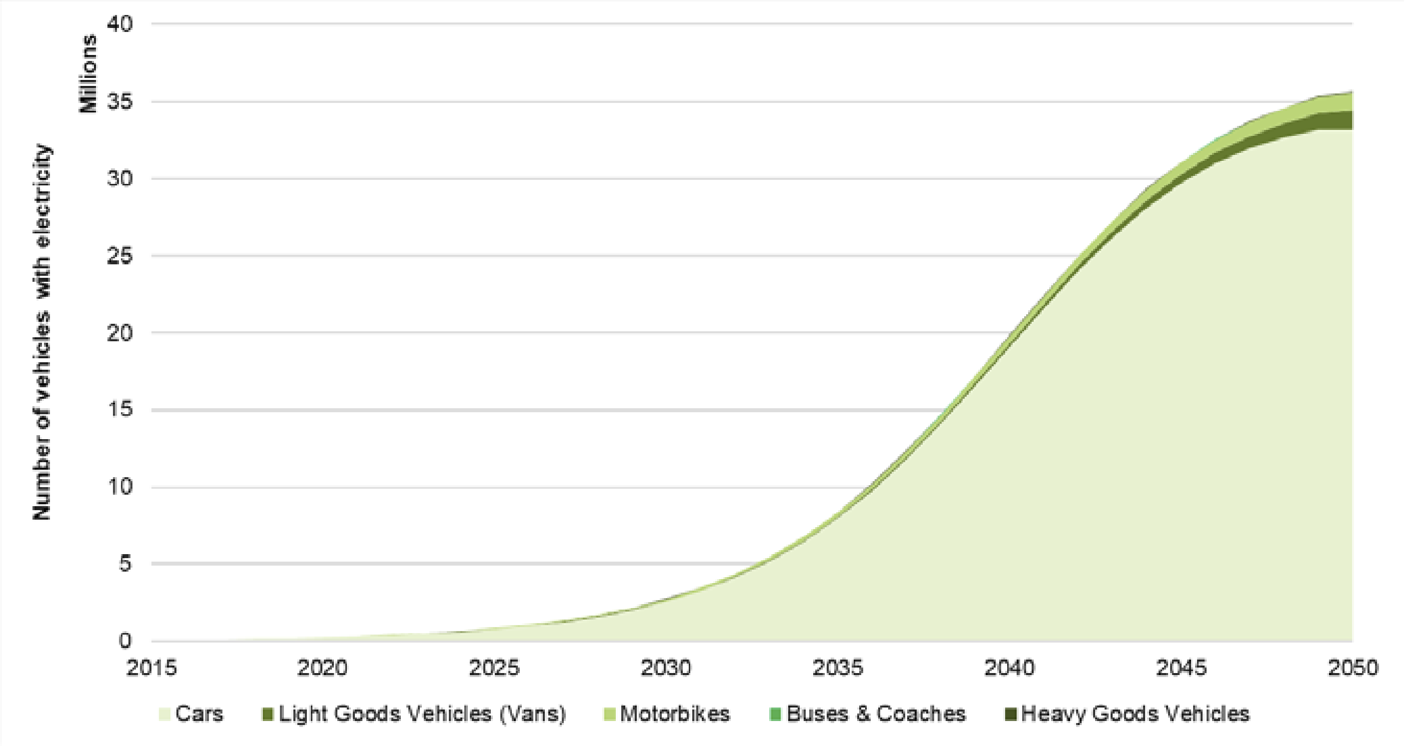
These forecasts are more pessimistic than the ADE's predictions, and the Steady Progression scenario suggests that DSR participation will increase from about 2 GW in 2018 to only about 3.4 GW in 2050, brought about by an additional three per cent of I&C DSR providers. FES with increased levels of community renewables will yield much high levels of DSR participation and volumes due to the flexibility of additional generation rather than demand reduction.

Electric vehicles and V2G

The UK government's aspiration to ban conventional vehicle engines by 2040[11] has led to a rising projection of EV uptake in the 2018 FES report [2]. It is currently estimated there will be 34 million EVs on the road by 2040. The Steady Progression scenario projects the uptake of EVs as shown in figure 215. Plug-in hybrid EVs (PHEV) are expected to gain steady popularity from 2020–2050, but is expected that there will only be around one million PHEVs on the road in 2050 which is low compared to EVs. There are expected to be as few as 20,000 Hydrogen fuel cell vehicles by 2050, and are therefore not seen as a technology that significantly impacts the uptake of EVs.

Figure 2.8

Expected EV uptake (Steady Progression scenario) [2]



Besides the quantity of EVs, there are a number of other factors that will influence the electricity demand form EVs. This includes:

- **consumer charging patterns** – EV peak demand is typically caused by private cars which are driven during the day and plugged in at offices or home during peak times. It is expected that the majority of EV chargers in the future will be smart which will avoid charging at peak times. Time of Use Tariff incentives are also likely to promote off-peak charging. It is estimated that 61 per cent of consumers will charge their vehicles outside of peak times by 2050.
- **charger technology** – Domestic AC chargers are typically 7 kW chargers which charge a vehicle over several hours. In contrast, future commercial DC fast chargers are expected to be 350 kW which could charge a car in as little as five minutes.
- **vehicle usage** – Vehicles parked on the road, place of work, or at transportation hubs, are more likely to make use of commercial chargers will result in local peak loads.

The changing peak demand caused from the charging of EVs under each of the FES is illustrated in figure 2.9. By 2030, the net peak demand from 2.5 million EVs is expected to be 2.8GW, rising to around 13 GW by 2050 (33 million vehicles) (Steady Progression scenario).

Besides the turn-down flexibility EV provides, aggregators would also be able to sell the vehicle-to-grid (V2G) service to network operators to help balance the system at times of high demand or high generation. It is estimated that up to ten per cent of EVs would be available to provide V2G services in 2050, based on the number of consumers with off-street parking that are expected to sign up, and cars that will be connected to a charging station and available to supply power to the grid.

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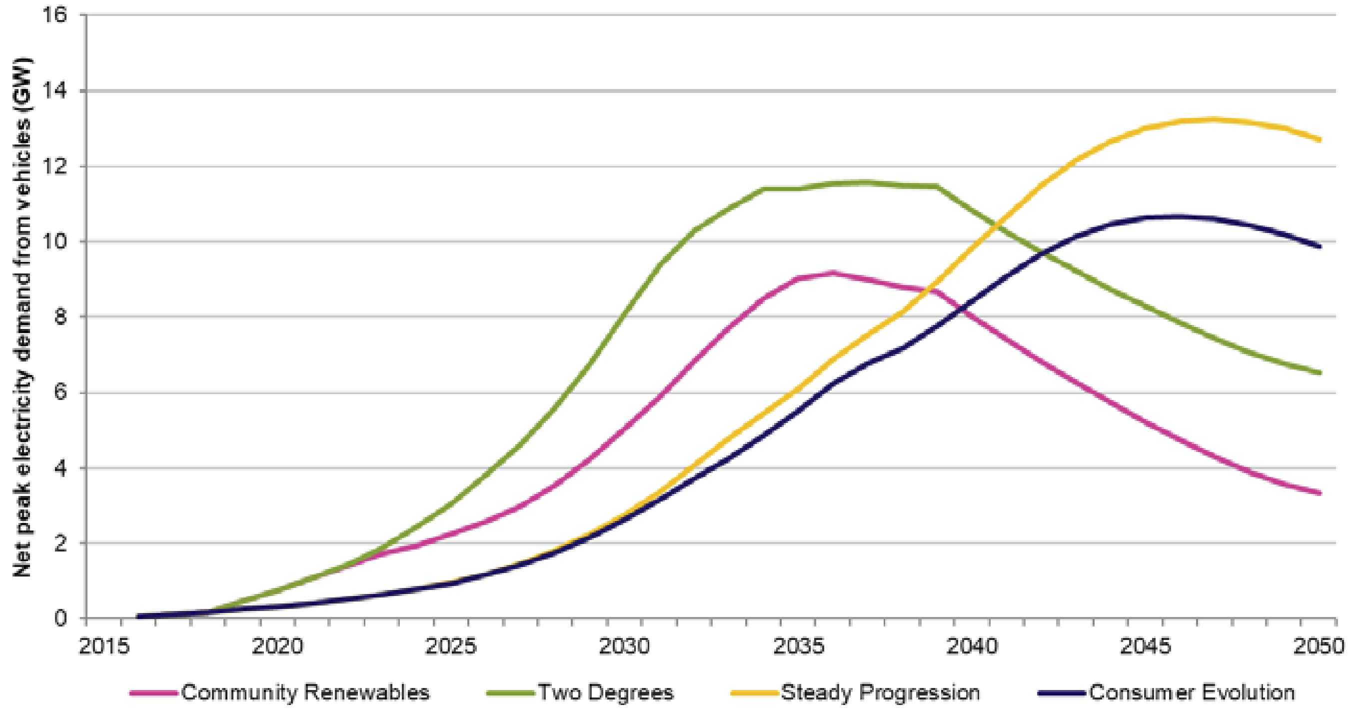
[11] https://publications.parliament.uk/pa/cm201719/cmselect/cmbeis/383/383.pdf

Figure 2.9

Peak electricity demand from electric vehicles



An analysis by Open Energi conducted in 2017[12] suggests that by 2020, with 1.6 million EVs on the road, EVs could provide between 200 MW–550 MW turn-up and between 400 MW–1,300 MW turn-down flexibility. This rises to 3 GW of turn-up and 8 GW of turn-down flexibility by 2030 (assuming 9 million EVs on the road). By 2050, an estimated 17 million EVs (based on the 2017 Two-Degrees scenario) could provide up to 6 GW of turn-up and 14 GW of turn-down flexibility.

With the peak electricity demand in GB projected as 62 GW in 2030 and 86 GW in 2050 (2018 Steady Progression scenario) it means that the flexibility of EVs and V2G could increase from around one per cent (2030) to 16 per cent (2050). In other words, EVs and V2G could play a major role in the future management of the grid.

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[12] https://www.openenergi.com/evs-can-help-fuel-sustainable-energy-future/

3 Existing Black Start technical requirements

The existing Black Start requirements for providers in GB is outlined by National Grid ESO, who are ultimately responsible for ensuring there are contingency provisions in place in the event of a total or partial shutdown of the national electricity transmission system (NETS).

The technical requirements of a Black Start provider are detailed in the Grid Code[13]. The code stipulates that a Black Start provider, known as a Black Start Station, will have Black Start Capability, meaning:

“at least one of its Gensets has the ability to Start-Up from Shutdown and to energise a part of the System or be synchronised to the System, within two hours upon instruction from NGESO, without an external electrical power supply.”[14]

Table 3.1

Key technical generator capabilities required for Black Start [Source: NGESO Black Start Strategy[15]]

Technical capability required	Why is this required?
High availability of Black Start Capability on both the main and auxiliary generating plant (typically 90%);	Whilst a system shut down is low likelihood, it could happen at any time.
Ability to start up the main generating plant (at least one unit/module) of the station from shutdown without the use of external power supplies.	In the event of a Black Start, the transmission system will not be energised so a provider will need to be able to start up independently and start to energise the system.
Ready to energise part of the NETS or, if appropriate, the Electricity Distribution System within two hours of instruction from National Grid ESO.	The sooner stations can start energising the network the sooner total restoration can be achieved. Establishing the initial status, preparation and switching will need to also take place between the System Operator (SO), TO and DNO) so two hours is considered a realistic timescale for all parties to be coordinated.
The reactive capability to energise the immediate Transmission/Network Distribution System(s). This capability will depend on the local system configuration, but generating plant connected at 400kV or 275kV with a capability of at least 100MVAr leading (as measured at the commercial interface) should almost invariably meet this requirement. The generator must also be capable of withstanding the magnetic inrush and transient voltages associated with this energisation.	Energising the local system is one of the first steps in restoring the network. The reactive capability must be sufficient to energise nearby substations.
The capability to accept instantaneous loading of demand blocks, preferably in the range 35 MW–50 MW, and controlling frequency and voltage levels within acceptable limits during the block loading process (under these conditions, frequency can be within the range 47.5 Hz–52 Hz);	The MW size of demand blocks being restored will be determined by the ability to separate the DNO system into areas. The size of these demand blocks will have some uncertainty.
The ability to provide at least three sequential Black Starts, to allow for possible tripping of the Transmission/Network Distribution System(s) during the re- instatement period or trips during the station’s starting sequence itself;	During system restoration, the system will be less stable than under normal operation so the likelihood of faults/trips is increased.
Facilities to ensure that all generating units can be safely shutdown without the need for external supplies, and can be maintained in a state of readiness for subsequent start-ups;	It may be that multiple attempts are required to deliver restoration.
Back-up fuel supplies (e.g. distillate fuel), if appropriate, to enable the provider to run for a minimum duration, ideally in the range three to seven days, following a Black Start instruction;	Alternative fuel sources will provide increased resilience in the restoration.
Resilience of Supply, Black Start Service – deliver contracted service for minimum time of ten hours.	Provide long term restoration.
Resilience of Supply, Black Start Auxiliary Units – run continuously at rated output for a minimum of three days.	Provide long term restoration.
Ability to control voltage level within acceptable limits during energisation/block loading (±10%).	Black Start Service Providers will need to maintain voltage (within limits) when creating, maintaining and expanding a Power Island.
Ability to manage frequency level when block loading (47.5 Hz–52 Hz).	Black Start Service Providers will need to maintain frequency within limits when creating, maintaining and expanding a Power Island.

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[13] The Grid Code is a document which specifies the detailed technical requirements for connection to and use of the NETS. It is maintained by National Grid ESO https://www.nationalgrideso.com/codes/grid-code

[14] Clause OC 9.4.5.1

[15] NGESO Black Start Strategy https://www.nationalgrideso.com/balancing-services/system-security-services/black-start

3.1 Existing technical capability requirements

The existing technical requirements of a Black Start Station fundamentally fall into three categories:

- the ability to start up independent of external supplies;
- the ability to energise part of the transmission network; and
- the ability to block load local demand.

The key technical capabilities required for current providers of Black Start services are summarised in table 3.1.

Previously, and indeed presently, one large provider is typically capable of delivering all of these features, but these requirements could be met by a combination of providers in some situations. The arrangement must be considered on a case by case basis, as not all provider combinations may be capable of providing the necessary services to execute a Black Start and perform a restoration.

In future, these requirements will definitely need to be met by a combination of providers, as it is very unlikely that any single non-traditional technology type or DER site will have the capability to provide all of these services.

3.2 Procurement of technical capability

Recognising this, National Grid ESO is now trialling a competitive procurement event for Black Start Ancillary Services, delivering on what was presented in their Black Start Strategy, Procurement Methodology[16], and Restoration Roadmap[17]. The trial for services covers two zones, provisionally in the South West and Midlands, for service commencement in April 2022. The service requirements requested by National Grid ESO can be seen in table 25. Many service requirements are the same as the existing ones, however the block loading MW capability has reduced by 15 MW. Crucially, this procurement event allows a number of parties to form a partnership or consortium to meet the outlined technical requirements, where one single provider cannot meet all of these on its own.

Table 3.2

Requirements for Black Start ancillary services
[Source: *NGESO Black Start EOI Technical Requirements and Assessment Criteria*]

Category	Requirement		Definition
	Existing	Trial	
Time to Connect	≤ 2h	≤ 2h	Time taken to start-up the BS Plant from shutdown without the use of external power supplies, and to energise part of the Network, within two hours of receiving an instruction from the Electricity System Operator (ESO).
Service Availability	≥ 90%	≥ 90%	The ability to deliver the contracted BS Service over 90% of a year. Note: It is the responsibility of the Provider to demonstrate its service availability. By submitting a tender, the provider commits to ensuring availability at least 90% of each year of the service.
Voltage Control	Existent	Existent	Ability to control voltage level within acceptable limits during energisation/block loading (±10%).
Frequency Control	Existent	Existent	Ability to manage frequency level when block loading (47.5 Hz–52 Hz).
Resilience of Supply, BS Service		≥ 10h	When instructed to BS, the minimum time the Provider will deliver the contracted service.
Resilience of Supply, BS Auxiliary Unit(s)	≥ 72h	≥ 72h	Run continuously at rated output for a minimum of three days.
Block Loading Size	≥ 35 MW	≥ 20 MW	Capability to accept instantaneous loading of demand blocks.
Reactive Capability	≥ 100 MVAr Leading	≥ 100 MVAr Leading	Ability to energise part of the network (MVAr>0, MW=0).
Sequential Start-ups	≥ 3	≥ 3	Ability to perform at least three sequential start-ups.

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[16] NGESO Black Start Procurement Methodology https://www.nationalgrideso.com/balancing-services/system-security-services/black-start

[17] NGESO Restoration Product Roadmap https://www.nationalgrideso.com/insights/future-balancing-services

As described, there will be a larger number of smaller generators likely to be procured to provide Black Start services at lower voltage levels in future. As such, opportunities for service providers to form a collective to meet the necessary requirement will almost certainly be necessary, and there may also be a case for giving concessions if a potential provider has a limitation on one of the technical requirements (where network or DNO factors may accommodate a reduced capability) but can meet the others.

Lessons learned from this event will be critical in forming any new Black Start strategy centred around procurement of a larger number of smaller sites offering varying levels of technical capability.

3.3 The role of a local joint restoration plan

Local Joint Restoration Plans (LJRP) outline plans and procedures agreed between National Grid ESO and Black Start Stations on the formation of power islands. In each plan, will be information regarding the scheduled activities and communications protocols that will be exercised in the event of a total or partial shutdown.

Each Black Start Station (contracted to meet all of the requirements outlined in the previous section) should have an LJRP agreed with National Grid ESO, and each is responsible for the creation and development of a Power Island. Agreement with the local onshore transmission owner (TO) (SHE Transmission, SP Transmission or NGE Transmission) is also required, and these LJRPs may also cover more than one Black Start Station. The different power islands will eventually be able to connect to adjacent power islands, ultimately achieving complete system restoration through this.

Typically, an LJRP will include, as a minimum, the following information:

- the part of the NETS and/or local Distribution System to be energised by the Black Start Station and the methods by which this will be achieved;
- how the block loading of the Black Start Station is to be achieved;
- manner of operation during islanded conditions;
- telephone numbers of all parties concerned and all other pertinent information; and
- the time periods required for the restoration of such necessary consumables.

The Grid Code stipulates the operation of an LJRP in seven main steps in OC9.4.7.6 (a)–(g), which can be summarised as follows:

(a) Once in the process of executing an LJRP, National Grid ESO can issue instructions to override those in a LJRP.
(b) A Black Start Station will be given the instruction to start up (from shutdown) by National Grid ESO as per the provisions of their LJRP.
(c) National Grid ESO will advise the relevant network operator of the requirement to make itself ready to carry out actions in the LJRP and operate in accordance with the provisions of the LJRP.
(d) National Grid ESO will ensure that switching carried out on the Transmission System and other actions are as performed as set out in the LJRP.
(e) The Black Start Station will notify National Grid ESO of its readiness to accept load, and National Grid ESO will then coordinate the block loading of demand and the creation of a Power Island, instructing on output levels.
(f) Execution of the LJRP will be terminated by National Grid ESO prior to connecting the Power Island to other power islands. It will also be terminated in the case of connection of the Power Island to another user system or network operator, or when synchronising gensets at other power stations.
(g) In Scotland, some gensets which are not Black Start Stations but are included in a LJRP will operate in accordance with the LJRP for the duration.

It should be noted that no offshore TO is presently included in any LJRP to avoid the situation of an onshore TO controlling the assets of an offshore TO.

3.4 Applying technical requirements to non-traditional technologies

The requirements set out in the Grid Code and associated documentation have been built up around, and are suitable for, large conventional power stations providing most, if not all, Black Start services. While the majority of the services that will be required in future remain the same e.g. frequency control, block loading, the Grid Code, and indeed procurement process, etc. will all have to be adapted to accommodate the changing generation landscape and the complexities this introduces when planning and executing a restoration. The process is already in motion, and this and the "Distributed ReStart" NIC project are anticipated to help accelerate this process.

In all likelihood, the relevant Black Start related documentation will retain the main principles that the present requirements outline but, for example, some specific quantities may be modified to reflect the capabilities of smaller and more distributed generators and other energy resources.

Table 3.3 below highlights how this might be carried out.

Table 3.3

Examples of proposed changes to technical specifications for Black Start

Existing Black Start requirement	Retained principle and proposed changes
Ability to start up the main generating plant (at least one unit/module) of the station from shutdown without the use of external power supplies.	Desired but not mandatory for all Black Start Stations. Onus would be on National Grid ESO to ensure enough Stations had self-start capability within a power island area.
Ready to energise part of the NETS or, if appropriate, the Electricity Distribution System within two hours of instruction from National Grid ESO.	More suitable timeframe could be appropriate given capabilities of fast acting technologies.
The reactive capability to energise the immediate Transmission/Network Distribution System(s). This capability will depend on the local system configuration, but generating plant connected at 400kV or 275kV with a capability of at least 100MVAr leading (as measured at the commercial interface) should almost invariably meet this requirement. The generator must also be capable of withstanding the magnetic inrush and transient voltages associated with this energisation.	To make provisions for lower voltage levels and lower levels of reactive power. Not feasible to dictate a MVAr value for a single generator as this will vary considerably. Withstand capability requirements should remain unchanged.
The capability to accept instantaneous loading of demand blocks, preferably in the range 35 MW–50 MW, and controlling frequency and voltage levels within acceptable limits during the block loading process (under these conditions, frequency can be within the range 47.5 Hz–52 Hz);	Smaller (less MW) blocks of demand in accordance with smaller distribution power island sizes. Ability to control frequency and voltage should remain unchanged.
Resilience of Supply, Black Start Service – deliver contracted service for minimum time of ten hours.	Smaller timeframes potentially required to account for less reliability and availability of resource.
Resilience of Supply, Black Start Auxiliary Units – run continuously at rated output for a minimum of three days.	Smaller timeframes potentially required to account for less reliability and availability of resource.
Ability to control voltage level within acceptable limits during energisation/block loading (±10%).	Requirement should remain unchanged.
Ability to manage frequency level when block loading (47.5 Hz–52 Hz).	Requirement should remain unchanged.

The 2017 System Operability Framework (SOF) [1] proposed some indicative values for the technical requirements regarding availability and reliability that could be set for smaller and distribution network-connected Black Start resources, highlighting that some thought has already gone into what would be realistic, as shown in table 3.4.

Table 3.4

Black Start Availability and Reliability Requirements

Technical capability for Black Start providers	Existing at 400/275 kV	Requirement at 132 kV	Requirement at 33 kV	Requirement at 11 kV
Availability of BS capability on main and auxiliary plant	>90%	>90%	>90%	>90%
Number of times able to start (at least one unit/module) without external power supplies	Three	Three	Three	Three
Facilities to ensure all plant can be shutdown safely without external supplies	Yes	Yes	Yes	Yes
Time to be ready for network energisation following instruction	2 hours	2 hours	2 hours	2 hours
Reactive range to energise the immediate network	Typically 100 MVar absorbing	Approx. 50 MVar absorbing	Approx. 5 MVar absorbing	Approx. 0.5 MVar absorbing
Ability to withstand inrush currents and transient voltages associated with network energisation	Yes	Yes	Yes	Yes
Demand block loading capability while controlling frequency and voltage within limits (47.5 Hz–52 Hz for frequency and 0.95 pu–1.05 pu for voltage)	35 MW–50 MW	35 MW–50 MW (Energise 33 kV circuits from a GSP)	10 MW–20 MW (Energise 33/11 kV Primary)	0.5 MW–1 MW (Energise 11/0.4 kV Secondary)
Time expected to run following a BS instruction, and therefore back-up fuel supplies to be available	Ideally 3 days–7 days	Ideally 3 days–7 days	Ideally 3 days–7 days	Ideally 3 days–7 days

Any eventual changes to Grid Code and other specifications and requirements will be made after significant study and review of the technical capabilities and limitations of conducting a Black Start in networks with significant penetrations of non-traditional technologies and DER. Learning from the competitive procurement event will also be informative.

It is also possible that LJRPs could be amended to accommodate the new requirements in establishing power islands, as they already have the building blocks of the process. However, it is likely that there will be significant changes to the content to account for the complexity of coordinating multiple Black Start Stations providing different services at different times throughout the restoration period.

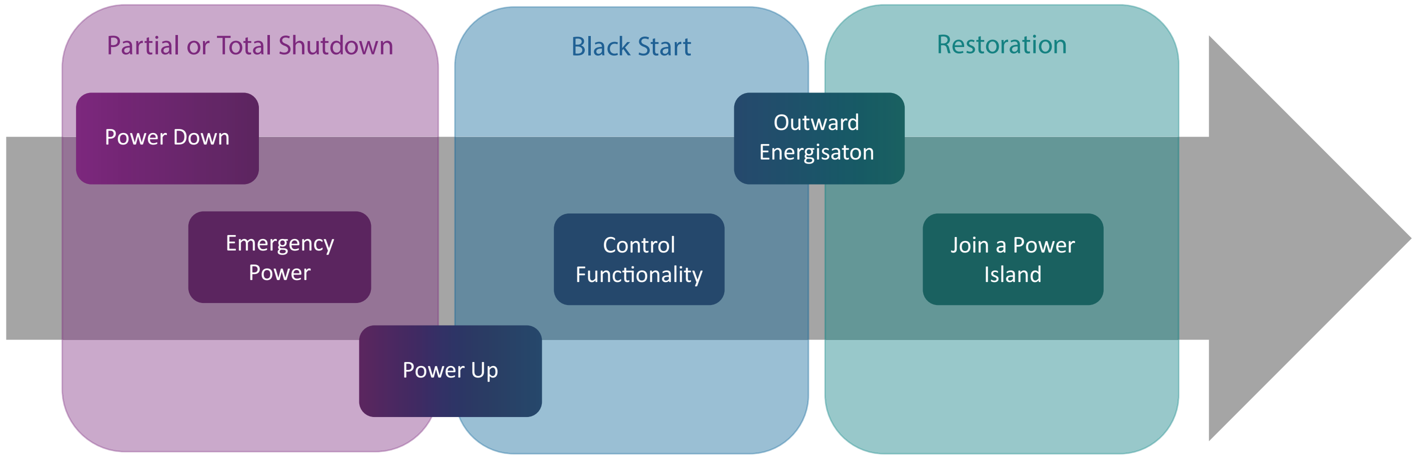
The outcomes of this project and the subsequent NIC project will serve to inform on any future decisions and changes that should be made in relation to the Grid Code, LJRPs and associated documentation.

4 Resilience and restoration performance characteristics

The diagram below, figure 217, illustrates the three principal phases of a Black Start event; with the partial or total system shutdown as a precursor, followed by the restoration phase where Black Start generation begins to energise the wider network.

Figure 4.1

Principal stages of Black Start and restoration



Each of the three phases is described further in the following sections, alongside more detailed descriptions of some specific characteristics and functionality required from Black Start providers during each phase. The non-traditional technologies investigated in this project have been assessed against each of the criteria listed below and their capabilities are detailed in Section 5.

4.1. Shutdown resilience characteristics

The shutdown phase will see all affected sites commence the de-energisation of their plant. The resilience of a site is dependent on the facilities it has to de-energise its equipment safely in the event of a partial or total system shutdown, and then the resources it has to supply emergency power to critical loads. The following sections detail several steps in the shutdown phase which each site will go through for de-energisation and in preparation for re-energisation and Black Start.

Site de-energisation

There are a number of ways a site can de-energise. The most typical options are:

- **trip** – where any generators, turbines, inverters, etc. are tripped from the network and no longer import/export any power;
- **ramp down** – where any generators, turbines, inverters, etc. are instructed to ramp down their output until they no longer import/export any power from/to the network; and
- **trip to house load** – where a sequence of tripping ensures that generators, turbines, inverters, etc., are tripped from the network and are no longer importing/exporting power; however, there are provisions in place to ensure power supplies to certain critical (“house”) loads are available.

Emergency power

If the de-energisation process of a site (see Site De-Energisation) is not “trip to house load”, there will be additional measures in place to provide emergency power to the site’s critical loads.

Some sites, particularly large ones, have full auxiliary supplies which are able to supply site load for several days. Other site back-up power supplies are often provided by batteries such as uninterruptible power supplies (UPS) which may only last a number of hours. It is important to know how long the back-up supplies at a site are likely to be able to continuously provide the necessary power supply to the critical loads (weeks, days, or hours); after which, what the consequences are for both the site and its ability to provide restoration services.

Intervention resources

The intervention resources of a site refer to whether or not there is personnel in attendance and in turn how quickly a response to the shutdown can be expected, to prepare the plant for re-energisation. The time-to-intervention is likely to be very site- and technology-specific with small solar farms in rural areas likely having longer response times than large onshore wind farms which will often have onsite management and a 24hour/day control centre.

The response times of different sites (and technology types) will be important in the restoration planning process, and in understanding when certain functions can be initiated or when a site can be restarted to join a Power Island. It is important to note that most sites, once shut down, will require manual intervention to start up and re-synchronise to the grid.

Control and communication system

The resilience of the control and communication system on a site is critical for a Black Start provider to be able to monitor the plant and execute remote failsafe operation, as well as send information and receive instruction from the SO during an outage. The MW output capacity of the site will typically determine the resilience of its control and communications through the prevailing Grid Code (ECC.6.5.5) and/or Distribution Code requirements, which are more demanding for larger capacity connections. Smaller sites may not require remote communication with the local network operator, however they will likely still have local provisions to operate and protect plant during emergencies in accordance with requirements set out in Engineering Recommendations G98 and G99.

Awareness of the control and communication system capabilities of sites, depending on technology type and capacity of connection, will be key in the restoration planning process and for the coordination of actions during the restoration itself.

Auxiliary starting generation

Auxiliary starting generation is typically provided for sites which are not able to self-start (capability described further in Self Starting). The auxiliary generation is used to energise the site before it re-couples with the wider network. The capacity (MW) of auxiliary generation will be a percentage of the total site capacity, typically 5 per cent–10 per cent, and be adequate to supply auxiliary loads and begin the re-energisation process. Where no auxiliary power is available, a site (or technology type) must rely on the external network for re-energisation.

4.2 Black Start performance

The Black Start phase involves the re-energisation of a site, through any number of means depending on the facilities available, and then the local/wider network. There are requirements for Black Start providers to be capable of specific control functionality of various parameters to keep balance between generation and load as it is brought back online. Traditionally, the full range of Black Start services has been procured from each of the large generating sites capable of providing them i.e. Black Start Stations, whereas in future it is likely that different services will be procured from multiple providers.

The following sections provide more detail on the various performance characteristics that Black Start providers could be assessed against in future, in terms of their capability to provide each service.

Self-starting

A site can be defined as self-starting if it is able to provide power to internal plant i.e. with no connection to the wider network. Sites with auxiliary starting generation, as described previously, are generally considered self-starting, and some of the technologies being investigated under this project are able to self-start without an auxiliary power supply e.g. a battery with sufficient residual charge at the time of a shutdown. This is the first step in the Black Start phase sequence of events, whereby sites that are able to energise internally are then matched with demand (see Block Loading), with the help of sites that are able to energise the network outward from their site (see Network Energisation) aiding the creation and eventual growth of power islands.

Understanding which sites (and technology types) can self-start (and equally those that can’t), and in what timescales, is vital to the restoration effort and in the successful creation of power islands.

Grid forming

Converter-connected technology will largely fall into two categories with regards to how it energises outward during a Black Start: grid-forming; or grid-following. A grid-forming converter is capable of creating its own voltage and frequency signal while a grid-following converter relies on an external voltage signal to which it synchronises and then follows.

A grid-forming converter will have a different role during a Black Start and restoration than a grid-following converter. A grid-forming converter will be able to initiate outward energisation from its own site onto the local and wider network to start creating a Power Island. Grid-following converters will latch onto the voltage signal created by the grid-forming converter(s) in the Power Island which will then grow as more sites are able to join.

Network energisation

The capability of a site to perform and achieve outward network energisation depends on the characteristics of both the converter (see Grid Forming) and of the dispatchability of the fuel source e.g. a solar PV site will not be capable of outward energisation at night, or a battery storage facility will only be capable up to the volume of charge they have at the time of the shutdown.

Network energisation for the creation of a Power Island could be attained through a coordinated process of grid-forming sites (or other synchronous sites able to energise) expanding out to grid-following sites and then, those sites which are capable implementing load restoration through block loading.

Block loading

During a Black Start, load restoration is achieved through block loading, the process by which demand (typically tens of MW at present) is brought online to balance this with the generation on the system, as more sites are steadily energised. A generation site must be able to manage the voltage and frequency of the network to within the acceptable limits for the duration of the load restoration process, noting that the frequency limits during a Black Start and restoration are less stringent than in normal operating conditions.

Knowing the capability of sites (and technology types) able to execute and manage block loading i.e. what quantities of demand can be brought on at a time, will be instrumental in the creation and growth of power islands.

Reactive range at zero active power

The ability of a site (or technology) to deliver reactive power while not producing any active power is particularly useful during a Black Start to provide improved voltage regulation and stability in the early stages of restoration, and this is becoming increasingly available with converter technologies. The level of reactive power that converters can provide at 0 MW output will vary by device, but some already offer full reactive range.

Reactive power

Larger sites will have reactive power requirements imposed by the Grid Code (ECC.6.3) and/or Distribution Code which specify the expected quantities of reactive power to be available, under normal operating conditions, depending on the active power output at the point of connection.

These quantities, if available during Black Start, could contribute to ongoing voltage regulation and balancing within a Power Island throughout the remainder of the restoration event. It should also be noted that many converter technologies can exceed the Grid Code required values of reactive power and so could potentially unlock even more capability during a Black Start.

Frequency Control

Similar to the reactive power capability of sites, there are Grid Code requirements (ECC.6.3.7) for frequency control which all sites must achieve. The sites must be capable of operating in frequency sensitive mode and the requirements vary depending on the capacity of the connection and are more stringent at higher voltages.

If this capability can be made available during Black Start and restoration, this could allow sites to contribute to the management of frequency on power islands. It should also be noted that many converter technologies have capabilities in excess of the Grid Code requirements and so it is possible that this could be further exploited in an emergency scenario.

Intermittency

Intermittency is a key characteristic of some of the technologies being studied here, specifically wind and solar. The capability of wind and solar sites to provide and perform a number of the services outlined in previous sections can depend heavily on whether or not there is the "fuel" resource available at the time it is required. Conversely, there are instances when there may be an abundance of a resource e.g. run of river hydro, which could also be problematic if not appropriately managed. The generation in either case is considered non-dispatchable and adequate control is required.

Other emerging technologies such as storage or DSR, on the other hand, can be considered "dispatchable" and could potentially be configured to moderate the impact of intermittency during a restoration and within a Power Island.

Availability and reliability

The availability and reliability of a site (or technology) is determined predominantly through forecasting which is done ahead of time. For renewable generation and DER, forecasting will include such things as weather forecasting or charge patterns for battery storage or EVs, however there is also a level of uncertainty (low confidence) in this type of forecasting.

Knowing to what extent technologies could be relied upon during a Black Start and restoration is important when considering how long power islands comprised in large part of renewable generation and DER could be sustained.

4.3 Restoration capabilities

As described, once a site is re-energised, and the surrounding network is slowly being brought back online through block loading, it can join a Power Island. The capability of a Black Start provider to do this, and the contribution of a site to the operation of a Power Island, is crucial to ensuring that power islands remain stable and expand as necessary until the whole system is restored. The considerations for a Black Start provider in relation to power islands are described in more detail in the following sections.

Joining a Power Island

It is critical to establish when a site (or technology type) can safely and effectively join a Power Island. The timescales of readiness of a site to join a Power Island, and overall coordination within an established Power Island, will be dependent on a number of factors, most predominantly:

- type of converter technology (grid-forming or grid-following);
- level of energisation (MW) and matching this with demand in the Power Island;
- availability and reliability of technology (fuel source); and
- establishment of communications with wider network and control centre.
- this is one of the focus areas of the "Distributed ReStart" NIC project and detailed power system studies will be carried out to assess the process of joining a Power Island and how the characteristics listed above impact the readiness timescales of different technologies (sites).

Performance in a Power Island

Considering the range of Black Start requirements listed in the preceding sections, the contributions that a site of a specific technology type can make to a Power Island should be evident, however the exact performance capabilities and consistency will be dependent on the individual site characteristics e.g. size/capacity, connection voltage etc.

Maximising the performance of technologies in a Power Island can be achieved through optimising the balance between Power Island requirements and service provision; utilising different technologies according to their strengths and advantages. This can be enabled by suitable communications (hardware and protocols) and other tools such as microgrid controllers.

5 Technology capability – Resilience and restoration characteristics of emerging generation technologies

As described in the previous section, there are a range of performance characteristics relating to the resilience, Black Start and restoration capabilities that are likely to be required in a future Black Start scenario. The following sections provide the findings from extensive research and stakeholder engagement activities and highlight the capabilities of each of the non-traditional technology types being considered in this project against each of the performance criteria.

5.1 Large and small wind power

5.1.1 Shutdown resilience characteristics

Site de-energisation

During a network outage through a shutdown or planned outage event, the network operator will disconnect the point of connection circuit breaker at a wind farm site preventing the generation from forming its own Power Island. In most instances, the wind farm loses its primary auxiliary power supply from the network and the wind farm protection and control systems become powered by the on-site battery backup power. On some sites, the LV auxiliary power is changed over to a diesel generator. The turbines shut down automatically and go into a standby/idle mode until power is restored to the grid. Some wind turbines have battery banks that operate the emergency pitch control of the turbines.

Emergency power and auxiliary starting generation

A wind farm site substation will have a battery bank to power the control and protection systems in the event of a network outage. Some wind farms tend to be coupled with diesel generators for their backup auxiliary power supply. Smaller wind farm sites rely on an auxiliary power supply from the network to run their on-site auxiliary, control and protection systems. The communication systems tend to have a small dedicated UPS to provide back-up power.

Intervention resources

The majority of wind farm sites in the UK tend to be unmanned with a certain level of control and communications observed from a remote-control centre. Intervention times would therefore vary considerably depending on the location of the site.

Control system and communication

Conventional on-site wind farm communication infrastructures are switch-based architectures, where each wind turbine is equipped with an industrial Ethernet Switch (ESW) at the base of the tower, and optical fibre cables are used to connect between wind turbines. In the case of large wind farms, independent sets of switches and communication links are considered to interconnect different applications such as those involved in monitoring, operation, and protection. The transmitted data from the wind turbines may take a path through many ESWs in order to reach the control centre side, depending on the turbine location and the wind farm topology. The limitations of conventional wind farm communication architectures are [20]:

- low reliability – the failure in a wind turbine ESW may affect the remaining turbines preventing them from connecting with the control centre;
- high cost – the price of the ESW is expensive, and independent sets of switches and communication links add more costs to the wind farms; and
- difficulty in guaranteeing real-time monitoring and control in case of sharing the same physical link with all wind turbine traffic.

For larger wind farm sites, the control between the network operator and the wind farm typically has a higher level of resilience than smaller wind farm sites. Communications and control between the wind farm substation and the network operator tend to have a battery back-up UPS with a dedicated fibre/microwave connection. In some instances, the communications can be copper hard-wired between the wind farm site and the network operator. Wind farms between 30 – 50 MW require remote communications to the grid as per the Distribution Code and/or the Grid Code (CC.6.5.) Below 10 MW, the Distribution Code does not require remote communications and control. If power were to be disconnected from the grid, the local communication systems will be powered by the on-site telecoms UPS.

Table 5.1
Shutdown resilience characteristics of wind

Site de-energisation	Turbines shut down automatically and go into a standby/idle mode until power is restored to the grid. Some wind turbines have battery banks that operate the emergency pitch control of the turbines.
Emergency power	The technology typically has on-site emergency power, sufficient for restoration of communications, protection and control. If the shutdown is extended over a long duration, the UPS may only have several hours' capacity. Current Black Start provision of three days–7 days running of the auxiliaries is not currently achievable unless on-site generation is procured.
Intervention resources	The majority of sites are unmanned.
Control and communication system	The UPS duration of a few hours most likely won't be long enough under an extended shutdown period. However, the site will be able to restore control and communication systems ready to receive notifications from the SO for as long as the UPS has capacity.
Auxiliary starting generation	Almost all sites rely on a primary auxiliary connection from the network for starting. Some sites have a diesel generator as a back-up supply for the auxiliary power. Some sites rely on contracts with diesel generator services to deliver the diesel generator to site as and when required.

5.1.2 Black Start requirements

Self-starting

For a wind turbine to be able to self-start, some form of auxiliary power supply would be required during start up. New and existing wind farms will not automatically have a sufficiently sized auxiliary power supply for Black Start purposes, but retrofitting such equipment is technically possible. Wind farm sites tend to rely on a primary auxiliary power supply connection from the network. A diesel generator or an electrical energy storage system has the potential to provide the power to start a wind turbine. It has been observed that some large international offshore wind farms tend to use diesel generators on the platform (or in the turbines) to provide the initial energy requirements of the wind farm [17].

Auxiliary power requirements should be expected to be about five per cent–ten per cent of the nameplate capacity of a wind farm. A staggered approach to starting up individual turbines could also be employed to reduce the required power rating of the auxiliary power supply. This approach would need to match the demand to the generator for the power ramping requirements of the network operator Black Start procedures [19]. If provision is made for the auxiliary power and with the availability of sufficient wind resource, start-up time can be rapid when compared to hydro or OCGT generation.

Network energisation and reactive power

Reactive power capabilities will depend on the wind turbine technology employed (full-scale inverter typically has the best capability) as well as whether or not additional reactive power compensation equipment is installed at a site. Certain large wind farm sites connected at 400 kV or 275 kV have the potential to provide at least 100 MVAr of leading (absorbing) reactive power (in line with the current requirement) and are able to withstand the magnetic inrush and transient voltages associated with re-energisation of lines, cables and transformers. Smaller wind farm sites are similarly able to provide the reactive power service but not to the level of the current requirements.

Grid forming

Wind farms are typically installed with parallel grid operation in mind, and so are not usually grid-forming capable. Most connections will be with an inverter that is grid-following so these inverters are not able to produce their own signal to energise a network, instead latching on to a pre-existing voltage signal. A software change coupled with a grid-forming inverter is understood to be a feasible option to unlock this capability.

Block loading

Load restoration capability will depend on wind farm capacity and wind speed at time of loading. Provided that sufficient wind is available, the ramping rate is closely related to bringing the turbine up to speed without effecting the mechanical stress on the turbine. Block loading is presently performed in steps of 25 MW–35 MW at least (to help simplify network switching requirements), however this will not strictly apply for wind, or any other renewable technology, as restoration utilising these types of generation will have to be based on smaller load blocks where applicable. Amending current restoration strategies is therefore necessary to account for the establishment and extension of smaller and more localised power islands, in comparison to current restoration procedure [19].

Frequency control

The grid-decoupled nature of both doubly-fed induction generators and fully converter-fed synchronous generators (electrically excited or permanent magnet) as applied in modern wind turbines implies a low contribution to network inertia in the conventional sense. Associated voltage and frequency control will be dependent on the technology of the wind farm-to-grid connection and the availability of compatible control algorithms. Some work has been done to incorporate algorithms into the wind turbine converter control systems to address this. In terms of frequency control, this will also depend on the available wind resource since low wind conditions will limit the capacity of the wind farm to ramp up active power supply [19]. The variability of wind is further explored in a separate report (Report 3 of this NIA series).

Availability and intermittency

Wind resource is intermittent and may not be available or sufficient for a Black Start demand at such times as it is needed. For a given wind speed however, there is the capability to control the output of a wind turbine.

Table 5.2

Black Start performance of wind

Self starting	Most wind farms rely on auxiliary power from the network to self-start. Ramp up times are comparably faster than that from some traditional Black Start providers. A suitably sized auxiliary power supply would currently be required to enable a self-start. Self-starting can be considered against the individual components of energising the turbines, energising the cable arrays and the substation.
Grid forming	Most wind farm connections are currently through grid-following inverters and these are not presently able to produce their own voltage signal to energise a network, instead latching on to a pre-existing signal.
Network energisation and reactive power	Large wind farm sites connected at 400kV or 275kV are expected to provide at least 100MVAr of leading (absorbing) reactive power (as per current requirements). Existing control and protection systems prevent wind farms from energising a network. The ability to energise the network will largely depend on the availability of the wind resource, the wind farm capacity and the energisation of the network load.
Block loading	Load restoration in smaller blocks could be achievable by wind farm sites depending on the wind availability and the duration of the supply.
Frequency control	Wind farms provide a low contribution to network inertia. Associated voltage and frequency control is dependent on the technology of the wind farm-to-grid connection and the availability of compatible control algorithms.
Availability and intermittency	Wind resource is intermittent and may not be available or sufficient for a Black Start at such times as necessary.

Restoration capabilities

The process of restoration should start with individual turbines being fed from auxiliary power (that is separate to power provided from the network), to begin energising and operating the wind farm. At present, this arrangement is not used in practice apart from at a few sites. A challenge would be for the turbines to provide reactive power to energise the inter-array cables of the wind farm. With this in mind, the controls for the turbine and internal converter need to be developed to operate in a weak grid and are currently not typically designed as such. A diesel generator or some type of energy storage back-up power supply would still be required to energise the substation. A further challenge is for the turbines to provide the reactive power to energise the main export cable. A point to note is that significant work in regards to control, communications, auxiliary power etc., would still be required to make this technically feasible.

Existing wind farms in GB are protected by Grid Code (CC.6.3.15.3) and Distribution Code requirements, and as such, are prevented from operating in islanded mode when the network is not available. The performance of the technology in a Power Island is largely dependent on the availability of wind. During the restoration phase, depending on the size of the wind farm, the technology could provide support by absorbing reactive power and being capable of withstanding a small block load pick-up while maintaining the frequency, voltage and RoCoF within the required range. This has been demonstrated at some large wind farm sites.

Major OEMs are developing variants of potential Black Start solutions for wind turbines and grid energisation. The turbine operates in an islanded mode and generates its own auxiliary power. Auxiliary power is tapped off in the rectifier/inverter stage of the turbine. A UPS can provide power during times of low wind. Figure 5.1 indicates such a system [17].

Figure 5.1

Example of a self-starting turbine diagram

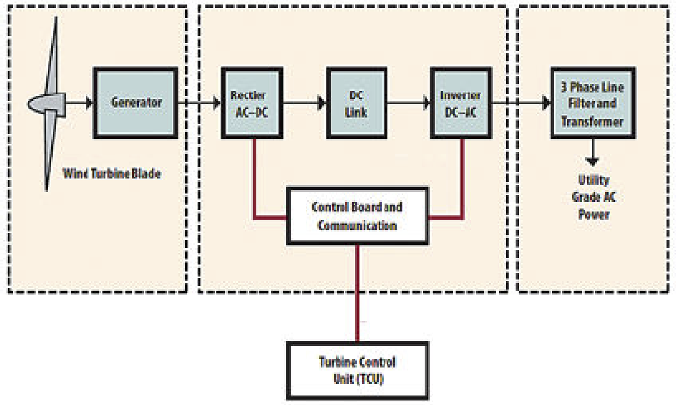


Table 5.3

Restoration capabilities of wind

How early can the technology join a Power Island?	Existing network regulations prevent wind farms in the UK from operating in island mode and joining a Power Island. However, if sufficient wind resource is available, and the control and protection systems are adapted, wind energy with its own internal auxiliary starting power will be able to join a Power Island early in a restoration process.
How will the technology perform once in the Power Island?	The performance of the technology is largely based on the availability of wind resource and the amount of power required in balancing the load. Coupled with energy storage and other generation, the technology will be able to provide support functions for frequency, voltage and inertia in a Power Island.
How can this performance be used to the advantage of the Restoration?	The technology is able to provide voltage support, frequency support, reactive power support and block loading depending on the power island strength, the size of the block load and the wind farm capacity. The technology has the ability to accelerate the overall restoration process.

5.2 Solar PV power

5.2.1 Shutdown resilience characteristics

Site de-energisation

The majority of solar PV farms in the UK are directly connected to the grid with no storage. During de-energisation, the plants will disconnect from the grid and enter into standby mode. If the site is co-located with battery storage, the plant will continue to charge the battery while solar resource is available until full capacity is achieved, and then it will remain in idle mode.

Emergency power and auxiliary starting generation

The solar PV substation will have its own emergency battery back-up supply to run its control, communications and protection systems.

Solar PV sites are largely dependent on an auxiliary supply from the network. However, solar PV sites with battery storage could inherently provide their own auxiliary starting generation through the battery storage systems. Most grid connected sites tend not to have any emergency back-up power to run the house load. Current Black Start provision of 37 days for powering of the auxiliaries is not currently achievable.

Intervention resources

Most sites are unmanned and remotely managed. Once a shutdown is registered, the response time for the site to be manned depends on the location of the operator from the site.

Control system and communication

Local communications and control will be resilient to manage and protect the solar PV system during emergencies, but the duration of the UPS is typically several hours, and less than the 72 hours stated in current Black Start procurement requirements.

Larger solar PV systems (>10 MW) will require resilient remote communications and control, however, this duration of resilience is unknown.

Table 5.4

Shutdown resilience characteristics of solar PV

Site de-energisation	During de-energisation, the sites will disconnect from the grid and enter into standby mode. If the site is co-located with battery storage, the plant can continue to charge the battery while solar resource is available until full capacity is achieved and then remain in idle mode.
Emergency power	The technology typically has on-site emergency power, sufficient for restoration of communications, protection and control. If the shutdown is extended over a long duration, the UPS may only have several hours' capacity.
Intervention resources	Majority of sites are unmanned. The site operator's availability and response largely depend on their distance from the site but typical response is within hours.
Control and communication system	The site will be able to restore control and communication systems ready to receive notifications from the SO for as long as the communication UPS has capacity.
Auxilliary starting generation	Largely dependent on an auxiliary back-up supply from the network. However, solar PV sites with battery storage could inherently provide its on auxiliary starting through the battery storage systems.

5.2.2 Black Start Performance

Self-starting

During daylight only, grid connected solar PV sites are readily available to rapidly self-start from cold and provide power to the network. Ability to absorb reactive power and to charge the network circuits in proximity of the site is dependent on the converter subsystem.

Network energisation and reactive power

The highest connection voltage of a solar PV site in GB at present is 132 kV, with most sites installed at EHV and HV i.e. 33/11 kV, and the average domestic panel connected to low voltage (LV) networks, at 400 V. Whilst this connectivity profile has the potential to facilitate the energisation of these less extensive networks, also comprising reduced system charging requirements; a lack of knowledge in this particular area suggests localised trials are required to verify this [19].

Inverters have reactive power management capability and are able to supply or absorb reactive power, usually up to a 0.8 power factor. Regardless of already existing response time and flexibility, the specified 100 MVar margin is not achievable by a single EHV site or any distribution connected sites. It could however, be provisioned on areas with high concentrations of solar power, provided there is a method to coordinate and control these sites [19].

Depending on weather conditions, including climatic concerns for GB, solar power coupled with energy storage or diesel generation can be designed to provide night time emergency power. Bottom-up restoration requires some form of energy storage or back-up generation to mitigate weather intermittency. Completely de-randomising solar power operation would of course require a storage rating equal to that of solar farm site. There is presently no such arrangement in GB, and it is unlikely such a system will be implemented in the immediate future due to significant installation costs. However, taking into account a review of the FES, expanding to 2035, possible technology maturity during this period may render such projects feasible [19].

Grid forming

Most solar PV connections are made through a grid-following inverter, which is not able to produce its own signal to energise a network, instead latching on to a pre-existing voltage signal. A software change coupled with a grid-forming inverter is understood to be a feasible option to unlock this capability.

Block loading

The current block loading requirements would not be achievable by solar PV sites, with the largest sites in GB outputting around 20 MW. As such, load restoration from solar power would have to commence on smaller blocks. As in the case of wind, where sufficient concentrations of solar PV sites exist, energisation of small electrical islands can provide an alternative response. Block loading and general geographical size of these islands would depend on the ratings of the solar PV sites and any associated storage systems [19].

Frequency control

Solar power inverters have inherent and rapid active power frequency control and voltage regulation capability. If the upper frequency limit is breached for example, active power output is de-rated to prevent tripping. The most prohibitive limitation is related to the absolute magnitudes of power that can be circulated.

Table 5.5

Black Start performance of solar PV

Self starting	During daylight only, grid connected solar farms are readily available to rapidly self-start.
Grid forming	Most connections are through a grid-following inverter dependent on latching onto a pre-existing voltage signal from the network.
Network energisation and reactive power	Network energisation is achievable with upgraded control and protection systems where current systems prevent this. Grid connected solar inverters have reactive power capabilities and are able to absorb or supply reactive power.
Block loading	Restoration based on solar power will have to be on smaller block loads since the capacity of large solar PV sites installed in GB are not sufficiently large to support current restoration block loading requirements.
Frequency control	Solar PV inverters have inherent and rapid active power frequency control and voltage regulation capability.
Availability and intermittency	Solar resource is intermittent and may not be available or sufficient for a Black Start demand at such times as it is needed. Day-ahead forecast up to a maximum of three days ahead to view production capability of the specific solar site. Not a high confidence level due to probability of resource unavailability.

5.2.3 Restoration capabilities

Solar PV can readily join a Power Island, dependant on the time of day and solar irradiation levels. Its performance once in a Power Island will be proportionate to the strength of this irradiation. The steep ramp rate and ability to energise quickly are both advantageous in a Power Island. If the solar plant is coupled with other intermittent generation and/or battery storage, this can greatly improve the overall service as the technologies are understood to complement each other extremely well. Stand-alone systems would require a large capacity of back-up power/storage for maximum benefit.

Table 5.6

Restoration capabilities of solar PV

How early can the technology join a Power island?	Existing network regulations prevent solar PV sites in GB from operating in island mode and joining a Power Island. However, if sufficient solar resource is available, and the control and protection systems are adapted, solar PV sites will be able to join a Power Island early in a restoration process.
How will the technology perform once in the Power Island?	The performance of the technology is largely based on the availability of solar resource. Coupled with energy storage and/or other generation, the technology could provide support functions for frequency, voltage and inertia in a Power Island.
How can this performance be used to the advantage of the Restoration?	The technology is able to provide reactive power support and block loading depending on the power island strength, size of block load and solar capacity. The technology has the ability to accelerate the overall restoration process.

5.3 Battery storage

5.3.1 Shutdown resilience characteristics

Site De-energisation

Upon site de-energisation, charging (or discharging) of batteries will cease. The site management system will shut down the batteries to prevent deep discharge in the event that an external supply is not restored.

Emergency power and auxiliary starting generation

Battery storage sites typically have a UPS from which emergency power is supplied. The energy stored in the batteries will depend on the state of charge/discharge when the shutdown occurs. The auxiliary generation is dependent on the installer and site but some may have a small diesel generator for emergency lighting and other on-site load, as well as enough power to partially recharge the battery storage system.

Intervention resources

Most sites are unmanned and remotely managed. Once a shutdown is registered, the response time for the site to be manned depends on the location of the operator from the site.

Control system and communication

Local communications and control will be resilient to manage and protect the battery system during emergencies, but the duration of the UPS is typically several hours, not the 72 hours outlined in current Black Start procurement requirements.

Large battery storage systems (>10 MW) will require resilient remote communications and control, however, this duration of resilience is unknown.

Table 5.7

Shutdown resilience characteristics of battery storage

Site de-energisation	The technology can safely shutdown when a widespread and extended shutdown occurs. Procedures in place to shutdown safely without external supplies.
Emergency power	The technology typically has on-site emergency power, sufficient for restoration of communications, control and charging the battery if needed. If the shutdown is extended over a long duration, the UPS may only have several hours' capacity.
Intervention resources	If unmanned, the response from the initial Black Start trip needs to be quick as the site should be ready to re-energise within 2 hours of instruction from the SO. A back-up communications link may be available on-site but typically is not a remote feature, therefore manned sites have an inherent time-advantage through restoration of local controls.
Control and communication system	A UPS will provide the site with enough power to restore control and communication systems ready to receive notifications from the SO and keep the battery charged for several hours. The battery may go into a power saving or standby mode so that it won't discharge or use excess energy until a notification from the SO is received. The UPS would not be able to provide continuous power in an extended shutdown.
Auxilliary starting generation	The auxiliary generation on a battery storage site typically is a UPS, as the battery itself is capable of self-starting. Thus, the main issue is the state of charge of the battery at the time of the shutdown and whether it holds enough capacity to perform as procured.

Black Start requirements

Self-starting

Battery storage will have an immediate response for self-starting since the technology is 'storing' energy for release, provided that the battery was not in a state of discharge prior to the shutdown event. Demand duration needs to be considered since the battery storage system will typically be able to store energy for several hours and provide power for a limited time.

Grid forming

Most battery installations are not connected via grid-forming inverters; rather they are grid-following inverters. On a grid that has synchronous generators there is not much need for a grid-forming inverter as the grid-following inverter is able to latch onto the voltage signal produced by these synchronous generators. Some are capable of providing a grid-forming signal, typically those that are part of a microgrid, but most that are currently installed are grid-following inverters due to the additional cost involved in the software and hardware upgrades.

Network energisation and reactive power

The energisation capability is related to the rated capacity of the given battery storage site, where battery storage systems can be built in combination with multiple storage sites and generation plants. The ability to energise the network needs to be carefully matched as the block loading process takes place. Most batteries installed in GB are four-quadrant controllable and are therefore able to optimally import or export reactive power up to the active power limit depending on the requirement of the network. The reactive power range is based on the inverter capacity, the battery storage capacity and the reactive power management capability.

Block loading

Battery storage block loading capability is dependent on the rated capacity of a site, and the discharge time is limited by the battery storage capacity. Storage sites can be installed as multiple units located at strategic points on the network to provide a net effect. As long as the battery has charge, the ramping rates are steeper than traditional generation although it depends on the power rating of the battery.

Frequency control

Battery storage inverters can have rapid active power frequency control and voltage regulation capability. If the upper frequency limit is breached for example, active power output is de-rated to prevent tripping. The most prohibitive limitation is related to the absolute magnitudes of power that can be circulated before the battery system needs to be recharged, thus limiting the operational window.

Availability and intermittency

Battery storage has no intermittency issues as such, since the resource depends on how much energy the battery has stored. The state of charge at the time of the shutdown will determine the amount of energy stored that is of use. The operational window will depend on this state of charge and therefore, the availability of the service.

Table 5.8

Black start performance of battery storage

Self starting	Battery storage sites will have a UPS on site that can power auxiliaries, and if the battery has enough charge at the time of a shutdown, the site is able to restore and self-start locally.
Grid forming	Battery storage sites are typically installed with parallel grid operation in mind and therefore are not usually grid-forming capable, instead latching on to a pre-existing signal via their grid-following inverter.
Network energisation and reactive power	Battery storage can contribute to network energisation in terms of balancing the network and supporting grid stability. The battery storage can respond to changes on the network instantly depending on the control settings and is also able to change between charging and discharging states fairly quickly. The reactive power capability of battery storage is usually four-quadrant controllable operation and therefore enabled to react and respond to the network to export or import the necessary compensation. The ability of battery storage to support grid stability and balancing generation and demand is a key attribute of this technology and is paramount in forming power islands where the frequency and voltage may vary out with normal network operating limits at rates faster than usual conditions.
Block loading	Battery storage is capable of energising block loads close to their rated capacity and may also be able to reduce the capacity of a block load if the system is in charging mode.
Frequency control	As battery storage can respond to changes on the network, large frequency swings are able to be eased by the settings in the control system of the battery. Frequency sensitive mode may be enabled and, depending on the size, the capability to provide more frequency support is there. Due to the fact that battery storage can act as generation or demand, the site may help the network by changing states as long as the controls of other battery storage sites on the network are all communicating so that two independent sites do not react to each other's changes immediately, commonly called 'hunting'.
Availability and intermittency	the availability of power from battery storage sites is dependent on their state of charge. Their operational window may be short however, often in an islanded network the role of battery storage is that of a network stabiliser and thus it does not fully charge or discharge. Instead, the battery storage responds in real-time to the network and will be charging and discharging interchangeably depending on the connections to the network, block loading, generation connecting to the Power Island etc. The main limitation of battery storage in this context is the size of the plant.

Restoration capabilities

A battery storage site could readily join a Power Island, with its performance dependant on the state of charge of the batteries at the time of the restoration effort, and the site's capacity. The performance once in a Power Island will be consistent until a high percentage of discharge, around 90 per cent, has been reached causing performance degradation and shutdown.

The steep ramp rate and ability to energise quickly are both advantageous in a Power Island. If the battery is co-located with intermittent generation e.g. wind or solar, this would greatly improve the service provision from each technology type as they would provide complementary capabilities. Stand-alone battery storage systems would require a large capacity to unlock maximum benefit in a restoration.

Table 5.9

Restoration capabilities of battery storage

How early can the technology join a Power Island?	If the battery storage had grid-forming capability, then the battery storage may create a Power Island and sustain this as other generation technologies and demand are energised and synchronised to the Power Island. If the battery storage is grid-following, as is currently the case, then it may have auxiliary generation ready to synchronise to the wider Power Island.
How will the technology perform once in the Power Island?	Battery storage will stabilise the Power Island by providing facilities that can be used to efficiently balance the network through the reactive range, charging and discharging of the battery. The operational window is short and so there are recognised benefits of co-locating with an intermittent resource to maximise benefit. It may also help with the large frequency swings when expanding the Power Island.
How can this performance be used to the advantage of the Restoration?	Battery storage may be used potentially to form a Power Island and then later in the restoration process as a grid stabiliser as either a source of demand or generation, depending on the needs of the Power Island. As the operational window is shorter than other technologies; if it is able to charge during the restoration then this will prolong the usability of a battery storage site in the restoration process as it is functionally capable of several important aspects of network restoration.

5.4 I&C DSR

5.4.1 Shutdown resilience characteristics

Site de-energisation

When a site is de-energised, the DSR scheme will enter a failsafe mode due to no communication/loss of communication i.e. no further demand response actions will be performed.

Emergency power and auxiliary starting generation

Following a partial or total shutdown, DSR has no emergency power unless the site has critical loads e.g. a hospital. It would be difficult, logistically, to implement back-up generation at DSR sites that are geographically separate and for the larger demand users, the auxiliary starting generation will, in the first instance, supply the on-site load. An oversized generator for back-up power with the capability to contribute to a shutdown network may not be cost-effective and wouldn't be an elegant solution for the scheme in most cases.

Intervention resources

DSR sites will typically be monitored and controlled remotely and therefore will be unmanned until a loss of communication triggers a response. The response action depends on the site location, criticality of the DSR sites within the scheme and availability of response personnel. The intervention time will depend on these and dictate the time taken to enact the required protocol after a shutdown.

Control system and communication

No further demand side response requests can be transmitted after loss of the communication system.

Table 5.10
Shutdown resilience characteristics of DSR

Site de-energisation	DSR can safely shutdown when a shutdown occurs. Procedures are in place to start failsafe mode upon loss of signalling and therefore no more demand response actions are performed.
Emergency power	The technology does not have on-site emergency power unless it is of particular importance, like a hospital.
Intervention resources	The large DSR sites are mainly unmanned and following a trip signal, the DSR will be treated as an inflexible demand. Thus, DSR will not be able to participate in the initial restoration but may participate once communication links are re-established and desired behaviour may be requested from the SO.
Control and communication system	DSR will lose communications to the SO or aggregator and will be treated as an inflexible demand until control and communications systems are restored.
Auxiliary starting generation	DSR sites will have no auxiliary starting generation unless it is a site that requires 24-hour security of supply. If the site does have on-site back-up generation, usually this is only sized to serve the demand to keep the emergency services running. With communications still down, the DSR site will be operating in island mode and may only reconnect to the network once energised and it is safe to do so with communication and control signals.

5.4.2 Black Start requirements

Self-starting
It is rare for DSR to have self-start capability due to the additional resource or infrastructure needed. Typically, the site will require auxiliary power after a shutdown to begin the restoration procedure and energise the generation equipment, unless external equipment was bought and stored on site, though this is an unlikely configuration for most DSR sites.

Grid forming
With DSR connected to the electricity network as a load, there are no inverter connections and thus, no ability to grid form.

Network energisation and reactive power
A load connection, such as DSR, requires the same build up and balancing when energising the network as generation sites would. DSR may be able to manage how it connects its loads to the network in a controlled manner, perhaps through a control system to ‘smartly’ match the load in a stable and controlled way. There are no sites where DSR can contribute to reactive power changes as it is the active power that is monitored and supplied.

Block loading
DSR could facilitate the load restoration process by managing its resource and reducing the size of the block load depending on the generation that is energising locally. With a control and communication system in place to interact with generators and other DSR sites, block loading could be much easier to manage and support the growth of a Power Island.

Frequency control
DSR sites will have no frequency control capability as they follow the systems voltage and frequency state.

Availability and intermittency
For DSR, typically the sites are a flexible demand customer meaning there is no intermittency and the user is always available to turn-up or turn-down demand depending on network conditions and the signalling with the operator/aggregator. The reliability of the control and communication system is typically low as there is only one channel type in use for all communications. If the channel isn’t powered, there are no secondary or back-up communications until on-site personnel reconfigures the site and restores the connection, if possible.

Table 5.11
Black Start performance of DSR

Self starting	DSR has no capability to self-start. DSR schemes with sites that require a constant electricity supply will have local back-up generation but this will likely not be configured to support anything other than its critical load. Other DSR schemes will have no capability to self-start as they will be purely demand users and. without any communications will not be able to perform as a flexible demand customer.
Grid forming	No inverter connection and therefore no grid-forming capability.
Network energisation and reactive power	DSR will not be able to energise the wider network nor contribute to reactive power import or export as the connection is only for demand.
Block loading	DSR services can contribute to block loading by being a flexible demand user, provided communication channels are restored or resilient enough to communicate during a restoration. In such conditions, the demand may be turned up or down to match the generation profile of the Power Island. Without communications, DSR will only be able to connect to the network with no flexibility and so it will be treated as inflexible demand.
Frequency control	No active frequency control is available with DSR. Frequency may be helped by DSR tripping off certain units but there is no active frequency controller as part of the scheme.
Availability and intermittency	DSR is always available and may match the generation on the Power Island. It is available to be synchronised and turned up or down providing there are communication and control signals available.

5.4.3 Restoration capabilities
If DSR schemes are able to reset their communication and control system manually, the DSR can join a Power Island immediately, and there is generation ready to support a specific size of demand.

Once in the Power Island, DSR can provide constant flexible demand that is adjustable to suit the need of the Power Island’s generating capability in real-time. The flexibility provided by the DSR allows demand to be more easily matched, through coordination, to the generation in the Power Island.

Table 5.12
Restoration capabilities of DSR

How early can the technology join a Power Island?	DSR may only join a Power Island once the network is re-energised due to most sites not having back-up generation.
How will the technology perform once in the Power Island?	DSR can provide flexible demand to ease the block loading requirements of the Power Island and also demand turn-up or turn-down to provide real-time responses to the network changes to help balance the local network.
How can this performance be used to the advantage of the Restoration?	A Power Island with DSR is able to have less onerous block loading requirements once communications are restored due to the ability of the flexible demand to match the generation available and stabilise the network.

5.5 Synchronous DERs

Through industry collaboration, certain synchronous distributed energy resources were also analysed to highlight the capabilities these generators have, as well as the unique feature of having embedded renewable or carbon abatement synchronous machines available.

The synchronous DERs considered are Energy from Waste (EfW); Liquified Air Energy Storage (LAES); Coal Mine Methane (CMM); and Landfill Gas (LFG). These four technologies are all very similar with the exception of LAES, having the capability of, and can be considered as, storage due to the stored liquid air.

CMM and LFG capabilities are very similar to a synchronous gas generator as it makes use of a gas turbine to generate electricity. The source of the gas these generators use however, are areas where methane may otherwise leak into the atmosphere without these technologies therefore, they have a large carbon abatement potential. EfW and LAES both use a steam turbine, from burning waste and evaporating liquid air respectively.

5.5.1 Shutdown resilience characteristics

Site de-energisation
The EfW, CMM and LFG plants typically, in the first instance, will disconnect in the event of a partial or total shutdown. Sites may trip to house load and begin islanded operation in order to keep the plant warm and ready to re-synchronise. A LAES plant is likely to trip to a safety shutdown, ready for communication and restoration.

Emergency power and auxiliary starting generation

Some sites will have on-site diesel back-up generation, sized to enable the running of the auxiliary loads required to restart the generator turbines. A UPS may also be connected for emergency power and its capability to support will depend on its size.

Intervention resources

Typically, these synchronous DER sites are unmanned as they are remotely monitored and controlled via signals either through a remote office or a third party. Some that are in secure compounds may be manned constantly and therefore would have a much faster response time as the control system will be on-site also.

Control system and communication

Following loss of communications and control, the site will be checked and the condition that led to tripping found. The back-up communication system is linked to the UPS and is run through that system following loss of power supply. This will typically have a duration of three hours–five hours but may be longer depending on the necessary output needed to be supported.

Table 5.13

Shutdown resilience characteristics of synchronous DER

Site de-energisation	Synchronous DERs have a safety shutdown procedure that activates upon loss of supply. The sites differ in what state they are willing to remain; whether they stay 'warm' and support house load until a resynchronisation procedure is issued or if the plant completes a shutdown and waits until notification to reconnect to then re-energise the auxiliary systems before generating.
Emergency power	Often, synchronous DERs will have either diesel generators or a UPS to energise the auxiliary systems that will begin the generation process. With LAES having stored fuel, the UPS will only power the pumps to warm up the plant again. These emergency power supplies will be ready to supply power following instruction.
Intervention resources	Unmanned sites will have a loss of signal trip and the speed of the response will depend on the site location. Some sites are manned and those are able to be locally controlled and configured quickly.
Control and communication system	These sites are typically not resilient enough for Black Start communications and control systems. However, the back-up communication system is likely linked to the UPS and ran through that system following loss of power supply. This will currently have a duration of three hours–five hours but can be longer depending on the necessary output needed to be supported.
Auxilliary starting generation	The auxiliary starting generation is either diesel generation on-site back-up and/or a UPS system. This ensures capability to self-start and serve house load.

5.5.2 Black Start requirements

Self-starting

These plants are capable of self-starting as the back-up auxiliary generation is able to re-energise the internal load that is needed to restore the processes, enabling the turbine to generate electricity. The UPS or on-site diesel back-up will mostly be sized in order to run the generator to service house load, ready to reconnect onto the wider network.

Grid forming

As these plants are synchronous generators, they inherently have the capability to be grid-forming as they are rotating machines. The generator may have controls available that generate electricity at specific frequency and voltage levels, these technologies are able to generate power at grid voltage and frequency.

Network energisation and reactive power

Once these sites are disconnected and back-up generation enables the restoration procedure to serve house load, they will be ready to synchronise with the wider network and supply up to their rated capacity if able to be kept in a 'warm' state. As these are synchronous machines, the ramp-up rates may be an issue but as the Black Start procedure is not a common occurrence it is likely that the turbines are able to push the upper mechanical limit of ramping up the generation to provide power.
Mostly, these turbines can provide active power within the range of 0.85 power factor leading to 0.85 power factor lagging however under the current connection agreements, this is generally limited to 0.9 power factor due to the DNO's operating restrictions. The reactive power is limited to when the generator is generating, as at zero active power export there is also zero reactive power available.

Block loading

These technologies are very capable of supporting the block loading process, bearing in mind that the level of support will depend on the connection voltage level and capacity of the generator. The generators are able to provide active power at different power factors to respond to network conditions and provide voltage stability.

Frequency control

The frequency of these types of generators will be adjusted through generator settings that allow the generator to speed up or slow down depending on the instantaneous demand and generation on the local network. The frequency is a product of this balance, and therefore may adjust by running the generator with frequency control settings.

Availability and intermittency

Synchronous generators will typically have a stock of fuel, either waste, landfill gas, methane in a coal mine, or the liquefied air that is stored. Thus, the availability depends on the auxiliary generation that enables the pumps and motors to start, thereby starting the fuel process and generation turbine. In a LAES site case, the availability will depend on how much liquefied air is stored at the time of the shutdown. These synchronous generators are non-intermittent and will be able to constantly output power while the sites have fuel resource available.

Table 5.14

Black Start performance of synchronous DER

Self starting	These technologies are capable of self-starting and in practice, some sites stay 'warm' and serve house load until notification is received to re-synchronise with the wider network.
Grid forming	Synchronous DERs are able to run at synchronous speed for a 50 Hertz voltage depending on the speed the turbine, as the rotating turbine dictates the signal produced.
Network energisation and reactive power	These plants may energise the network from their site upon receiving notification to do so. With the reactive capability around 0.85 power factor leading and lagging, these DER sites should be able to play a role in supporting the network with their reactive power.
Block loading	As the sites may reconnect to the wider network fairly quickly upon instruction, these plants will be very useful to match the demand profile with the generation and the generators are also able to ramp up the amount of power generated in a timely manner. If the communication and control systems are restored, then these generators will also be able to ramp-down the generation depending on the network conditions.
Frequency control	As these plants are synchronously connected, the frequency control will mainly come from frequency control settings if installed at the generator. Otherwise, the sites will only be able to operate within the limits set out in their Connection Agreement documents.
Availability and intermittency	These sites will typically have high availability as they will have a supply of fuel source on-site. The LAES may have an issue with availability, similar to battery storage, if the shutdown condition occurs when the LAES has no store of liquefied air.

Restoration capabilities

Due to the self-starting capability of the synchronous generators at these types of sites, these DERs are able to form a Power Island and support its development. The controls of the generator allow electricity generation within bounds of frequency and voltage depending on the speed of the turbine and active power export. These technologies should therefore be able to rely on their on-site back-up generation or UPS to energise the starting procedures as well as communications and signalling to the SO. This will enable the SO to determine under what settings and parameters the technology should export power to the local network and when.
These generators have high availability and are adjustable, and so can contribute to grid stability through block loading, provision of system inertia and receiving generation instructions from the SO. The ramp up and down times of these turbines are average, typically responding within 30 minutes. These performance characteristics mean that synchronous DERs can be utilised as a first responder following a shutdown, and enable the non-self-starting sites and sites without back-up generation to contribute once these plants have begun their restoration process.

Table 5.15

Restoration capabilities of synchronous DER

How early can the technology join a Power Island?	Synchronous DERs can form a Power Island and also join one upon a synchronisation notification.
How will the technology perform once in the Power Island?	These sites are able to provide inertia for the network as well as rapidly changing generation capacity upon instruction. The ramping rates are important for balancing the network to provide grid stability and these sites can match the demand within the Power Island. They are able to continuously provide generation to supply the Power Island.
How can this performance be used to the advantage of the Restoration?	Provision of inertia is a crucial aspect of DERs as most distributed resources are inverter-connected and therefore cannot provide inertia. The flexible generation to match the power island load is also a key advantage and the plants will be able to communicate and control their export based on the network conditions. Synchronous DERs may form Power Islands due to their self-starting capability but may need support from other sources to balance the network and stabilise voltage and frequency within the Power Island.

5.6 Electric vehicles and V2G

An electric vehicle (EV) may be considered as a small, mobile battery with the ability to import power back into the grid through what is named vehicle-to-grid (V2G). Due to this, the capability of their performance during a shutdown could be useful, however the proliferation of EVs means that the network operator cannot safely rely on there being sufficient reserve capacity from EVs at any one time. This means that until at least around 2030, where they are projected to have a peak demand of 2.8 GW, EVs cannot be considered seriously as a reliable service provider for Black Start. EVs and V2G capabilities are briefly described below and are mainly included for completeness.

5.6.1 Shutdown resilience characteristics

Site de-energisation

Upon a partial or total shutdown, the charging point for an EV will be de-energised and any connected car batteries will no longer charge. A car battery, if it remains connected, could be available to provide services to the grid, provided there is a market for it.

Emergency power and auxiliary starting generation

The energy stored in a car battery will depend on the state of charge/discharge when the shutdown occurs, much the same as battery storage sites. There will be no auxiliary generation and therefore, it is entirely dependent on the state of charge of the EV as to whether it is able to re-power itself.

Intervention resources

An EV will have an owner/driver, and if the car has been procured to provide Black Start services, there should be a means in which to contact the appropriate SO/aggregator, otherwise this will not work in practice. Charging points are also unmanned and considered as any other network asset.

Control system and communication

There are no communications or control systems installed with EVs presently. A software update could be enabled to allow the EV to communicate with an SO or aggregator, however this would require the explicit consent of the owner/driver. There would be opportunities for multiple channels of communication with the owner/driver, including mobile communication.

Table 5.16

Shutdown resilience characteristics of EV

Site de-energisation	When a charging point is de-energised, any connected EVs will cease charging. They will also be unable to discharge and provide power to the network via V2G.
Emergency power	If an EV battery is charged before the shutdown occurs then there will be a source of power similar to battery storage, however, it will generally be on a much smaller scale.
Intervention resources	An EV will have the driver/owner, however there will be no intervention on the charging points.
Control and communication system	No controls or communications currently.
Auxilliary starting generation	Not feasible to have auxiliary generation except at the charging point but this is not typical of current installations.

5.6.2 Black Start Requirements

Self-starting

EVs and V2G will have an immediate response for self-starting since the technology is 'storing' energy for release, provided that the car battery is in a charged state at the time of the shutdown. Demand duration, as well as the number of EVs available, needs to be considered since the EV battery storage system will typically be able to store energy for several hours and provide power for a limited time.

Grid forming

As the technology is still facing design choices to establish the most economical charging options, presently there are both DC and AC chargers available. AC chargers will not have any inverters, and the EV battery inverter will be small and limited in capability. The DC chargers will have inverters; however, it is not anticipated that these will provide much additional functionality, and so it is assumed these inverters will be grid-following.

Network energisation and reactive power

The energisation capability from EVs is dependent on the capacity and number of EVs that are available in a geographic region. EVs and V2G could be incredibly useful at this stage of the process as they can charge or discharge depending on the network requirements and respond to the actions on the network. EVs could support a stable grid by balancing the demand and generation by changing the charge and discharge profile as more demand or generation is connected to a Power Island.

As EV batteries are comparatively small and lean, the capability is not the same as battery storage and as such they are assumed to have no reactive power capability. As long as the EV battery has charge, the ramping rates are steeper than traditional generation although it depends on the power rating of the battery.

Block loading

EVs would need to have widespread deployment in order to contribute to block loading, similar to DSR. Although due to the small size of the EV battery, the confidence in having a certain amount of batteries connected needs to be increased through the proliferation of EVs.

Frequency control

The EV battery will not have any active power frequency control or voltage regulation capability. If the upper frequency limit is breached for example, the EV will discontinue charging or discharging.

Availability and intermittency

EV and V2G have no intermittency issues since the resource only depends on how much energy the battery has stored. As long as the battery is in a state of charge at the time of the shutdown, there will be energy stored that is of use. The operational window will then shorten or lengthen based on the state of charge of the EV and the number of EVs procured for provision of the service.

Table 5.17

Black Start performance of EV

Self starting	EVs are able to self-start however due to the size of the EV battery and the lack of proliferation of EVs this is not likely to be feasible for grid reenergisation.
Grid forming	EVs are not expected to have grid-forming capability.
Network energisation and reactive power	As EVs have low deployment and growth rate presently, and inverters are sized close to the EV battery size, it is unlikely to be able to energise any local network area nor provide reactive power support.
Block loading	EVs connected to the grid could charge or discharge to either increase demand or increase generation, through V2G, depending on the network requirements. However, the lack of communication and control systems in place mean that currently V2G will not be possible as liaising with the SO will be necessary.
Frequency control	No frequency control from EVs currently as the inverter isn't designed or deployed for extra capability due to cost.
Availability and intermittency	EVs have low availability due to low deployment rates. Therefore, this coupled with small EV battery sizes make the potential impact minimal as it is probable that there will not be enough EVs connected to the network to contribute to the restoration process until at least 2030.

Restoration capabilities

EVs could readily join a Power Island, dependant on the state of charge of the EV battery and its capacity (or combined capacity of an area). The performance once in a Power Island would be similar to that of battery storage systems and so, would be consistent until a high percentage of discharge, around 90 per cent, has been reached causing performance degradation and shutdown. The steep ramp rate and ability to energise quickly as well as the capability of balancing the charge/discharge in response to network changes are all advantages for EV and V2G performance in a Power Island.

Table 5.18

Restoration capabilities of EV and V2G

How early can the technology join a Power Island?	No communication or control systems in place with the SO mean that EVs can't currently participate in the restoration process of forming a Power Island until the local network is re-energised.
How will the technology perform once in the Power Island?	EVs do not have the deployment levels nor the inverter capability to usefully perform as a mobile battery. If EVs were to connect to a Power Island, they are able to charge and increase demand and with V2G ongoing trials, this may also allow EVs to be used as mobile generators in the future.
How can this performance be used to the advantage of the Restoration?	Currently, the performance and deployment of EVs mean that it is very unlikely to contribute to any initial part of the restoration process. Without communications, they may not even be able to connect to chargers as this adds more demand and stress onto a weak, initial Power Island.

5.7 Performance matrix

A visual representation of the performance and capability of each technology that is under investigation has been created in the form of a performance matrix. The matrix highlights the capability in specific areas related to Resilience, Black Start and Restoration. Each technology has been ranked as per its capability to provide services along the restoration event timeline illustrating what services each technology can provide and when.

The ranking has been formed on a sliding scale from 1 to 5 that is based upon the capability and functionality of the majority of the installed technology (i.e. there may be a few sites with additional or specific capabilities). It was found that a scale from 1 to 3 did not give enough detail and nuance to the capabilities of each technology with respect to each other. And a scale similar to the TRL scale (used later in this report), from 1 to 9, was too in-depth and granular for an 'at-a-glance' overview and summary. Therefore the 5 scores were decided upon to express how the majority of technologies are deployed and currently function. The five scores are described below:

Score	Descriptor
1	Majority have proven capability, commercial operation
2	Majority have some capability, pilot/ testing phase
3	Majority have limited capability, under development
4	Majority have low capability, concept phase
5	Majority have no capability, research stage

The descriptor ranks the technology based on the majority of that specific technology. Where a certain unique feature of the technology is present, this exception may be stated although the score remains lower than expected due to the majority of the technology not utilising this same feature. Thus, the score is not indicative of the complete wide-ranging functionality of any particular technology rather it is an indication of how the technology may be utilised today, as part of a Black Start restoration strategy. The matrix is also useful for comparing, relative to other DER, the strengths and weaknesses of each technology and the potential for co-location strategies or other combined resourcing where a Power Island may be formed with certain combinations of the technology available.

The performance matrix is an outcome of a significant research and stakeholder engagement effort which focused on the technologies currently deployed and operating around GB, as well as the potential for each technology to develop more capability specific to Black Start service provision. The previous chapter detailed each technology's capability in respect to Black Start services, and the matrix provides a visual summary to accompany this. It covers the three main phases detailed previously: shutdown resilience, Black Start performance and restoration capabilities.

Table 5.19

Restoration event timeline	Site capability	Non-Traditional/DER Technology						
		Large Onshore Wind (>30 MW)	Small Onshore Wind (<30 MW)	Commercial Solar (PV)	Battery Energy Storage	Demand Side Response (I&C)	Electric Vehicles/V2G	Synchronous DER
1. Shutdown resilience	Plant resilience (shut-down, standby)	2	2	2	2	4	4	1
	Comms and control resilience	2	3	3	3	5	5	2
2. Black start performance	Self-starting of plant	3	3	3	2	5	5	1
	Grid-forming capability	3	3	3	2	5	5	1
	Demand block loading	2	3	4	3	3	5	1
	Reactive power support	1	1	4	1	5	5	2
	Frequency control	1	1	1	1	5	5	2
	Dispatchability	2	3	4	2	1	5	1
3. Restoration capability	Power Island joining and support	2	2	2	1	2	5	1
	Sustainability (reliability)	2	3	4	3	1	5	1

The performance matrix shows that synchronous DER has useful capabilities across all phases of a Black Start event. It is the only technology to have a majority of the operational sites able to self-start and participate in the formation of a Power Island. Battery storage and large onshore wind sites are capable of meeting most of the requirements for Black Start service provision, while there are some performance gaps in communication resilience, self-starting ability and availability/sustainability of resource.

Small onshore wind sites typically have fewer capabilities (or a lower level of service provision potential) than large onshore wind sites due to less onerous connection requirements placed on them. For example, smaller wind farms connected to lower voltages will have a lower minimum requirement for communication infrastructure resilience.

Solar PV technology has a lower performance level, compared to wind and battery storage, mainly because of the capability of the inverters used, where solar PV farms were commonly connected with cost being the major factor influencing design choices, and therefore their capability is limited compared to those installed at battery storage or wind sites.

I&C DSR can make useful contributions in the later stages of restoration, helping with block loading demands while maintaining flexible availability depending on what the SO requires.

EVs are not currently deployed on a large enough scale to be considered as a service supplier for Black Start, especially with the lack of resilient communication infrastructure.

Some sites were noted to incorporate a mixture of generation technologies behind the connection point (co-location) and therefore may be able to offer a cumulative service provision. Co-location (in GB) is typically a battery storage system connected alongside renewable (often intermittent) generation, where the battery is used to smooth the power output of the whole site by charging/ discharging in response to the renewable generation output profile.

An additional performance matrix has been prepared, as below, to illustrate the benefits of co-locating battery storage with solar PV and wind. It can be seen from the matrix below that, on the whole, the performance of wind and solar PV, when co-located with battery storage is improved. Such sites would be able to offer Black Start services with more certainty.

Table 5.20

Restoration event timeline	Site capability	Co-located DER technology		
		Solar PV + BESS	Small onshore wind + BESS	Large onshore wind + BESS
1. Shutdown resilience	Plant resilience (shut-down, standby)	2	2	2
	Comms and control resilience	3	3	2
2. Black Start performance	Self-starting of plant	2	2	2
	Grid-forming capability	2	2	2
	Demand block loading	2	1	1
	Reactive power support	1	1	1
	Frequency control	1	1	1
	Dispatchability	2	2	1
3. Restoration capability	Power island joining and support	1	1	1
	Sustainability (reliability)	2	1	1

Through comparison with the original matrix, co-location shows the greatest improvement to the performance of Solar PV, specifically in self-starting, dispatchability and availability. This strategy would allow intermittent generation to provide a more reliable service by reducing or removing the main barriers to participation in Black Start. Co-located sites could be a real asset in a future Black Start strategy, however there remain lingering issues around the communications and control infrastructure. The resilience of such systems is dependent on the size of the plant or resilience preference of the site owner, also the duration of storage the battery is capable of is another important influence.

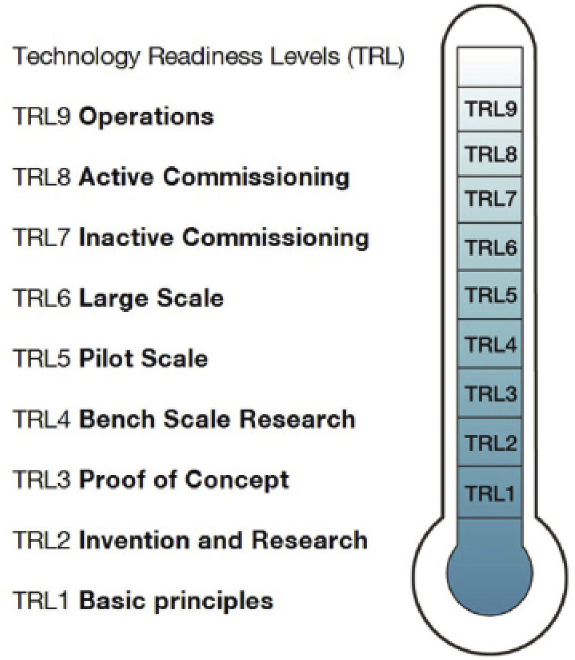
6 Technology readiness

To assess the maturity level of each of the non-traditional technologies investigated in this study in the context of their capability in providing Black Start services, a qualitative assessment has been carried out to determine their technology readiness level (TRL), an industry-recognised development scale.

A technology can only be classed at a specific TRL once all the descriptors at that stage have been fulfilled. NASA developed the TRL methodology in the early 70's and since then is in widespread use, however care must be taken to ensure that the parameters at each stage are relevant to the technology that is being assessed. The nine levels stretch from establishing the basic principles at TRL1, the lowest stage, to a TRL9 where the technology is operational and commercial.

Figure 6.1 below illustrates the bands of TRL increasing from TRL1 up to TRL9. It is worth noting that as a qualitative measure, TRLs may not be evaluated or compared arithmetically. That is to say a technology at TRL4 is not twice as mature as a technology at TRL2, nor can an average be ascertained of a technology through two TRLs of different components.

Figure 6.1
Technology readiness level scale



The Nuclear Decommissioning Authority (NDA) released guidance on TRLs to capture good practice and this is referred to throughout our descriptions, although the TRL descriptions and stages apply to the nuclear industry, most are still relevant and all descriptions have been updated to accurately reflect the technology development process.

Even though most technologies will take a longer time to get from TRL3 to TRL9 than it will to go from TRL7 to TRL9, care must be taken not to always assume that a technology with a low TRL today is a riskier choice than that of a higher TRL.

Table 6.1 describes each stage and TRL through objective scenarios and checkpoints. This helps in clearly identifying where a particular technology is in regards to achieving full commercial operation.

Table 6.1

TRL Descriptors [Source: NDA Report "Guide to Technology Readiness Levels for the NDA Estate and its Supply Chain", 2014]

Phase	TRL	Stage	Descriptor
Operations	9	Operations	The technology is being operationally used in an active facility.
Deployment	8	Active commissioning	The technology is undergoing active commissioning.
	7	Inactive commissioning	The technology is undergoing works testing and factory trials but it will be on the final designed equipment, which will be tested using repeatable and accurate scenarios reflective of operational conditions. Testing at or near full capability will be expected.
Development	6	Large scale	The technology is undergoing testing at or near full-scale size. The design will not have been finalised and the equipment will be in the process of modification. It may only participate in a limited range of input conditions and won't be running at full capability.
	5	Pilot scale	The technology is undergoing testing at small- to medium-scale size in order to demonstrate specific aspects of the design.
	4	Workbench scale	The technology is starting to be developed in a laboratory or research facility.
Research	3	Proof of concept	Demonstration, in principle, that the invention has the potential to work.
	2	Invention and research	A practical application has been invented or the investigation of phenomena, acquisition of new knowledge, or correction and integration of previous knowledge.
	1	Basic principles	The basic principles of the technology have been established and confirmed.

For some proven technologies, there are cases where TRL levels may vary, depending on the environment. For example, a technology may be considered TRL9 in a specific area, however the TRL may be adjusted to reflect uncertainty in performance if in a new environment, or where a new capability which has not featured operationally in the same environment, is added.

Table 6.2 highlights certain applicable scenarios and details the evaluation of new TRL levels (assuming a starting TRL of 9), where a particular proven technology is used in a new environment.

Table 6.2

TRL special circumstances

Change applied	Description	New TRL
Testing the existing technology in a new setting.	The technology/capability is used commercially in another environment, but the new setting is similar.	8
The technology/capability is commercially available but used in a different industry.	No expected modifications and expected to work within operation ranges, therefore only needs to undergo Inactive Commissioning.	7
The technology is in use elsewhere for a similar requirement but the operational conditions may change.	Technology is not expected to require modification; it still needs a full-scale test that simulates the new operational conditions.	6
The technology is in use elsewhere for a similar requirement but the operational conditions may change and a modification is required.	Well-understood modifications are needed to be implemented for the technology to perform under the new operational conditions.	5
The technology is in use elsewhere for a similar requirement but the operational conditions may change and major modifications are required.	Modifications that may not be very well understood are needed to be implemented for the technology to perform under the new operational conditions.	4
Individual items are used elsewhere and these are combined to create a new offering.	Information on all individual components should be available and the information for the modifications required. Testing may begin at bench scale.	4
The technology is used commercially but the operational conditions need to be changed.	Although the technology is well-established, the difference in environment and operational changes means significant changes are envisaged.	4

In the context of Black Start, table 42 is particularly relevant, as the use of non-traditional technologies and DER for Black Start is essentially making use of operational technology in a new environment.

7 Technology readiness level of non-traditional technologies

Using table 41 in the previous section, each of the technology types being considered in this study has been assigned an indicative TRL value to identify the current capability of that technology in regards to the different Black Start categories: shutdown resilience; Black Start performance; and restoration capability, where these categories reflect the three distinct phases of a total or partial shutdown. These TRL values are discussed with justification in this section.

It should be noted that the assigned TRL values are based on the findings of this study and are therefore not definitive. Rather they provide an indication as to where in the restoration process a technology may be capable of providing services, what those services are, and any areas where the technology can or should be improved.

A TRL has been assigned to the non-traditional technologies and DER under investigation in this study across each of the three phases described above. Since TRLs cannot be averaged, the lowest value assigned across all services within a category was taken to represent the readiness of the technology in that particular category in the most realistic way. For example, if a technology type has varying scores across the services in a category, with the lowest score being TRL5, then this would be the overall TRL value assigned to that technology for that particular category.

It is also worth noting that in some cases, a technology with a TRL of 4 in one category might actually be better suited to provide more services or need less development than a technology with a TRL of 6. This is attributed to the fact that one service in the former may be assigned TRL4 while the rest may be TRL9, and in the latter all the services may be assigned as TRL6. This means a more granular look at the TRLs and corresponding barriers is recommended. Appendix A provides the indicative TRLs for each of the services individually to support this process, while the section below presents the overall TRL for each technology across the three Black Start phases.

7.1 Large wind

For large wind sites, a TRL of 6 is the lowest resilience score for this technology and this is largely influenced by sites being typically unmanned, with no back-up generation available for the on-site auxiliary load. Sites display a good level of resilience for the control and protection systems, with a UPS built into the communications system and battery back-up for the protection system.

The TRL score of 6 for Black Start performance is indicative of the inability of the sites to self-start, as well as their grid-following (rather than grid-forming) capability.
Large wind sites demonstrate good capability for providing reactive power support and frequency control. In respect of demand block loading, the capacity of a site coupled with the wind resource forecast can provide a certain amount of confidence in determining its capability.

Large wind sites are a good supporting asset for network restoration as the majority of the sites can latch onto a grid signal and then provide balancing services, reactive power and frequency control.

Table 7.1 summarises the TRLs assigned to the three categories of Black Start for Large Wind.

Table 7.1
TRL Assignment for Black Start Capability of Large Wind

Technology	Shutdown resilience TRL	Black Start performance TRL	Restoration capability TRL
Large Wind	6	6	8

7.2 Small wind

For small wind sites, a TRL of 5 is the lowest resilience score for this technology. Sites are typically unmanned and tend to have no back-up generation available for the on-site auxiliary load. Sites which are >10 MW typically have a high level of resilience for the control and protection systems, but this reduces considerably for sites below 10 MW, corresponding to the minimum requirements set out in the Distribution Code and subsequent Connection Agreements.

As in the case of large wind, a TRL score of 6 for Black Start performance is indicative of the inability of the sites to self-start, as well as their grid-following (rather than grid-forming) capability. Small wind sites can provide reactive power support and frequency control. In respect of demand block loading, the capacity of a site coupled with the wind resource forecast can provide a certain amount of confidence in determining its capability, although this is considered to be lower than that of Large Wind.

Small wind sites are a good supporting asset for network restoration as the majority of the sites can latch onto a grid signal and then provide balancing services, reactive power and frequency control.

Table 7.2 summarises the TRLs assigned to the three categories of Black Start for Small Wind.

Table 7.2
TRL assignment for Black Start capability of Small Wind

Technology	Shutdown resilience TRL	Black Start performance TRL	Restoration capability TRL
Small Wind	5	6	7

7.3 Solar PV

For solar PV sites, a TRL of 5 is the lowest resilience score for this technology. Even though most solar sites de-energise the site safely, triggering an automatic safety shutdown procedure with most of them able to supply auxiliaries and house load, the solar PV site will not typically have on-site emergency power other than a battery back-up unit. Sites are typically unmanned, leading to slower response times to site.

A low score of TRL4 for Black Start performance is indicative of the nature of the service provided by solar PV sites. Although a solar PV site can self-start, it can only do so if there is sufficient solar resource i.e. during the day, and sites otherwise must rely on the network for a start-up auxiliary supply. Most installed sites do not have grid-forming capabilities and, due to the relatively small capacity of individual sites, there is minimal ability to provide block loading and reactive support. Most sites are able to provide frequency control support to the network.

Solar PV sites demonstrate a restoration capability of TRL6. They require a signal from the grid to latch onto, however, once this is achieved, they are able to provide power generation and frequency control in a Power Island for as long as there is solar resource available.

Table 7.3 summarises the TRLs assigned to the three categories of Black Start for Solar PV.

Table 7.3
TRL assignment for Black Start capability of solar PV

Technology	Shutdown resilience TRL	Black Start performance TRL	Restoration capability TRL
Commercial Solar PV	5	4	6

7.4 Battery storage

Battery storage systems have been assigned a low score of TRL5 for resilience. Most battery storage sites can de-energise the site safely, triggering an automatic safety shutdown procedure and are able to supply auxiliaries and house load, however the site typically won't have emergency power other than the battery itself (and this is dependent on the state of charge of the battery at the time of the shutdown). Additionally, these sites are typically unmanned leading to slower intervention response times.

The TRL score of 8 in the Black Start performance phase is indicative of a capable system for Black Start, and displays the versatility and functionality of battery storage sites. Most sites are able to control frequency and provide reactive power support, where some sites are also four-quadrant controllable. Batteries are also able to self-start, provided there is sufficient charge in the system at the time of the shutdown.

Battery storage is able to provide a block loading service, both as a generator and as demand; however, this would be limited due to the typical installed size of these sites, and the short duration times available (before the battery needs to switch charging cycle). Grid-forming functionality is not typically installed unless the battery storage is part of a converter-dominated microgrid, hence it has a lower TRL in this service requirement. Intermittency, in the context of a battery, is related to the duration of the operational window of interaction with the wider network, which may change depending on the service provision.

Battery storage sites are functionally a great asset for network restoration as the majority of the installed units will be available to latch onto a grid signal and then provide balancing services, reactive power and frequency control as well as alternate between charging and discharging to either alleviate block loading requirements or match demand when there is excess generation.

Table 7.4 summarises the TRLs assigned to the three categories of Black Start for Battery Storage.

Table 7.4

TRL Assignment for Black Start Capability of Battery Storage

Technology	Shutdown resilience TRL	Black Start performance TRL	Restoration capability TRL
Battery storage	5	8	8

7.5 I&C DSR

The resilience TRL for I&C DSR has a low score of 4, primarily as a consequence of the nature of this technology and not having any emergency power or auxiliary generation. DSR schemes are able to shut down safely, but they rely on external supply to be brought back online. Since DSR schemes do not have wide-reaching capabilities in Black Start performance, they have been assigned a TRL of 4 for this phase. The schemes are typically a normal demand connection with additional controls and therefore cannot be expected to provide reactive power or frequency support. They mainly serve as a flexible demand, which can be advantageous in helping to stabilise network conditions through the block loading process, and in turning up or down the demand requirements.

I&C DSR sites are unable to support the early restoration process where these sites cannot contribute much, however upon the formation of a Power Island, it is then able to play a role in matching demand with the generation available. DSR performance in a Power Island could be very useful and can be used to support ongoing grid stability, however, as they typically won't interact with the restoration process before the Power Island is formed and is fairly stable, I&C DSR is therefore given a lower TRL rating of 4.

Table 7.5 summarises the TRLs assigned to the three categories of Black Start for I&C DSR.

Table 7.5

TRL Assignment for Black Start Capability of I&C DSR

Technology	Shutdown resilience TRL	Black Start performance TRL	Restoration capability TRL
Demand side response	4	4	4

7.6 Synchronous DER

Synchronous DER including: EfW, CMM, LFG and LAES, all operate in a similar way and are therefore grouped together for the TRL assignment. This does lead to some lower TRL scores as different technologies may be more suited to a certain functionality than others, however this does give an overview of the general type of technology and its uses in the different phases of Black Start.

The low resilience in the communications infrastructure for these sites results in a TRL score of 6, despite the provision of emergency power at the sites, which is achieved through fuel reserves, or auxiliary starting generation that is housed on-site.
Frequency control with synchronous DER is enacted through the mechanical speed of the turbine and therefore the generator has the capability to provide frequency support. However, this also impacts on the performance as well as the delivery of active and reactive power. Since this capability hasn't been widely examined in a Black Start scenario, the TRL has been assigned as 8 since it has not yet been proven in a different operational setting. The other Black Start requirements are well-matched with synchronous DER due to their capability in self-starting the generator, providing a grid-forming signal and ramping up and down the active power export to match block loading requirements. All of these services are readily available and don't require any modification.

Synchronous DER can participate early in a restoration effort using its self-starting capabilities and the ability to form voltage and frequency signals for a Power Island. These sites will have the capability to be in contact with the SO (following re-energisation of the site) and adjust their outputs accordingly. These types of generation could generally be very beneficial and valuable contributors to restoration through the variety of services they could provide to the wider network in order to form, energise and stabilise a Power Island. Thus, the restoration capability TRL has been assigned as a 9.

Table 7.6 summarises the TRLs assigned to the three categories of Black Start for Synchronous DER.

Table 7.6

TRL assignment for Black Start capability of synchronous DG

Technology	Shutdown resilience TRL	Black Start performance TRL	Restoration capability TRL
Other (synchronous DER)	6	8	9

7.7 Electric vehicles

Electric vehicles can de-energise safely in the event of a shutdown if connected to a charging station, where the charging would cease and the EV would retain the charged capacity in the battery. However, due to current vehicles and chargers not having sophisticated communications infrastructure or connection to the local network, nor any auxiliary generation, the TRL scores are low across most services of resilience, with the exception of site de-energisation. A low score of TRL4 has been assigned.

In terms of Black Start performance, EVs are not yet suited to any of these functions. The most likely is network energisation and reactive power capability as the EV battery is similar to, albeit smaller, battery storage. Consequently, with further deployment of EVs and wider spread usage, it may be possible to enact V2G performance. This is currently undergoing further research and trialling so may not be prolific until around 2030 or later. The size of the EV battery combined with the low deployment rates means that EVs can't contribute in a meaningful way for Black Start presently, nor realistically before 2030 resulting in a TRL low score of 2.

Performance of EVs in a Power Island is understood to be quite poor. The necessary communication and control systems are not available, block loading is unlikely to be possible and so EVs may only have a small balancing role at the final stages of grid restoration. A TRL of 2 is appropriate for this phase, however this could be improved with the proliferation of EVs in the coming years.

Table 7.7 summarises the TRLs assigned to the three categories of Black Start for EVs and V2G.

Table 7.7

TRL assignment for Black Start capability of EVs

Technology	Shutdown resilience TRL	Black Start performance TRL	Restoration capability TRL
Electric vehicles and V2G	4	2	2

7.8 Summary of TRLs

Table 7.8 provides an overall summary of the TRL levels of each technology.

Table 7.8
TRL assignment summary

Technology	Shutdown resilience TRL	Black Start performance TRL	Restoration capability TRL
Large Wind	6	6	8
Small Wind	5	6	7
Solar PV	5	4	6
Battery Storage	5	8	8
I&C DSR	4	4	4
Other (Synchronous DER)	6	8	9
Electric Vehicles and V2G	4	2	2

It can be seen that Resilience appears to be one of the most challenging areas for non-traditional technology and DER in terms of meeting the requirements to participate in Black Start. It offers the lowest TRL for all technologies except in the case of Solar PV and EVs.

Wind and battery storage technologies show promise, particularly in the Restoration phase, given the right circumstances (available wind resource, state of charge of battery).

The capabilities of the technologies vary considerably, with Synchronous DER demonstrating the most capability at all stages, while EVs are not likely to be able to participate for the foreseeable future due to myriad of factors, including significant increase in uptake of the technology, minimal communications infrastructure and little ability to control or influence the wider network during the Black Start and Restoration stages.

Adequate planning and coordination of Power Island formation and growth would be required to ensure all technologies are exploited to maximise their use and value in a Black Start situation.

8 Barriers and roadmaps

Thus far, this report has detailed the capabilities of a number of non-traditional technologies and DER to provide services across the timeline of a Black Start event. The capabilities have been assessed against the technical requirements at each stage: shutdown, Black Start and restoration, and a TRL has been assigned to these capabilities to indicate to National Grid ESO, and industry in general, the challenges and barriers that currently inhibit reliable participation.

This section presents these barriers and proposes mitigations such that they may be reduced, or eliminated entirely, with indicative interventions for each given in a "roadmap". The roadmap aims to effectively highlight the key developmental requirements to overcome specific barriers.

Acknowledging the likelihood that the technologies investigated as part of this study will never be capable of providing the full set of Black Start requirements such as is offered presently from large synchronous generation power stations; the barriers and roadmaps cover more discrete options. Specifically, they align with the three stages of a Black Start event and the following three developmental pathways are considered:

1. Self-starting and initial stages of restoration;
2. Connecting to a weak or unstable Power Island; and
3. Connecting to an established Power Island.

Technical barriers

The tables below (table 8.1, table 8.2 and table 8.3) describe the principal technical barriers for each of the technologies studied as part of this investigation at the three stages listed above. These barriers are those which are considered the most prohibitive at each stage and presently prevent the technologies from participating effectively in a Black Start and restoration.

Table 8.1
Technical barriers of technologies in early stages of Black Start and restoration

Self-starting and initial stages of restoration		
Technology	**Barrier**	**Mitigation**
Wind Solar Battery storage	The majority of sites require some form of auxiliary power to self-start, typically relying on an auxiliary power connection from the network to provide this. Some sites (e.g. larger wind farms) might have on-site back-up power provision from diesel generation or a battery.	The installation of on-site auxiliary power generation would enable the sites to self-start without the need of an external auxiliary supply from the network. A potential enabling solution for these technologies to participate earlier in a restoration process could be through co-location. The combination of various technologies could provide a less distorted and more stable voltage to the local network, as well as less resource uncertainty.
Wind Solar Battery storage	These technologies are typically connected to the network via grid-following inverters which have no capability to form a Power Island, instead they require a voltage signal created by another generator to latch onto.	Installation of inverter technology with grid-forming capabilities, and corresponding software modifications to the control and communications system, would enable these sites to restore a local network and begin to form a Power Island.
Wind Solar Battery storage	Current regulations on Loss of Mains protection (EREC G99/1-3 (2018)- 9.6) prevents all long-term parallel-connected sites from operating in island mode following a partial or total shutdown, to prevent the formation of power islands without a prior contractual agreement or generators that are part of the LJRP and subject to Grid Code clause OC9.5.	Modifications to the appropriate regulations would be required to amend or caveat this condition in the event of a Black Start, where these types of sites could remain energised and, in effect, self-start and contribute to the formation of a wider network power island.
All	The control and communications infrastructure for typical sites will have back-up for several hours and so cannot meet the current Black Start requirements set out in the technical procurement of Black Start services from NGESO which stipulates resilience of 72 hours.	Major modifications would be needed for these types of sites to provide the required resilience in their control and communications systems during a partial or total shutdown. This could be achieved through an upgrade on the wider communications network, or individually at each site. The latter would depend on whether the benefit (revenue from Black Start services) of additional communications resilience would outweigh the additional cost and infrastructure.

Table 8.2

Technical barriers of technologies in connecting to an unstable Power Island

Connecting to a weak or unstable Power Island

Technology	Barrier	Mitigation
Wind Solar	The variability of resource at the time of the restoration effort, whereby a wind or solar site may only be able to operate for a short duration or not at all depending on the time of day, season, etc.	The uncertainty of renewable resource variability could be reduced through better forecasting and the development of more probabilistic methods of analysing data and performance trends. Based on the modelling exercise carried out as part of this study (presented in Report 3), a much clearer picture of wind power availability can be determined. Tools such as these could be employed to determine the viability and reliability (longer-term) of wind (and solar) resource in different areas to contribute to restoration.
Battery storage	The capacity of a battery, and the state of charge at the time of the partial or total shutdown, whereby the battery storage unit may only operate for a short duration due to the available capacity at the site.	The capacity of battery storage sites installed is expected to increase as regulation continues to encourage larger schemes to connect. This additional capacity should improve the likelihood of there being sufficient charged capacity available to meaningfully contribute to a weak or unstable Power Island. Development of other battery storage technologies, such as flow batteries and sodium sulphur, means that there should be a varying degree of capacity and duration available from the installed battery storage sites around the network.
Wind Solar Battery storage	Inverter technology installed at these sites may struggle to adapt and manage performance with rapidly changing conditions characteristic of a weak Power Island. In particular, the changes in frequency and voltage phase angles have been found to cause many issues. A wind farm behaving in this way has been found to further weaken the power system to which it is connecting, and as a result, further exacerbate the deterioration of the performance of its wind turbines [24].	Improvements to controllers and/or algorithms could better equip the inverters to manage performance under these conditions. Additionally, the installation of ancillary devices could support and enhance site performance. Ancillary supporting solutions such as Synchronous Compensators (SC) and Static Synchronous Compensators (STATCOM) could aid in the performance of the technology.
Wind Solar Battery storage	Small DER sites, and even some larger sites with resource variability concerns, are unlikely to have the capacity to support the current block loading requirement.	Current restoration procedures would need to be modified to consider smaller block loads and less onerous reactive power requirements, to enable smaller DER sites to participate in the restoration procedure.
All	Communication channels at the majority of DER sites are not yet of a high enough specification to ensure secure transmission of signals and controls between the site and the SO, such as is required in the early stages of a restoration to balance and manage generation and demand.	Resilience of communication channels would need to increase such that secure transmission of control signals is enabled.

Table 8.3

Technical barriers of technologies in connecting to an established Power Island

Connecting to an established Power Island

Technology	Barrier	Mitigation
Wind Solar Battery storage	One concern is the UPS duration. These do not have enough charge to outlast a partial or total shutdown which extends more than a few hours. National Grid ESO requirements currently stipulate a resilience of 72 hours.	Mitigation of the issue around UPS duration could be achieved through provision of an auxiliary power unit installed on-site, whereby upon notification it would supply the auxiliaries. A UPS may also be installed to be resilient to a loss of the communications and control system, or sized with sufficient capacity to last for the Black Start resilience requirements.
I&C DSR	Upon a partial or total shutdown occurs, a DSR scheme will revert to being inflexible demand until the communications infrastructure has been restored.	A more resilient communications infrastructure would allow restored I&C DSR schemes to be used in the latter stages of a restoration to provide flexibility of demand during block loading.

Table 8.4 describes barriers specific to EVs which would have to be overcome prior to any consideration of their participation in a Black Start or restoration.

Table 8.4

Technical barriers of EVs and V2G

Electric vehicles and V2G

Barrier	Mitigation
The absence of an infrastructure for resilient communication and control channels to receive notifications from the SO. Once a partial or total shutdown occurs, an EV will cease charging (if connected at the time) and will not be visible to the network.	Communications infrastructure in charging points or within vehicles would need to be developed to provide and maintain a link to the SO.
The proliferation of EVs.	Present deployment rates are so low that the availability and reliability of this technology for a participation in Black Start services is close to zero. It is forecast that post-2030 there will be a higher proportion of EVs to provide for some flexibility on the network, as well as the advent of vehicle-to-grid (V2G) where this will be a more common feature, meaning there should also be some level of communications to allow the EV to feed power back into the network.

9 Technology roadmaps

In view of the barriers presented in the previous section, the necessary mitigations for each of these has been considered alongside the required interventions from industry. These have been presented in a summary diagram in figure 9.1.

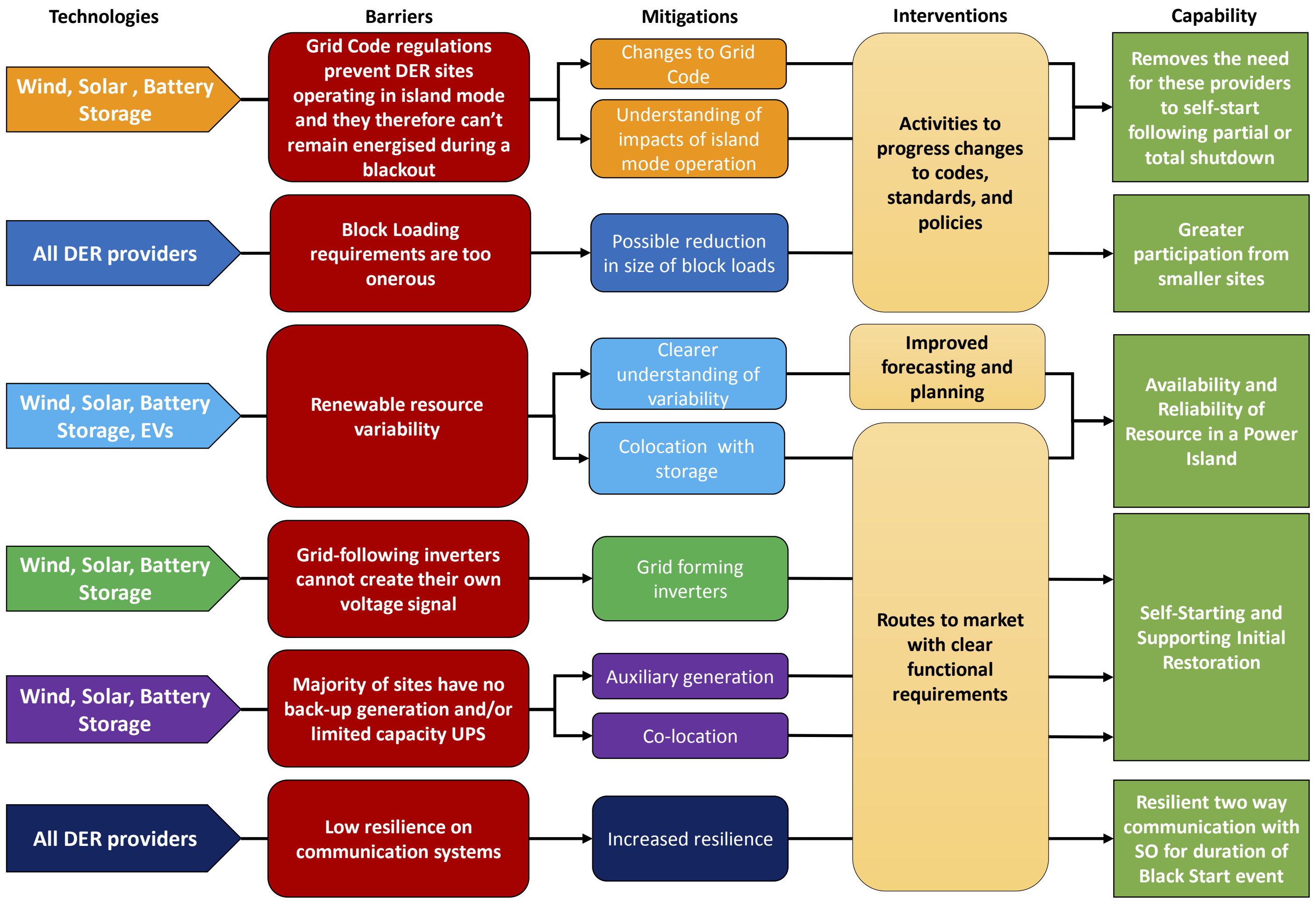
It is well-understood than many of the barriers identified in the course of this study are applicable to multiple technology types, or in some cases, all DER providers. The most prolific barrier is understood to be in the area of communications and control system resilience, with very few sites able to execute a variety of Black Start services as and when needed as a result of this. The mitigation for this is reasonably straightforward in technical terms, and involves the installation of communications with a higher resilience. This is not likely to happen, however, without a clear route to market (for the provision of Black Start services) to offset the additional cost of such infrastructure.

Access to back-up generation and installed inverter technology are the other principal barriers affecting at least all wind, solar and battery storage sites currently connected in GB. The combination of these means that, as it stands, none of these sites are able to self-start nor participate in the formation of power islands, rather relying on external supplies and signals to enable this. There are a number of options to overcome these challenges. In the case of self-starting capability, there are two feasible interventions to enable this in DER sites: the provision of on-site back-up generation and co-location with another technology. Grid-following inverters can be replaced like-for-like with grid-forming inverters, or the existing control algorithms can be upgraded within the grid-following devices. As with the installation of high resilience communications however, there must be a route to market to offset the costs of these upgrades.

Closely related to this are some of the regulations and requirements set out in the Grid Code, Distribution Codes, Engineering Recommendations and specific Connection Agreements, whereby the former sets Black Start requirements, and the latter documents outline conditions of connection and operation for DER sites which prevent them from being able to meet those outlined in the former. The specific condition regarding Loss of Mains protection for DER sites prevents them from remaining energised in the event of a partial or total shutdown and operating in island mode. The result is all of these sites having to shut down and subsequently rely on external supplies to re-energise (as described above). The interventions for these barriers are less straightforward and would require extensive evidence, consideration and consultation if changes were to be proposed to codes, standards and policies. It is acknowledged that some of this will be explored in more detail in the NIC “Distributed ReStart” project, with proposed changes to specific Grid Code clauses being made as part of the scope.

The issue of renewable resource availability (and variability of the state of charge of battery storage and EVs at the time of a partial or total shutdown) is not solely an issue for Black Start service provision, and efforts to improve forecasting and analysing performance trends has been ongoing across the industry to support planning activities. In the case of Black Start, the window of time required for resource certainty is more well-defined however, and this study has carried out an extensive modelling exercise to examine this in more detail (in this case it has been performed specifically for wind – see Report 3). Further work in this area is necessary to improve confidence in resource predictions.

Figure 9.1
Summary of mitigations and interventions to overcome technical barriers



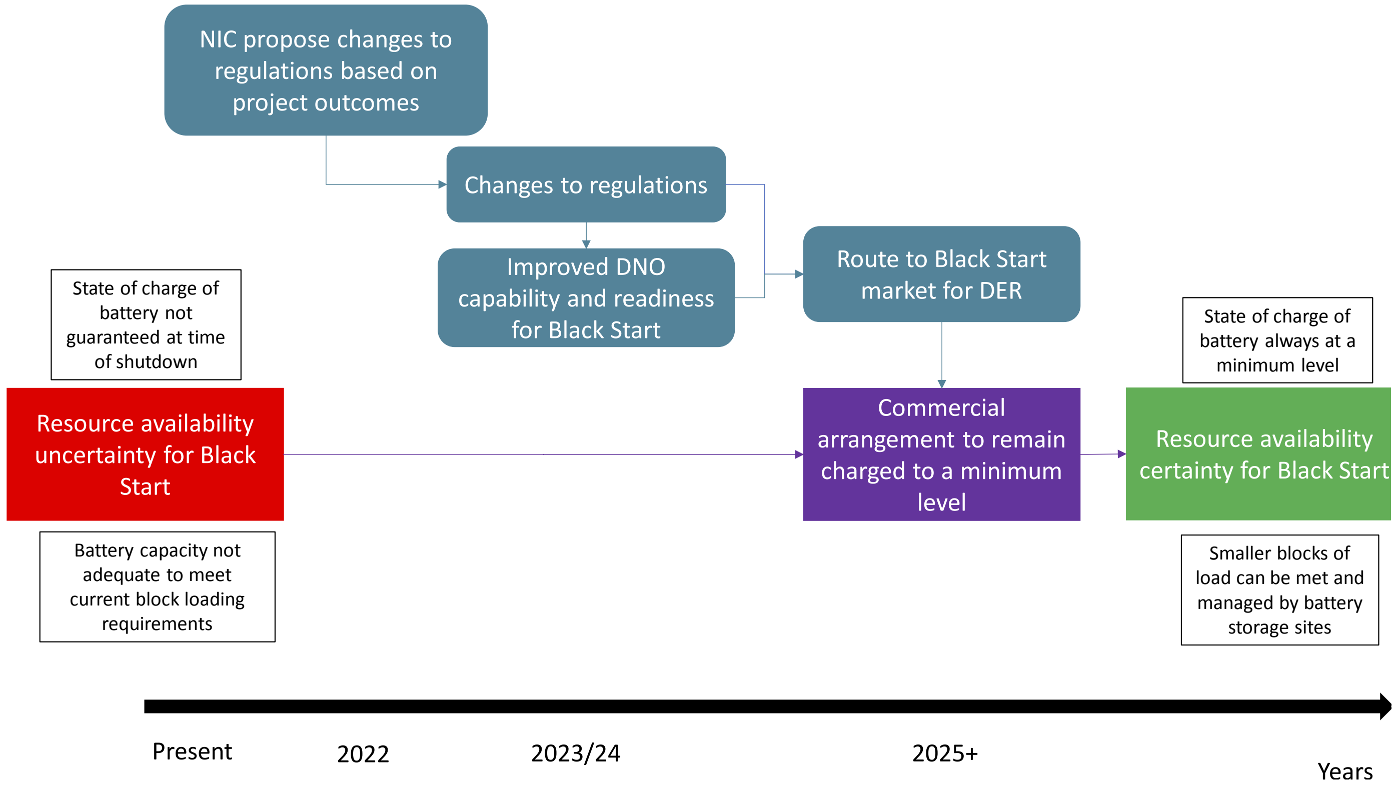
A series of roadmaps have been produced, drawing out some of the key barriers and proposing timescales for intervention and mitigation.

Battery storage resource availability roadmap

From the investigation into the capability of battery storage to participate in a Black Start and restoration, it is clear the technology could play an important role in the process and provide support at several points along the restoration timeline. One key barrier that was identified for battery storage was the uncertainty of the availability of resource, in this case the state of charge of a battery, at the time of the shutdown. Battery technology would be able to provide a number of services, but most are dependent on a certain level of charge being available e.g. self-starting capability, or provision of power for balancing. As such, reducing the uncertainty of this resource could unlock a great deal of potential for this technology and provide National Grid ESO with a secure Black Start asset portfolio.

The goal would be to ensure that procured battery storage sites will always have a minimum level of charge available for specific services in a Black Start. Most importantly, there should be a route to the Black Start market for DER, otherwise there is no incentive to perform as required to provide the service. The route to market will lead to the appropriate commercial arrangements being put in place. The route to market will depend quite heavily on the outcomes of the “Distributed ReStart” NIC project, and the changes it proposes to implement to regulations and processes (both within National Grid ESO and DNOs).

An indicative timeline is provided with the roadmap, noting that commercial arrangements for battery storage to maintain a minimum level of charge could be in place by 2025.



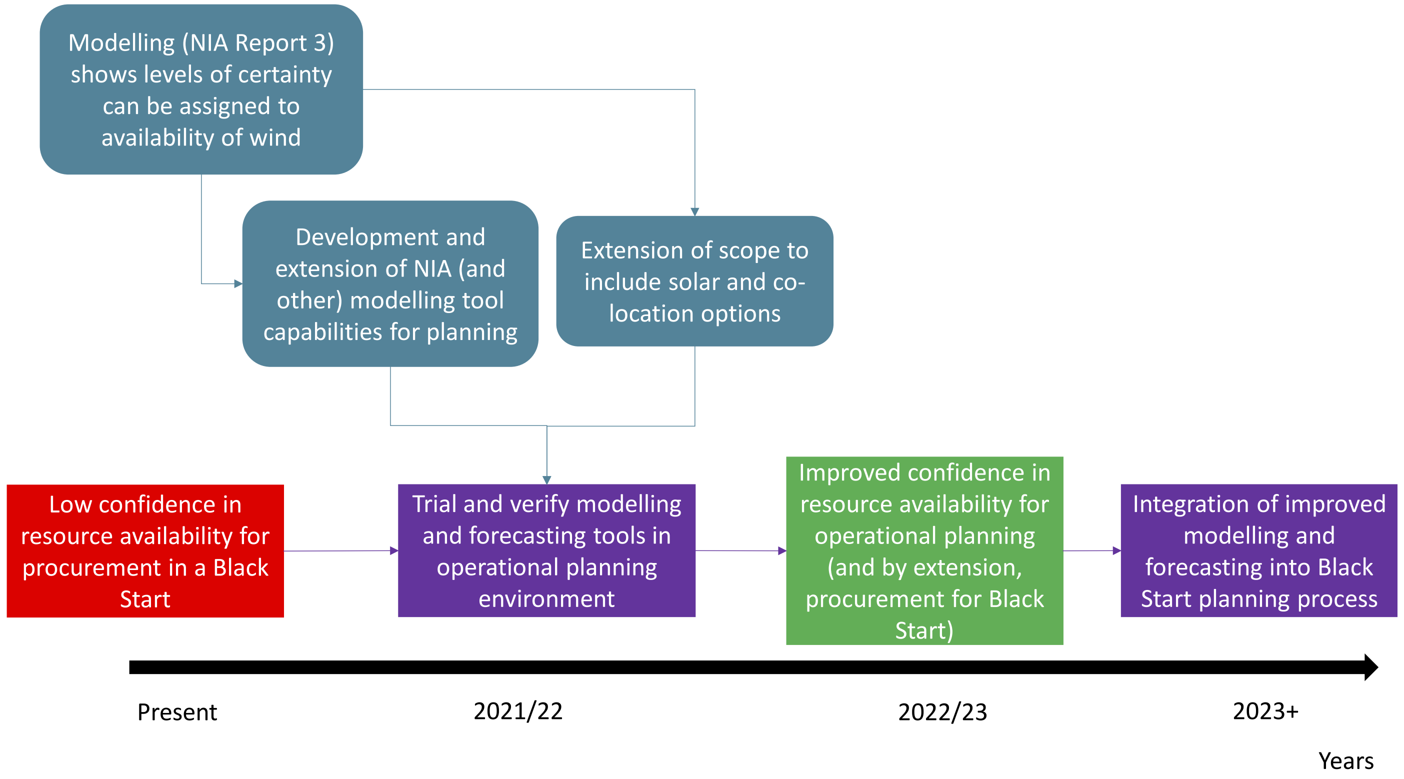
Renewable resource availability roadmap

Similar to battery storage, there is uncertainty surrounding the resource availability of renewable generation, specifically wind and solar. This uncertainty inhibits the potential procurement of vast quantities of generation which could provide a range of useful services during a Black Start and restoration, such as frequency and reactive power regulation in a Power Island.

A sophisticated modelling tool developed as part of this project (see Report 3) has demonstrated that it is possible to reduce this uncertainty, and estimate the amount of wind generation that would have to be procured to guarantee the different levels of certainty. A tool such as this is not only useful for Black Start planning, but also operational planning and even long-term planning.

Logical next steps would therefore be to expand the tool capabilities e.g. the inclusion of forecasting, etc., as well as extending the scope into solar and even co-location options. This would help National Grid ESO in their planning efforts and increase confidence in the tool and the information it provides in a less risky setting. This will be a crucial step in ensuring it can be considered as a reliable planning tool in the context of Black Start.

Given the development work involved in improving the tool and its capabilities, it could be around 2021/2022 before this would be trialled for use within operational planning, and then at least a year of successful operation before being considered for use in Black Start planning and procurement processes.

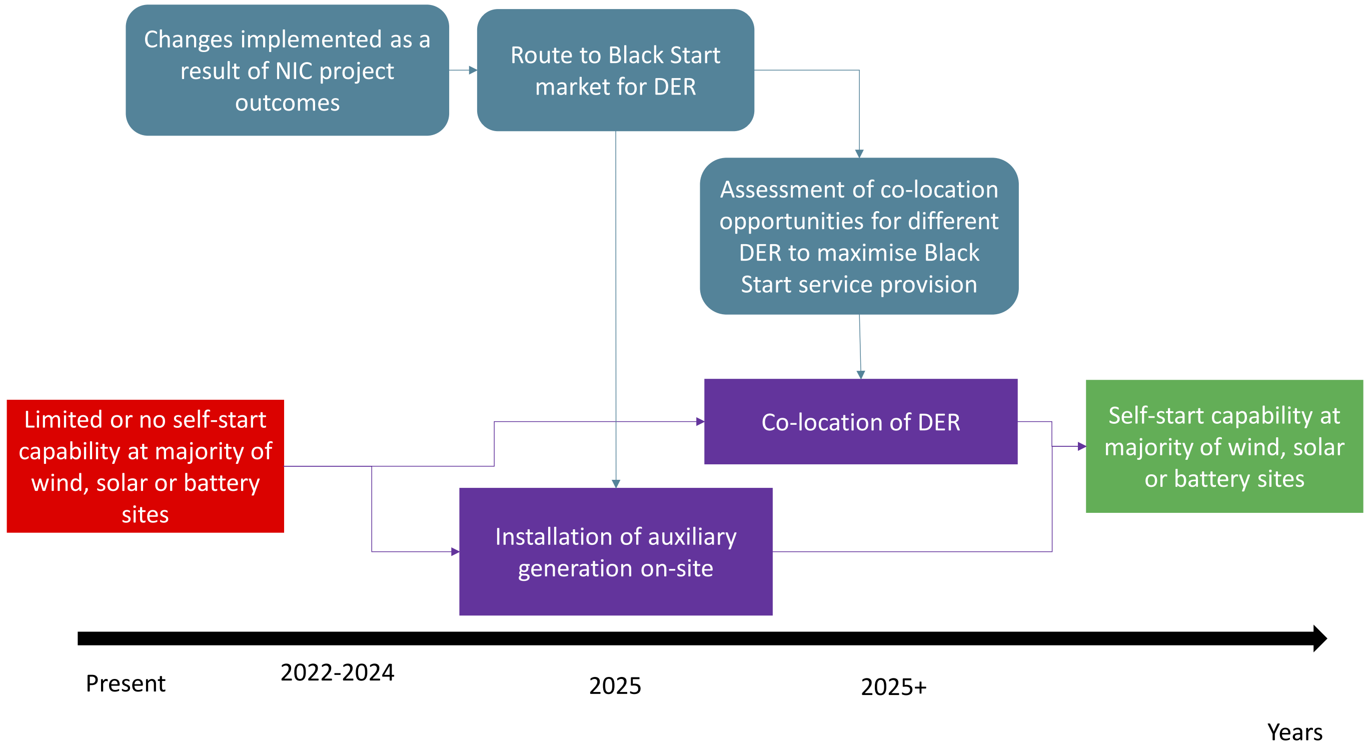


Self-starting capability roadmap

The ability of a site to self-start is one of the key attributes that conventional synchronous power stations offer, and one which non-traditional technologies cannot meet on a large enough scale at present. Solar PV and battery storage are able to self-start, but this is somewhat limited by resource availability (addressed in the previous roadmaps) i.e. solar could not self-start during the hours of darkness, and battery storage may shutdown with insufficient charge.

To increase the certainty of the self-start capability of a site, the simplest solution is to install auxiliary/back-up generation with sufficient capacity to meet the Black Start requirements. Another option would be to co-locate different types of DER, most likely battery storage with wind or solar, such that one generation type can be used to start the other e.g. solar could charge a battery, or a battery could provide power to wind turbines. For this to happen, a route to the Black Start market for DER is a pre-requisite whereby the sites (developers) are incentivised to incur this additional cost.

It has been assumed that this route to market for DER will follow the same rough timeline of that in the Battery Storage Resource Availability Roadmap and will be a natural progression from the outcomes of the NIC project. As such, the self-start capability of wind, solar and battery storage sites could potentially be relied upon from around 2025 onwards.



There is an alternative option to enable these DER sites to self-start, but it is potentially more complex and riskier. As stated in table 8.1, there are requirements set out in EREC G99 which prevents long-term parallel connections i.e. DER sites, from operating in island mode in the event of an outage or shutdown. If this condition were revised, and the necessary safety procedures put in place, then sites could remain energised and this would negate the need for additional self-start capability and improve the overall starting position of National Grid ESO as it prepared to execute a Black Start.

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Appendix A – TRL tables

	Shutdown resilience TRL				
Technology	**Site de-energisation**	**Emergency power**	**Intervention resources**	**Communication and control systems**	**Auxiliary starting generation**
Demand side response (DSR)	9	4	6	5	4
Battery energy storage system (BESS)	9	5	5	6	5
Synchronous DERs	9	9	8	6	9
Electric vehicles (EVs)	9	4	4	4	4
Large wind farms	9	6	8	6	6
Small wind farms	9	5	8	5	5
Solar	9	5	5	5	6

	Black Start performance TRL					
Technology	**Self-starting**	**Grid forming**	**Network energisation and reactive power capability**	**Block loading**	**Frequency control**	**Availability and intermittency**
Demand side response (DSR)	–	–	–	5	–	9
Battery energy storage system (BESS)	9	8	9	8	8	9
Synchronous DERs	9	9	9	9	8	9
Electric vehicles (EVs)	3	3	4	3	3	2
Large wind farms	7	6	8	8	9	7
Small wind farms	7	6	6	8	9	7
Solar	7	4	7	6	8	7

	Restoration capability TRL		
Technology	**How early can the technology join the Power Island?**	**How will the technology perform in a Power Island?**	**How can this performance be used to the advantage of the Restoration?**
Demand side response (DSR)	4	8	8
Battery energy storage system (BESS)	8	9	9
Synchronous DERs	9	9	9
Electric vehicles (EVs)	2	3	3
Large wind farms	8	8	8
Small wind farms	7	8	8
Solar	6	8	8

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