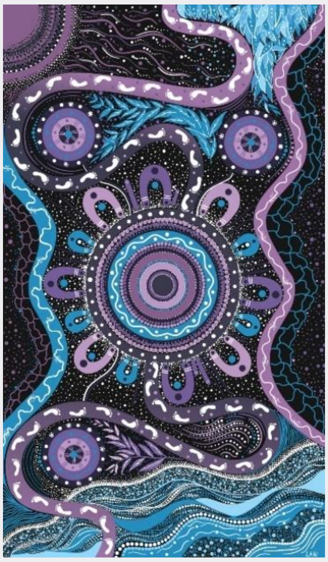
AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

System Restart Technical Advice

June 2025

Technical advice to inform the Reliability Panel's review of the System Restart Standard



We acknowledge the Traditional Custodians of the land, seas and waters across Australia. We honour the wisdom of Aboriginal and Torres Strait Islander Elders past and present and embrace future generations.

We acknowledge that, wherever we work, we do so on Aboriginal and Torres Strait Islander lands. We pay respect to the world's oldest continuing culture and First Nations peoples' deep and continuing connection to Country; and hope that our work can benefit both people and Country.

'Journey of unity: AEMO's Reconciliation Path' by Lani Balzan

AEMO Group is proud to have launched its first Reconciliation Action Plan in May 2024. 'Journey of unity: AEMO's Reconciliation Path' was created by Wiradjuri artist Lani Balzan to visually narrate our ongoing journey towards reconciliation - a collaborative endeavour that honours First Nations cultures, fosters mutual understanding, and paves the way for a brighter, more inclusive future.

Important notice

Purpose

The purpose of this publication is to provide AEMO's technical advice on system restart as requested by the Australian Energy Market Commission (AEMC) to inform the Reliability Panel's review of the System Restart Standard (SRS). This publication is generally based on information available to AEMO as at 19 June 2025 unless otherwise indicated.

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Executive summary

Power systems worldwide are planned and operated to be reliable and secure, with resilience to a range of contingency events. In rare situations disturbances are too extreme to arrest, causing protection systems to operate to avoid damage to equipment or harm to people. This can lead to cascading tripping where sections of the system lose power or are islanded, or an entire shutdown of the system, called a black system event. In these circumstances, resilient power systems must have the capability to rapidly recover and restart.

AEMO is responsible for ensuring this capability for the National Electricity Market (NEM) and has been tasked to provide Technical Advice to inform the Reliability Panel's review of the NEM System Restart Standard (SRS). The Panel requested review of both the system restart regulatory framework and new settings for the system restart standard. This report:

- provides that advice, examining the technical envelope for system restart events and updated success criteria for system restoration, and exploring restart scenarios with a future technology mix
- outlines operational restart pathway conditions, processes for reconnecting and resynchronising sections of the power system, and the short-term challenges and opportunities in providing each, and
- discusses future investment opportunities in system restart, pathways to support improved confidence in technological capability, and approaches to determining the new SRS, with suggested areas for future policy and regulatory reform.

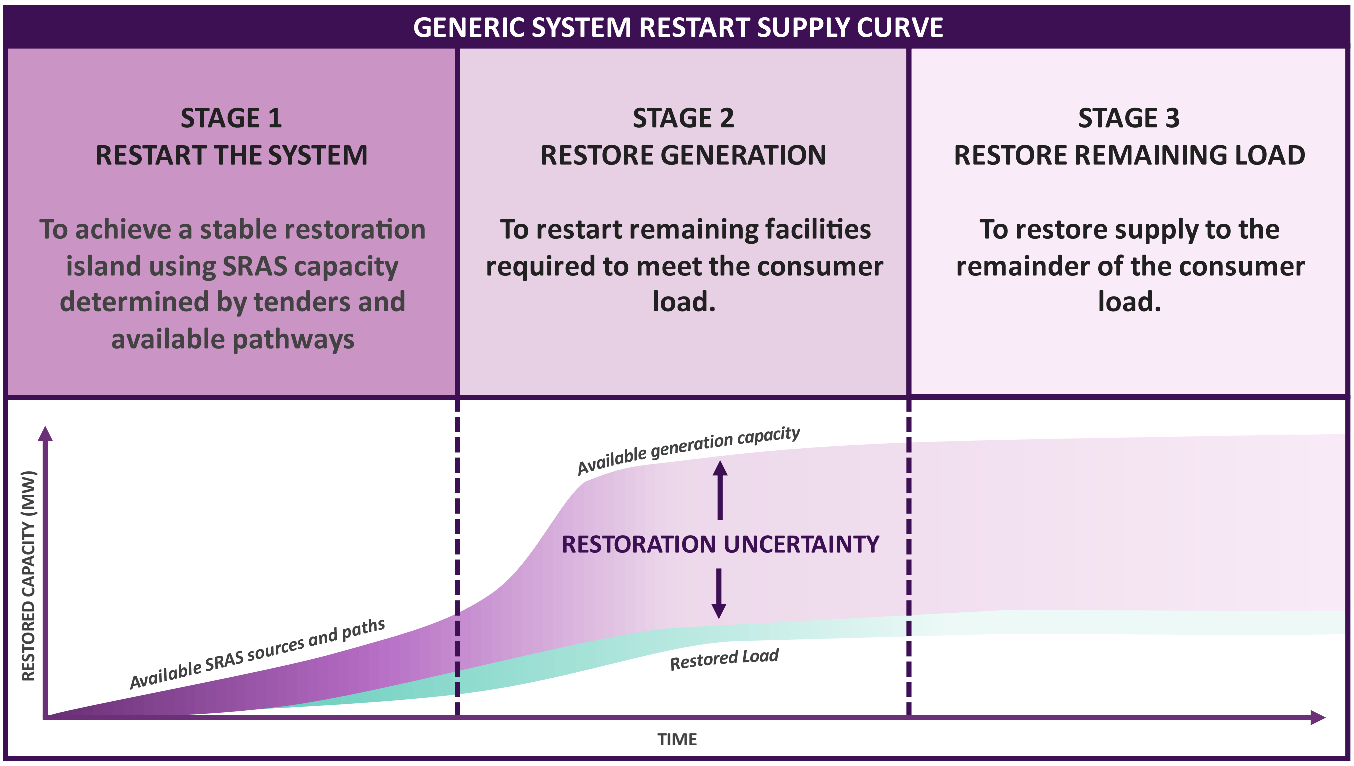
While Australia has not experienced a state-wide black system event since South Australia in 2016, major power outages do occur around the world, with a recent widespread outage in Spain and Portugal in April 2025 affecting more than 50 million customers. These events have significant consequences and can cause considerable impact, and AEMO welcomes the opportunity to provide advice to the Reliability Panel on this important issue for Australia's power system security.

Amending the SRS definition to provide flexibility

AEMO recommends that the SRS be amended to give AEMO flexibility to determine the appropriate System Restart Ancillary Services (SRAS) to create and maintain stable restoration islands (as defined in Section 2.2 and illustrated below in **Figure 1**).

Creating and maintaining stable restoration islands, along with options for AEMO to procure SRAS further along the supply curve, will support the valuation of restoration support services (RSS) such as frequency and voltage control, stable load and generator flexibility. Providing AEMO with the flexibility to determine the amount and types of SRAS – both black start and RSS – to procure based on available tenders will support more restart cost-effectiveness for consumers while increasing power system resilience to return to operation after black system events.

Figure 1 System restart stages



Stable restoration island requirements

Minimum attributes of stable restoration islands include:

1. Self-sufficiency, through maintenance of supply-demand balance, and voltage and frequency within acceptable ranges, including tolerance to reasonable changes to the island.
2. The ability to maintain a stable state for the duration of a successful restoration process. This includes ensuring sufficient system security capability to support reenergisation of both transmission and distribution systems.
3. The ability to return network and load to service commensurate with the available generation throughout the rest of the restoration process.
4. The ability to synchronise with other islands and the main grid.
5. Adequate communication systems to facilitate stable operation of islands.

Managing load to facilitate system restart

In the absence of targeted early action, there is an emerging risk that under some conditions it may not be possible to restart the system during daylight hours due to an inability to source stable load blocks impacted by distributed energy resources (DER) growth. AEMO requires access to manageable and stable load blocks (5-10 megawatts [MW] initially, up to 10% of available generation) during restart. This includes incentives to reenergise larger industrial loads individually as required, options to additionally support AEMO visibility of system loads throughout the restart process and options to increase distribution network service provider (DNSP) controllability of DER on certain restart pathways. AEMO is undertaking further work to model DER behaviour and impacts (Section 4.2.3) to ensure any risk is properly understood and appropriate solutions put in place.

Investment incentives for SRAS capability

The current SRS and associated procurement practices have not delivered consistent investment in new SRAS sources. AEMO would like to engage with the Australian Energy Market Commission (AEMC) and Reliability Panel on options to support adequate investment in SRAS capability. These could include allowing AEMO to procure more SRAS (above minimum levels) to encourage new plant to tender, and defining clear roles and responsibilities for the identification and notification to market of potential SRAS gaps.

A review of the Standard also provides an opportunity for AEMO, the AEMC and industry to consider ways to enable co-investment incentives. This will ensure that new plant or resources are planned and designed with the capability to deliver multiple system services at their outset, such as new gas turbines being fitted with black start capabilities so they can support system restart as well as reliability.

Supporting restart through the transition

As the technologies underpinning the power system change, so too must the approach to supporting system restart. AEMO's view is that the new Standard should be determined via an updated methodology to avoid needing to continually update the standard prior to each procurement round to account for updated information, plant availability, network configuration changes and new investments.

The technical analysis in this report has identified some key insights on the capabilities required for network service providers (NSPs) (including renewable energy zone [REZ] operators), market participants and market customer assets to contribute earlier in the restoration process than current processes allow. To improve understanding of some technologies that have not previously been demonstrated for supporting system restart in Australia, AEMO is considering undertaking priority technology trials to identify how they may meet the technical needs of system restart. Type 2 Transitional Services may be considered by AEMO to accelerate demonstration of system restoration capabilities from new technology.

To enable system restart to operate effectively now and into the future, the process for obtaining Local Black System Procedures (LBSPs) should also be reviewed to ensure LBSPs are available, accurate and up to date for all plant, alongside defined communications and availability protocols to maintain consistent communication during a restart event[1].

[1] AEMO (March 2021) *System Restart Communication Protocol,* https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2019/lbsp-amendments/system-restart-communications-protocol.pdf.

AEMO high-level advice

System Restart Standard

- The SRS should be amended to allow AEMO the flexibility to create and maintain stable restoration islands, along with an option to procure SRAS further along the restoration curve.
- The Standard should include the following:
  - A requirement for AEMO to determine the amount of SRAS to procure to create and maintain stable restoration islands in Stage one and extend the islands through Stage two of system restoration.
  - Flexibility for AEMO to determine the quantity of SRAS (both black start and restoration support services) to procure.
  - Specific ability for AEMO to procure a prudent amount of additional or alternative SRAS to cater for reasonable network risks.
  - Improved ability to consider services and implementations that support the restoration of smaller islands or sub-sets of the grid.

Technical

- Communications and availability protocols for plant participating in SRAS should be reviewed to ensure consistency and resiliency under all restart scenarios, including cyber disruption.
- The LBSP process and obligations should be reviewed to ensure AEMO receives accurate, up to date and reliable information for plant to ensure they can be securely energised during restart.

Regulatory reform

- Options to support adequate investment in SRAS capability should be explored, given the current SRS has delivered limited investment in new SRAS sources and the significant risk of insufficient new SRAS sources coming online prior to the possible exit of existing providers.
- The above options should also consider co-investment decisions so that new plant, resources and network assets are planned and designed considering the capability to deliver multiple system services, including system restart.
- National Electricity Rules (NER) 4.3.6 should be reviewed to expand obligations for system restart network testing to involve existing and potential new restart paths with appropriate mechanisms for cost recovery.
- Enhanced coordination with DNSPs will be required to effectively account for and manage the interactions between distributed photovoltaics (DPV) and the power system during restart. AEMO is currently engaging with DNSPs on the data and models required to assess the interactions between DPV and system restart, and the ability to actively manage DPV on restart pathways. The National Consumer Energy Resources (CER) Roadmap Distribution System and Market Operation workstream is considering actions necessary to formalise these DNSP planning and operational coordination roles.

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1 Introduction

AEMO has responsibilities for maintaining power system security in the NEM, including obligations through clause 3.11.7 of the NER to acquire SRAS. These are acquired to meet the SRS as determined by the Reliability Panel, and are critical to restoring one or more regions of the NEM to an energised state quickly following a black system event, or where sections of the system lose power or are islanded. AEMO seeks to acquire SRAS to meet the standard at the lowest long-term cost (the SRAS procurement objective).

System Restart Ancillary Service (SRAS) Definition[2]

System restart ancillary services cover two types of services provided by plant or facilities with:

a) Black Start Services capable of starting without drawing power from the power system following a major supply disruption, and delivering power to a Delivery Point within a nominated timeframe, sufficient to allow supply to be made available to other generating units; or

b) Restoration Support Services (RSS) with the capabilities described in AEMO's SRAS Guideline.

SRAS has historically been supplied by the synchronous coal, hydro and gas generators that have been foundational to the grid landscape for almost 100 years, but the supply mix is rapidly changing, with synchronous generation being rapidly displaced by inverter-based resources (IBR) including wind, solar and batteries.

With reduced thermal synchronous generator availability to supply SRAS, the pool of SRAS options has rapidly declined. Traditional SRAS sources have not been replaced by IBR, which have not tendered for SRAS provision, in part due to a lack of practical power system experience in the use of IBR to participate effectively in the system restart process.

The future power system will, at times, comprise very high levels of IBR generation and storage, operating alongside a fleet of synchronous machines such as gas turbines, hydro, and synchronous condensers. This technology mix brings unique challenges and opportunities, such as variable output, limited energy capacity, and system stability performance that need to be managed to allow effective participation in system restart scenarios.

The dwindling pool of SRAS options has reached the point in some NEM regions where, without timely action, there is significant risk that the current SRS may not be met. This could result in restorations being slower or less predictable following a black system event. Compounding these issues further, many traditional SRAS options have operational requirements which are increasingly difficult to meet with growing levels of DPV contribution that are decreasing the size of stable load blocks, by reducing the net load on distribution feeders.

AEMO attempted to overcome these operational challenges in the 2024 procurement round through the procurement of RSS. These efforts were constrained by the specific MW and time targets in the SRS and the aligned SRAS Guidelines, along with a general reduction of capable SRAS offers. AEMO now considers current targets in the SRS, which were based on historically available SRAS options, cannot be met in the short term or

[2] AEMO (2021), SRAS Guideline, Section 3.1, https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/sras/sras-guideline-2021.pdf.

further into the future without intervention. Ongoing efforts are underway to investigate and procure RSS where feasible under current arrangements.

The last Australian black system event occurred in South Australia in 2016, although major power outages do occur around the world, most recently in Spain and Portugal in April 2025, affecting more than 50 million customers. These events can have significant consequences and can cause considerable impact.

AEMO welcomes the opportunity to provide technical advice to the Reliability Panel's Review of the System Restart Standard[3], and acknowledges the Panel's request for review in two stages:

- Stage 1 – a review of the system restart regulatory framework to make recommendations to the Commission, and
- Stage 2 – new settings for the system restart standard informed by Stage 1, including consideration of the risks of major supply disruption, and the costs and availability of SRAS.

The report has combined AEMO's review of both stages:

- Section 2 outlines the system restoration process and defines success criteria.
- Section 3 provides detailed information of the various technologies and opportunities available for augmenting the future system restoration process – the majority of the requested Stage 1 advice from the AEMC's Request for AEMO Advice[3] is addressed in this section.
- Section 4 discusses SRS transitional opportunities and challenges, and includes the remaining elements of the requested Stage 1 and Stage 2 advice.

[3] Available on the AEMC website, https://www.aemc.gov.au/market-reviews-advice/review-system-restart-standard-0.

2 Defining system restoration

Before assessing the possible scenarios in which system restart could occur in the future, and the technical requirements that would make that future possible, it is important to first define the elements of a successful system restoration, and the relevant stages in the process. This section also discusses emerging major supply disruption and restoration risks.

The key findings and messages from this section are summarised in **Table 1** below.

Table 1 Summary of Section 2 key messages

Advice	Report section/s
System Restart Standard	
The SRS should be amended to provide AEMO the flexibility to determine the appropriate SRAS to create and maintain stable restoration islands (as defined in Section 2.2) ahead of each procurement round. Creating and maintaining stable restoration islands, along with an option for AEMO to procure SRAS further along the restoration curve, will support the valuation of restoration support services, such as services to support system security, provide stable load and value generator flexibility. This will resolve several of the short-term challenges identified in Section 4.1 of this report. The Standard should include the following: • A requirement for AEMO to determine the amount of SRAS to procure to create and maintain stable restoration islands in Stage one and extend the islands through Stage two of system restoration. • Flexibility for AEMO to determine the quantity of SRAS, (both black start and restoration support services) to procure. • Specific ability for AEMO to procure a prudent amount of additional or alternative SRAS to cater for reasonable network risks. • Improved ability to consider services and implementations that support the restoration of smaller islands or sub-sets of the grid.	2.3

2.1 Technical envelope for a system restart event

The technical operating envelope of the power system defines the range of technical system parameters where satisfactory operation is possible. The technical envelope for normal operation is significantly different from that during system restart and recovery events when the system is in a smaller and weaker state in advance of and during restoration.

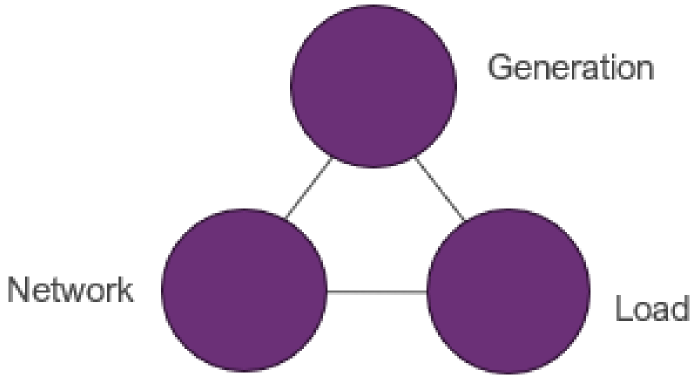
During restart, some system parameters of the technical envelope have stricter requirements, while others are slightly relaxed. The technical parameters that are relevant to normal operation are also critical during restart, including minimum fault levels, minimum inertia requirements, voltage control requirements, generator and line thermal limits, stability requirements and plant loading requirements. System restart events have additional communication requirements, synchronising requirements and time critical considerations for sensitive loads that either should not cease operation for long or are damaged without external supply for too long.

AEMO advises that consideration of the technical envelope during restart should continue to underpin success criteria and restoration pathways both now and into the future.

2.2 Success criteria

Power systems consist of three key components that together enable the effective delivery of electrical energy to where it needs to be consumed (**Figure 2**). A successful system restart plan, and hence standard, will appropriately consider all three pillars. The future functional requirements of these three pillars for system restart are discussed in Section 3.3 of this report.

Figure 2 Three key components of a power system



The general functional requirements for system restart that are essential for a successful system restart are discussed below. These each consider one or more of the three pillars of a power system and are essential to achieving the ultimate target of a system restart event – the timely restoration of supply to consumer load. This is achieved by creating and maintaining stable restoration islands (see Section 2.3) which are used to progressively energise and restart the remainder of the grid and restore supply to consumers.

2.2.1 Quick and effective restoration

The sooner restoration begins following a black system, the more likely it is that generators and necessary systems will be available to aid in restoring the system to its previous state. Successfully initiating restart to form a stable restoration island quickly (within hours) is essential to avoiding longer delays (up to days) to overall system restart. For example, action within hours will mean telecommunication systems are still available to issue instructions to participants, aggregate load is less challenging to re-energise as warm-load pickup is more achievable than cold-load pickup, network elements will not have exhausted backup supplies, and large industrial loads will not have yet suffered catastrophic damage, all supporting the likelihood of a successful and effective restart.

Therefore, quick and effective coordination of restoration efforts, such as the ability to issue instructions to relevant parties (operating generators, network and loads), is necessary to minimise the impacts of the black system event.

2.2.2 Forming and maintaining stable restoration islands

Developing stable and capable restoration islands is a key priority immediately following a major supply disruption and a milestone to system restoration from which the rest of the network can be energised. The more adaptable and resilient these islands are to the mix of system components and conditions that may be present on the day of the restoration event, the higher the chance of success when restoring the broader network.

Once islands are established, AEMO must endeavour to maintain a secure operating state. Islands should be capable of operating independently for long periods of time while the status of the remainder of the network is assessed. This could take hours, or longer. For this duration, the technical envelope must be maintained and sufficient energy supplies (supporting generation), and stable load blocks (supporting minimum loading requirements of generators in the island and maintaining voltage and frequency control) must be available to achieve extended operation of islands.

Further detail on stable restoration islands is in Section 2.3.

2.2.3 Network protection and control susceptibilities

During system restart, the power system is at its weakest while network elements and generators are re-energised one by one. Non-ideal manifestations of a weak system – such as large temporary overvoltage and undervoltage, excessive harmonics, highly distorted voltage and current waveforms, and phase angle jumps – are likely to be present. To ensure a stable system throughout the restoration process, and thereby maximise success of restoration, all elements of the island, including network protection and control mechanisms, must have the ability to operate correctly under the types of conditions that could occur during restoration. This will improve the likelihood of a successful restart, and increase the speed of network restoration while maintaining the system technical envelope.

2.2.4 Redundancy to cater for unplanned contingencies

Black system events are likely to include some form of network damage or unavailability. As a result, robust system restart plans should allow for the possible unavailability of network infrastructure, generation, and load to be brought online.

Therefore, it is crucial that any restart plan has multiple pathway and circuit contingency options which provide greater resilience during system restart events which have high levels of uncertainty. This is particularly important as natural disaster frequency increases, potentially rendering whole transmission corridors unviable (for example, due to bushfire or tornados).

2.2.5 Adaptability against changes in generation availability and load conditions

A power system with increasingly higher proportions of IBR generation must be equally capable of restarting as a synchronous generation dominated power system. Load restoration must have an insensitivity to the type of load restored, meaning embedded generation such as DER[4] should not preclude a section of the network from restoration. System restart must be technically feasible with the available generation, network and load configurations in the system at any time. This is particularly relevant for parts of the network where DER or weather-dependent variable renewable energy (VRE) will increasingly become the main source of generation that meets load.

[4] This report refers to distributed energy resources (DER), which includes larger distribution-connected generation as well as smaller consumer energy resources (CER) such as household rooftop solar.

Furthermore, different regions will be operating in different generation mix and load paradigms. Procurement and procedures for restart must therefore be flexible to address the unique capabilities and limitations of technologies and network typology in each region, now and into the future.

2.3 System restoration process

Following a major supply disruption requiring SRAS, the process to restore supply to consumers is complex and can be prolonged. While the detailed process and timeline for restoration can differ between sub-networks, there are some common principles to achieving successful restoration.

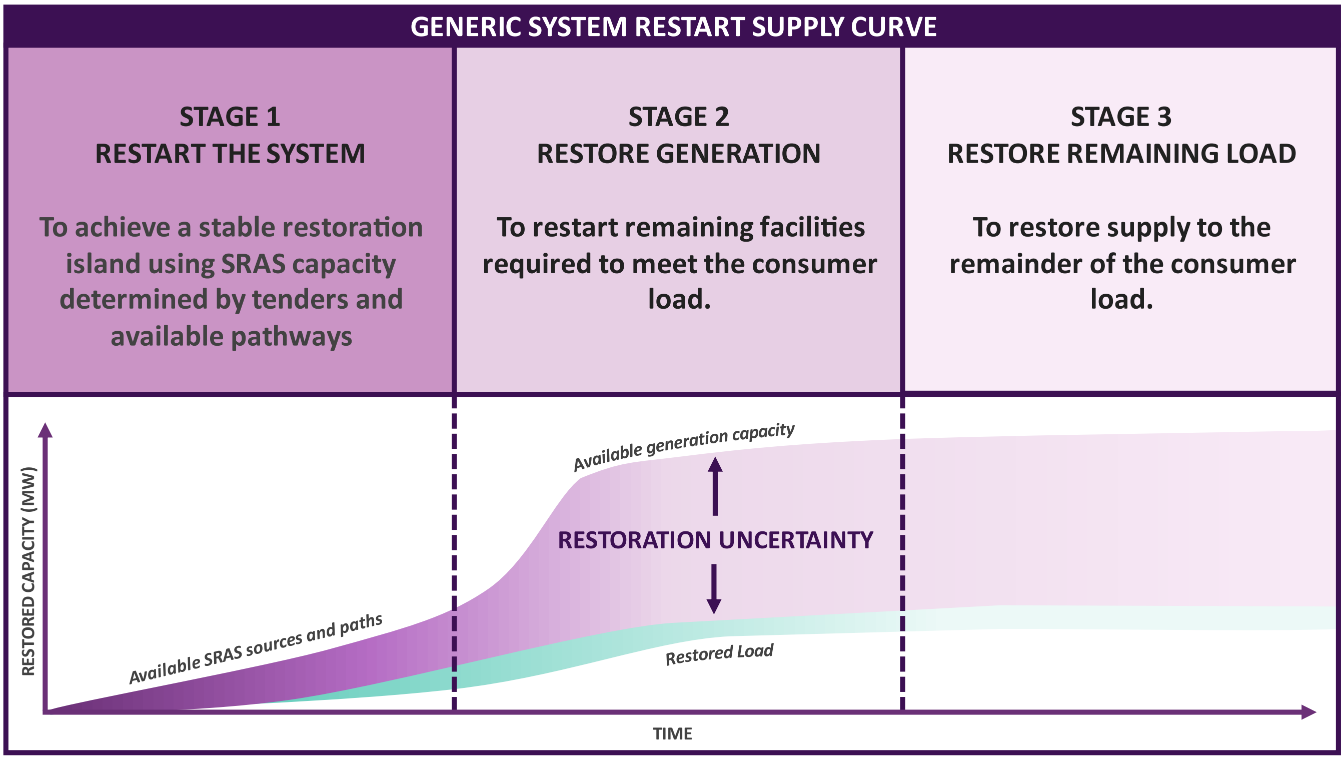
First, stable restoration islands must be formed from which the remainder of the sub-network can reasonably be restored. This includes the initiated operation of contracted black start SRAS units to energise network elements immediately, and supply the auxiliaries of neighbouring (generally larger) power stations within restoration islands so they can be restarted. Following the restart and stable operation (through ensuring load is available) of these power stations, larger areas of the disrupted network can be progressively restarted, any islands resynchronised, and supply to consumer load restored. **Table 2** provides an overview of the restoration process, including a description of each of the three main stages of the process.

Table 2 Updated summary of the restoration process

	Stage 1 – restart system	Stage 2 – restore generation	Stage 3 – restore load
Primary focus	• To achieve stable restoration islands from which the remainder of the sub-network can be restored.	• To restart sufficient network, generation and other plant required to progressively restore consumer load.	• To restore supply to the remainder of the consumer load.
System operator and generation activities	• Initial assessment of events and system conditions. • If possible, begin restoring the transmission network from a neighbouring network. • Initiate the operation of available SRAS sources, both black start and those required to maintain restoration islands. • Supply auxiliaries of other selected generating units. • Restart the selected generating units.	• Commence restarting all the required generating units. • Additional SRAS sources might be activated to stabilise the system as the restored network expands.	• Energise the remainder of the transmission and distribution network, and to restore supply to the remainder of the consumer load.
Network energisation	• Initially only the minimum network is energised to manage the voltage level. • The transmission network is progressively energised to be able to energise the auxiliaries of other power stations. • Network RSS may be activated if required to maintain stable restoration islands.	• Most, or all, the undamaged transmission network is energised. • Energise more distribution network as further load is restored. • Additional network RSS may be activated if required to expand the restored network.	• All undamaged transmission network is energised. • The distribution network is all progressively energised.
Load restoration	• Initially only a small portion of the consumer load is restored, primarily only to stabilise the system voltage and frequency. • Load may be activated as RSS to provide stable load blocks if required, and not otherwise provided, to maintain stable restoration islands. • Priority given to sensitive loads where practical considering system stability and where load restoration supports the restart process.	• More consumer load is energised as the available generation increases and the network is progressively restored. • Additional load RSS may be activated if required to expand the restored network.	• All consumer load is progressively restored, unless prevented by network damage.

The general restoration process described in this table can be represented graphically in a supply curve as shown in **Figure 3** below. It is important to note that depending on available generation, network and load, the time and MW points at which each restoration stage is achieved are likely to change significantly.

Figure 3 Restoration stages



The first stage of the restoration process is to form stable restoration islands by initiating the operation of relevant SRAS units and restarting selected generating units. This will also include the restart of sufficient stabilising load to maintain these islands. At the end of this first stage, sufficient transmission network and generator capacity would be available to restart all other units required to meet consumer load by Stage 3. Stage 2 therefore is the bridge between the formation of stable restoration islands and the reconnection of remaining consumer load. This is achieved by the incremental reconnection of equivalent generation and load blocks.

Stable restoration islands

Minimum attributes of stable restoration islands include:

1. Self-sufficiency, through maintenance of supply-demand balance, and voltage and frequency within acceptable ranges, including tolerance to reasonable changes to the island.
2. The ability to maintain a stable state for the duration of a successful restoration process. This includes ensuring sufficient system security capability to support reenergisation of both transmission and distribution systems.
3. The ability to return network and load to service commensurate with the available generation throughout the rest of the restoration process.
4. The ability to synchronise with other islands and the main grid.
5. Adequate communication systems to facilitate stable operation of islands.

2.3.1 Power system characteristics impacting the restoration process

The actual restoration process followed on the day of a restoration event will depend on the characteristics of the affected part of the power system and the specific circumstances that have occurred. AEMO is required to prepare the System Restart Plan for managing and coordinating system restoration activities during any major supply disruption[5], while NSPs and generators are required to develop, and provide to AEMO, LBSPs that can be initiated during a major supply disruption[6].

LBSPs from generators include all procedures, requirements and generator performance during their restart (when the external network is de-energised), as well as the generator's behaviour when generator is restarting from its auxiliary supplies. NSP LBSPs detail procedures for reconnecting load, network switching capabilities, and available options during restart. AEMO may also request LBSPs from market customers in respect of major loads if relevant to developing restart plans.

The power system characteristics that can affect the restoration process include types of generation available, the physical distances between generating units and load centres, and the degree of interconnection with other regions. Restoration speeds can sometimes be increased if there are relatively short electrical paths between SRAS sources and other large generating units to be restarted, and to the consumer loads that are being restored. The development of REZs in often more remote parts of the network will make up an increasing portion of generation capacity in coming years, so the speed at which REZ areas will be restored should be considered in future restoration processes.

Some of the other circumstances that could affect the speed and reliability of the restoration process include:

- the extent of the power system that is in a black system condition
- the presence of adverse weather or bushfire conditions that could place the security of the system at risk during restoration

[5] NER 4.8.12, Clause (a)

[6] NER 4.8.12, Clauses (d, e, f)

- the extent of equipment damage that could reduce available options for restart
- the availability of communication infrastructure
- the availability of stable load blocks
- the time taken to supply generating unit station auxiliaries
- whether the system can be restarted from an unaffected neighbouring network, for example using an interconnector
- whether any pockets of operating load and generation exist within the affected network, and
- which SRAS, black start and RSS sources are available within the affected network.

These factors reflect some of the uncertainties that could occur on the day of a restart event that need to be planned for. A procurement standard which supports AEMO to plan for more uncertainties and procure diverse RSS would improve the chances of a successful restoration.

2.3.2 Restoration of the network and consumer load

Restoration of the network and consumer load is a gradual process. Each network element needs to be energised individually, and load must be re-connected in small blocks to deliver stabilising load to support restoration of the power system.

In effect, this means that during a system restoration, load being restored to consumers also provides the important purpose of balancing the re-energisation of transmission lines and new generation. In the early stages of a system restart, including Stage 1, the size of the blocks of load that can be connected are typically limited to approximately 5-10 MW to maintain the voltage and frequency stability of the network as it is being restored. As the electrical island increases in size, load block size may increase, with blocks of equivalent size to approximately 10% of the total energised generation capacity.

Step changes in voltage and system frequency due to the re-connection of network elements or blocks of consumer load are particularly pronounced when a small number of generating units are operating and minimal network elements are connected. As such, particular care must be taken when reconnecting load in the early stages of power system restoration by limiting the size of energised load blocks. Apart from being limited in size, other sought-after characteristics for load that is re-energised in Stage 1 and 2 of the restart process include being reasonably predictable and constant.

2.3.3 Prolonged restoration

The process of power system restoration can become significantly harder once certain time thresholds are passed. If supply is not restored to key substations within approximately 10 hours following the major supply disruption, the restoration process will become significantly more difficult.

The operation of control and protection systems in transmission and distribution substations relies on local back up energy supplies, typically in the form of energy limited batteries. If there are no backup generators, the supply batteries can become flat, preventing the operation of the protection and control systems and thereby preventing energisation of the substation.

Other factors that can further prolong the restoration process include the following:

- On sunny days, some sub-networks might encounter problems sourcing sufficient stable load to progress the restoration process beyond Stage 1, due to high contributions from DPV. Based on current operating conditions with an inability to discriminate between stable load and DPV, and limited remote control of DPV by DNSPs, progression of system restart stages might be delayed until mid to late afternoon to ensure sufficient load is available in the region.
- Often, NSP transmission line reenergisation protocols include electrical safety requirements such as a need to physically patrol lines prior to enabling reenergisation. The travel time taken for crews to arrive and safely perform the patrol, including weather limited helicopter patrols, can cause further delays to restart.
- Major damage to network equipment due to natural disasters such as cyclones or widespread fires can cause prolonged delays to the energisation of key transmission lines.
- Inability to remotely operate deenergised transmission equipment could result in a need to manually operate the substation, introducing significant delays where travel is required.

2.3.4 Supporting smaller island restart

The current SRS and system restart plans in the NEM cater for region-wide black system scenarios. This allows system restart via use of local black start sources located within the region, and restart from adjoining regions via interconnectors.

However, there are instances where a small subsection of the region's grid can become islanded, requiring a different restoration approach. Restoration for a smaller island would typically occur by restarting from adjoining areas of the grid, rather than reliance on a high availability system restart source within the island. Considerations that can improve the speed of restart to smaller islands include:

- increased availability of sync-check relay equipped breakers at key locations
- generation that is capable of riding through severe grid disturbances and operating an islanded system, such as battery energy storage systems (BESS) with grid-forming (GFM) inverters and an associated synchronous machine, and
- transmission plant with appropriate specifications to be capable of being re-energised by local plant, noting this would need to be considered in conjunction with normal operational needs.

While some of these steps can be facilitated with system support services, others are outcomes of planning decisions. AEMO would appreciate the Panel's input into how these benefits may be better captured through regulatory investment processes.

In some areas that are at risk of being islanded for extended periods – such as loads at the end of long radial connections (for example Broken Hill and Port Lincoln) or either side of specific transmission corridors (such as the north and south of Tasmania) – it may be appropriate to consider investment in local restart services, and services that would support the operation of an island for extended periods. Where applicable, these arrangements (including the ability to re-synchronise with the larger grid) should be tested ahead of time to provide confidence in the ability to operate these local islands for extended periods. Any technical limitations or risks identified in the operation of such islands should be managed by the relevant NSP.

2.4 Emerging major supply disruption and restoration risks

This section explores NEM-specific characteristics that may influence the likelihood, severity, or nature of a major supply disruption or impede a successful restoration. System changes and behaviours relevant to the NEM's evolution that may not have previously been considered in the context of major supply disruptions and restart are also discussed.

2.4.1 Contributing factors for major supply disruptions

Unknown generation and load performance

The complexity of IBR generation and load is such that it is not realistic to identify every possible behaviour prior to it being commissioned and operational. While extensive studies are undertaken using plant/load and power system models prior to connection, there is potential misalignment between the models and physical plant/load. The models are an approximation of the plant, and attributes such as control and protection mechanisms may have been simplified out of the model. Further, the models are largely designed to study system normal operations. While all due diligence is taken to confirm that a plant will behave correctly when operational and during power system events, there remains a potential for unknown or unexpected behaviour to occur. This risk is covered in greater detail in the *2024 General Power System Risk Review*[7].

Uncoordinated remedial action schemes

Remedial action schemes (RAS) are seeing increasing use throughout the system to facilitate new generation connections while avoiding additional investments in network infrastructure. RAS serve to rapidly reduce generation output or disconnect plant upon the loss of certain key network circuits, enabling increases in generation capacity to be accommodated while still allowing the transmission network to run to a N-1 secure state.

These schemes are generally developed on a per-case basis, at the time of a new generator connection study process. There is a potential risk that RAS maloperation or multiple RAS interactions could result in unexpected behaviour of the schemes. Such unexpected behaviour may include tripping more generation than originally intended, or failing to trip and associated overloading of assets resulting in protection operation. This risk and mitigation efforts can be found in the 2024 AEMO General Power System Risk Review[8].

Increased DER concentration within distribution networks and UFLS relay interaction

During an underfrequency event, underfrequency load-shed (UFLS) protection relays may inadvertently shed feeders providing a net infeed of energy to the system[9] in areas with high levels of DER generation. Operation of UFLS at times of high DER therefore has the potential to contribute to a major supply disruption. AEMO is working

[7] AEMO (July 2024) *2024 General Power System Risk Review – Report*, Section 6.8, https://www.aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/draft-2024-general-power-system-risk-review-report-consultation/2024-gpsrr.pdf.

[8] AEMO (July 2024) *2024 General Power System Risk Review – Report*, Key Recommendation 9 and Section 6.6, https://www.aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/draft-2024-general-power-system-risk-review-report-consultation/2024-gpsrr.pdf.

[9] AEMO (July 2024) *2024 General Power System Risk Review – Report*, Section 6.2, https://www.aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/draft-2024-general-power-system-risk-review-report-consultation/2024-gpsrr.pdf.

with DNSPs to consider such risks and potential mitigation measures such as recommendations on dynamic arming[10].

Shifting centres of generation

As the NEM transitions to greater concentrations of IBR generation, new sites are hosting large-scale generation capacity that was not originally contemplated in the power system. Often, this means new generation is connected to the power system with minimal network redundancy[11]. Additionally, the sites for renewable energy generation in some regions tend to be remote from major load centres. By contrast, traditional generation projects such as large synchronous plant are often highly interconnected with the remainder of the network.

While the transmission system will always be run to accommodate the potential loss of a circuit, during major weather events it is possible that many credible and non-credible contingencies could occur. Plant connected with low-redundancy or remote locations increase their exposure to risk of disconnection due to weather events. Without sufficient network redundancy connecting organically emerging remote generation centres to the remainder of the NEM, there is increased potential for events to sever connections between generation and load, precipitating major supply disruptions. This is discussed in greater detail in the *2024 General Power System Risk Review*[12].

Wind gusts and tornados

There have been multiple occasions in Australia where high winds and tornados have felled major transmission infrastructure, with one such occasion precipitating the South Australian black system event. Such extreme wind events are projected to increase as the climate continues to change, increasing the risk of major transmission lines and other transmission infrastructure being destroyed during such events. Risk from major weather events is discussed further in the *2024 General Power System Risk Review*[13].

2.4.2 Contributing factors that may impact system restoration

Increased remote plant operation and overreliance on public telecommunications

Due to the nature of the new IBR generation technology being remotely located and largely self-sufficient, an increasing trend in plant management and control is un-manned, remotely operating generators. For some plant, relevant technical expertise and support does not reside within Australia, requiring specialists to remotely connect to the plant from overseas locations for any required support or operational intervention. This paradigm creates a dependency on public communication networks (specifically, the internet) being available to access the plant.

During a major extended supply outage, it is possible that public communication infrastructure may exhaust its backup energy supply more quickly than dedicated power system communication infrastructure. This means that

[10] AEMO (October 2023) *Under frequency load shedding: Exploring dynamic arming options for adapting to distributed PV*, https://aemo.com.au/-/media/files/initiatives/der/2021/vic-ufls-data-report-public-aug-21.pdf.

[11] AEMO (July 2024) *2024 General Power System Risk Review – Report*, Section 6.14.1, https://www.aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/draft-2024-general-power-system-risk-review-report-consultation/2024-gpsrr.pdf.

[12] AEMO (July 2024) *2024 General Power System Risk Review – Report*, Section 6.14.1, https://www.aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/draft-2024-general-power-system-risk-review-report-consultation/2024-gpsrr.pdf.

[13] AEMO (July 2024) *2024 General Power System Risk Review – Report*, Section 6.9, https://www.aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/draft-2024-general-power-system-risk-review-report-consultation/2024-gpsrr.pdf.

any generation or DER that is reliant on shared public communication infrastructure may be uncontrollable and unusable during a major event.

A similar reliance on public telecommunications is emerging for DPV. While much of the existing fleet of DPV is not controllable by any remote mechanism, newer DPV systems and distributed storage systems are increasingly installed with remote control capabilities. These capabilities may be used by aggregators and retailers optimising for market value and customer needs, by DNSPs to manage network capacity via flexible export limits, or by DNSPs to manage minimum system load following AEMO directions, through emergency backstop mechanisms. The majority of such control is enacted via remoted servers through public communication networks.

High levels of DPV generation may impede the availability of stable load blocks and in turn limit the capability to perform power system restoration during daylight hours. Options such as curtailing DPV generation at these times would assist in retaining these stable load blocks. On the other hand, distribution-connected storage may be able to provide local support services (such as excess DER energy absorption at a medium voltage level). To utilise these opportunities during system restoration, DER management solutions need to consider methods that are robust to loss of communications.

Additional consideration in this space lies in cyber-related risks, where internet-connected devices bring additional complexity and security concerns, as well as risk of common-mode failure (the internet). These risks are identified and discussed in further detail in the *2024 General Power System Risk Review*[14].

[14] AEMO (July 2024) *2024 General Power System Risk Review – Report*, Sections 6.12 and 6.13, https://www.aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/draft-2024-general-power-system-risk-review-report-consultation/2024-gpsrr.pdf.

3 Considering future system restart

Section 3 aims to illustrate the restoration pathways that may be followed in the long term, and technology considerations once major thermal plants with relatively large minimum stable generation levels have retired. The scenarios discussed highlight the uncertainty in technology mix and the need for technical and regulatory flexibility in system restart planning and operation. AEMO provides regulatory recommendations to inform consideration of any long-term paradigm shift and navigation of interim transitional challenges, and detailed technology descriptions and requirements for awareness and consideration of future restoration conditions.

The key findings and messages from this section are summarised in **Table 3** below.

Table 3 Summary of Section 3 key messages

Advice	Report section/s
AEMO has identified technical considerations that could enable REZs and concentrated VRE to be capable of black start or RSS.	3.2.1
Relevant functional requirements discussed in this section will assist with addressing extended undervoltage associated with energisation of large transformers in the path of future restart options, such as REZs.	3.2.1, 3.3.4, 3.3.5
AEMO has identified capabilities for interconnectors that can increase their reliability if used during the operation of restart events.	3.3.6
High voltage direct current (HVDC) links seeking to participate in black start must be of the GFM variety.	3.3.7
AEMO has identified specific functionality that enables installed network assets, including converter-based dynamic volt-ampere reactive (VAR) compensators and synchronous condensers, to support the grid during a restart event.	3.3.1, 3.3.2, 3.3.3
There are specific functional requirements that best enable existing and new generating technologies to participate in SRAS, both black start and RSS.	3.4
AEMO will continue to undertake identified high priority work to improve AEMO and NSP visibility, predictability and management of DER during restart events.	3.5.2
There are specific functional requirements for loads that best support their re-energisation early in the restoration process.	3.5.1

3.1 Restart scenarios in a future technology mix

Section 3.1 provides insight into the present-day challenges and future opportunities of the system restart process as the power system evolves. The section begins with a present-day restart scenario and highlights the increasing challenges operating the power system with high levels of DPV, stable load blocks, high minimum loading for generation, and other challenges with the current process. This is then compared to a potential future restart scenario which integrates currently available technologies with increased flexibility in procurement and dispatch to achieve a successful system restart. Before this future scenario can be realised, these existing technologies will require further investigation and demonstration to determine that they are able to appropriately provide the services assumed below.

3.1.1 Emerging challenges during restart

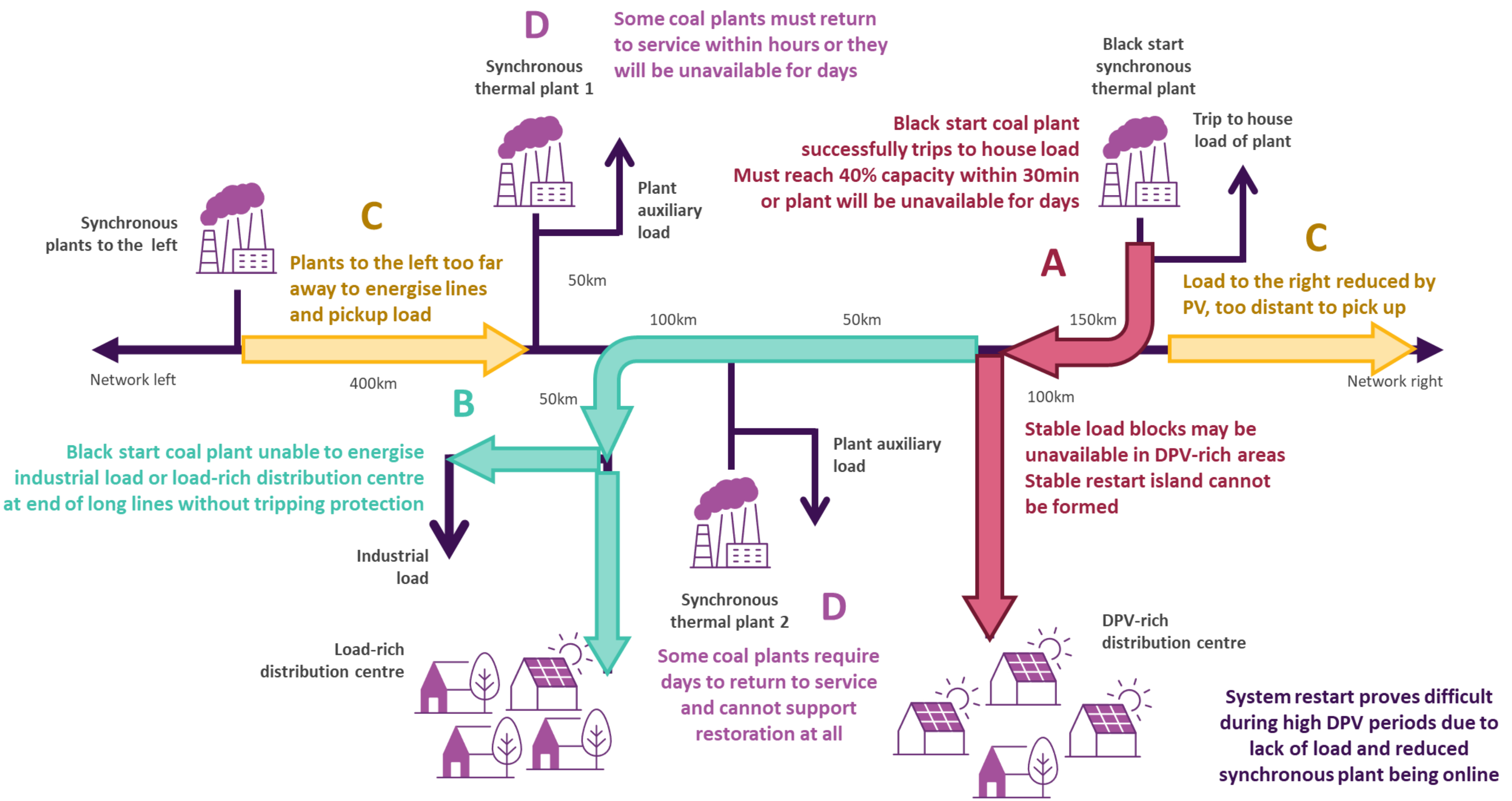
The example outlined below in **Figure 4** and **Table 4** illustrates potential challenges faced by AEMO if a restoration event was required in the current system. The example aims to build a stable restoration island to allow broader network energisations. The black start source is a large trip-to-house-load (TTHL) coal generator, although other existing pathways with synchronous black start generators may experience similar challenges.

The example summarises some of the acute challenges experienced in the early stages of restart with the current system restart standard in a grid with decreasing traditional restart options and increased IBR penetration at all levels.

Solutions to the following technical issues are limited within the current SRAS framework:

- It is increasingly difficult to find stable and consistent loads to maintain the stability of the restoration island.
- Sufficient power system security services need to be available during restoration.
- There is limited ability to procure more services, including restoration support services (such as load availability), once the current SRS MW-time restoration target has been met.

Figure 4 A figure highlighting potential challenges for the emerging system using the current system restart framework



System security requirements to maintain during restart:

- Voltage stability
- Frequency stability
- Fault current levels (megavolt-amperes [MVA])

Table 4 Description of potential stages and uncertainties of the current restart process using the above example

Location	Description	Uncertainty
A	The coal black starter successfully tripped to house load. Safety checks are completed. This unit has an urgent need to reach 40% of its rated output within 30 minutes, otherwise it is at high risk of tripping offline with a substantially longer time to restart, potentially up to days.	Attempting to re-energise distribution load at a nearby township may be unsuccessful during daylight hours due to excessive DPV generation. The nearest town with reduced DPV contribution could be too far away for stable restoration without tripping network protections or avoiding voltage collapse.
B	There is a large industrial load relatively close by which could be used to meet the minimum load needs of the black start unit with ramping energisation.	The black start unit may not be capable of energising the very large transformers or large load blocks without generator or network protection relays tripping.
C	Load could be found further right via a long transmission line. Alternatively, generators to the left with less strict startup requirements could be used rather than the TTHL black starter.	Energising lines to the right may encounter similar distribution load unavailability while also being challenging to energise a long distance of high voltage (HV) line. Generators to the left may not be able to provide the necessary voltage support to counter line charging from exceptionally long transmission lines.
D	Other nearby coal generators may need to have supply restored quickly to avoid extending their time to return to service from hours to days. If they also TTHL, they will require stable load to be found quickly to remain viable.	If restoration is delayed until load is available, the adjacent thermal plants required in the restart pathway may go cold and significantly extend the restart timeframe. Additionally, some nearby coal generators have return to service times of days even with prompt restoration and cannot assist in the restoration process at all.
Notes	Using the transmission corridor to the left region as an aggregate MW load or generator could potentially aid in finding load or increasing the generation potential capacity simultaneously, providing a stable island to allow restoration to progress.	

3.1.2 Possible post-transition restart

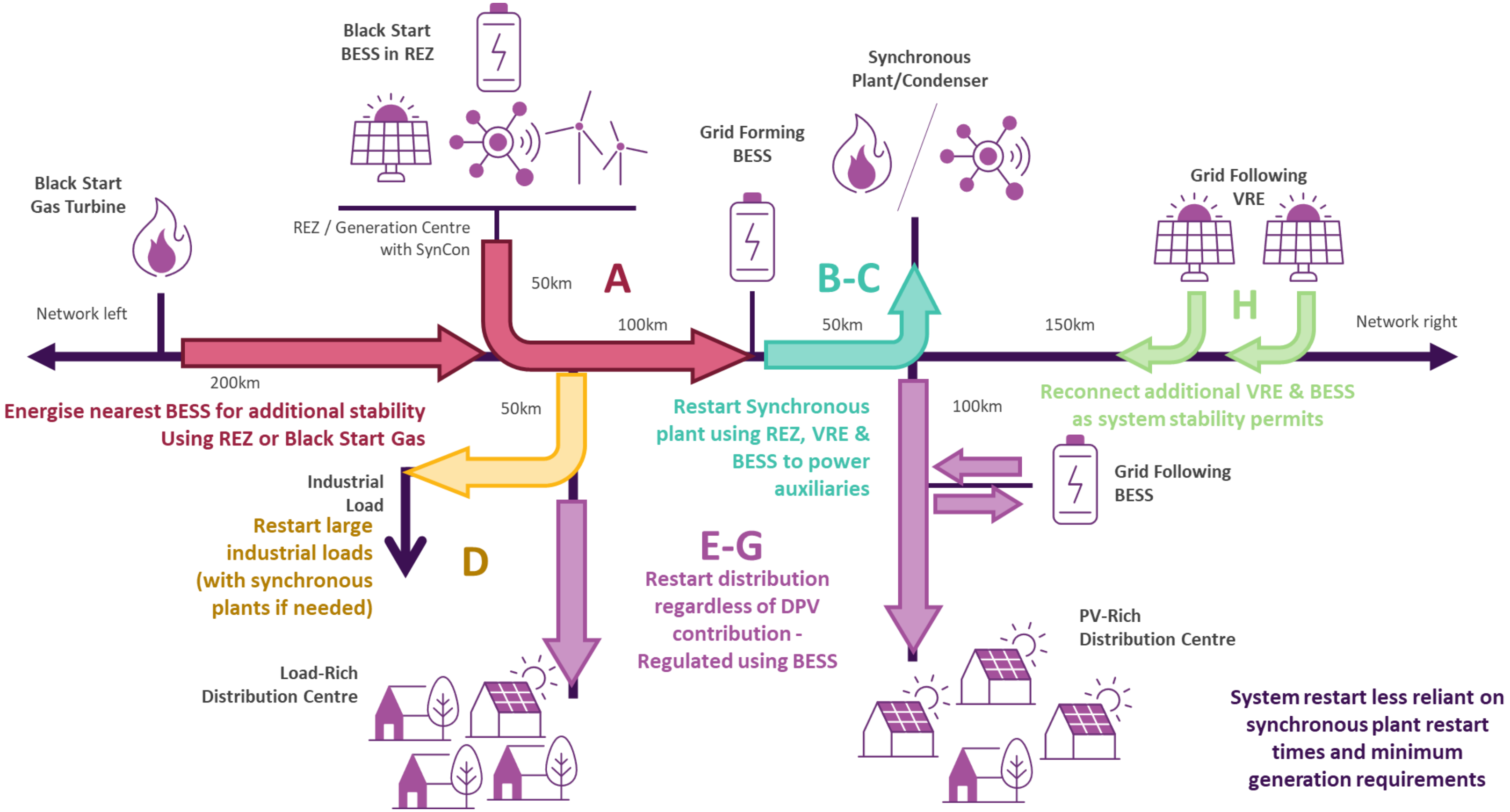
The following example in **Figure 5** and **Table 5** highlights a potential future showing how system restart could be delivered by an array of technologies as existing restart sources retire. This hypothetical idealised example of a potential future restart scenario incorporates proposed generation (in the form of REZs) and synchronous generation retirement, based on the same network as **Figure 4**. It is built on assumptions that:

- technical requirements for restoration as detailed in Section 3.3 are met by each the technologies present, and the technical capabilities have been tested and proven for black start conditions, and
- sufficient investment in black start capable generation has occurred in appropriate locations on the power system.

Such assumptions would need be confirmed for an actual pathway in future.

In this scenario, a REZ can provide a restart service by restarting nearby plant and network to form a stable island. The primary black start service in this example is a GFM BESS within the REZ, with feasibility contingent on a synchronous condenser being in an appropriate location started by the BESS to provide sufficient fault current requirements to stably energise other generation in the REZ. While black start capability from a GFM BESS has not yet been procured as an SRAS in the NEM, it is considered here as a potential future restart scenario, contingent on the technology demonstrating this capability in a relevant part of the network. Additionally, this scenario assumes that functional requirements detailed in Section 3.3 have been met, enabling the build-up of a restoration island and broader network. **Table 5** outlines a potential restart sequence to restore the REZ island quickly before stably energising nearby load.

Figure 5 Illustrative possible future system restart pathway reliant on proving of technology and additional investment



System security requirements to maintain during restart:

- Voltage stability
- Frequency stability
- Fault current levels (MVA)

Table 5 Description of the stages and technology differences of a future restart pathway

Location	Description	Assumptions
A	The GFM BESS within the REZ self-energises, and together with nearby synchronous condensers can energise nearby wind and solar plant, and begin restoring parts of the network. If the VRE plant within the REZ have generation potential at the time of restoration, output from the VRE of the REZ can contribute to active power and voltage support. The GFM BESS provides the main grid-forming capability, along with voltage and frequency control. Nearby synchronous condensers add stability through their contribution of fault current. In parallel, or as an alternative pathway, a black start synchronous unit energises the network and synchronises to the energised REZ.	• Sufficient investment has occurred in black start capable gas turbines or BESS and have been located appropriately. • IBR do not have large minimum loading and cooling risks of traditional thermal plants. • VRE is sufficiently firmed with storage state-of-charge (SoC) to provide stable supply (noting commercial implications of SoC reserve). • IBR has been tested and shown capable of restart. • IBR and synchronous condenser can provide sufficient system needs. • IBR for restart comply with AEMO's System Restart Communications Protocol.
B	A portion of the network is energised to connect to another nearby large BESS, and synchronous generators. Additional schedulable generation and load is now available, along with additional voltage and frequency control.	• Already energised network can provide sufficient system support for energisation of adjacent network and generation.
C	A synchronous condenser or gas turbine in the region is started to aid in the provision of fault current.	• Synchronous machine is appropriately located to support the restart pathway and provide fault current where it is needed.
D	The load can now ramp to levels determined by the availability of energy in the BESS and the REZ as well as already energised synchronous generators.	• IBR capability has been proven to allow a feasible restart within the technical envelope of the system. • Sufficient energy storage is present in the relevant BESS to support the full restoration, whether present inherently due to operation patterns before the black event or procured in advance.
E	Nearby town loads can be energised. Additional energy provided by DER (and any fluctuations that may occur) can be moderated by the large-scale BESS in the system.	• Sufficient DER visibility and controllability to AEMO and DNSPs to ensure the township can be energised without risk to the restarting system during daylight hours.
F	Additional large nearby BESS can be brought online either to help with generation or provision of load, depending on their state of charge. This may also include other generator types, including large-scale PV and synchronous options, depending on what is available.	• Acceptable SoC is present in the relevant BESS to support the full restoration, whether present inherently due to operation patterns before the black event or procured in advance.
G	Additional large DER-rich townships can be brought online without needing to wait until evening to avoid negative loads.	• Sufficient DER visibility and controllability to AEMO and DNSPs to ensure the township can be energised without risk to the restarting system during daylight hours.
H	Transmission-connected IBR can provide restoration support services to aid with voltage management on the energisation of large corridors.	• IBR have been constructed in advance with reactive power capability even when solar energy is unavailable.

3.2 SRAS possibilities for REZ and distribution

Historically, SRAS have been provided by individual synchronous generators providing a complete black start service. However, the increases in REZ and distribution-connected resources in the NEM warrant investigation of their potential applications in system restart.

3.2.1 Concentrated VRE/renewable energy zone utilisation

Capacity installed in concentrated regions of VRE or REZs will likely make up a significant portion of the generation fleet in the NEM over the next 10-20 years. Current REZ plans mostly consist of a combination of solar, wind and battery technology spread across a geographical region, with their energy output aggregated into one or more high-voltage connection points to the broader transmission network. Pumped hydro storage may also be present in some REZs. It is therefore beneficial to understand how REZs can contribute to system restart, whether as a black start source, a support service, or a smaller island capable of eventually joining a primary restart pathway. If a large REZ has network assets – such as very large transformers – that cannot reasonably be re-energised by the external network, it may be necessary to require that REZ to provide restart capability for its key network components up to its point of connection. This could involve the installation of a synchronous black start source within the design of the REZ.

In the context of system restart, there is currently limited experience using variable generation such as wind and solar as a black start source. A trial was completed in Scotland in 2021 demonstrating a wind farm's capability to energise itself and a portion of the connecting network, although the extent of network that was energised is unknown[15]. Emerging research consistently suggests that GFM BESS technology is capable of system restart and extended network energisation. This suggests that the combination of GFM BESS with wind and solar could provide black start-capable SRAS when designed for these capabilities from the outset, if adequately supported by assets such as synchronous condensers to provide fault current and other system security needs.

However, holding sufficient energy reserve to be able to restart could have commercial impact on SRAS-tendering plant within REZs. Such energy either needs to be stored in a BESS or provided by VRE, limiting BESS energy arbitrage ability or having unacceptably low reliability values due to weather variability. REZs would likely need firm generation installed, such as diesel or small-scale gas generators, to have enough energy adequacy to meet acceptable reliability and fault current requirements.

The following technical and non-technical factors must be considered before assets within a REZ can offer black start or restoration support services.

REZ-specific technical challenges

REZs will be commonly connected to the surrounding network at 500 kilovolts (kV) nominal voltages using large transformers and long transmission lines. To be feasible for REZ participation in system restart, sufficient fault current will need to be provided to energise large transformers and long transmission lines to form a stable restoration island. Many REZs will face the challenges outlined in Section 3.3.1, dealing with large transformers, network protection settings and high voltage connections.

Particularly, energisation of very large transformers from a REZ during a black system is unlikely to be considered in REZ design without specific incentive. This would also limit the REZ from energising its connection point transformers to resynchronise with the external system if it is undergoing restoration separately.

[15] See https://www.scottishpowerrenewables.com/pages/innovation.aspx.

Multiple parties

There may be multiple parties involved in a REZ which must coordinate to deliver the required service to the system on the day, requiring clear communication channels and consideration of operational implications. Coordination of multiple stakeholders can introduce operational challenges for system restart testing and SRAS utilisation on the day. Therefore, AEMO requires that SRAS resources comply with the System Restart Communications Protocol and have a 24x7 single point of contact, coordinated responses and test plans, along with regular testing of compliance with communication protocols[16]. Similarly, the coordination between physical communication systems between each party must ensure the same reliability as current SRAS specifications for single parties, as the coordination may be reliant on multiple telecommunication systems.

Roles and responsibilities

Under the NER, SRAS is predominantly an AEMO-managed service in coordination with Jurisdictional Planning Bodies (JPBs) and transmission network service providers (TNSPs) and within a centralised framework. However, some REZs have bespoke management arrangements that will need to be considered to integrate effectively into the system restart process for the wider NEM. This requires close collaboration between AEMO, regional authorities, and developers to determine a mutually acceptable method to integrate REZs into system restart.

AEMO considers it prudent that any SRAS requirements on REZs remain consistent with centralised requirements, allowing for consistent procurement, performance, and operational expectations.

3.2.2 Distribution island utilisation

Distribution system restart is a concept emerging from large uptake of embedded generation in the medium to low voltage distribution system, particularly in the United Kingdom[17,18] where trials have been held. The case study below describes work underway to enable distributed restart in the United Kingdom.

Distributed restart in the United Kingdom

The Distributed ReStart initiative by the National Energy System Operator (NESO) in the United Kingdom leverages DER for a bottom-up restoration approach. However, DER and distribution definitions are different in the United Kingdom compared to the NEM. There is a broader definition of DER and distribution in the United Kingdom – reasonably large (~50 MW) medium voltage (MV)-connected gas turbine units may be DER in the United Kingdom context, while this would be sub-transmission-connected scheduled generation in Australia, and is comparable to several actual black-starters in the NEM. There is considerably less distributed rooftop solar penetration in the United Kingdom compared to the NEM and WEM.

Therefore, distributed restart would require a different approach in the NEM, and is not something AEMO understands to be feasible in the near term using existing DPV, embedded generation and distribution-connected resources.

[16] AEMO (2021), System Restart Communication Protocol, https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2019/lbsp-amendments/system-restart-communications-protocol.pdf.

[17] Refer to the National Energy System Operator (NESO) project page, https://www.neso.energy/about/our-projects/distributed-restart.

[18] ReStart Project Final Findings, https://www.neso.energy/document/271831/download.

United Kingdom restart process

Anchor DER Units:

- Selected distribution-connected generators act as anchors to form stable microgrids or distribution restoration zones (DRZs).
- These zones grow outward by sequentially energising lines and loads until connecting to the transmission network.

Control System Innovations:

- The DRZ Control System (DRZ-C) automates coordination between DER, ensuring stability in voltage and frequency during restoration.

Restoration from the distribution versus transmission networks

Table 6 below highlights the strengths and challenges of transmission- and distribution-led system restart approaches. While there is limited experience with distribution-led system restart, particularly in Australia, international trials of the approach show promise and merit further investigation into how distribution resources can contribute to system restart across the NEM. As per the United Kingdom example above, it is anticipated that a distribution-led restart would need to be initiated by distribution-connected synchronous generators to meet technical requirements for successful restart.

Table 6 Comparison of transmission and distribution led system restart

Transmission network	Distribution network
Inherent strengths	**Inherent strengths**
• Strong capability to manage large-scale generation and transmission of power over long distances. • Easier to form large, stable islands with synchronous generators providing natural inertia and voltage support. • Higher capacity and fewer operational complexities compared to distribution-led approaches.	• Higher flexibility and localisation well-suited for microgrid-based solutions or areas with high renewable contribution. • Local loads could be restored sooner. • Synchronising a balanced distribution island with a transmission island would be low risk due to both being balanced. • Opportunities for parallel restoration rather than sequential could increase efficiency if manageable.
Inherent challenges	**Inherent challenges**
• Reliant on fewer restoration pathways/options. • Energising large transformers and extra-high voltage transmission lines can be problematic under low fault level conditions.	• Limited in scale and power-handling capacity, with challenges in energising long distances or supporting large loads. • Highly dependent on the type, capacity, and control capabilities of distribution-connected generation. • Increased risk of cyberattacks due to reliance on digital communication and control systems. • Many control services for DPV are dependent on the internet being available through public telecommunication networks. • Complex stakeholder coordination and difficulty maintaining stability in small islands formed by distribution-connected generation. • Australia has a considerable amount of inverter technology installed that does not meet the latest controllability and performance standards. • Distribution restoration struggles with energising high-voltage transmission lines or supporting heavy industrial loads.

In the NEM, distribution network-initiated restart utilising DER is not envisaged or expected to provide a black start service capable of energising the broader network in the near term. However, distribution island restoration using distributed synchronous machines may be able to address localised needs and enable faster recovery for specific areas. With sufficient development of network and operator capability, distribution islands could be a useful tool to quickly restore parts of the distribution network while broader system-level restoration functions are being conducted in parallel at the transmission level.

3.3 Functional network requirements for system restart

This section highlights key capabilities and considerations of current technologies expected to be readily available and potentially capable of supporting system restoration. To facilitate the technologies and pathway options discussed above to accommodate a high-IBR future for the power system, technical factors of existing network infrastructure should be carefully considered.

3.3.1 Static VAR compensators (SVCs)

SVCs are dynamic reactive power devices installed in the network for dynamic voltage control over a wide range of system conditions. Their performance, however, is impacted under system restoration conditions. In particular, their ability to regulate voltage depends on the presence of sufficient system strength (specifically fault current), which is weak during restoration. Additionally, SVCs may experience resonance issues or reactive power hunting, further impacting stability in weak grid conditions. Therefore, SVCs are currently avoided where possible during restoration due to potential instability.

However, the following characteristics enable SVCs to support restart pathways:

- Automatic gain reduction when oscillations are detected, reducing the likelihood of sustained instability during restart, and preventing potential primary equipment damage and restoration collapse.
- An ability to remotely switch to open-loop control mode to remove instability-prone closed-loop Q or remove voltage control altogether, allowing operators to manually adjust reactance as required.
- Ability for staged reintroduction or temporary blocking of SVCs during early restoration stages and reintroduction as fault level increases.

SVCs can provide valuable dynamic voltage control when synchronous generators involved in system restoration reach their maximum reactive power limits and other options are exhausted.

3.3.2 Static synchronous compensators (STATCOMs)

STATCOMs are voltage source converters that provide similar reactive power support as SVCs but have slightly different performance characteristics. They have similarities to IBR, including a susceptibility to instabilities in low fault level conditions, common during system restoration. These instabilities are primarily caused by fast control loop dynamics, phase-locked loop (PLL) interactions, low inherent system inertia, and fault current.

To enhance the stability of transmission-connected STATCOMs during system restart conditions, the following functionality is recommended:

- Automatic gain reduction when oscillations are detected, reducing the likelihood of sustained instability during restart causing restoration collapse or equipment damage.
- Ability to remotely switch to manual operating mode to allow operators to adjust reactance as required.
- Tolerance to larger swings in frequency and voltage than seen during system normal and set in the Frequency Operating Standard.
- Ability to operate in low fault level scenarios, with co-optimised inner and outer control loop gains to be compatible with both system normal and weak systems.

Some GFM STATCOMs have been deployed globally[19], which could alleviate low fault level instability issues and bolster stability during system restart. This is an emerging technology that merits further consideration in the Australian context.

STATCOMs generally cannot self-energise and require external energisation before being operational in system restart. However, certain GFM STATCOMs equipped with supercapacitors or other energy storage systems may be capable of limited self-energisation or of providing initial voltage support before external energisation. Even if self-energisation is not possible, these enhanced STATCOMs (E-STATCOMs) with GFM capability could play a valuable role in system restoration, particularly in weak grid scenarios where traditional STATCOMs might struggle to remain stable.

3.3.3 Synchronous condensers

Co-optimising the design of some suitably located synchronous condensers to assist with system restoration may be essential to supporting future system restart scenarios. The following functional requirements for relevant synchronous condensers may support network future system restoration:

- Black start capability via pony motors and the ability to re-energise the point-of-connection transformer. This allows synchronous condensers to contribute early to the restoration process by reducing startup current requirements on the system.
- Tolerance to large swings in frequency and voltage which are likely to occur under system restart conditions. Synchronous condensers and protection settings must operate effectively under these conditions without premature tripping or loss of stability.
- Significant reactive power absorption capability as high voltage energisation is commonly challenging during system restart with low loading conditions. Overvoltages are common in these instances and traditional synchronous condensers may struggle to absorb enough reactive power to mitigate this. Modifications to the excitation system – such as improved voltage regulators, alternative excitation controls or coordinated operation with other reactive support devices – may extend the operable reactive absorption range.
- Damping capability through Power System Stabiliser (PSS) integration to minimise oscillations in weak, low inertia power systems. Undamped oscillations in synchronous condensers can lead to sustained low-frequency oscillations or restoration island collapse if not controlled.

[19] See https://www.esig.energy/first-grid-forming-300-mvar-statcom-in-germany/.

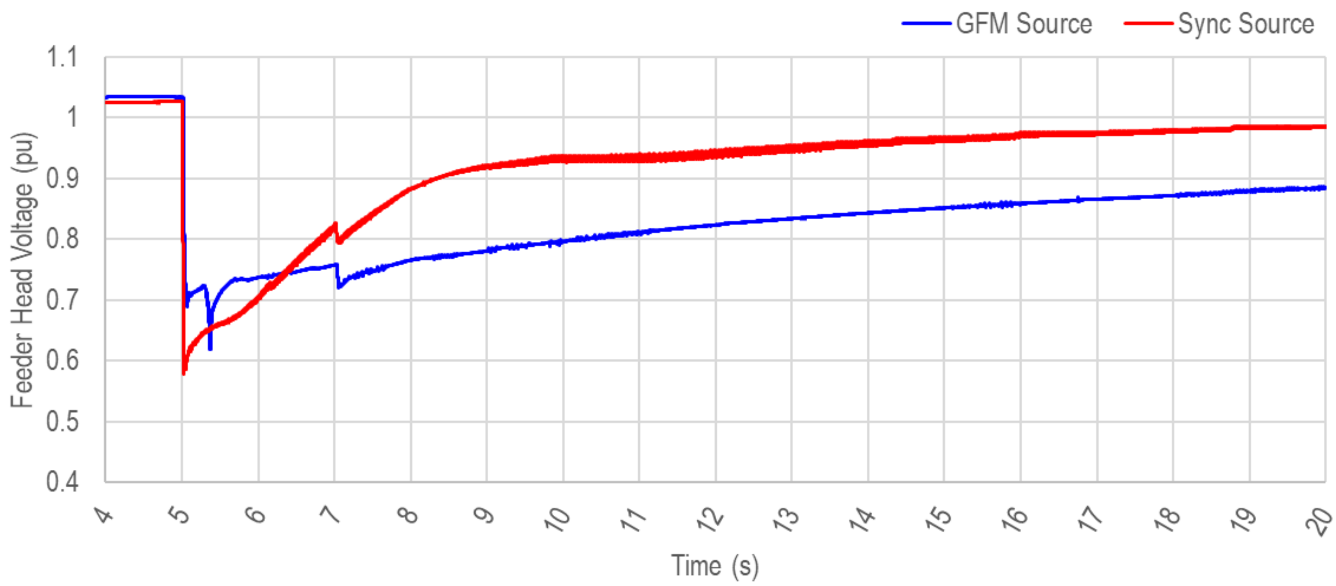
- Modern synchronous condensers, such as those installed by Terna in Italy, incorporate PSS to enhance damping capability during normal system operation[20]. A PSS improves the dynamic response of the synchronous condenser by modulating the excitation system to damp power swings effectively. While such functionality is important during normal system operation, it may not be necessary for system restoration.
  - The inclusion of a PSS is particularly beneficial when multiple synchronous condensers are present in a weak system, as poor damping could result in interactions or poorly damped inter-area oscillations.
  - If a PSS is not implemented, alternative methods for supplementary damping control should be considered, such as modifications to the excitation system or coordination with other damping sources (for example, SVCs/STATCOMs with damping controllers).

In summary, there is significant opportunity for synchronous condensers being installed for system strength purposes to include functionality that will assist in the weak grid conditions present during a system restart event. This includes black start capability, tolerance to large frequency and voltage swings, reactive power absorption capability, and damping capability. This co-investment opportunity is discussed further in Section 4.2.

3.3.4 Large transformers

Very large transformers are likely to be in the path of future restart options, particularly as they are likely to be used as the connection point of REZs. Using IBR devices to establish a restoration island via connections to the extra-high voltage (EHV) network using very large (600 MVA+) transformers may be difficult. IBR devices have limited to no overcurrent capacity, meaning transformer energisation from purely IBR devices may be challenging due to the large transformer inrush current requirements. This results in extended undervoltages, risking tripping of equipment. **Figure 6** shows this extended undervoltage profile compared to a synchronous machine source.

Figure 6 Example system voltage profile differences based on type of restart source



[20] G.M. Giannuzzi, *An innovative power system stabilization method with augmented inertia synchronous condensers*, CIGRE Science and Engineering Journal, CSE N°27 - January 2023.

This challenge may halt restart pathways from being able to energise past these transformers at the EHV level if dependent on IBR sources. Testing of restart pathway transformer energisation is therefore recommended for SRAS sources. Some potential alleviations are listed below with varying complexity and expense requirements:

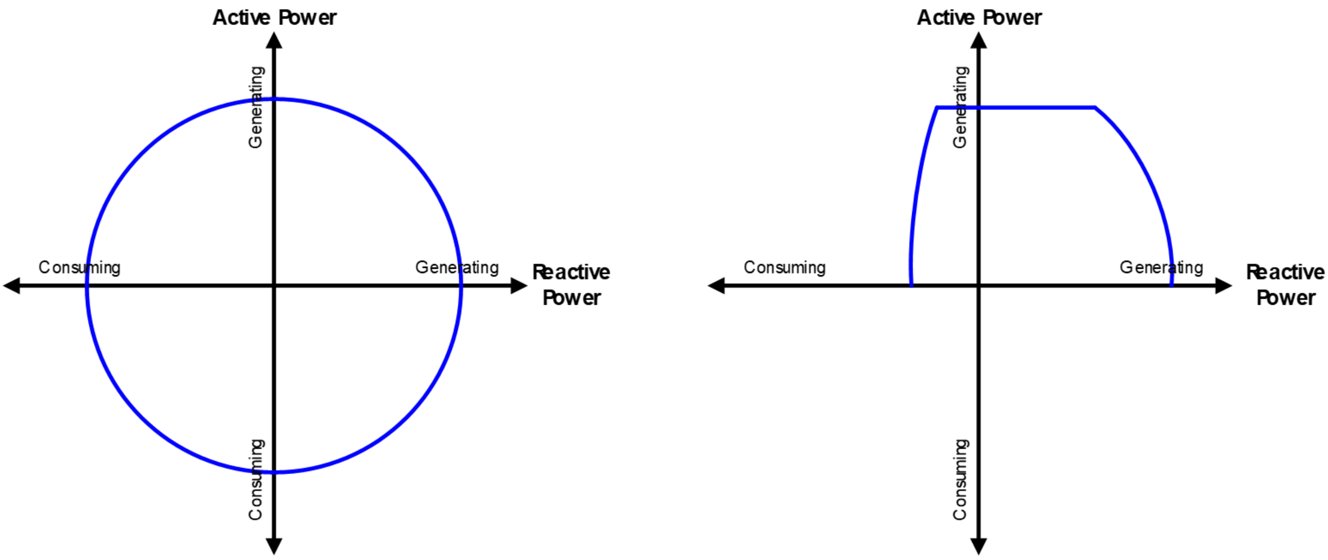
- Energising the transformer at the correct moment in the voltage wave cycle via point-on-wave switching. This can significantly minimise inrush currents, but from a practical perspective, experience has generally been that the dependence on the timing of mechanical action complicates accuracy, varying with equipment age, ambient temperature, and other factors.
- Transformer soft-starting over 10-30 seconds, significantly reducing the current drawn by the transformer to re-establish the flux in its core. Historically used by IBR and synchronous plant with great success, although requiring alterations to protection systems only applicable to the first major transformer to be energised. Additional transformers encountered along the restoration path cannot be soft-started, and instead must be energised via switchgear at nominal voltage.

3.3.5 High voltage connections

Extra-high connection voltages (voltages greater than 230 kV) are already present throughout the NEM and are expected to be used by many future sources of generation, including REZs.

Extra-high connection voltages (such as 500 kV) are generally avoided during system restart due to lightly loaded EHV lines usually requiring large absorption of reactive power (megavolt-amperes reactive [MVAr]) by restarting units. MVAr absorption has historically been a problem for synchronous generators during restart, as their operating point under these conditions leads to reduced stability, increased oscillation magnitudes in dynamic responses and protection risks. However, MVAr absorption is less challenging for IBR devices. They have more reactive absorption capability compared to synchronous machines, shown in the stylised diagram in **Figure 7**.

Figure 7 Stylised typical nominal capability diagram for IBR BESS (left) and synchronous generator (right) at unit terminals



However, if a restart is reliant on synchronous condensers for restart services, synchronous generator challenges may apply due to reactive power absorption requirements. Voltage compensation must be carefully considered and included in the network pathway as required. Additionally, centralised or per-plant filter capacitance may be common in future to mitigate IBR generated harmonics. Such capacitance may need to be deactivated during restart to preserve reactive power absorption headroom while re-energising EHV transmission lines.

3.3.6 Role of interconnectors

In historical restart circumstances, interconnectors have proven to be highly reliable in assisting the restoration of a region via a nearby unaffected region. While not procured as SRAS, the use of interconnectors for restart in the event of a shutdown of one region is already considered under current black start plans and was successfully used during the 2016 South Australia black system event.

When including an interconnector in a black start plan, the following reliability attributes may be considered:

- The presence of at least two circuits.
- Historical resilience to major weather events and bushfires.
- A low rate of forced outages along with a strong maintenance regime.

Interconnectors used during restart should also be a natural electrical breakpoint in the network. Should a regional system collapse occur, interconnectors can typically form a breakpoint between the regions, resulting in the healthy region not being pulled down along with the collapsing region. Lower-impedance, shorter interconnectors should not be used during restart unless specialised protection devices have been installed to ensure they remain a natural breakpoint between regions.

Additionally, the selection of an interconnector for use in a system restart plan will largely be based on network reliability factors and historical data of both its dynamic performance and availability. If the interconnector has not already been contemplated as an intentional network breakpoint, protection studies will be required to implement the necessary relays in the field to maximise the success of a clean regional separation during system collapse (for example, installation of a loss-of-synchronism relay).

In summary, if an interconnector is to be used to form part of a black start plan, it must be highly reliable, regularly tested and a natural breakpoint.

3.3.7 High voltage direct current (HVDC) links

HVDC links are interconnectors that operate as direct current (DC), with DC-to-alternating current (AC) conversion at each end. HVDC links may form part of restart pathways in the future, and different types of DC-to-AC conversion will likely perform differently with respect to system restart. Notably, if an HVDC link is to be used as primary black system-starter while supplied by other generation, it must be of the GFM variety. However, grid-following (GFL) systems could still prove useful following early re-energisation to assist with maintaining system properties within nominal bounds.

The three main types of HVDC technology are line-commutated converter (LCC) HVDC, GFL voltage-source converter (VSC) HVDC, and GFM VSC HVDC. At a high level:

- LCC HVDC has lower construction costs and can generally provide the highest fault current. LCC does require external energisations, has a minimum acceptable fault level, and is unable to provide black start stability.
- GFL VSC HVDC can support voltage and frequency with droop control but cannot provide the reference for each of these and will have limited fault current capability. Black start capability is therefore not possible unless local auxiliary synchronous generation is installed.
- GFM VSC HVDC can provide the frequency and voltage reference to enable primary black start stability while also offering fault ride-through. GFM HVDC has similar limited fault current characteristics as GFL HVDC, unless the GFM converters are oversized to increase current capability.

Table 7 outlines in more detail the technical capabilities of these common HVDC types, including any functionality that could enable them to assist with restart events.

Table 7 Comparison of technical capabilities of HVDC link types

Aspect	LCC HVDC	GFM VSC HVDC	GFL VSC HVDC
Black start capability	• Requires an energised AC network or synchronous generators for commutation. • Some LCC HVDC systems with auxiliary energisation and synchronous condensers can support limited black start.	• Can independently provide black start, generating voltage and frequency autonomously.	• Cannot independently black start; requires an external grid reference for operation. • A small auxiliary generator (such as a diesel generator) could be used to provide the necessary reference for black start.
Voltage and frequency control	• Relies on external AC voltage for operation, limiting its control capabilities.	• Establishes and regulates grid voltage and frequency autonomously.	• Requires a stable grid voltage and frequency reference for synchronisation and cannot independently set system voltage or frequency. • Can operate using both voltage and frequency droop control, coordinating with other sources in the system, including black start synchronous generators.
Fault current contribution	• Thyristors generate higher fault current than insulated-gate bipolar transistors (IGBTs), and most LCC HVDC links incorporate synchronous condensers, further increasing fault current contribution. This results in relatively high fault currents but does not contribute to improving system stability.	• Limited fault current contribution but offers fault ride-through with advanced controls and oversized converters.	• Same as GFM VSC.
Reactive power support	• Requires external reactive power compensation (for example, capacitor banks and synchronous condensers).	• Provides dynamic reactive power support, enhancing grid stability and energising transmission lines.	• Can provide dynamic reactive power support when enabled but requires an external voltage reference.
System strength	• Relies on a minimum level of system strength provided by synchronous generators or condensers. Does not inherently contribute to strengthening the system.	• Provides system strength via GFM capabilities.	• Does not improve system strength and relies on an established grid to operate effectively. • Compared to LCC HVDC, requires much lower fault levels and system strength to operate stably.

Aspect	LCC HVDC	GFM VSC HVDC	GFL VSC HVDC
Inertia support	• No inherent inertia contribution and relies on synchronous generators in the network.	• Provides fast frequency response (FFR). • Due to limited local energy storage capacity compared to BESS, GFM HVDC cannot directly provide inertia. Instead, it modulates power transfer between interconnected grids to emulate inertia-like behaviour. Actual inertia contribution depends on the characteristics of the connected systems.	• No inertia contribution, increasing reliance on external systems for frequency control.
Transmission distance	• Highly efficient for long-distance, high-power transmission in strong AC networks.	• Equally efficient for long distances but better suited for weak grids and islanded systems.	• Efficient for long distances but unsuitable for weak or islanded grids during black start.
Startup requirements	• Requires a pre-energised AC grid or a small synchronous island for startup. Some LCC HVDC systems can be designed with auxiliary startup mechanisms.	• Needs auxiliary systems (such as BESS) to pre-charge converters but can establish a grid once energised.	• Requires a pre-existing grid voltage for synchronisation. • Cannot initiate black start on its own, but an auxiliary generator (such as diesel) can provide the necessary reference.
Integration with IBR	• Can integrate with IBR but requires strong system conditions and reactive power support to operate reliably.	• Fully compatible with IBR, enabling GFM and low-inertia operations.	• Compatible with IBR but dependent on GFM sources for operation.
Control complexity	• Simple controls but less flexible for weak grids or isolated systems.	• Advanced controls needed for GFM operations and fault management.	• Simple controls but reliant on grid stability and external systems for restoration tasks.
Fault recovery	• Slow fault recovery due to reliance on external commutation and reactive power support.	• Robust fault ride-through capabilities with modular multilevel converters (MMC).	• Limited fault recovery capability due to lack of GFM controls.
Geographic application	• Suitable for strong, interconnected grids with large synchronous generator or condensers nearby.	• Ideal for weak, remote, or islanded grids, and systems with high IBR penetration.	• Can operate under low system strength conditions during system restoration, although less effective than a GFM VSC.

Currently, there are three existing HVDC links in the NEM, and a possible fourth coming in the future. While existing HVDC links in the NEM may not be black start capable, they could be capable of providing restoration support services. Future participation of HVDC in NEM system restoration will require modelling, testing, and possible retrofit or augmentation depending on the type of SRAS desired from these resources (see Section 4.2.2). Regardless of the type of SRAS they could provide in future, each HVDC link presents a potential SRAS resource to be explored further.

3.3.8 Network protection and control schemes

During the early phase of system restart, fault level may be low, which could result into excessive harmonics, easily corruptible voltage waveforms, and phase angle jumps. Such conditions should be tolerated during system restart if they do not pose a genuine risk to network assets. The severity of this weak system challenge could intensify and vary locationally if synchronous plant are withdrawn and integration of IBR into the restart process is increased. A key consideration will be the presence of system strength solutions, such as synchronous condensers or other synchronous machines (Section 3.3.3). In summary, during system restart, network control devices and protection relays along restoration pathways will continue to rely on existing protection requirements and fault levels met by synchronous sources, as per existing requirements for protection-quality fault current.

Comparisons between system normal and restoration conditions

Further to the above, **Table 8** defines some of the major changes in system characteristics between system normal and system restoration which must be factored into the design of any protection schemes likely to be in use at the time of restoration.

Table 8 Changes in network conditions between system normal and restoration

Parameter	System normal (low IBR, traditional grid)	System restoration (with or without IBR)
Fault current levels	High, dictated by synchronous generators.	Highly variable, dependent on available resources (IBR versus synchronous machines).
System impedance	Stable, well-defined impedance zones.	Unstable, changes frequently due to switching, islanding, and re-energisation.
Coordination	Consistent with pre-determined relay settings.	Requires dynamic relay coordination as topology changes. Communication-assisted schemes may be necessary.
Relay sensitivity	Calibrated for high fault current conditions.	Variable, and at times low, fault current conditions.
Transients (inrush)	Significant inrush during transformer and motor energisation.	Transformer and line inrush can be severe with synchronous machines, but less pronounced if IBR dominate restoration.
Dynamic conditions	Power swings are rare under stable grid conditions.	Frequent transient swings, especially when resynchronising islands. IBR-heavy restoration may introduce additional PLL-induced instability.

3.4 Functional generation requirements

The following outlines performance requirements from generators that are likely to comprise a part of a restoration plan for a system with high IBR penetration. Some proposed capabilities are difficult to retrofit to existing plant but are described for understanding and future provision.

3.4.1 Black start service versus restoration support service from IBR

IBR technologies make up a growing proportion of the generation base in the NEM and are expected to become ubiquitous by the end of the transition. IBR could assist system restart in multiple ways. An IBR-based black start service uses an IBR plant to re-energise itself and a portion of the nearby system without requiring the supply of electricity from any external source. Black start services must be capable of energising up to their step-up transformer and enough transmission network to reach another nearby generator to form an island, including the ability to energise that generator’s step-up transformer or auxiliary supplies without soft-starting. This capability must be demonstrated in the NEM to allow an IBR to be procured as a black start service.

A restoration support service from an IBR would have fewer challenges than a black start service. The critical requirement for a restoration support service is to have a function in restarting the system that will support either maintaining the system within operational envelopes (for example, voltage or frequency control) or supplying or absorbing energy that will allow the system to meet any operational requirements (such as operating as a stable load within a restoration island to meet minimum generator loading). The plant providing this service need not be black starting and could instead be re-energised by another black start service.

It is important to note, however, that even where IBR installed on the grid today can provide network support services under steady-state conditions, inherent limitations in terms of their total steady-state and fault current mean not all these capabilities can be provided simultaneously, and enabling one capability could negatively impact another. Additionally, some of these capabilities may only be delivered at specific fault levels, which may not be achievable under the extremely low fault level conditions associated with system restoration conditions.

3.4.2 Generation energy adequacy

Many of the current and future SRAS tendering plant rely on an adequate stored supply of fuel, water, or energy to be available on the day to provide SRAS as needed. Without adequate energy reserves, these plant risk being unable to provide SRAS and in an actual restart scenario, could significantly impact the restoration process. For each generation type, there are energy adequacy risks and associated mitigations to consider.

Some generation types, such as BESS, only have internal energy storage capacity of up to a few hours at full output. For BESS, this energy supply may vary greatly throughout the day based on market conditions and determine what types of SRAS can be provided during a supply disruption. Other generation types, such as hydro, gas, and coal, typically can store enough fuel/energy reserves for many hours or days of continuous generation.

For coal and gas plant types, maintaining adequate on-site storage of fuel is necessary for providing SRAS. While both plant types are capable of significant on-site fuel storage, gas plant are at greater risk for fuel inadequacy due to their reliance on the gas pipeline network. Gas compressor stations without backup power capability may be impacted by a major supply disturbance and fail to provide adequate fuel flow to gas plant. SRAS-tendering gas plant can mitigate energy adequacy risks in several ways, such as dual-fuel capability with on-site diesel storage. This is discussed in greater detail below in the gas subsection of Section 3.3.2.

SRAS-tendering hydro plant should always ensure adequate water reserves to ensure energy is available on the day. The possibility of extreme weather patterns, mainly droughts, may necessitate a long-term strategic approach to ensuring energy adequacy for SRAS-tendering hydro plants. Some mitigations include:

- diversity in system restart procurement, ensuring that hydro alone is not the only restart source in a region (where practicable)
- requiring additional water reserve to be held for hydro sources designated as black-starters or providing system restoration services, and
- requiring additional water reserve to be held when an El Niño year is declared.

GFM BESS plant can provide multiple types of SRAS, such as generation or stabilising load services. For BESS plant, energy storage reserves largely determine what type of SRAS they can provide. For example, BESS with a low state of charge will be best suited to provide load services, and BESS with a high state of charge will be best suited to provide frequency support, inertia, and other GFM services. Depending on the form of SRAS tendered by the respective BESS plant, an appropriate state of charge should be reserved during required hours of the day to ensure capability of the service tendered when required so the power system can be restarted at any time. It is possible that a single SRAS offering could tender for different functions based on potential restarting scenarios and availability during each one.

3.4.3 Grid-forming plant

While there is limited experience and standardisation for GFM plant use in black start, their advantages and synergy with the NEM's high-IBR future present a clear opportunity. **Table 9** details the differences between GFM inverters and traditional synchronous machines. While GFM inverters have some drawbacks compared to synchronous machines, they are typically more capable than GFL inverters.

Table 9 Comparison of GFM inverters and synchronous generators for black start

Aspect	GFM inverters	Synchronous generators
Speed of response	Within a cycle for both voltage and frequency.	Fast response to voltage disturbances, but often the frequency response takes several seconds.
Fault current capability	Typically limited to ~1–1.2 per unit (pu), unless designed with overcurrent boosting. Currently, fault current from GFM inverters is not considered 'protection-quality' with further investigation required before they could potentially meet this need.	High fault current capability, at least 2 pu and potentially up to 3 pu at the time of fault clearance for a primary protection cleared fault.
Energy source dependency	Requires sufficient SoC, which could be a limiting factor particularly during system restart.	Hydro can operate indefinitely unless limited by head pond water level. Coal and gas plants can run for hours or days if adequate fuel is available (pipeline storage or dual-fuel capability with diesel storage for gas, on-site stock for coal).
Startup and complexity	Requires complex controls and auxiliary systems for startup.	Hydro and gas plants have simpler startup, but coal plants require significant warm-up time, making them slower to restart (hours for cold start), unless they have TTHL capability.
Presence of other plants during system restoration	May become unstable if the MVA ratio of GFL to GFM exceeds a threshold. Potential for control interaction with other GFM units, though no significant issues have been observed to date.	No inherent instability due to nearby GFL/GFM plants, unless torsional interaction risks exist, particularly in large thermal units.

There are several other advantageous capabilities of GFM inverters that can be of assistance during system restart events.

GFM plant are capable of soft energisation, able to energise transformers and transmission lines with controlled voltage ramps, reducing inrush currents during black start. While most synchronous generators can achieve soft start through controlled excitation, GFMs offer superior controllability and flexibility since their behaviour is fully defined by software rather than inherent machine characteristics. This allows precise regulation of voltage, frequency, and current, independent of mechanical constraints.

Additionally, multiple GFM plant generally have reduced synchronisation challenges compared to synchronous machines. This is because GFM inverters do not require precise phase-matching during connection, helping with progressive network re-energisation while reducing concerns over out-of-step conditions.

Despite these advantages, the use of GFM inverters in system restart must consider the specific challenges the technology may face in the near to medium term. For example, advanced control algorithms are required for stable operation of GFM plant, including managing unbalanced loads and coordinating across multiple GFM inverters. There is also a lack of industry standards and experience for GFM plant use in system restart. Interoperability challenges between different GFM technologies and vendors may also complicate system restart planning.

In summary, GFM plant is a promising technology that has capabilities that can be of assistance during system restart events. Further research and real-world testing is required to validate these capabilities and address any interoperability challenges between different GFM technologies that could complicate system restoration planning.

3.4.4 Battery energy storage systems

Large-scale BESS are increasingly common throughout the NEM as the daytime solar generation availability increases. Where such BESS are also GFM, often to avoid system strength charges in particularly weak areas of the system, these devices could be used during the restoration process as a potential black start source if capable of self-energisation. GFM BESS could provide the primary voltage reference the system requires to allow synchronisation of network devices, along with the ability to supply or consume energy as required.

GFL BESS, while not capable of providing black start capability as per a GFM BESS, could be used during the restart process as a restoration support service. Depending on state of charge, GFL BESS could also deliver high quality stabilising load, voltage control, and frequency control.

In using a BESS for provision of SRAS, the main technical considerations to allow the BESS to perform as a load or generator while supporting the system are:

- an appropriate state of charge to deliver a supply or consumption service for a pre-defined time
- sufficient inverter headroom (including system strength for operation in a weak network) to provide frequency and/or reactive power compensation to the network, and
- sufficient fault current to support the system's technical envelope.

BESS devices have finite energy storage and cannot continuously export energy. Therefore, they provide limited opportunity to be black start sources on their own, because these should have the capability to energise the network and reach to the next generator to continue restoration. Tendering plant owners would need to ensure a portion of energy reserve is always maintained so the battery has sufficient energy to initiate restart if required. This has commercial implications and will need to be considered, as the storage reserved for restart cannot be used for energy arbitrage.

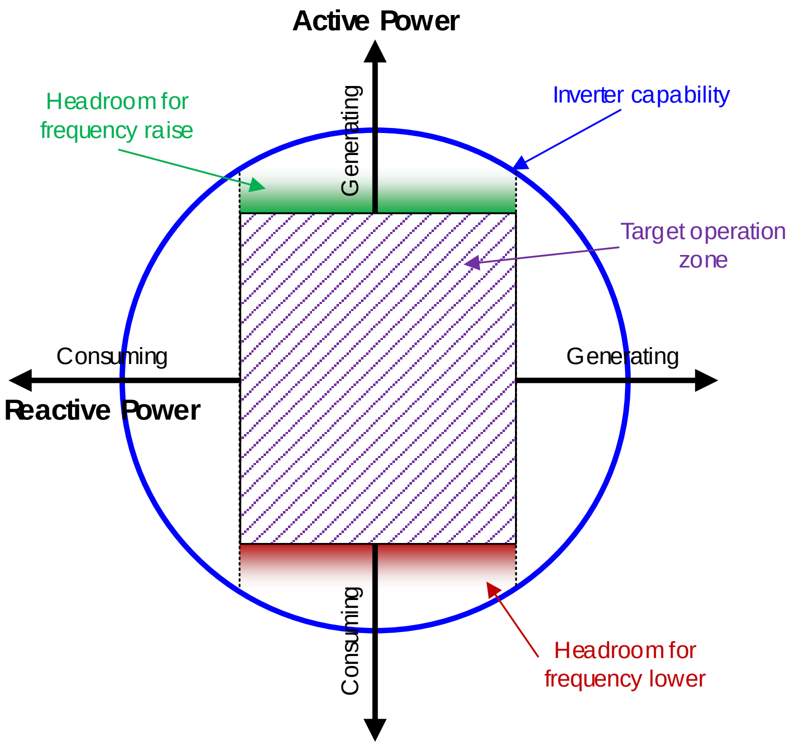
When considering financial incentives to hold sufficient reserve, there are opportunities to explore cooperative SRAS arrangements involving BESS whereby energy is supplied from other sources to maintain supply during restoration. Two such examples are:

- AC-coupled hybrid restart – the GFM BESS restarts itself and a small local network with minimal energy reserve. Another nearby plant with non-limited energy sources would supply the bulk energy required through the AC network. The GFM BESS provides the necessary GFM, voltage and frequency control to maintain a stable restoration island, without needing to hold large amounts of reserve prior to the event.
- DC-coupled hybrid restart (single plant) – the GFM BESS restarts itself and any auxiliaries. Another DC-coupled generator with non-limited energy sources supplies the bulk energy required through the BESS DC link. The GFM BESS is then able to provide SRAS without needing to hold large amounts of reserve prior to the event.

Note that this issue is equally applicable when a BESS is applied as a restoration support service in the form of a stable load. Acting as a load requires a portion of the BESS's energy reserve not to be charged to provide energy consumption at will. This issue does not apply as strongly if a BESS is used for other RSS, such as voltage support.

For use in system restoration, additional BESS capabilities such as GFM, inertia or black start must be considered on a case-by-case basis, due to their additional costs to include. **Figure 8** shows the typical capability curve of a BESS, which has been overlaid with a target operational zone to allow for a safety margin for unexpected network events.

Figure 8 Example capability curve and target operation zone for a BESS aiding with system restart



To be able to use batteries reliably during a system restart event, the functional requirements in **Table 10** should be considered.

Table 10 Functional generation requirements for BESS

Function	Black start	Restoration support service
Self-energisation capability	Must be available.	Optional.
Synchronisation mode	GFM.	GFM or GFL.
Reactive capability	Substantial part of nameplate rating, ideally meeting the NER automatic access standard under S5.2.5.1, without degradation for high and low voltages.	
Voltage	Direct voltage control, capable of moving to voltage droop later in restoration.	Direct voltage control or droop based voltage control.
Frequency	Determined by GFM algorithm, but ideally isochronous-like behaviour, capable of moving to frequency droop once multiple plant online.	At least frequency droop control.

Function	Black start	Restoration support service
Connection tolerance	N/A	Ability to reconnect and begin export to a system with wide frequency and voltage variations from nominal.
Energy storage	Dependent on the device's function in the specific system restart plan, but likely to require a reserve that is neither fully charged nor fully discharged.	
Protection capability	Increased tolerance to wider and longer under- and over-voltage conditions, underfrequency and overfrequency conditions (including fast rate of change of frequency [RoCoF]), large phase-angle jumps and extended fault conditions.	
Multiple restart capability (if island collapses)	Required.	Depends on support service offered.
General	Proven tolerance to low system strength conditions, both for individual inverter control system and the power plant controller.	

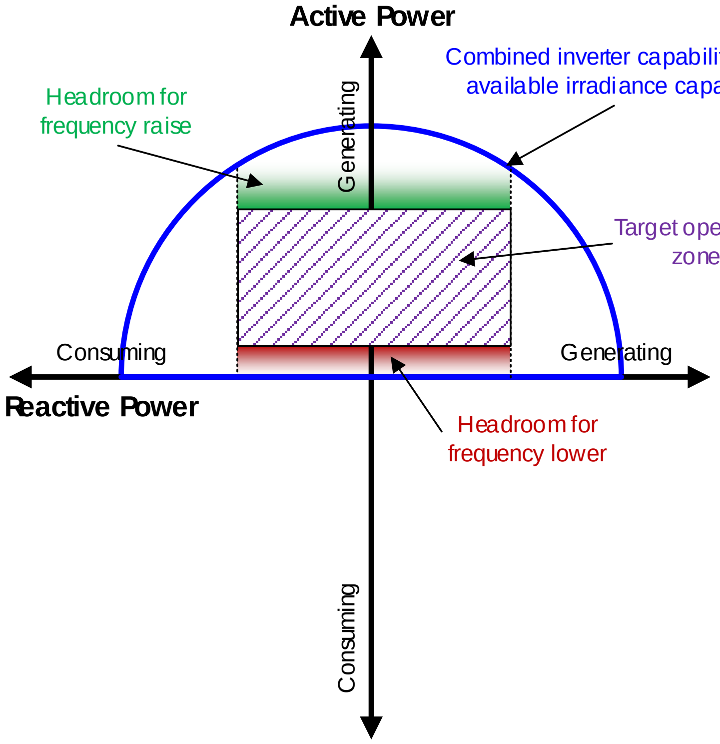
3.4.5 Solar plant

Solar plant have the potential to contribute to system restart, provided sufficient irradiance is available to sustain energy production. Compared to what BESS can offer for system restart services, solar plant:

- cannot absorb energy, so downward frequency regulation is not possible unless the plant is supplying a dedicated load to provide frequency lower headroom, and
- will need to curtail solar energy to ensure enough headroom to increase energy injection to provide frequency raise.

Figure 9 shows diagrammatically how these requirements map to an example solar farm capability curve, assuming no limitations on irradiance.

Figure 9 Example capability curve and target operation zone for a solar farm aiding with system restart



Compared to BESS, it is difficult to maintain the necessary conditions to enable the necessary tolerance to extreme disturbances during restart. The additional functional requirements from a solar source participating in system restart are summarised in **Table 11**.

Table 11 Functional generation requirements for solar

Function	Black start	Restoration support service
Self-energisation capability	Must be available.	Optional.
Synchronisation mode	GFM (currently not available).	GFM or GFL.
Reactive capability	Substantial part of nameplate rating, ideally meeting the NER automatic access standard under S5.2.5.1, without degradation for high and low voltages.	
Voltage	Direct voltage control, capable of moving to voltage droop later in restoration.	Direct voltage control or voltage droop control. Ideally with voltage control capability in the absence of irradiance.
Frequency	Determined by GFM algorithm, but ideally isochronous-like behaviour, capable of moving to frequency droop once multiple plant online.	Depends on whether GFM or GFL available, at a minimum frequency droop control.
Connection tolerance	N/A	Ability to reconnect and begin export to a system with wide frequency and voltage variations from nominal.
Energy source management	Capped below maximum potential to eliminate unbalances from irradiance variations.	Depends on support service offered (for example, if voltage-only, then no energy production required)
Protection capability	Increased tolerance to wider and longer undervoltage and overvoltage conditions, underfrequency and overfrequency conditions (including fast RoCoF), large phase-angle jumps and extended fault conditions.	
Overcurrent capability	>1.2 x desirable but not required.	
Multiple restart capability (that is, if island collapses)	Required.	Depends on support service offered.
General	Proven tolerance to low system strength conditions, both for individual inverter control system and the controlling park power controller (PPC).	

3.4.6 Hybrid plant

In addition to solar and BESS considerations, the following should be considered for hybrid plant:

- Hybrid power plant controllers may introduce instabilities. Care must be taken to ensure controller settings used for a hybrid plant are applicable during a black start scenario.
- AC power exchange behind the connection point must be kept to a minimum.

Due to different reticulation lengths between major components in hybrid plants, voltage disturbances will be different across the plant. This may mean fault ride-through (FRT) triggers across the plant may not operate together. If one device is closer to the point of the connection (typically the battery), the closer device may enter FRT while the remainder of the plant continues energy export. The large AC energy exchange may flow to the grid, potentially destabilising the system and causing a restoration collapse.

3.4.7 Onshore wind

All connected and committed onshore wind farms in the NEM are GFL. However, GFM onshore wind turbines have been proposed by some original equipment manufacturers (OEMs) and being currently assessed in practical grid connection applications.

Wind turbines can contribute to black start operations but are subject to significant mechanical stresses during these events. Proper integration with energy storage systems, use of advanced controls, and mechanical enhancements are critical to mitigating these impacts and ensuring the long-term reliability of wind turbines for system restart.

The following capabilities of wind generation must be installed before reliable inclusion in system restart:

- Plants should implement curtailment controls to stabilise power output and avoid rapid fluctuations during restart.
- Plants require supplementary systems like BESS to ensure consistent operation during restoration.
- Plants should include "park idle" mode to maintain system stability before being ramped up.
- Plants require advanced pitch and converter controls to handle mechanical and electrical dynamics during black start.
- More complex FRT design and coordination of electrical and mechanical system responses are needed to avoid excess torque on the turbine drive train.

In summary, while wind turbines can contribute to black start operations, they are subject to significant mechanical stresses during these events. Proper integration with energy storage systems, use of advanced controls, and mechanical enhancements are critical to mitigating these impacts and ensuring the long-term reliability of wind turbines for system restart.

3.4.8 Offshore wind

Offshore wind largely requires the same considerations as onshore wind farms. However, where offshore wind installations are connected using HVDC links, their ability to provide SRAS is reliant on the configuration of the HVDC system as well as the wind farm.

As HVDC links between the wind farm and the network are common in offshore wind farms, HVDC links must be GFM if used as a primary stabilising source during a black start. If the HVDC system is not GFM, an auxiliary onshore BESS, or external black start generator, must first stabilise the grid before the offshore wind farm can contribute.

Offshore wind farms typically feature an AC collector network before connecting to an HVDC transmission link. In a black start scenario, this offshore AC network must be energised first, requiring a GFM source before HVDC activation. Most current offshore wind farms installed globally lack GFM capability, requiring additional energy storage or external startup sources. As with other VRE technologies discussed, offshore wind can be paired with a BESS to further enhance its capabilities.

There are additional considerations for offshore wind farms at the onshore end of the network. Offshore wind farms may be located far from main load centres, requiring long AC transmission corridors or HVDC connections.

Energising long transmission lines from an offshore wind farm can result in high charging currents and overvoltages, requiring additional voltage control devices.

Considering the requirements necessary to provide black start capabilities for HVDC and offshore wind farms, a solution could entail the hybrid combination of GFM wind turbines, GFM HVDC link, and GFM BESS. During a restart scenario, the GFM BESS and HVDC would initiate the black start and stabilise the grid. With sufficient wind available, the wind farm would contribute to active power generation once established. **Table 12** further compares the roles and considerations of GFM offshore wind farm hybrid options.

Table 12 Comparison of GFM technologies in offshore wind farms

Aspect	GFM wind turbines	GFM HVDC	GFM BESS
Primary role	Provides voltage and frequency once stabilised but requires initial energisation.	Establishes voltage and frequency for wind turbines and offshore AC networks.	Initiates black start, provides stability, and supports other technologies.
Dependence on wind	Highly dependent on wind availability, making it unreliable for black start without storage.	Independent of wind conditions but requires an external energy source to sustain operation.	Independent of wind conditions, fully dispatchable.
Reactive power support	Limited by turbine design, may require external STATCOMs or synchronous condensers.	High reactive power capability, can support offshore and onshore grids.	High reactive power capability, particularly useful for weak grid restoration.
Flexibility	Requires favourable wind conditions to operate efficiently and may not provide continuous power.	Flexible, but may require onshore synchronous support when energising weak grids.	Highly flexible, capable of stabilising both offshore and onshore networks.

3.4.9 Pumped hydro energy storage (PHES)

Several major PHES projects are currently in development across the NEM, as it can provide long-duration storage, black start capability and essential system stability services. The suitability of PHES for system restoration depends on its design, particularly the choice of turbine and power conversion technology. PHES units can be fixed-speed or variable-speed types. For variable-speed PHES, there are doubly-fed induction machines (DFIM) and fully-fed system types. These design variations impact dynamic performance, efficiency, and the ability to support black start operations, particularly in grids with a high concentration of IBR:

- Fixed-speed PHES resemble synchronous generators, providing inertia, voltage support, and natural frequency stabilisation suited for system restoration in high-inertia grids but less adaptable to modern grids with a high share of renewables and variable loads.
- Variable-speed PHES (DFIM) have improved efficiency and operational flexibility compared to fixed-speed units but are only capable of limited GFM operation, making them more adaptable to IBR-dominated grids but requiring auxiliary systems for black start.
- Variable-speed PHES (fully-fed – full power conversion) have maximum efficiency and flexibility, allowing precise frequency, voltage, and power control. They are capable in high IBR grids and can provide black start support in weak or islanded networks, though practical demonstrations are limited.

Given these variations, careful selection of pumped hydro technology is essential to match the evolving needs of restarting the grid. **Table 13** provides a detailed comparison of these PHES variants.

Table 13 Comparison of pumped hydro variants

Aspect	Fixed-speed PHES	Variable-speed PHES (DFIM)	Variable-speed PHES (fully-fed)
Benefits	Simple design with synchronous machines.	High efficiency: Operates turbines near optimal efficiency across varying loads.	Maximum efficiency: Full control over speed and power output for precise grid support.
	Proven black start capability with natural voltage and frequency control.	Cost-effective: power electronics (converters) rated for slip power (10-30% of total power), reducing costs compared to fully-fed systems.	Full power control: Power converters handle 100% of the machine's power, enabling extensive flexibility in operation.
	Inertia contribution stabilises system frequency.	GFM capable: Advanced controls allow for black start capability and dynamic frequency and voltage regulation.	Enhanced grid support: Provides robust voltage and frequency stability in highly dynamic conditions, particularly in low-inertia grids.
	Widely tested and deployed for restoration scenarios.	Reduced mechanical stress: Variable speed operation minimises wear and tear on turbines.	Compatibility: Suitable for high IBR-based systems and offers advanced functionality for future grid requirements.
Challenges	Limited to fixed speed, reducing efficiency in variable load conditions.	Complex control: Requires advanced control systems (for example, DFIM).	High cost: Power electronics need to be rated for the full capacity of the system, increasing capital expenditure.
	Requires additional devices for dynamic reactive power and grid stability management.	Black start dependency: Requires auxiliary systems (such as batteries) for initial excitation and voltage build-up.	Higher losses: Fully-fed systems may incur higher losses due to full-scale power conversion.
	Less flexibility in handling modern grid challenges like high penetration of IBR.	Limited fault tolerance: Sensitive to grid faults; converter protection may trip under severe conditions unless designed robustly.	Increased complexity: Requires advanced power electronics, thermal management, and sophisticated control systems.
Differences	Operates at a single speed, limiting operational adaptability.	Partial conversion: Converters handle only slip power, reducing cost and complexity.	Full conversion: Converters handle 100% of the power flow, offering complete control of the machine.
	Provides natural inertia and reactive power from synchronous machines.	Balances between cost and functionality: Ideal for applications requiring moderate flexibility.	Maximum flexibility: Capable of advanced GFM operations and grid support.
	Lower cost due to reduced system complexity.	Suitable for grids transitioning to high renewable penetration.	Best for grids with very high renewable penetration where flexible, fast response is crucial.
	Simple black start operation without auxiliary systems.	Advanced GFM capability allows support in low-inertia restoration scenarios.	Extensive GFM features provide stability even in complex or weak grid conditions.
Restoration considerations	Best for high-inertia grids dominated by synchronous generators.	Ideal for grids with moderate levels of IBR; supports flexible restoration paths with partial power electronics.	Essential for grids with high IBR penetration, enabling frequency and voltage support during complex restoration scenarios.
	Provides synchronous frequency and voltage support immediately.	Handles long line energisation with significant reactive power contribution.	Energises long lines, regulates weak grids, and supports dynamic load pick-up during restoration.
	Limited to standard synchronous operation with fewer control options.	Auxiliary systems (such as batteries) required for black start and voltage build-up.	Fully powered by converters, enabling advanced black start scenarios even in low-inertia or islanded grids.

3.4.10 Gas

Gas generation has historically been a well-proven black start provider in the NEM, able to start independently from a de-energised grid and supply stable power during the system restart process. This section considers functional technical requirements for open-cycle gas turbines (OCGT) to include capability that enables the provision of black start SRAS. It also focuses on retrofitting units that were not originally designed with this functionality.

For gas generation to be made black start-capable, several technical requirements need to be considered.

First, in black start mode, auxiliary systems such as lube oil pumps, starting motors, gas valves, control systems, and air compressors must be energised by an independent on-site power source. Options include diesel generators, and BESS.

Control and automation systems must also be capable of supporting the following requirements. If retrofitting a non-black start capable gas plant, this would require upgrades to control and automation systems:

- Stable voltage build-up on a de-energised bus.
- Synchronise with other generation sources or with grid sections once restored.
- Provide frequency control in islanded operation, often in coordination with other resources such as synchronous condensers, diesel gensets, or BESS.
- Dead bus detection and auto-excitation schemes.
- Modified governor and automatic voltage regulator (AVR) settings suitable for island operation.
- Frequency and voltage droop control to coordinate load pickup and avoid instability.
- Isochronous mode operation.

Protection systems and anti-islanding capability may also need to be reconfigured if considering a non-black start-capable gas plant for SRAS provision. This includes:

- adjusted settings for under/overvoltage, under/overfrequency, and rate of change of frequency (RoCoF)
- islanding detection logic that permits intentional off-grid operation, and
- sync-check and reclosure protection for reconnection with other generation or restored grid sections.

Most gas turbines rely on natural gas supplied via high-pressure pipelines when generation is required for longer duration. During a widespread blackout, gas delivery may be interrupted if the associated pipeline network depends on electrically powered compressors or if the pressure in the pipeline drops below the level required to fuel the turbine. Any gas turbine including black start capability should therefore consider:

- installation of on-site gas compression equipment (electric or engine-driven) to ensure fuel delivery independent of grid power
- dual-fuel capability, enabling the turbine to operate on diesel or another stored liquid fuel during black start events
- installation of fuel storage tanks, such as diesel or liquefied petroleum gas (LPG), fuel forwarding pumps, and safety systems for liquid fuel operation, and

- auxiliary diesel generation on site to power key services, such as power, control, and fuel supply loads.

These requirements depend on plant configuration, as well as operating and fuel supply paradigms. SRAS-tendering plant should be assessed to ensure fuel adequacy, cold-start capability, and sustained operation during system black events.

It is likely that gas generation will be a key component of the system restoration in the future. Therefore, gas infrastructure would need to be reviewed for its adequacy in supporting system restoration.

3.5 Functional load requirements

3.5.1 Large loads

Large loads – including large industrial loads and sensitive loads – that may be restored early in the restoration process should have performance capabilities that support flexibility and reliability. The grid is at its weakest during the early stages of restoration, so access to stable and reliable loads is critical.

Ideally, large loads should demonstrate a tolerance to abnormal operating conditions likely to be present during system restoration. Example conditions might include not having power supply for up to several hours, and wide variations in operational voltage and frequency. Loads should have voltage and frequency ride-through capability to prevent unnecessary disconnection and demonstrate short-term resilience to phase jumps and unbalanced conditions.

Large loads themselves should also not cause adverse outcomes for a weak grid. For example, they should not introduce excessive harmonics into the grid, create resonances with problematic reactive impedances, or cause excessive transients considering in both warm and cold load pick up scenarios. Loads should also have defined factor-versus-time curves so nearby network capability can be assured to support any challenging reactive draw requirements.

Additionally, these loads should be flexible enough to be restored in an adjustable fashion to provide more manageable load blocks. Currently, load blocks of approximately 10 MW are required, although this may change in future with the technology mix used during restart. This might include a staggered or priority-based reconnection strategy which would also prevent sudden large inrush currents. Emergency load reduction capability is also desirable, so that if required, the load can operate at a reduced capacity to help stabilise the system.

3.5.2 Distribution network load

DER connected within distribution MV and low voltage (LV) networks may consist of DPV, home or commercial BESS, and electric vehicle (EV) charging infrastructure. Technical standards for DPV have recently been improved and implemented to support power system operation and avoid adverse operation such as tripping during disturbances. This is particularly important as the volume of DPV continues to increase in the power system. Compliance monitoring with these standards is also important to ensure there is a predictable response. Further analysis and monitoring for compliance with standards, and an improved understanding of DPV behaviour during the initial phases of system restart where grid conditions are abnormal and weak are required.

DPV active power export behaviour

Once supply has been restored following a black system event, DPV devices typically reconnect one minute after stable frequency and voltage conditions have been satisfied, and then ramp to maximum export (over six minutes).

When significant DPV is generating, this reconnection reduces the demand of the local network and across the entire system. While this is acceptable (and desirable) during system normal, the sudden (in minutes) and uncontrolled injection of energy from reconnecting DPV during restart may have a detrimental effect on a restarting system when stable load blocks are needed to support large scale generation operation. Should generators along the restart path have insufficient load available to meet their minimum active power export requirements, the unit may become unstable or trip offline to avoid mechanical damage. This may slow the restart process, or collapse the system again, extending restoration times and risking sensitive loads being exposed to long delays. Additionally, if TTHL black-starters were the primary restart source, typically having high minimum active power export requirements and unable to trip to house load a second time in short succession, the restart pathway may no longer be viable, and drawing energy from a neighbouring subnetwork may be the only possible restart pathway.

Management of the operation of DPV during a system restart is therefore important for the predictability and stability of load blocks required in the initial energisation stages of the restoration process.

3.5.3 Inverter-based loads

Inverter-based loads, such as data centres and electrolysers, are likely to become a growing proportion of industrial load across the NEM. They must perform with the same characteristics detailed in the large loads section and also have some additional considerations. Key requirements for both include the following:

- Tolerance to restoration delays – some loads have internal protection or control logic that may trigger a permanent shutdown or lockout if power is not restored within a narrow time window. This can require manual intervention or full re-initialisation during restoration. Designing loads to tolerate restoration delays helps avoid unnecessary restarts and supports system recovery.
- Gradual reconnection and load ramp-up capability.
- Defined power factor-time curve to ensure necessary reactive power support is available from the network.
- FRT compliance and defined performances consistent with pre-agreed voltage and frequency parameters.
- Voltage and frequency tolerance to avoid tripping after minor fluctuations.
- The ability to avoid exacerbating network instabilities by injecting excessive harmonics to the network.

Additional key requirements for data centres are:

- soft start capability to reduce demand spikes by gradually increasing power consumption over time (that is, do not operate in constant power mode), and
- uninterruptible power supply (UPS) coordination to sustain loads during initial restoration before synchronising smoothly with grid voltage.

Additional key requirements for electrolysers are:

- should only restart if voltage exceeds around 70% of nominal to ensure a stable chemical process
- restart must be delayable for a configurable period (typically 10-30 minutes) to avoid grid instability, and
- start-up should be prevented unless system conditions are within pre-defined operating limits.

4 Transitional opportunities

The scenarios and functional requirements described in Section 3 of this report help explain what is required for system restart to be low-risk, resilient, and successful in a high IBR future, including restarting with high amounts of IBR. However, before that future is achieved, there are some immediate to medium-term considerations that must be addressed.

There are several priority challenges already being observed when planning and procuring services for system restart (Section 4.1). Understanding how the current system restart framework and the SRS contribute to some of these challenges is important as a first step prior to considering solutions to address them.

Details on different technology types and capabilities in Section 3.3 inform how they can be considered during restoration events, however work needs to be done to understand the opportunities and viability of these resources in the near term.

The key findings and messages from this section are summarised in **Table 14** below.

Table 14 Summary of Section 4 key messages

Advice	Report section/s
Deployment of assets that support provision of essential system capabilities, such as fault current, should consider the abnormal and weak conditions that arise during system restart.	4.1.1, 4.1.3
Sourcing of appropriately sized stable load blocks during system restoration is crucial to maintaining a stable restoration island and enable continued re-energisation of the network.	4.1.6
The LBSP obligations and process should be strengthened to ensure AEMO receives accurate, up to date and reliable information for plant to ensure they can be securely energised during restart.	4.1.7
Communications and availability protocols for plant participating in SRAS should be reviewed to ensure consistency and resiliency under all restart scenarios, including cyber disruption.	4.1.7
Options to support adequate investment in SRAS including RSS capability should be explored, given the current SRS and associated procurement practices have not delivered consistent investment in new SRAS sources. Without this, there is a significant risk that insufficient new SRAS sources come online prior to the exit of existing providers. This should include consideration of ways to enable co-investment incentives so that new plant, resources and network assets are planned and designed with the capability to deliver multiple system services, including system restart.	4.1.10
To improve understanding of candidate technologies that have not previously been considered for SRAS, such as GFM plant, AEMO will undertake a program of priority technology trials. This may include the use of Transitional Services.	4.2.1
Network testing of SRAS pathways will become increasingly important as the system transitions. NER 4.3.6 should be reviewed to expand obligations for system restart network testing to involve existing and potential new restart paths where testing is required, with appropriate mechanisms for cost recovery.	4.2.2
Enhanced coordination with DNSPs is required to account for and actively manage the interactions between DPV and the power system during restart. AEMO is currently engaging with DNSPs on the data and models required to assess these interactions, and actively manage DPV on restart pathways. The National CER Roadmap Distribution System and Market Operation workstream is considering actions necessary to formalise these DNSP planning and operational coordination roles.	4.2.3

4.1 Short-term challenges

In the absence of pre-emptive action, there are several challenges expected to hinder a successful system restart following a major supply disruption in the short term – that is, in the next five to seven years, during which the next two SRAS procurement rounds are scheduled. These issues need to be considered and mitigated, if possible, when updating the SRS and when considering revisions to operational restart guidelines and procedures.

4.1.1 Capabilities required for a successful restart are not valued appropriately

Currently, procurement of SRAS by AEMO in line with the SRS is aimed at capability to reach a target number of MW in a relatively short timeframe. As the network, generation mix and load availability continues to evolve, confidence in the ability to restore the system beyond this initial target is declining. However, the current MW and time targets mean that the procurement of additional services, such as RSS that could be required at later stages of the restoration process, is not a likely outcome under the current SRS.

Furthermore, these MW-time values were set based on possible generation restoration with the historically available fleet of resources, and not because these values will allow for a successful and ongoing system restoration. The assumption that these values will allow for the energisation of other generators and loads to form a restoration island sufficient to restart the region to completion becomes increasingly uncertain unless it is continuously reviewed as the generation mix and network topology changes.

Another aspect not valued by the current SRS is the support services required to stabilise the system during a restart event when the network is weak and being carefully recovered following a black system event. The early-stage MW-time targets in the SRS do not create incentive for the procurement of services such as adequate fault current provision, negative-sequence current control, inertia, frequency control and voltage control. This is particularly important as the system evolves to have higher levels of IBR, some of which may be restart sources or reenergised early in the restart process when the grid is still weak.

Capabilities such as those mentioned above may not be available from all IBR plant, and therefore should be incentivised and valued, or where necessary procured as an SRAS to ensure they are provided. Confidence in the availability of these capabilities can no longer be maintained as was the case historically where all restart sources and reenergised generators were synchronous.

Even where IBR installed on the grid today can provide capabilities to support system restart, inherent limitations in terms of their total steady-state and fault current mean not all these capabilities can necessarily be provided simultaneously, and enabling one capability could negatively impact another. Additionally, some of these capabilities may only be delivered at specific system fault levels, which may not be achievable under the extremely low fault level conditions associated with system restoration conditions. As mentioned in Section 3.4, IBR are current limited plant, so the right network support services will need to be valued from IBR and all potential services cannot necessarily be provided simultaneously.

AEMO encourages the Reliability Panel to consider the SRS having a target further along the supply curve (as defined in Section 2.3), to enable the procurement of additional services where required to meet the technical envelope. This could be a point where sufficient supply to meet a high percentage of load is reconnected, allowing for the procurement of services that improve the ability to reach this point effectively and with a high level of confidence. As explained in Section 2.3, supply curves have a level of uncertainty which must be accounted for. Therefore, a target further along the supply curve should provide flexibility to define the right mix of services to procure based on available resources and viable restart pathways.

4.1.2 Generator and load flexibility

The system restart framework does not appropriately consider flexibility, resilience and minimum power requirements for SRAS sources. Some generators have physical limitations which make them extremely rigid in their requirements for delivering supply, despite being capable of meeting various metrics such as the MW-time targets stipulated in the SRS. Current drivers stemming from the SRS could therefore be preventing slower, but more capable, SRAS sources from being procured.

One example of a flexibility challenge for some generators is that they have minimum power levels they must deliver to the grid within a fixed time before they will disconnect from the power system or risk tripping offline. Most traditional restart sources, including TTHL, hydroelectric and gas turbines, have minimum active power export requirements. As such, they require supply of their minimum load to be able to remain online and operate stably for long periods of time. If minimum load is not met in time, the restart source risks tripping offline, requiring the restart process to begin again. With traditional black start sources and synchronous generation likely to remain part of restoration pathways in most regions for at least the next procurement round, the need to source sufficient load to meet their minimum stable loading of these generators will continue for some time.

Conversely, some generators are unable to energise moderately large load blocks without tripping offline. If the only load available in the nearby network is relatively large and must be energised as a whole, this may be beyond the capability of many generators. A generator capable of load pickup for loads of larger sizes is therefore more useful in some restart scenarios than one that is limited to small load blocks.

Alternatively, load which has the flexibility to be reenergised in manageable sized load blocks can assist in the early stages of restart. Of particular significance is that where large industrial loads must be energised in a significant bulk step, which requires sufficient step-capability of nearby generators. Step-capability refers to a generator’s ability to maintain voltage and frequency stability when there is a sudden change in load. Where the energisation of a load exceeds the step-capability of a generation plant, the plant cannot energise this load without tripping offline. This risk is exacerbated during system restart when the grid is especially weak. The current definition of manageable load blocks in the AEMO System Restart Plan is 5-10 MW during early phases of system restoration, and this definition extends to up to 10% of available generation capacity in later phases of system restoration. The preferred functional requirements for loads during future restart are discussed further in Section 3.5, and loads wishing to engage in the early stages of the restart process could improve their ability to be picked up under weak network conditions by being capable of restarting load in small enough blocks.

Often, multiple restoration pathways from different black start sources are run in parallel to form a restoration island, whereby their combined capacity can energise further into the network. However, to be able to run in a stable state with multiple units online, a minimum amount of load that meets the aggregate of all the unit requirements online must usually be connected early in the restoration path. Different generators have different load requirements, which are generally not considered in the current framework and procurement process.

In summary, flexibility in plant capability could be considered to have a higher reliability because it could better respond to a variety of potential restart scenarios where the size of available load blocks varies. To help encourage the procurement of flexible generation and load, the SRS could explicitly support AEMO valuing flexibility as a higher value service via service reliability requirements to assist with maintaining a stable restoration island.

4.1.3 Network protection performance

The current system restart framework does not adequately recognise and consider the need for increased tolerance of network protection and control systems during restart. During the early phase of system restart, fault level will likely be extremely low which could result into excessive harmonics, easily corruptible voltage waveforms and phase angle jumps. Such conditions should be tolerated during system restart, if they do not pose a genuine risk to network assets.

The severity of this weak system challenge could intensify and vary locationally as synchronous plant is withdrawn and the integration of IBR into the restart process is increased. A key consideration will be the design of replacement solutions, such as synchronous condensers, as discussed in Section 3.3.3. Design of such plant should consider system restart conditions, regardless of the investment driver or delivery mechanism for this equipment.

Where possible without compromising system security, network restoration pathways and their protection systems should be tested in the field to confirm the viability of their inclusion in any plan (see Section 4.2.2).

4.1.4 Considerations for network availability

The SRS is limited regarding the ability of AEMO to consider failures of network elements in restoration, and therefore consider alternative procurement options to cater for restart paths being unavailable. Although not impossible, a major supply disruption is unlikely to occur without network damage, particularly as weather extremes in Australia grow[21]. The diversity requirement in the SRS notes that AEMO must consider the failure of a significant transmission element, such as a single line or corridor that is downstream of the first transmission substation in the restoration path. This is relatively restrictive and relates to AEMO's current obligation to procure only to a point relatively early in the restoration path. If the procurement obligation were moved further along the restoration curve, AEMO would have some ability to consider the reliability of transmission infrastructure later in the restoration process.

Other approaches might enable AEMO to consider forced outages or unplanned constraints of restoration corridors where necessary to do so. Such methodologies would need to be transparent, but with an appropriate level of flexibility and allowance for imprecision.

Additionally, the current SRS results in precision in procurement to exactly meet the obligation. This does not suit a system which is currently undergoing a material amount of change and growing levels of uncertainty. Even in situations where the SRS is met, there may be known challenges or concerns with network equipment or corridors at high risk of network damage along the restoration pathways. Increased flexibility in the SRS could allow AEMO to procure a prudent amount of additional or alternative SRAS, in addition to the diversity requirement in the current SRS, to cater for these known challenges so that during an actual system restoration event, multiple options are available even if there is network damage.

[21] See http://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Integrated-Final-Report-SA-Black-System-28-September-2016.pdf.

4.1.5 Procurement of load

Sourcing load during the early stages of restart events is crucial to maintaining power system stability and allowing expanded network energisation. While the definition of SRAS is broad and enables AEMO to define the services it needs to meet the SRS, including load as a restoration support service, the MW-time target in the current SRS is met without the need to procure load to provide stabilisation. The procurement of load to maintain a stable restoration island and enable the continued expansion of the network is required for several reasons.

As discussed in Section 4.1.2, many traditional restart sources have minimum active power export requirements which require supply of their minimum load to be able to remain online and operate stably for long periods of time. The procurement of load to meet these minimum load requirements for long periods of time can increase the reliability and stability of a stable restoration island.

Similarly, when multiple smaller generators need to be operated in parallel to allow extended network energisation, there is a propensity for these units to oscillate against one-another if there is no load present in the restoration island. Such oscillations due to no load can also cause these units to trip offline to protect themselves from reverse active power oscillations.

The presence of load on the network acts to reduce excessive over voltages during restoration. High voltages due to lightly loaded EHV lines are a major challenge during restart, and the increased use of 500 kV interconnections for future REZs and *Integrated System Plan* (ISP) projects may only exacerbate this problem due to excessive line charging.

There is a clear need to procure load to help maintain power system stability in restoration islands and assist with expansion of the reenergised network. Moving the restoration target in the SRS further along the restoration curve with the obligation to maintain a stable restoration island at that level will support the procurement of load as an SRAS.

4.1.6 Stable load blocks

Further to the need to support the procurement of loads to maintain a stable restoration island discussed in Section 4.1.5, loads reenergised early in the process must be predictable and stable.

The prevalence of DPV across Australia is making it difficult to source stable and manageable load blocks. At times, particularly during sunny days, there is simply no load available to help stabilise the restarting system. In such cases, energisation of the distribution network could result in a net export of energy into the restoration island, exacerbating the stability problem or creating high frequency and therefore tripping synchronous plant. Options to improve the size of distribution load during periods of high DPV contribution are discussed further in Section 4.2.3.

4.1.7 Communication and control requirements

There is a need to review communication and control requirements for plant participating in SRAS, or NSPs operating network along restart paths, to ensure consistent and reliable operability during a restart event. Without confirming these requirements, there is a risk that SRAS delivery timelines will vary in real-world scenarios, or that SRAS sources may not be controllable at all. This needs to be evaluated with consideration of emerging cyber risks and use of evolving telecommunications technologies.

Communication with generators, NSPs and operators of aggregated plant during restart may become increasingly unreliable for several reasons. Under circumstances where public telecommunication networks are relied on to operate generators, failure or reduced availability of the telecommunication system could result in a contracted SRAS becoming inoperable.

There are several items for consideration to mitigate the risks of reliance on public telecommunications, such as 4G and 5G networks:

- Identify any dependencies of generators and network equipment on public telecommunications networks, identify how telecommunication failures would impact the plant, and if necessary, implement alternate arrangements to enable the device to participate reliably in restart.
- Consider controllability of generation to extend down below the 5 MW threshold where appropriate.
- Develop failsafe mechanisms which would allow plants both impacting local network performance and reliant on public networks to default to a known, useful state to aid in the efficient restoration of the system.
- Evaluate options to consider communication requirements in generator connections standards.

4.1.8 Staffing considerations

With generators increasingly being operated remotely, necessary expertise may not always be available on site, resulting in potential delays to restart times while staff travel to site if that is required. This has already led to inconsistent restart timeframes in at least one region, resulting in a failure to meet the SRS at certain times of day. Depending on the mode in which the generator trips from the grid during the black system event, there may also be need for staff to attend the plant on site to enable its reconnection to the grid. Further to this, satellite phones, typically stored onsite, are the dominant option for plant to meet current communication requirements. This can also introduce delays if staff need to travel to site to obtain them.

To mitigate the risks of remotely operated and supported plant, several topics are relevant for consideration:

- Require each plant to routinely demonstrate their ability to respond to NEM RTO directions within a specified timeframe, and through redundant systems.
- Impress the importance of the ability for plant operators to respond to NEM RTO requests with local expertise.
- Consider stronger repercussions for generators that fail to comply with a reasonable NEM RTO request in a timely manner due to an overreliance on infrastructure with low quality of service.

Without well-defined and consistent requirements, SRAS providers, particularly new ones, may not by default include any additional costs for local physical presence in their SRAS tenders.

4.1.9 Local Black Start Procedures

Under NER 4.8.12, generators, Integrated Resource Providers and NSPs must develop LBSPs in accordance with AEMO's guidelines. These LBSPs are used to create the System Restart Plan and relied upon by AEMO's control room during a system restart event to securely reconnect generation and network elements.

Due to the importance of LBSPs to the System Restart Plan, it is critical that accurate and comprehensive LBSPs are provided for all plant and network providers. Additionally, to maintain accuracy of LBSPs, plant and network providers should provide updates as changes occur which may affect their LBSP. Missing or out-of-date LBSPs, or LBSPs that may not match the technical capabilities of plant could lead to additional risk or delays when executing the System Restart Plan, and controls are needed to ensure these situations do not arise.

AEMO recommends that the LBSP process, framework and obligations be revisited and potentially strengthened following this review to ensure AEMO receives accurate, up to date and reliable information for all plant to ensure they can be securely energised during restart. Robust LBSP obligations and processes for all plant will also ensure AEMO can consider new viable restart pathways which may include facilities not previously reenergised during early restart.

4.1.10 Investment opportunities

The energy transition is occurring at pace, with a significant level of expected investment in new generation, network and loads in the coming years, providing an opportunity to ensure these resources have the ability to assist with system restart. This section highlights specific regional outlooks for SRAS investment and the relative investment costs required to include black start or restoration support service capability in new plant.

Given the limited investment in new SRAS sources in recent years, AEMO considers it a priority that the Reliability Panel explore options to incentivise future investment for SRAS. These could include enabling AEMO with the option to procure more SRAS (above minimum levels) to encourage new plant to tender and defining clear roles and responsibilities for the identification and notification to market of potential SRAS gaps. Per the ISP, there is a significant amount of investment needed in VRE generation centres, including REZs, and gas turbines. Considering options for this plant include incremental investment to enable either black start or restoration support capability will increase the amount and diversity of SRAS capable plant on the network.

In this context, co-investment incentives for different system services should also be considered to enable efficiencies for end use consumers where investments can provide multiple services, including system restart. Assessing new frameworks to support system restart provides a timely opportunity to consider how best to enable such co-investment signals and incentives. This could include opportunities where different parties hold the investment incentives for separate services. For example, TNSPs have incentives or regulatory requirements to build synchronous condensers in particular parts of the network (Section 3.3.3) but may not currently have sufficient incentive to consider system restart services in the design or location of these assets. Similar opportunities for co-investment might apply for other network or generation elements.

4.2 Improving confidence in technology capability

The energy transition is occurring at pace, with a plethora of new technology sources, including IBR generation, BESS and DER, entering the system. Despite the significant opportunities these new technologies bring to the system, there is a lack of real-world demonstration of their ability to contribute to system restoration. A mix of in-depth technology trials, wider network testing and ongoing research is required to better understand how these devices can contribute to end-to-end system restoration.

4.2.1 Specific technology trials

As IBR becomes a leading energy source in the grid, it is critical that there is sufficient confidence and understanding to enable its use early in the restoration process. This includes as a tenderer for SRAS procurement, as a provider of both black start and restoration support services, and also as a critical part of future restoration pathways. This requires an enhanced understanding of IBR behaviour during Stage 1 and Stage 2 of system restart to determine when and which IBR can be securely reconnected and reenergised during a system restoration event, potentially unlocking valuable capacity to support network and load restoration.

One of the technologies showing promising applications for SRAS, both black start and restoration support services, is GFM plant (outlined in Section 3.4). While studies suggest that GFM can establish voltage and frequency reference, energise network components and coordinate with other generation sources, real-world demonstrations remain limited[22]. The practical effectiveness of GFM in large-scale black start events has not been sufficiently verified. As a priority, technology trials will be undertaken to validate black start and restoration support service capability in GFM inverters. For restoration support services, this could include voltage and frequency control, fault current contribution, reactive power support and inertia support. For example, for GFM BESS to provide inertia support, dedicated control algorithms may be required, necessitating testing. Additionally, physical tests can validate anticipated plant performance and confirm there are no unexpected interactions with other nearby plant.

Other key trials to explore include:

- interoperability dependencies between different GFM and IBR technologies co-located on the network
- the contribution of hybrid facilities to black start or restoration support services, and
- the response of GFL and GFM IBR when re-energised during a restart scenario.

Until such trials and further work is undertaken, IBR generation would not be considered until late in the restoration process. AEMO is considering whether the use of Type 2 Transitional Services could enable and accelerate demonstration of system restoration capabilities from new technology, along with sharing experience with international partners[23].

4.2.2 Network testing

Many of the SRAS sources and restart pathways in the NEM remained unchanged for a significant amount of time. These pathways historically underwent extensive network testing and detailed modelling was able to incorporate physical experience with a high level of confidence. Given the changing pool of SRAS sources and plant on restoration pathways, there are potential black start options on new pathways that have not yet been tested, or that AEMO and wider industry do not yet have confidence to rely on in a restart event.

AEMO considers that there is a strong need for a dedicated ongoing program of work to test new and existing restart paths, and how different technology options work together in the early stages of a restart event. Some key scenarios AEMO believes there would be merit in testing include:

- the ability of BESS to restart nearby network and other generation plant
- the restoration of select IBR from traditional black start providers, and the impact on the stable restoration island, including the nearby network

[22] See https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Topic-5-Blackouts-and-System-Restoration-Final-Report-with-alt-text-2.pdf.

[23] See https://aemo.com.au/initiatives/major-programs/international-system-operator-collaboration.

- the ability to use/procure existing HVDC interconnectors as an SRAS resource, and
- the ability of REZs to form an independent restoration island.

These real-word tests will help validate information AEMO can then use when performing detailed system restart modelling for the purpose of both procurement and the development of operational procedures.

Stronger obligations could also be considered under the NER to require more regular and extensive testing of restart pathways. Relevant rule changes to amend NER 4.3.6(b) may help TNSPs recover the costs of these tests and enable AEMO to select relevant restart scenarios for testing. Additionally, under NER 4.3.4 (a1)(3), each NSP must take all reasonable steps to facilitate effective deployment of system restart ancillary services. Enhanced testing will become increasingly important to meet these obligations as the range of SRAS sources and network elements included in restart paths expands, many of which have not previously been demonstrated physically in the NEM.

4.2.3 Considerations for DER

Most DPV devices are GFL inverters, making them susceptible to instability and adverse IBR interactions in very weak grids. Different manufacturers have different controller stability performances and settings. This may also depend on the region the unit is installed in. Therefore, there is a risk that DPV controller instabilities may manifest in the distribution system from high DPV contributions, particularly during weak system restart conditions.

Enhanced coordination with DNSPs will be required to effectively account for and manage DPV during system restart. Roles and responsibilities associated with managing DER in the distribution operating zone during system level emergencies (including system restart) are being considered in the National CER Roadmap Distribution System and Market Operation workstream.

In addition, AEMO is engaging with DNSPs on data and models required to assess the management of DPV during system restart, and the ability to actively manage DPV on restart pathways, and collaboration on functional requirements for operating a high DER power system. Aggregate models must be used and tailored to specific regions. Using these models, the following three behaviours must be studied further to be confident in future system restart performance:

- The impact of uncontrolled generation on a restarting system whether helping or hindering.
- Whether DPV will exacerbate any inverter instability phenomena.
- Required controller changes, technical requirements or standards to allow system restart to successfully progress during periods of high PV export.

Key priorities under consideration for DPV modelling include the following:

- EMT models that accurately represent DPV and load behaviour suitable for system restart studies.
  - Fit-for-purpose models are required, given the heightened sensitivity and risk of system restart scenarios, especially in the initial formation of stable restoration islands, with low load, low system strength and largely radial supply.
  - Simulations must reflect these conditions. The behaviour of DPV systems and how they synchronise needs to be appropriately understood and modelled. This sensitivity reduces as more generation comes online.

- Improving DNSPs' awareness of DPV impact on re-energising load blocks, role clarity and capability to select between different load restoration pathways by time of day based on this impact.
- Mechanisms to actively manage DPV on energisation pathways:
  - In initial restart stages during the formation of stable islands – robust active control with a level of redundancy given the likelihood of limited communications availability during restart scenarios and/or well-designed, standardised autonomous behaviours for systems without communications.
  - In subsequent stages – autonomous, preset behaviours for DPV systems to contain aggregate DPV variability within manageable levels, to reduce restoration uncertainty.
  - Once permissible – defined ramp rates and reconnection procedures for DPV systems that were being actively managed.
- Longer term, new options could eventually enable the active participation and contribution of DER to system restoration, but as discussed in Section 3.2.2, this is not feasible in the near term.

This enhanced coordination with DNSPs will help effectively account for and manage the interactions between DPV and the power system during restart and increase the likelihood of a successful restart.

A1. Short-term modelling outputs

A1.1 Supply curve interpretation

A black start supply curve provides a representation of a plausible system restart process showing the growth in online generation capacity following a black system event. To support the SRS review, curves have been modelled for the projected generation portfolio in the NEM in 2027.

Interpreting the supply curves presented in this appendix requires understanding of the modelling behind their creation. These curves are built using viable restart pathways through the network, TNSP, DNSP and generator LBSPs to build the MW-time capability as generators restart, ramp their supply, energise network elements, pick up load and energise additional generators. They were created for each specific subnetwork of the NEM with different combinations of black start plant portfolios and as discussed further, abstract many system parameters away in their derivation.

A1.1.1 Viable restart pathway modelling

Finding viable restart pathways through the network is very complex and time-consuming. The system is very weak during restart and minor changes to the network – such as changes in network elements, protection system or BESS algorithm – can invalidate a previously known pathway. To be confident in restart pathways, AEMO undergoes extensive, detailed dynamics modelling of every network element in the pathway, including transformers, protection systems, lines and generators, which often takes around three months to complete each subnetworks' restart procedures. This complexity in achieving pathway confidence makes it difficult to build supply curves for networks far into the future as differences in single network elements can invalidate pathways.

A1.1.2 SRS Review modelling methodology

Completing detailed restart pathway modelling was not feasible as part of this review and modelling the current network would have reducing relevance into the future as the grid changes. Therefore, previously completed pathway modelling was used for the higher-level analysis in this review.

These pathways were modelled prior to the SRS instantiation in 2016 and have been periodically updated during each procurement round and standard review, and on an ad hoc basis to account for minor changes to relevant network elements and ensure continued viability. Most of this existing modelling is performed in the electromagnetic transient (EMT) domain, to capture the transient and sub-transient characteristics of the pathway, along with fault level and short circuit ratio (SCR) analysis in the root mean square (RMS) domain as required to ensure enough fault level is available for appropriate operation of protection systems, so additional loads and generation can be picked up without issue. All this modelling requires detailed and accurate models of every generator, line, protection scheme and network element used in the potential restart pathway.

For this review, AEMO used the latest restart procedures in each electrical subnetwork in the NEM to build indicative supply curves for 2027. With high synchronous generation still expected to be present in 2027, the existing pathways were assumed to still be viable, although this will need to be confirmed over time with AEMO's ongoing restart modelling operation.

A1.1.3 Inputs and assumptions

Table 15 presents a summary of the inputs and assumptions used for the modelling of supply curves presented in this appendix.

Table 15 Inputs and assumptions to 2025 SRS Review supply curve modelling

Input	Assumption	Source
Viable restart pathways per subnetwork	Current subnetwork restart procedures.	AEMO's ongoing restart modelling, last updated 2024.
Local black start procedures	LBSPs provided by existing generators and TNSPs. Similar LBSPs assumed to apply to future generators.	Provided by generators, as part of their NEM registration process, and TNSPs as part of their requirements.
Telecommunication availability	Considered generators compliant with system restart communication protocol[A].	Consistent with standard requirements to contract as an SRAS provider.
Available load can be broken into appropriately sized load blocks as required	Capability to pick up load in 10 MW increments.	Historically possible through DNSP switching.
Network energisation timings	Transmission elements (such as lines, transformers, SVCs) can be energised in five minutes. Loads can be energised in 15 minutes.	Consistent with historically possible energisation timings.
IBR connections	IBR resources can be connected at SCR ratios of 4 or greater.	Requires detailed modelling to ensure, but likely feasible.
Load availability	All required load assumed available for faster restarting case. Load availability delay of three hours for slower restarting case.	Historically seen behaviour of load unavailability during high DPV periods from approximately 11.00 am until 2.00 pm.
Staffing times	Time for staff to reach black starting plant between 30 minutes and two hours depending on plant.	Matches generator LBSPs, dependent on plant. Non-black start plants in the restart pathway assumed similar staff times.
Hot and cold restart time of thermal plants	As per LBSPs provided by existing generators. Similar LBSPs assumed to apply to future generators.	LBSP of the relevant generators.
Electrical sub-network boundaries	Current boundaries of electrical sub-networks will remain into the future.	Electrical sub-network boundaries based on transmission topology and likely locations for islanding to occur. Topology not expected to materially change for the purpose of this standard review.
Procured headroom for load of relevant BESS on viable restart pathways	20% charging headroom can be procured for each BESS on viable restart pathways to assist in load availability for up to 3hrs where stable load blocks are unavailable.	Investigations as part of this review show top 10%-15% of BESS SoC could potentially be procured if needed, subject to availability at appropriate cost.
Availability of units with TTHL capability during contingency events	In the best-case scenario presented in the supply curves, the assumed number of operational units prior to the contingency event is based on typical system conditions of operation. Additionally, TTHLs trigger successfully during the black event.	This assumption is consistent with historical system security requirements applied by TNSPs. It is further assumed that these units execute the TTHL successfully.

A. See https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2019/lbsp-amendments/system-restart-communications-protocol.pdf.

The following curves are to capture the uncertainty AEMO considers inherent in planning system restart, and do not necessarily represent how a restart would perform in practice. The range shows the uncertainty in expected outcomes from known combinations of restart sources and restart scenarios. As the curves do not depict deterministic outcomes for a future restart scenario, it is critical the full uncertainty range is considered when basing a procurement standard on them to avoid leading to false confidence conclusions being drawn from them.

A1.1.4 Graph interpretation

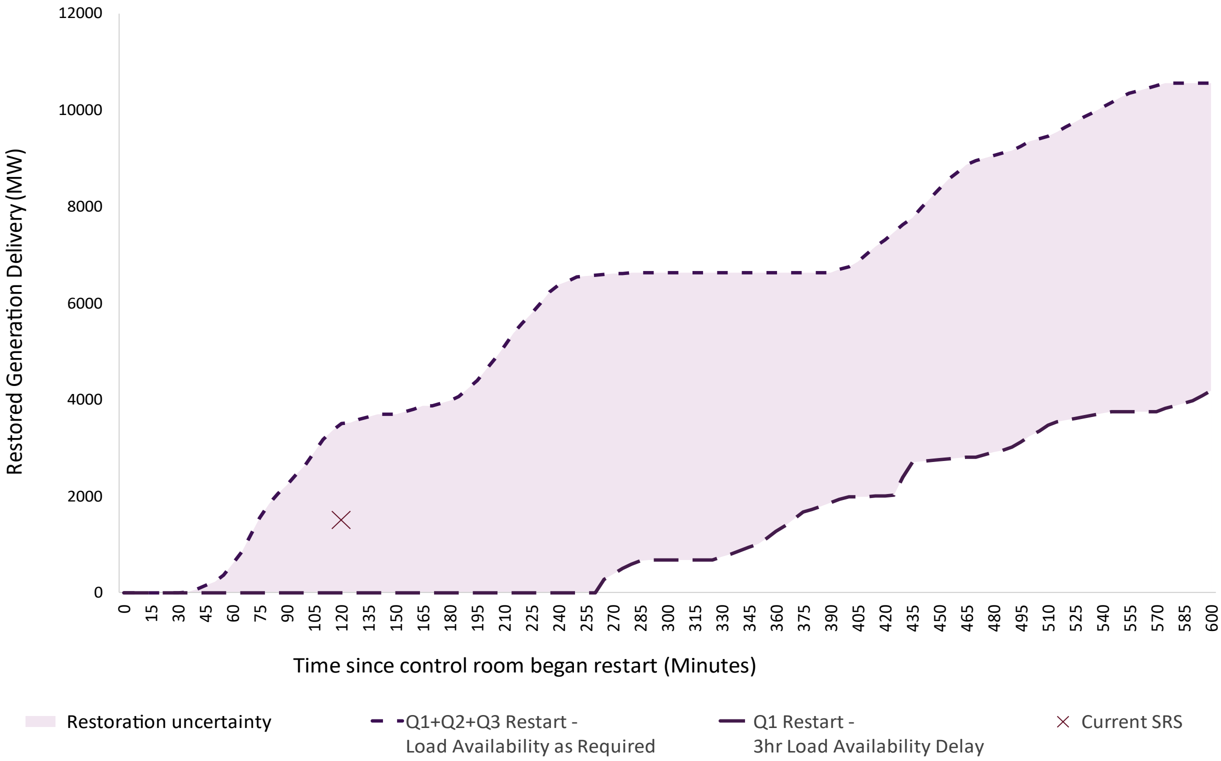
The supply curves show active power (MW) on the vertical axis and time on the horizontal. The vertical active power (MW) axis represents actual restoring output of generators. The generator names have been excluded for confidentiality and the curves should be interpreted indicatively. Current SRS targets are also plotted for completeness, comparing the exact precision that the current SRS requires against planning uncertainties.

Each subnetwork shows a cone of uncertainty covering possible scenarios post-black event as well as differing viable synchronous sources of black start service. Where practical, this has been highlighted in graph legends. “Qx” notation has been used to describe individual procurement black start portfolios, which could include more than one black start unit where relevant.

A1.2 New South Wales

New South Wales is projected to have three feasible synchronous black start options in 2027, reflected in **Figure 10** with the faster restart bound comprising of three sources.

Figure 10 New South Wales supply curve procurement region, 2027



Note: curves capture inherent uncertainties in planning system restart given the potential range of restart sources and scenarios in each sub-network.

Key restart pathway drivers in New South Wales are the availability and restart performance of vital synchronous generators, feasibility of energising the pathway (with respect to both steady-state and transient voltage profile), demand erosion from high DPV contribution, and risks of synchronous generators cooling between a black event and when their auxiliaries receive supply to begin restarting.

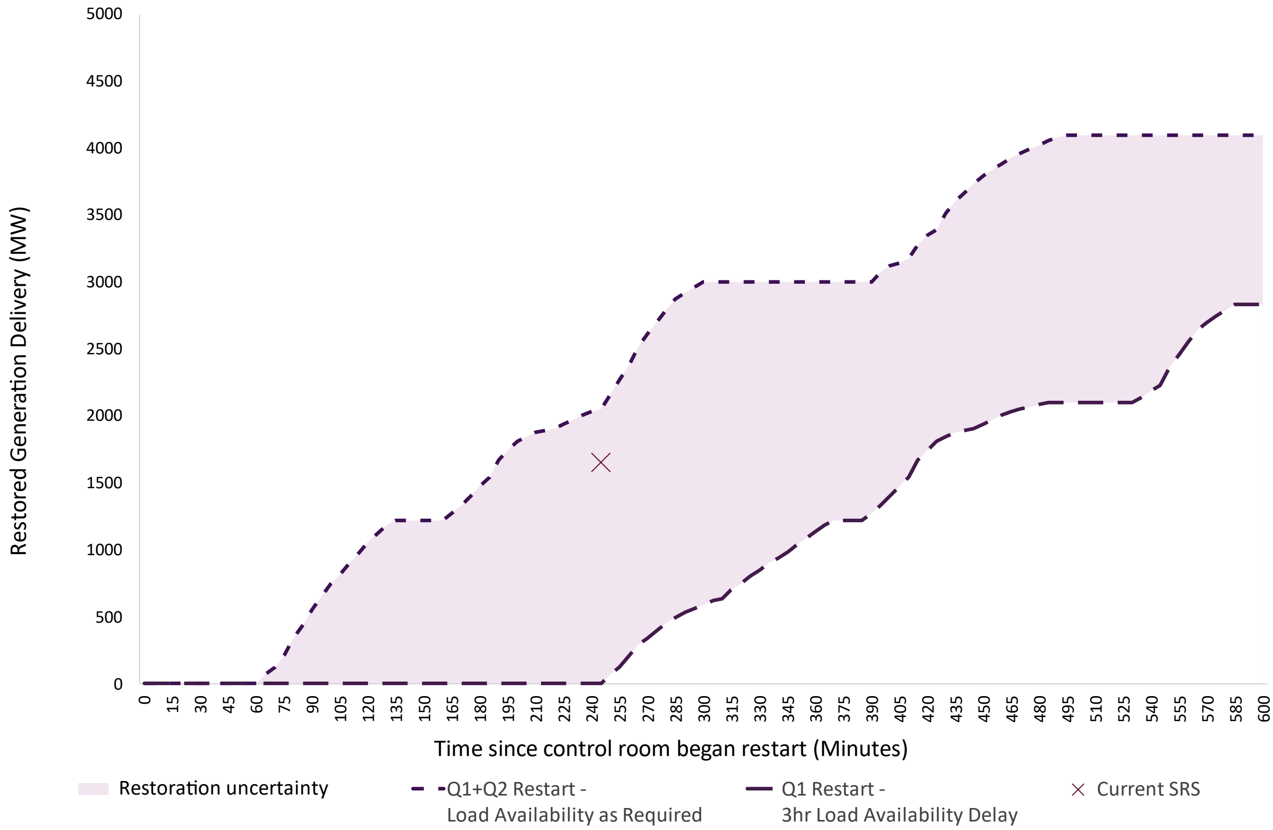
A1.3 Queensland

The Queensland region is broken into two electrical sub-networks, North and South. This is due to some longer transmission lines through central Queensland that make restart entirely from the South or North difficult to achieve in a timely manner. Therefore, per the current SRS, Queensland North has an additional restart requirement over the requirement for the whole Queensland region that is modelled with an additional supply curve. Consequently, Queensland South and Queensland North supply curves are shown separately below.

A1.3.1 Queensland South

Queensland south of Bundaberg is projected to have two feasible synchronous black start options in 2027, reflected in **Figure 11** with the faster restart bound comprising of two sources.

Figure 11 Queensland South supply curve procurement region, 2027



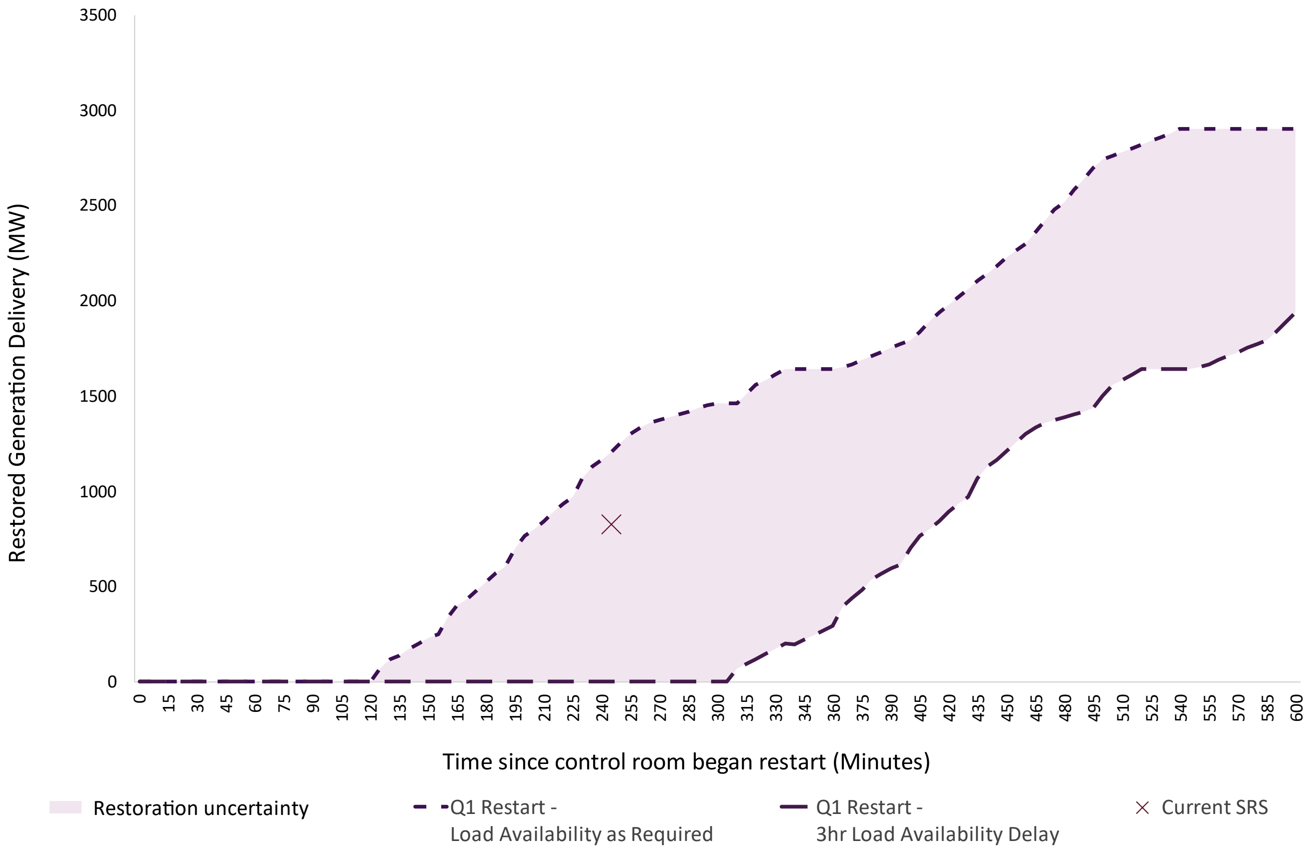
Note: curves capture inherent uncertainties in planning system restart given the potential range of restart sources and scenarios in each sub-network.

Key restart pathway drivers in Queensland South are the availability and restart performance of vital synchronous generators, demand erosion from high DPV contribution, and risks of synchronous generators cooling between a black event and when their auxiliaries receive supply to begin restarting.

A1.3.2 Queensland North

Queensland North (north of Bundaberg) is projected to have one feasible synchronous black start option in 2027, reflected in **Figure 12** with the faster restart bound comprising of one source.

Figure 12 Queensland North supply curve procurement region, 2027



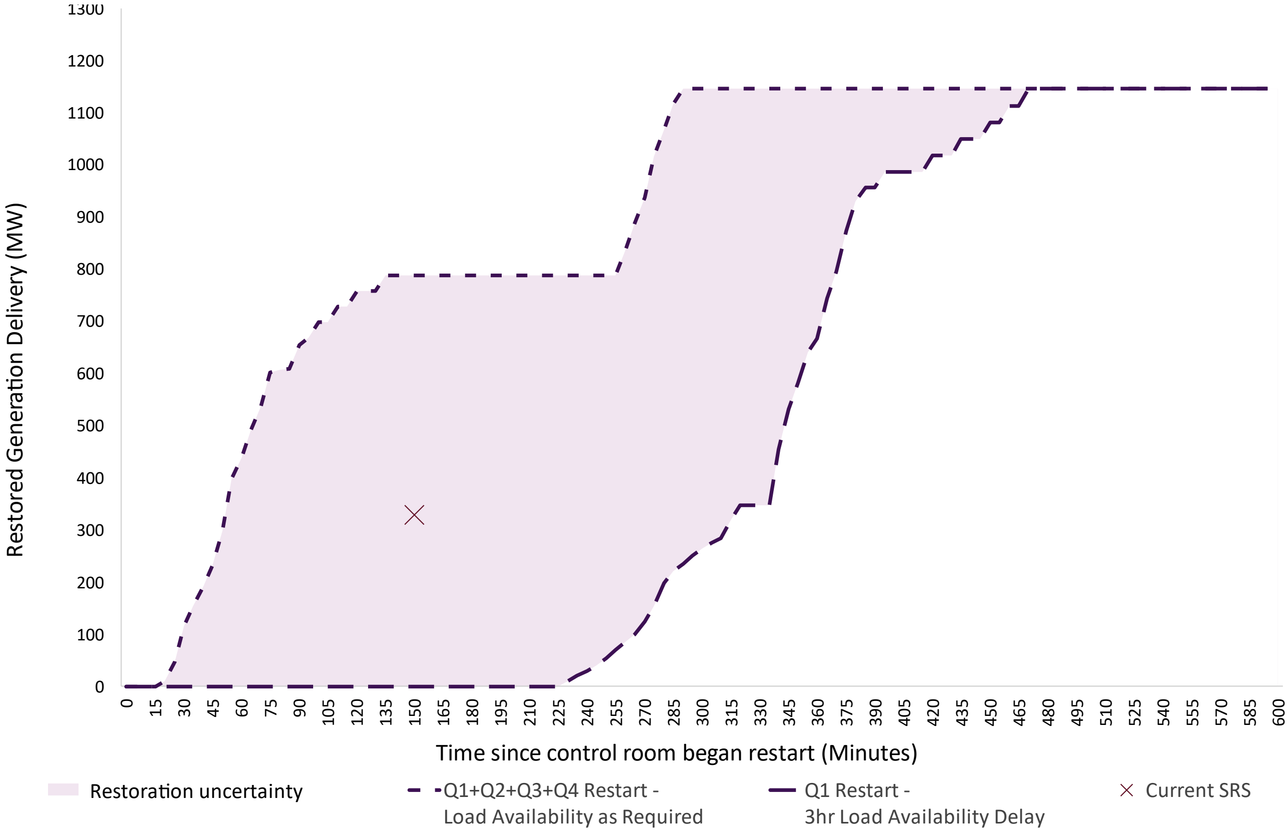
Note: curves capture inherent uncertainties in planning system restart given the potential range of restart sources and scenarios in each sub-network.

Key restart pathway drivers in Queensland North are the reducing availability and restart performance of vital synchronous generators, demand erosion from high DPV contribution, and risks of synchronous generators cooling between a black event and when their auxiliaries receive supply to begin restarting. In the fastest restoration scenario illustrated in **Figure 12**, it is assumed that three synchronous units of the Q1 SRAS provider were operational prior to the black event. This assumption is consistent with historical system security requirements applied by Queensland's TNSP. It is further assumed that these units were able to successfully execute their associated black start procedures. The slowest restoration scenario in **Figure 12** corresponds to the conservative scenario where fewer Q1 synchronous units were online prior to the black event and stable load is unavailable for the first 3 hours of restoration. Alternative scenarios yield supply curves between the fastest and slowest restoration curve boundaries.

A1.4 South Australia

South Australia is projected to have four feasible synchronous black start options in 2027, reflected in **Figure 13** with the faster restart bound comprising of four sources. Key restart pathway drivers in South Australia are the availability and relatively fast restart performance of gas generators and demand erosion from high DPV contribution delaying restart.

Figure 13 South Australia supply curve procurement region, 2027

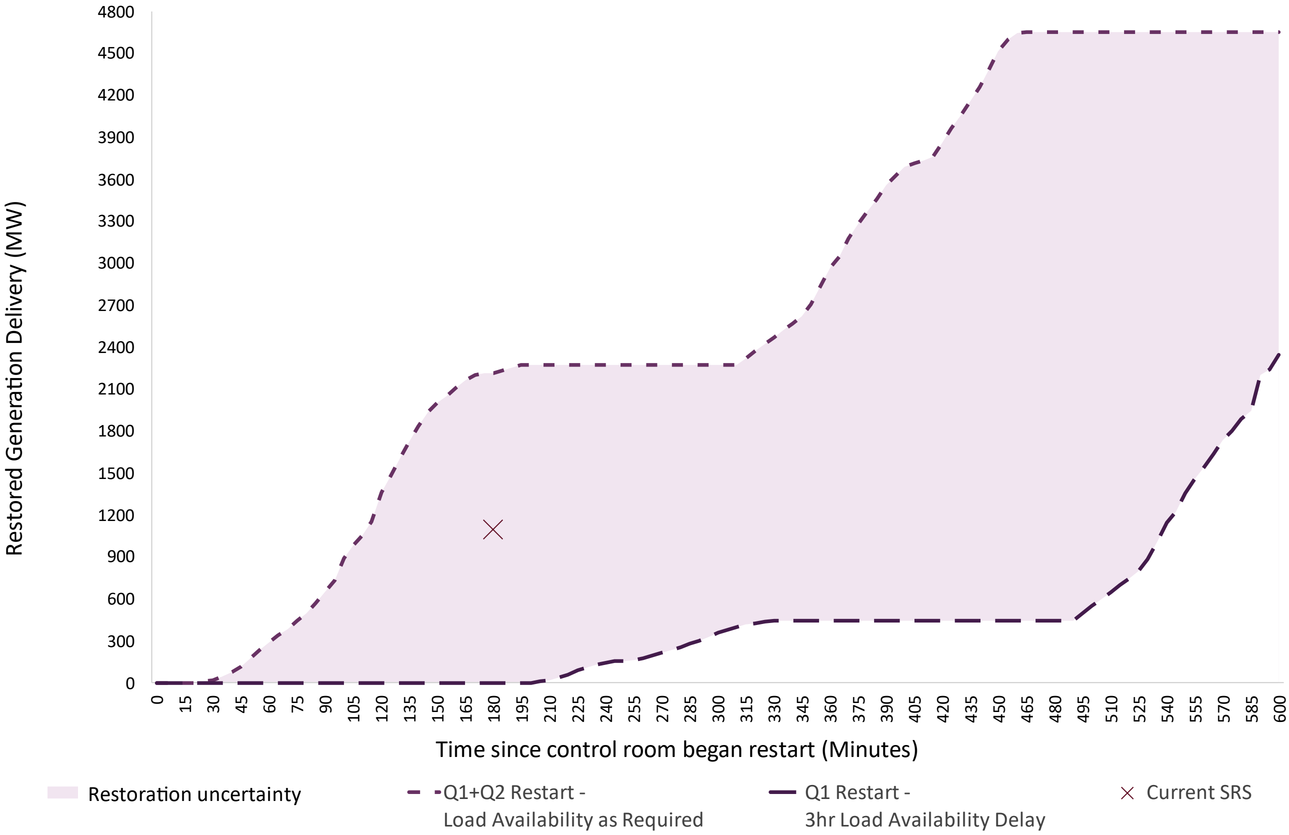


Note: curves capture inherent uncertainties in planning system restart given the potential range of restart sources and scenarios in each sub-network.

A1.5 Victoria

Victoria is projected to have two feasible synchronous black start options in 2027, reflected in **Figure 14** with the faster restart bound comprising of two sources. Key restart pathway drivers in Victoria are the availability and restart performance of vital synchronous generators, demand erosion from high DPV contribution, and risks of synchronous generators cooling between a black event and when their auxiliaries receive supply to begin restarting.

Figure 14 Victoria supply curve procurement region, 2027

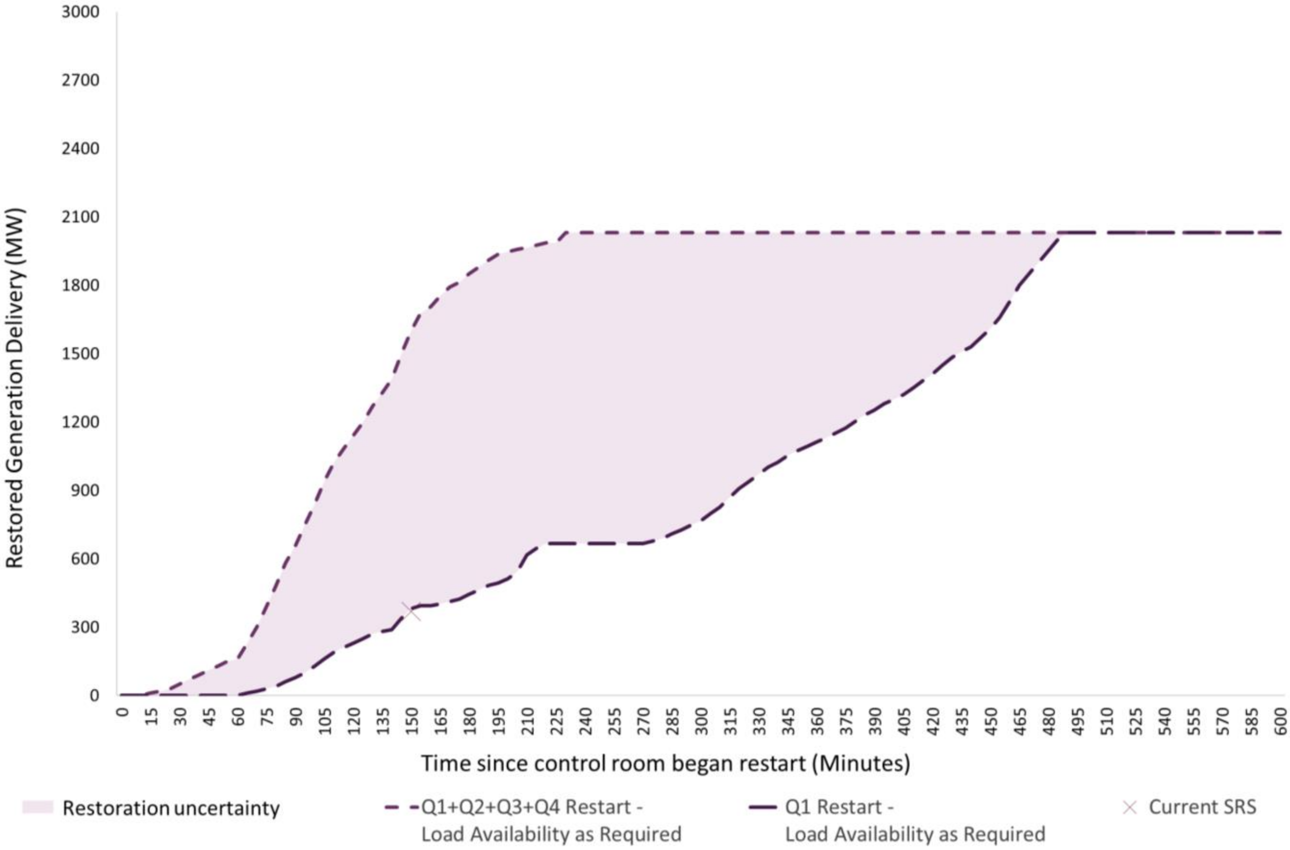


Note: curves capture inherent uncertainties in planning system restart given the potential range of restart sources and scenarios in each sub-network.

A1.6 Tasmania

Tasmania's significant portion of generation mix being from hydro reduces the challenges faced during restart. Hydro generation does not face the challenge of cooling down, nor the challenging minimum stable generation requirements of large coal units. Additionally, the generation fleet in Tasmania is not expected to change significantly in the future and reduced DPV contribution significantly reduces load unavailability risks and uncertainty. The restoration uncertainty in Tasmania is shown in **Figure 15**.

Figure 15 Tasmania supply curve procurement region, 2027



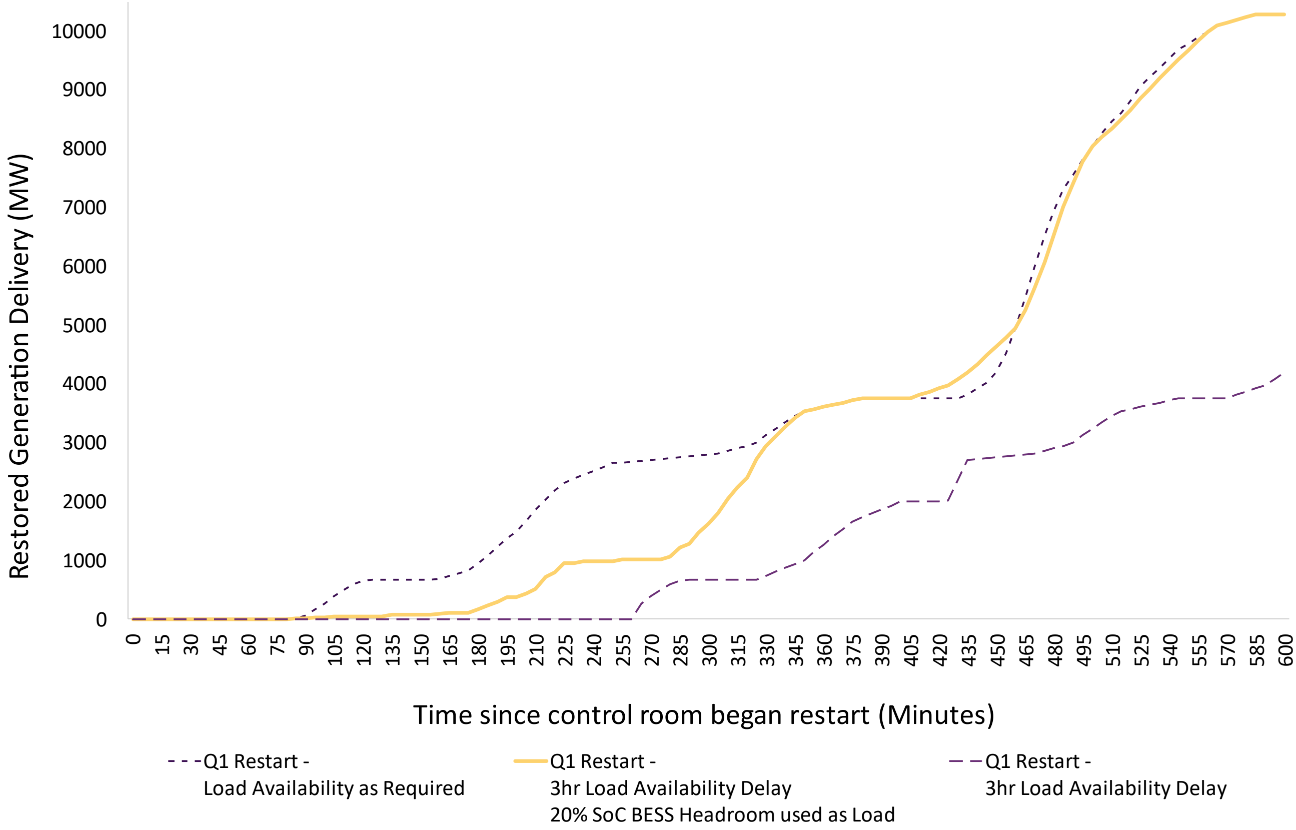
Note: curves capture inherent uncertainties in planning system restart given the potential range of restart sources and scenarios in each sub-network.

A1.7 Indicative example of RSS possible effect on supply curves

An indicative example of the effect of an RSS is shown in **Figure 16** for one primary restart source pathway in New South Wales in 2027.

Detailed modelling has not been performed on this curve, as it is provided purely to illustrate the potential benefit of procuring RSS. It is important to consider that many RSS do not show benefit on a supply curve and instead either support the reliability of restart or enable new restoration pathways. The RSS shown below relates to procurement of a portion of multiple utility-scale BESS SoC headroom providing load to support synchronous generator loading requirements until stable distribution load becomes available.

Figure 16 Indicative benefit of RSS on supply curve, 2027



Glossary and abbreviations

Term	Abbreviation	Explanation
Alternating current	AC	
Australian Energy Market Commission	AEMC	The rule maker for Australian electricity and gas markets. AEMC makes and amends the National Electricity Rules, National Gas Rules and National Energy Retail Rules. Also provides market development advice to governments.
Automatic voltage regulator	AVR	
Battery energy storage system	BESS	
Black start service		An SRAS procured for the purpose of providing black start capability
Cold-load pickup	-	Re-energisation of load where greater than average load is initially expected due to both the in-rush of current and the recovery needs of machines that have been off supply for an extended period.
Consumer energy resources	CER	
Direct current	DC	
Distributed energy resources	DER	Distribution level resources which produce electricity or actively manage consumer demand (examples include solar rooftop PV systems and batteries, and demand response via hot water systems, pool pumps, smart appliances and air conditioning control).
Distributed photovoltaics	DPV	
Distribution network service provider	DNSP	A business that owns, operates or controls an electricity distribution network.
Distribution restoration zone	DRZ	
Doubly-fed induction machine/s	DFIM	
DRZ Control System	DRZ-C	
Electric vehicle	EV	Residential and business battery powered vehicles, such as motor bikes, cars, and large commercial trucks
Electromagnetic transient	EMT	
Enhanced STATCOM	E-STATCOM	
Extra-high voltage	EHV	Defined in AS 61000-3-6 as transmission voltages greater than 230 kV.
Fast frequency response	FFR	
Fault ride-through	FRT	The expected behaviour of a resource to remain connected during voltage and frequency excursions
Grid-following inverter	GFL	Inverters that synchronise to the grid voltage waveform, adjusting their output to track an external voltage reference.
Grid-forming inverter	GFM	Inverters that set their own internal voltage waveform reference and can synchronise with the grid or operate independently of other generation.
High voltage	HV	
High voltage direct current	HVDC	Interconnectors that operate as high-voltage DC, with DC-to-AC conversion at each end
Insulated-gate bipolar transistor	IGBT	
Integrated System Plan	ISP	AEMO's whole-of-system plan that provides an integrated roadmap for the development of the National Electricity Market (NEM).
Interconnector	-	A transmission line, or group of transmission lines that connects the transmission networks in adjacent regions

Term	Abbreviation	Explanation
Inverter-based resource/s	IBR	
Jurisdictional Planning Body	JPB	
Kilovolt/s	kV	
Line-commutated converter	LCC	
Liquefied petroleum gas	LPG	
Local Black Start Procedure	LBSP	Local black system procedures developed by a Generator or Network Service Provider under NER clause 4.8.12.
Low voltage	LV	
Medium voltage	MV	
Megavolt-ampere/s	MVA	
Megavolt-ampere/s reactive	MVAr	
Megawatt/s	MW	
Minimum Restart Path	-	A restoration path required to energise sections of the transmission network and auxiliaries of non-black start generating systems sufficient to meet the SRS in an electrical sub-network.
Modular multilevel converter	MMC	
National Electricity Market	NEM	
National Electricity Rules	NER	The rules made under the National Electricity Law (NEL). They govern the day-to-day operations of the National Electricity Market (NEM) and provide the framework for network regulation.
National Energy System Operator	NESO	
Network service provider	NSP	A party that owns, operates or controls an electricity transmission or distribution system.
Open-cycle gas turbine	OCGT	
Original equipment manufacturer	OEM	
Park power controller	PPC	
Per unit	pu	An expression of system quantities as fractions of a defined base quantity
Phase-locked loop	PLL	
Power System Stabiliser	PSS	
Pumped hydro energy storage	PHES	
Rate of change of frequency	RoCoF	
Remedial action scheme/s	RAS	
Renewable energy zone	REZ	Combination of photovoltaic solar, wind and battery technology spread across large geographical areas. Their energy output aggregated into one or more high-voltage connection points to the transmission network
Restoration island	-	An electrically isolated portion of the electrical system, containing energised load and generation, from which the system may be restored.
Restoration support service/s	RSS	An SRAS procured for the purpose of sustaining the stable energisation of generation and transmission following initial energisation.
Root mean square	RMS	
Sensitive loads	-	Loads defined as sensitive for each participating jurisdiction by the Jurisdictional System Security Coordinator for that participating jurisdiction.
Short circuit ratio	SCR	

Term	Abbreviation	Explanation
SRAS provider		A Generator with whom AEMO contracts to provide SRAS, or who submits or has been invited to submit an expression of interest or offer to provide SRAS to AEMO.
Stabilising load blocks	-	Blocks of load connected during the system restart process to assist stable operation of generation. Typically 5-10 MW during initial restart stages, 10% online generation capacity in later stages.
Static synchronous compensator	STATCOM	STATCOMs are voltage source converters that provide similar reactive power support as SVCs but have slightly different performance characteristics
Static VAR compensator	SVC	SVCs are dynamic reactive power devices installed in the network for dynamic voltage control
Supply curve / restoration curve	-	An assumption-based representation of the critical path times and export rate for black start generation and loads
System restart ancillary services	SRAS	System restart ancillary service, including a proposed service where the context requires
System Restart Standard	SRS	The system restart standard determined by the Reliability Panel under the NER.
Transmission network service provider	TNSP	A party that owns, controls or operates a transmission system.
Trip-to-house-load	TTHL	An electrical islanding scheme using generating units that can disconnect from the transmission network following a major supply disruption and continue to supply their own auxiliaries or an isolated segment of system load.
Underfrequency load shedding	UFLS	
Uninterruptible power supply	UPS	
Variable renewable energy	VRE	Renewable energy that fluctuates, such as solar or wind.
Volt-ampere/s reactive	VAR	
voltage-source converter	VSC	