International System Restoration Review

Important notice

Purpose

This document has been prepared by ISON, an international network of system operators, based on information available as at the date of publication.

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Version control

Version	Release date	Changes
1.0	13/08/2025	Report finalised for publication

Executive summary

Recent large-scale power system blackouts underscore the growing complexity and vulnerability of modern electricity grids. As system blackouts become more frequent and impactful, the economic costs and public pressure to restore power swiftly have intensified, in an environment where the technology underpinning supply is rapidly evolving from traditional rotating machines to inverter-based resources (IBR). These events and system changes highlight an urgent need to rethink restoration planning such that system restoration remains feasible and timely in the new energy paradigm.in the new energy paradigm.

On behalf of ISON members, AEMO engaged Etik Energy[1] to perform a review of system restart practices, with a focus on system restart capability in the context of a power system with a high penetration of IBR, and few (or no) synchronous generators.

Areas of this review targeted:

- a summary of the current system restoration requirements administered by AEMO, CAISO, ERCOT, Energinet, EirGrid and NESO,
- a benchmark of key practices between the system operators,
- a summary of any recent system restart operation experiences, including the restarting of regions or testing of restart paths,
- commentary and recommendations on how future restart plans could adapt to changing generation, including:
  - anticipated changes to power systems and the implications for the approach to system restoration including associated risks, and
  - identification of improvement opportunities to restart processes by leveraging current or emerging technology and best practices, and
- the development of a system-neutral methodology framework to restore a system with high levels of IBR / variable renewable energy (VRE).

Insights

Through analysis of public documentation and interviews, the following high-level insights regarding ISON member system restart practices were found.

- Independent System Operators (ISOs)/ Transmission System Operators (TSOs) have greatly varying needs and approaches to how restart is to be conducted in their jurisdictions; however, all ISOs/TSOs are currently considering, in some form or another, how IBR resources (particularly battery energy storage systems [BESS]) can play a role in the restart process.

[1] Etik Energy is an engineering consulting specializing in power systems, particularly in the context of the energy transition. For more details see https://etik.energy/

This may be as a replacement for diesel gensets at existing gas plants, through to providing a restoration support service (e.g. voltage or frequency control in early grid restoration) or even consideration as a primary restart source.

Such considerations are only at the emerging stage in most jurisdictions, with the notable exception of NESO, which has undertaken extensive process changes to better facilitate participation of potential IBR sources. A formal review is also underway in AEMO's National Electricity Market (NEM).

In most cases, changes to rules, definitions and legally binding requirements are necessary to facilitate this accommodation.

Of the systems considered, AEMO's NEM and Western Australian[2] (WA) systems appear to face the largest reductions in daytime load due to distributed photovoltaics (DPV), to the point that in some solar-rich regions of Australia, system restart in some seasons during daylight hours may be significantly impeded due to the lack of available stable load and unknown performance of DPV within the network. Other jurisdictions worldwide also see the impact of DPV on daytime loads, but sufficient alternative loads are available such that this it has not yet reached the same level of impact for system restart.

Many ISOs/TSOs expressed a preference for interconnector-based (i.e., top-down) restoration as their primary operational option for restart. This included some jurisdictions where interconnectors could not be expressly procured as a restart source but are assumed available. This preference is based on speed of restoration and operational convenience in areas with many interconnection options.

ISOs/TSOs strongly valued maintaining engineering flexibility of the restoration process, with most electing not to apply a numerical target (e.g., megawatts [MW] or time) for restoration of the broader system. Only AEMO NEM and NESO elected to provide such numerical targets (e.g. 60% of demand within 24 hours), with AEMO NEM's targets being highly regional specific.

- Through discussions it was understood that most ISOs/TSOs instead prefer to procure sources based on demonstrated ability to restart surrounding network and non-black start generators, sufficient operational flexibility (e.g., speed of restart, long energy storage, ability to energise a variety of block loads) and technology and locational diversity to withstand a range of restart scenarios..
- Many ISOs/TSOs did apply several numerical targets on the procurement of individual restart units. This included items such as "ready to begin network switching within X hours", "able to maintain nominal output for at least Y hours" and "able to undertake at least Z restart attempts".

Unit or station testing was seen to be the "ultimate proof" of restart capability by almost all ISOs/TSOs interviewed. In particular, the ISOs/TSOs interviewed discussed their desire to regularly perform network and next-start generator / load pickup tests to confirm validity of both units procured and their restart plans. However, only ERCOT and Energinet have been able to routinely perform such network-based testing, with others struggling to secure the necessary outages to facilitate this procedure, meaning such network and load testing may need to be indefinitely postponed.

Approaches to simulation of system restart plans varied significantly between ISOs/TSOs. Several reported that effectively no simulation is completed by the ISO/TSO, with the burden of proof falling either to the transmission operator or the restart-tendering party. Approaches to deterministic testing varied from simple load-flow analysis only, right through to Electromagnetic Transient (EMT) analysis with both network and

[2] Comprising the South-West Interconnected System (SWIS) operated by AEMO.

generator protection mechanisms being modelled. Notably, NESO uses probabilistic simulations to validate restart plans, with ERCOT also using a timing optimisation approach that does not include power dynamics simulations.

A growing concern from several ISOs/TSOs interviewed was the increased reliance on remote staffing of restart units / stations, and a dependency on public communication networks with the assumption that remote staff will have access to plant controls during a general loss of supply in the region. Three jurisdictions had formal requirements in this regard, with the majority relying on assumed staffing levels:

- ERCOT has an explicit requirement that a black start unit must be adequately staffed 24/7, or the appropriate staff can be on site within one hour of a blackout event occurring.
- Energinet has a similar requirement to ERCOT where offsite staff must be contactable through secure communications (SINE (Safety Network)) and activation time for offsite staff must be included in the overall "ready to energize" time requirement.
- AEMO WA has an explicit requirement that staff must be on site within two hours of a blackout event occurring, or if this is not possible, the unit is to be under complete remote control of AEMO WA control room staff.

Procurement in most jurisdictions is a competitive process, with contract terms varying from yearly rolling agreements to potentially decade-long agreements with an aim to facilitate investment certainty in restart sources.

Recommendations

Based on the survey conducted and with the aim of developing a system restart plan that is resilient to the changing energy mix, the following non-system specific recommendations are made. Further information on each of these recommendations is available in the corresponding section of this report.

- **Recommendation 3.2.1:** Define performance-based criteria for restoration services that account for broader system technical needs in increasingly IBR-dominant grids. Avoid over-simplified procurement based solely on active power capacity.
- **Recommendation 3.2.2:** Reassess minimum technical requirements for black start participation where legacy requirements preclude new technologies. Where suitable, enable limited-duration units (e.g. batteries) to fulfil specific support roles in a modular restoration plan.
- **Recommendation 3.2.3:** Where stable load is unavailable, actively procure suitable industrial or demand-side loads as restoration resources. Address regulatory or commercial barriers that operate in outdated paradigms that assume stable load is always available and hence are preventing controlled load from being integrated into restoration frameworks.
- **Recommendation 3.2.4:** Create flexible frameworks that allow multiple sources, such as gas generation, hydro, wind and solar IBR, grid-following (GFL) and grid-forming (GFM) batteries, each with partial capabilities, to work in coordination. Based on regional factors, procurement of interconnectors may be explored as a potential viable restoration point if sufficient safety and synchronisation controls exist.
- **Recommendation 3.2.5:** Establish standardised, internationally aligned performance requirements for restart services and communicate them well in advance of tender cycles. This has the potential to support cost-effective design and testing by original equipment manufacturers (OEMs).

- **Recommendation 3.2.6:** Ensure the commercial terms for restoration services are proportionate to risk and compliance obligations. Consider revising remuneration structures where appropriate to attract diverse participants.
- **Recommendation 3.2.7:** Prioritise live energisation trials beyond the point of connection, ideally up to the next planned restart unit, in particular involving one or more IBR. Establish mechanisms for technical and commercial remediation of issues found during testing.
- **Recommendation 3.2.8:** Model restoration pathways beyond the next busbar, ideally to cover major load centres and parallel start-up units. Require EMT-based analysis for deterministic evaluation of all restoration services, including integrated protection behaviour and distributed energy resources (DER) reconnection dynamics.
- **Recommendation 3.2.9:** Require physical presence or local control capability at restart plants following an event. Where not already in place, establish alternative communications or fallback mechanisms to ensure continued operability.
- **Recommendation 3.2.10:** Develop explicit treatment strategies for DER in restoration plans. Establish clear performance criteria for large industrial or IBR loads used during early restoration to prevent unexpected dynamic performance from destabilising a restoration attempt.

Overall, the prevalence of new IBR technology across the ISON jurisdictions surveyed will require at least some adaptation of existing restart plans to have robust restart capability with fewer synchronous generators available. Better accounting of IBR during system restart will aid in achieving this. However, the urgency behind such adaptation depends strongly on the specifics of each system, particularly regarding the interconnection to other capable regions, the rate at which traditional restart resources are being displaced by IBR, and changes to the type, amount and performance of load and embedded generation permeating the distribution network. Care must also be taken that non-power system trends such as increased reliance on remote workforces and public communication infrastructure do not undermine the capability of system restart sources when called upon.

Contents

Abbreviations and definitions

Abbreviation	Definition
A	Ampere/s
AC	Alternating Current
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
CAISO	Californian Independent System Operator
CET	Central European Time
CIGRE	International Council on Large Electric Systems
DER	Distributed Energy Resources
DPV	Distributed Photovoltaics
DSO	Distribution System Operator
EMT	Electromagnetic Transient
ENTSO-E	European Network of Transmission System Operators for Electricity
ERCOT	Electric Reliability Council of Texas
ESR	Electricity System Restoration
EU	European Union
EWIC	East-West Interconnector
GFL	Grid-following
GFM	Grid-forming
GW	Gigawatt/s
HV	High voltage
HVDC	High Voltage Direct Current
Hz	Hertz
IBL	Inverter Based Load/s
IBR	Inverter Based Resource/s
ISO	Independent System Operator
ISON	International System Operator Network
kV	Kilovolt/s
LCC	Line Commutated Converter
LDC	Load Dispatching Centre
LFSM-O	Limited Frequency Sensitive Mode - Overfrequency
LFSM-U	Limited Frequency Sensitive Mode - Underfrequency
ms	Milliseconds
MVA	Mega Volt-Ampere/s
MVA.s	Mega Volt-Ampere/s per second
MVAr	Mega Volt-Ampere/s Reactive
MW	Megawatt/s
NCER	Network Code on Emergency and Restoration
NEM	National Energy Market

Abbreviation	Definition
NER	National Electricity Rules
NERC	North American Reliability Council
NESO	National Energy System Operator
OEL	Overexcitation Limiter
OEM	Original Equipment Manufacturer
ONS	Operador Nacional do Sistema Elétrico (National Electric System Operator)
PDT	Phasor Domain Transient
PMU	Phasor Measuremet Unit
PoC	Point of Connection
PSCAD	Power System Computer Aided Design
PSLF	Power Flow Software (from General Electric)
PV	Photovoltaic
RCW	Renewable, Cogeneration and Waste (generation)
RFP	Request for Proposal
RMS	Root Mean Square
RoCoF	Rate of Change of Frequency
SCE	Southern California Edison
SGU	Significant Grid User
SIN	Sistema Interligado Nacional (National Interconnected System)
SPS	Special Protection Scheme
SRAS	System Restart Ancillary Services
SWIS	South-West Interconnected System
TO	Transmission Operator
TSO	Transmission System Operator
TTHL	Trip to House Load
UEL	Underexcitation Limiter
UFLS	Underfrequency Load Shedding
UK	United Kingdom
VPN	Virtual Private Network
VSC	Voltage Source Converter
WA	Western Australia
WAMS	wide area monitoring system

1 Practice summary and benchmark

	CAISO	EirGrid	Energinet	NESO	ERCOT	AEMO NEM	AEMO WA
Restart objective / target / purpose	Ensure plans, Facilities, and personnel are prepared to enable System restoration from Black Start Resources to ensure reliability is maintained during restoration and priority is placed on restoring the Interconnection. No specific timeframe or restoration amount considered.	Achieve restoration of continuous supply to all consumers as quickly and as safely as possible with minimum adverse consequences.	"to ensure full restoration and stabilisation of the transmission grid following a blackout, power shortage, or other critical situation affecting the quality of supply in the transmission grid."	NESO to have sufficient capability and arrangements in place to restore 100% of Great Britain's electricity demand within five days. This should also be implemented regionally, with an interim target of 60% of regional demand to be restored within 24 hours.	To successfully start contracted Black Start Resources, energize cranking paths, start next start units, reach synchronizing points to tie islands, synchronize two islands, and finally synchronize all black start islands.	To manage and coordinate the restoration of supply following a major supply disruption. The NEM has a system restart standard requiring a minimum amount of generation and transmission capability to be restored within a specific timeframe after system black in each NEM region.	AEMO must use its reasonable endeavours to ensure the SWIS is restarted and restored in the event of a system shutdown or major supply disruption. Note that timeframes for specific supply restoration levels are not specified.
High level black start procurement requirements	Technically feasible, financially reasonable, and sufficient reliability.	"…whatever services are necessary to ensure grid security". However, there are not many units that can provide restart services currently.	Generally, consider a balance between technical capability, financial competitiveness, and reliability. The unit's key ability assessed is to energise the transmission system to the next unit and supply the next-start generator auxiliary load.	A balance between technical capability, financial competitiveness, and reliability. Engineering judgement to determine how many providers are required.	Competitive tender, technically feasible, and demonstrated through physical testing of being capable.	To use reasonable endeavours to procure black start and restoration support services to meet the system restart standard requirements at the lowest long term cost.	AEMO must use its reasonable endeavours to procure system restart services to meet the system restart standard.
Restart modelling analysis aim	Transmission Operator (TO) dependent, but noted an example of a typical objective to be energising the network to a nearby generating facility.	As per the Network Code on Emergency and Restoration (NCER) Article 51, covering at least: • the energising restoration path from restoration service providers with black start or island operation capabilities; • the supply of power generating modules main auxiliaries; • the demand reconnection process; and • the process for resynchronisation of networks in island operation. However, since restart units and paths have not changed recently, studies have not been updated. If new sources appear (inc. interconnectors), they will be obliged to demonstrate through studies how they can restore the system.	As per NCER Article 51, covering at least: • the energising restoration path from restoration service providers with black start or island operation capabilities; • the supply of power generating modules main auxiliaries; • the demand reconnection process; and • the process for resynchronisation of networks in island operation.	Probabilistic modelling is used, where it is attempted to replicate real-world non-dynamic concepts (e.g., staff availability, resource availability, block loading levels, etc.) to determine the likelihood of success for restart, including timing. Dynamic studies are not conducted internally to NESO, but TOs conduct load flow and protection studies to provide pathways to determine viable restart paths / options.	Time-based simulation: ERCOT simulates restoration of at least 90% of forecast peak load assuming a fixed speed of travel for restoration crews, fixed switching time for breakers/disconnects, and a cold start for all resources.	Verify the capacity of the proposed restart service to start and supply auxiliaries of other power stations, assist the stable energisation of generation and transmission and pick-up of stabilising load blocks, facilitating a restoration of the Minimum Restart Path and consequently to achieve the standard.	To confirm the initial sequence of operations and pathways that are required to establish a secure and stable power system.
Definition of a black start unit	Able to be started without support from the grid or designed to remain energised without connection to the grid. Able to energise a bus. Meets TO's need for real and reactive power, frequency and voltage control.	Have the ability to start up without an external power supply (both generators and interconnectors)	… the capability of recovery of a power-generating module from a total shutdown through a dedicated auxiliary power source without any electrical energy supply external to the power-generating facility	1. To start-up (following a Total Shutdown or Partial Shutdown) independently of external supplies; 2. To be able to energise part of the network, and; 3. To be able to provide block loading of local demand	As per NERC: A generating unit(s) and its associated set of equipment which has the ability to be started without support from the System or is designed to remain energised without connection to the remainder of the System, with the ability to energise a bus, meeting the TO's restoration plan needs for Real and Reactive Power capability, frequency and voltage control, and that has been included in the TO's restoration plan	Capability of a facility or combination of facilities, after disconnection from the power system and without taking power from it, to deliver electricity to a connection point or other suitable point from which supply can be made available to other production units.	Ability of a registered facility with an energy producing system to start without requiring energy from a network, to assist in the reenergisation of the SWIS in the event of a system shut down or major supply disruption.
Physical restart testing aim	Energise the closest (dead) bus	Energise the spare busbar in the station within an hour (unit test). OR To energise to the point of connection (PoC) within an hour (station test). OR	"for power-generating modules with black start capability, this technical capability to start from shut down without any external electrical energy supply shall be demonstrated" … "within a time frame specified by the relevant system operator".	Primary restoration source: Energise from dead a local busbar, a circuit(s), a transformer(s) and a remote busbar and then synchronise onto a live busbar. Other sources may only need to restart from a disconnected system and resynchronise to the PoC bus.	Restart the unit without drawing supply from the wider grid, energise a dead bus, energise a dead line, and re-energise the largest auxiliary motor of the next generator to start in the test plan. All without tripping and maintaining voltage and frequency within bounds. Also an option to energise load available.	Confirm that the unit can be isolated from the grid and start up on its own to reach its point of connection. Some testing may include the energisation of network and loads to confirm ability of the service to reach a key network node if determined to be necessary and practical given the network configuration.	To confirm that the potential or contracted unit can meet its continuous operation time requirements and its network energisation capability requirements.

	CAISO	EirGrid	Energinet	NESO	ERCOT	AEMO NEM	AEMO WA
		Energise the network to, and the auxiliaries of the next-start generator in the plan. However, generally, this is difficult to implement due to outage restrictions.					
Testing	Yes – Routine testing (at least once every three years, some areas yearly)	Yes – one unit per station annually, one station test (complete disconnection) once every two years. **N.B.** Penalties exist for lack of performance (loss of payment)	Three distinct tests: 1. Testing that the auxiliary power unit of the black starter functions correctly (seven times a year). 2. Testing that the black start unit can energise to its point of connection with all external supply disconnected (once a year). 3. Testing that the black start unit can energise the transmission system to the next-start unit and energise its auxiliaries (once every four years). May also include the energisation of load.	Yes, but different requirements for different categories of plant. For the primary restoration service: A capability assessment every three years, and a dead line charge test & resynchronisation every two years. Other plant types may be less. Notably, there is a "random phone call test" where a provider is called randomly to confirm availability.	Extensive testing is required, including individual unit testing, network re-energisation, load energisation, and energisation of the next generator's auxiliary units.	Yearly testing of contracted black start services is required, which primarily considers re-energisation to the unit's point of connection and performing a series of minor tests. Network energisation tests are contemplated in NEM rules, but are not routinely undertaken due to difficulty establishing the necessary test conditions.	Unit testing to occur every six months. If multiple options to access the service exist (e.g., different fuel types), this may be tested too.
The role of IBR	Potentially the use of BESS may play a role to provide both an initial restart source for gas turbines, or large-scale BESS could potentially be used as a load if required. However, it is not expressly considered in any current plans.	Wind power is explicitly required to be disconnected during system restart. Same with transmission-connected solar. However, EirGrid will soon begin a review as to how IBR can be potentially accommodated, with a focus at least on BESS voltage control during restart.	Currently IBR devices such as wind and solar would be considered to reconnect relatively early during system restoration as a support service for frequency or voltage, but not as a primary black start unit. Such devices would not be procured but would be expected to respond when required.	NESO are encouraging new restart sources, including IBR, to provide services both from top-down and bottom-up approaches. There was a notable but unsuccessful tender for wind power to provide primary system restoration services. However, this led to successful contracting for energy top-ups from wind, reinforcing the potential of the strategy. NESO are clearly considering IBR as a part of the system restart mix.	Not currently considered as part of the restart plan as existing sources are not GFM, but explorations are ongoing as to how BESS can aid in restart for voltage and frequency control.	IBR can tender to be both a primary restart source or restoration support service, so long as it can meet the requirements for availability and reliability, and be shown to be stable in EMT dynamic studies. BESS are more likely to be considered for primary restart sources as they are controllable and not reliant on environmental conditions.	Currently the last to be re-energised but work underway to bring participation of some form of IBR earlier in the process (e.g., use of BESS services).
The treatment of DER	Not an issue in this jurisdiction – most solar is large-scale and hence controllable. Distribution-connected BESS capacity is large, but not of a high enough proportion to be of concern.	Not a major issue. Potentially some minor load undermining in later stages of restoration, but not of major concern.	DPV/DER is a growing concern, but not yet clear exactly how big of a risk. This is considered an issue for the DSO to manage, and following a recent detailed technical survey of DER, both DSOs and Energinet have increased confidence in supplying sufficient load during restart.	It is known that DPV may undermine available load during restart, and as such, distribution operators have determined priority restoration plans which aim to restore critical load and avoid feeders with high DPV penetration.	Not currently considered.	It is a considerable problem in regions where coal-based primary restart sources dominate with large minimum load. There is currently a non-zero chance that restart will need to be delayed in some high DER regions during periods of high irradiance.	A problematic issue given high DPV penetration, however it is not actively managed due to lack of visibility and control, and instead feeders with likely stable load are prioritised for restoration.
Restoration support services considered	Not considered – sufficient traditional options available combined with a top-down approach.	Not currently considered.	Not contracted but any unit can (and likely, will) be called upon to assist in such an event.	Yes, there are a variety of restart types considered as part of the Distributed ReStart program. "Top-up generators" in particular are a form of restoration support services.	Not currently considered, however BESS may have a role to play in future plan iterations.	Yes, any generator can potentially be a restoration support service if it is strategically located on a restart path. Self-starting is desirable, but not a requirement.	Not considered but would like to be implemented.
Bottom-up restoration considered from distribution network embedded generation	No – sufficient large-scale options available.	Not currently, but considering as an option for the long-term future.	Generally not considered. If black start units are technically within the distribution system but close to a transmission connection, they can be used.	Yes.	Not currently considered due to the challenge of coordinating many small <1MW units.	Not currently considered. Although restart units may connect into the distribution system, the required capability is to energise a path to the transmission network.	Not currently considered.
Criteria for independent sub-networks within which black start sources should be procured	Divided by transmission owner areas.	Defined by generator and load centres (known as sub-systems). Each sub-system has a primary generator and load target.	Two subnetworks based on separate synchronous systems, connected by line commutated high voltage direct current (HVDC).	By distribution operator licence area. 7 regions in total.	Transmission entities determine sub-network restoration at ERCOT.	Based on technical characteristics needed to respond to major supply disruption, , including number and strength of transmission corridors to the rest of the NEM power system, electrical distance between generation centres and ability to maintain satisfactory/secure operation.	Based on transmission corridors connecting to the rest of the SWIS, electrical distance between generation centres, quantity of generation and load, and location of synchronising facilities
Inherits requirements	Yes, from NERC	Yes, from COMMISSION REGULATION (EU) 2017/2196 of 24 November 2017	Yes, from EU regulations, and supplemented by Danish electricity law for operational matters.	Government mandated.	Yes, from NERC.	Requirements set by Reliability Panel – independent panel managed by the AEMC.	No – System & Market Rules regulations require AEMO WA to

	CAISO	EirGrid	Energinet	NESO	ERCOT	AEMO NEM	AEMO WA
							specify the detailed system restart standard.
Interconnectors can be used as black start (inc. HVDC)	Cannot be procured as a service, however given the large number of interconnectors (48), it is assumed that several will be available to initiate the top-down restoration process (first preference).	Yes, EWIC is considered a viable option (HVDC), potentially new interconnectors to be included too.	Yes, and top-down restoration would be a preference if available.	Yes, this is explicitly mentioned as a methodology for re-energisation and a focus of the recent strategy.	Not considered as a black start source, however a VFT link can be used as a backup in practice should other options fail.	They can be used in practice, but cannot be procured as a system restart service.	No inter-regional interconnectors in the SWIS, however there are sub-networks based on distance, transmission corridors and generation centres. AEMO uses reasonable endeavours to procure restart capacity in each sub-network, but restart could be sourced from another sub-network over an alternating current (AC) interconnector if no options are available.
Load considered in plan	Under inherited requirements from NERC, requires restoration plan to consider how to use load to maintain island stability, however in practice this is not required.	Yes, priority of restoration given to "high priority significant grid user" or load areas where the lack of supply could result in 'significant risk' (determined in conjunction with DSO). The initial target load is mapped out beforehand through planning. Once an island is available, the DSO advises where the next load will be, typically targeting hospitals, airports, etc.	There is currently no need to procure any load. The distribution system can connect what is required to maintain stability during black start. There are also large amounts of centralised heating loads that could be called upon.	It is for the distribution operator to work with government to determine which national infrastructure loads need to be restored as a priority.	Under inherited requirements from NERC, the restoration plan should consider how use load to maintain island stability. However, the primary concern for ERCOT is the restoration of nuclear auxiliaries within 4 hours, and the restoration of critical loads such as hospitals and water supplies.	Existence of sensitive loads must be considered by the Reliability Panel in determining the overall targets for the restart standard. AEMO's System Restart Ancillary Services (SRAS) guideline contemplates that a restoration support service may provide stabilising load.	Proximity to stable load is a noted requirement for the strategic location of the restart source. Restoration of any 'sensitive loads' must be considered in the plan development.
Supports storage or interconnector technology	Dependent on each TO to determine. Current technical requirements from at least one TO have continuous export requirements that intermittent and storage generation are unlikely to meet (e.g., sustain output for 12+ hours, or in the LA Basin procurement, 48 hours).	EWIC HVDC link forms a part of the top-down restart option, however all variable sources (e.g. wind) are currently explicitly excluded until later stages of restoration.	Yes, however the requirement to have sufficient fuel storage for running at nominal output for at least 24 hours may be a limiting factor. **N.B.** One study identified that a combination of wind and solar plants with sufficient geographical distribution within Energinet's area, could be capable of meeting these energy 'storage' requirements, with only a small shortfall in energy availability across a year.	Yes, their black start strategy (2021) specifically seeks to enable new technologies (including interconnectors) to participate given the changing generation mix and boost competition. It is noteworthy that no wind restart options were selected as primary resources in the recent wind-only tender (but were selected as 'top-up energy' resources).	The NERC definition doesn't exclude novel generation types (although it does exclude interconnectors), but there are repeated requirements in the ERCOT protocols for 72 hours of fuel storage sufficient to operate at maximum output during this time. However, these can be waived at ERCOT's discretion.	Interconnectors cannot currently be procured as a source, but can be used in the restoration process. Storage can bid for both primary restart source as well as restoration support services (aiding network as it restores), subject to meeting reliability criteria and sufficient operating duration.	System restart services are limited to registered energy producing facilities. The current standard uses language that is synchronous-machine centric. These would require amendment to consider non-synchronous machines. .
Locational diversity requirements	The TO should determine – noted that at least one TO considered locational diversity as a key factor in procurement.	Yes, at least 2 units per region (4 regions).	Yes, one unit per synchronous island.	Yes, different regions are to be supported by local generators, often multiple (according to tender results). Potential for many other support services to be procured.	Protocols 3.14.2 (6) require consideration of location.	Yes, standard requires consideration of geographic diversity and strategic location	Yes, standard requires consideration of geographic diversity and strategic location.
Fuel diversity requirements	None noted, however both gas and hydro are notably plentiful in the region.	Hydro, pumped hydro, gas turbine and AC & DC interconnectors form part of options.	No – only one unit per synchronous island.	Yes, a point is made not to procure multiple sources with the same fuel types within the same region.	Yes – with particular note that backup fuel sources and fuel switching is considered in detail in the assessment of the black start resource. However, this requirement can be waived at ERCOT's discretion.	Diversity in energy source or fuel is part of aggregate reliability assessment.	Diversity in technology (including fuel) is a consideration but not a requirement.
Technology diversity requirements	None noted.	Yes – hydro, gas and interconnectors.	No – only one unit per synchronous island.	In part - Related to fuel above.	Not defined, but all data appears to be heavily synchronous-machine focused.	Not explicitly required.	Yes, as a consideration
Availability / Reliability requirements	The TO should determine – noted that at least one TO required black start units to be capable of at least three restart attempts.	Yes – each station must have a minimum number of black start units to be considered black start capable, and payment is only made if said minimum numbers remain available. Reliability is determined by yearly testing.	No official requirements, however procured units must be available 24/7. If not available, a financial penalty applies.	Yes, ≥80% Black start units must be capable of at least 3 restart attempts.	Noted that there were no requests in tenders for defining availability percentages, however there is a general strong focus on physical testing, with "resource availability tests" required every quarter, with short notice (~2 hours). Failure to perform when dispatched results in financial claw back.	Individual service reliability considers availability, start-up performance and local network reliability. Aggregate reliability of all services in a given sub-network generally ≥t 90% , with one at 95%. Additional requirements (with lower reliability) apply for specified parts of two sub-networks.	Yes, each service must have ≥95% availability for a 'specified period'. If components of a restoration pathway are unavailable for more than 5% of the year, network operator to propose a rectification plan. Black start units (as opposed to Trip to House Load [TTHL]) must be

	CAISO	EirGrid	Energinet	NESO	ERCOT	AEMO NEM	AEMO WA
							capable of at least three restart attempts.
Maximum time to energise network requirements	TO dependent. One TO requires a maximum of three hours to begin re-energising the network.	Yes, be energised at their point of connection within 60 minutes.	2 hours. Larger, cold steam units may have relaxed requirements (e.g. 9 hours) given their technology limitations.	Yes, 2 hours from primary sources. 8 hours from distributed restart sources.	Accomplish switching within 1 hour after a black out event and the maximum start-up time of 6 hours.	Each sub-network has a different MW-time target to be met. The services procured must energise the network sufficiently promptly to meet those targets.	Black start units to be at PoC within 60 minutes. TTHL units to be at PoC within 30 minutes.
Personnel requirements	Manned in line with Good Utility Practice (Tariff Appendix D).	Many/most of the generators are staffed 24/7 already. But not interconnectors, where if they are not staffed 24/7, staff must be on site within one hour – this can be a concern as interconnectors may well be the most viable option for restart in some circumstances.	Personnel are not required to be on site, but each unit must have a reliable contact point. Two people acting as an operational contact are required to be immediately contactable 24/7, using Denmark's special secure telecommunications network.	Not explicitly for restart, however it is a general expectation that the larger units are to be staffed 24/7.	Required to be staffed 24/7, or if this is not possible, the necessary staff must be on site within 1 hour ready to initiate a response after a system black is declared.	No explicit requirements.	Network staff to be onsite within two hours for key network nodes that may deplete their energy source. If a restart provider is not 24/7 manned, AEMO to have remote control of the generator.
Maximum start time requirement	Yes, start within 10 minutes (Tariff Appendix D), but not ready to switch.	Energise the PoC by 60 minutes.	Energise the PoC by two hours.	Two hours from primary sources, eight hours for distributed sources.	Six hours as an absolute maximum.	Services procured must meet the sub-network MW-time target.	Black start units to be at PoC within 60 minutes. TTHL units to be at PoC within 30 minutes.
Extended runtime requirement	TO dependent, but noted a requirement of 12 hours at full output.	None.	Must be capable of running for at least 24 hours at nominal load and attempt at least two restarts within these 24 hours.	Primary restart unit must exceed 10 hours runtime. There must also be 72 hours' worth of resiliency for these units.	72 hours, unless waived by ERCOT.	Services procured are expected to deliver sufficient energy to meet the MW-time requirement for their sub-network.	Generators must hold sufficient reserve operate independently for 14 hours at nominal output. Networks must have backup supplies for eight hours.
Level of technical data collected from provider	TO dependent. Noted from one example the data was relatively basic, and assumes synchronous machine – e.g., capability curves, basic machine and transformer parameters and minimum power requirements.	Potential new providers must do their own studies to prove efficacy. Existing providers, once efficacy has been proven, do not need to repeat studies.	The data collected during the generator connection process is also used for black start studies. A comprehensive set of data and models are collected, including both Phasor Domain Transient (PDT) and EMT models and protection functions. The tender process requires additional information to be submitted if found needed through EMT studies.	High level data collected through a staged feasibility assessment process, delivering studies that focus on proving the capability of the plant as described. Modelling requirements for generator connections is comprehensive and data could be re-used for restart studies. Nothing additional is collected for restart.	Technical information is collected through the comprehensive model requirements during the generator interconnection process and on-going model updates. ERCOT RFP includes other basic information and ERCOT may request additional technical data as needed. Note that simulated demonstrations of capability are considered by ERCOT.	Detailed information required, such that all relevant elements (including crucial auxiliary loads) can be modelled in EMT. Network service providers are also expected to provide details on protection relays and transmission assets (e.g. transformer saturation curves) to facilitate EMT studies.	AEMO is able to request any additional information from the potential provider to help facilitate its selection process. This may include dynamic models.
Dynamic modelling	Required through NERC EOP-005-3 R6. One example of TO modelling required PDT modelling only.	EU NCER Article 51 requires simulations to be completed every 5 years, but given no changes recently, studies have not been updated. Could be done for new providers, however.	EU NCER Article 51 requires simulations to be completed every five years. Detailed EMT modelling is used.	Not conducted by NESO (probabilistic modelling used instead), but TOs will inform the viability of certain paths based on protection and load-flow studies. TOs can get access to detailed modelling data.	Required through NERC EOP-005-3 R6. However, ERCOT does not use EMT modelling for restart plan development. ERCOT relies on physical testing to demonstrate capability.	Yes, detailed EMT models required. May require additional information above what is submitted during the connection process.	Yes, specifically required to confirm viability of the restart plans. EMT modelling is used to model primary energisation paths only.
Network protection considered in studies	Dependent on each TO to consider – implied possibility given data collected.	Not used.	Not yet, however relay experts evaluate fault curves to identify the potential for issues.	TOs consider network protection relays in path formulation. Changes in real relays are considered.	No.	Yes, with a focus on network transformer differential relay modelling.	No – seen as a known gap.
Generator protection considered in studies	Dependent on each TO to consider – implied possibility given data collected.	Not used.	Yes, EMT models collected require generator protection functions to be captured.	Yes, as models collected are the same as those defined in the Guidance for Modelling Requirements (detailed EMT and PDT). TOs could access this information if required.	No.	Yes, protection is modelled for both synchronous and IBR technology, including for synchronous machines negative phase sequence, over-fluxing, and loss of field.	No – seen as a known gap.
Procurement is competitive?	It can be, but there are also some regulatory contracts for assets that are owned by the local TO.	"Under SI445/2000, EirGrid as TSO is mandated to procure whatever services are necessary to ensure grid security" (although this must be approved by the regulator), and "Payment rates are reviewed annually and subject to the approval of the Regulatory Authority".	Yes.	Yes, it is a core pillar of their strategy, with clearly defined assessment criteria for all tenderers, and extensive Q&A clarifications.	Yes, with published assessment criteria for tenderers to address, based on both technical and economic elements.	Yes	Yes

	CAISO	EirGrid	Energinet	NESO	ERCOT	AEMO NEM	AEMO WA
		Essentially, all possible units are procured as there aren't enough options currently. May move to a competitive process in the future when more options are available.					
Contracting options	Long-term (multi-year) with exit provisions, plus regulatory contracts for black start assets in a region that are also owned by the TO. Noted that strong compliance obligations may have disincentivised some restart-capable sources from tendering.	Rolling yearly contracts, approved by the regulator yearly.	Three-year contracts.	Five-year restoration service contract	Three year contracts.	Contract periods are negotiable, but three years (with one plus one year extension options) generally used to date.	Contract periods are negotiable but generally five- year contracts (with one plus one year extension options).

2 System restoration operational experiences

The following examples draw on relevant CIGRE Technical Brochures 911 [1] and 712 [2], supplemented by public reports. Focus is given to large-scale supply interruption events that required the invocation of black start procedures, both from top-down and bottom-up strategy. Events where there were interruptions of supply or tripping of multiple generators that did not result in a regional blackout were not considered.

2.1 Iberian Peninsula 2025

The official investigation to the Iberian Peninsula blackout in April 2025 is still ongoing, and information may be incomplete. In forming this summary, reports from Red Electrica [3] and ENTSO-E [4] are used.

2.1.1 Blackout event

According to the Red Electrica report, the Iberian power system experienced low-frequency oscillations, suspected to originate from a photovoltaic (PV) plant, which led to undervoltage risks and the temporary removal of shunt reactors. As the system tried to stabilise, a lack of dynamic reactive power absorption – especially from renewable sources operating in power factor mode – combined with sudden demand shifts, triggered increased voltages across the system and subsequent cascading generator trips. Within 30 seconds of an "inappropriate" generator trip, over 2,000 MW of renewable generation was lost, interconnectors disconnected on protection, and load shedding accelerated, leading to the entire system collapse.

2.1.2 Restart Issues

Details regarding challenges faced during restoration are not yet available. However, it is noted that system restart was executed quickly with much of the system restored within approximately 12 hours. Prompt re-energisation of interconnections between Spain, France and Morocco within minutes of the event helped quickly re-establish the backbone of the system, while bottom-up restoration from black start plant occurred simultaneously. Reconnections to Portugal occurred later in the day. By 4:00 AM on the following day, full transmission grid restoration was completed in both Portugal and Spain.

2.1.3 Lessons learned

Whilst the Red Electrica report provides a series of recommendations, these are focused on the prevention of a system collapse, rather than improving system restart. More restart-focused recommendations may be provided as further analysis is completed.

2.2 Chile 2025

It is acknowledged that a major blackout event occurred in Chile on 25 February 2025, however sufficient details from official sources are not yet available. From public news sources [5] [6], it appears that protection maloperation on the 500 kilovolts (kV) system backbone was the primary cause of system collapse.

2.3 Brazil 2023

2.3.1 Blackout event

According to [7], the blackout began at 8:30 AM on 15 August 2023 when the Quixadá–Fortaleza II transmission line unexpectedly disconnected due to a maloperation of its protection relay, causing a sudden drop in voltage across the region. This triggered a cascade of transmission line disconnections and separated key subsystems from the National Interconnected System, prompting emergency load shedding that interrupted over 23,000 MW of power. Restoration took place throughout the morning, while analysis later revealed that wind and solar farms in the region heavily contributed to the initial voltage drop, which did not align to the behaviour predicted by their plant models.

2.3.2 Restart issues

Not currently available in public reports.

2.3.3 Lessons learned

Not currently available in public reports, but it is conceivable that as a result of the event:

- plant modelling requirements may be revisited to prevent such performance mismatches occurring in the future, and
- additional scrutiny will be placed on protection relay settings and testing.

2.4 Brazil 2018

2.4.1 Blackout event

The blackout was triggered by misconfigured protection relays, including an overcurrent relay set below circuit breaker capacity resulting in an erroneous circuit trip and a special protection scheme failing to disconnect unstable generation at Belo Monte HPP. This led to a major power imbalance between northern and southern systems, causing network separation, underfrequency load shedding (UFLS) in the south, and overfrequency shutdowns in the north. 9 Hz oscillations persisted for two minutes in the northern subsystem before stabilizing after further generator disconnections.

2.4.2 Restart issues

The following issues were identified as impeding the restoration of the system:

- Voltage oscillations during restoration caused appreciable loss of generation. This, in turn, caused high voltages at several substations resulting in additional equipment to trip.
- In the Northeastern area, after the frequency was restored to nearly 60 Hz, there was an additional loss of hydro generation units due to voltage oscillations.
- The restart time for some of the hydropower plants in Northeastern region was not compliant with the requirement set out in ONS Grid Procedures (30 minutes) and those observed in regular black start tests conducted on those units previously.
- There were difficulties during the remote energisation of the 500/230 kV autotransformer at Paulo Afonso IV substation and of the 230/69 kV (T2) transformer at Abaixadora substation. Both events delayed the fluent restoration of Paulo Afonso IV Area.

- Unsuccessful attempts to close the parallel and loop paths were experienced as the criteria for angle, voltage and frequency profiles for synchronisation was not achieved.
- Misunderstandings between the transmission and distribution system operators resulted in a load pickup in excess of the values defined in operational instructions for some areas. This excess load pickup caused load rejection and automatic shutdown of the substation due to overvoltage protection.

2.4.3 Lessons learned

Many of the recommendations focused upon preventative measures to avoid a blackout in the first place, however notably ONS determined that to improve system restart performance:

- There was a strong need to improve the restart time and performance of hydropower plants in Northeastern region.
- There is a need to study the inclusion of wind power generation during the restoration.
- Stronger enforcement of load pickup size limits at the distribution level are required.
- Conclusions on parallel line usage during restoration must be revisited.

2.5 South Australia 2016

2.5.1 Blackout event

On 28 September 2016 there was a sequence of faults on the transmission system in South Australia over a two-minute period during a severe storm. This resulted in the almost simultaneous shutdown of nine wind farms (about 450 MW of generation in total), which overloaded the interconnection between South Australia and the rest of the NEM interconnected system. The interconnection tripped, islanding South Australia. The UFLS scheme in South Australia was unable to halt the rapid decline in frequency. The island collapsed, interrupting about 1,800 MW of load.

2.5.2 Restart issues

Two black start units had been successfully tested a few months earlier, but different issues prevented their successful use during the actual event. In one case, the test assumed network conditions which were not fulfilled in the event. The other black start source experienced a stator earth fault causing the emergency diesel generator to trip, which meant that the main black starter could not be restarted.

The system was ultimately restarted using a top-down approach from the alternating current (AC) interconnector to a neighbouring region.

2.5.3 Lessons learned

To improve the performance of system restart, it was identified that there must be more comprehensive testing of black start generators and the need to include redundancies in the black start generator and part of network to be used during system restoration.

2.6 Türkiye 2015

2.6.1 Blackout event

On the day of the event, much of the generation for the region was being supplied from the eastern region of the country to the western population centres. Immediately prior to the event, four major lines and 16 capacitors banks were out of service, leaving the system in an insecure state.

The heavily loaded east-west 400 kV interconnector then tripped on overcurrent protection. This resulted in a cascaded tripping event, with the western demand centres seeing a rapid decline in frequency and activation of UFLS schemes. While the western frequency stabilised, the remaining generators in the western region then began tripping on underfrequency, leading to system collapse. In the eastern part of the country, large power swings were experienced, leading to generators tripping on overfrequency.

2.6.2 Restart issues

The following issues were identified as hampering the restoration efforts:

- disconnection of Türkiye-Bulgaria interconnection due to tripping of the Special Protection Scheme (SPS),
- tripping of several 400 kV lines due to SPS being taken out of service during system restoration, and
- failure of automatic UFLS following loss of generation in one of the restoration islands.

2.6.3 Lessons learned

It was determined that the restoration could have been faster if the disconnected thermoelectric generating units were required to have a trip to house load (TTHL) / islanding to station service capability.

2.7 India 2012

2.7.1 Blackout event

The event was triggered by a weakened interregional corridor and heavy power transfers between the Northern and Western regions, placing significant stress on transmission links. When a critically loaded link tripped, it caused cascading failures of other circuits, large angular separations, and destabilising oscillations that led to system collapse. It was noted that the system had insufficient generator frequency support, malfunctioning protection and load-shedding schemes, and the blocking of high voltage direct current (HVDC) links due to under-voltage protection.

2.7.2 Restart issues

A hybrid top-down bottom-up restart strategy was followed during the restoration on both days, however, there was greater reliance on the bottom-up strategy on 31 July due to reduced interregional power availability. Notable challenges included:

- several trips of 400 kV lines on overvoltage during supply restoration to thermal units,
- the collapse of some restoration islands due to generation-load imbalances, including unplanned islands,
- secondary disturbances in a power station in Western region which caused delays in restarting the Northern region on 30 July,
- a gas turbine generator tripping on reverse power protection on 31 July, and

- a hydro unit in Eastern region tripping on overvoltage on 31 July.

2.7.3 Lessons learned

The lessons learned from this event were numerous and far reaching, including changes to technical requirements and equipment, improved testing regimes, a review of operational planning mechanisms, regulatory changes, greater system visibility, and improved coordination between entities. In regard to the restoration process itself, it was noted that there was a need to implement requirements for black start tests at regular intervals and formation of islands during these tests, and a need for improved communication and telemetry protocols during restart.

2.8 Testing operational experiences

It was noted from the feedback of the ISOs/TSOs during interviews that regular plant testing that includes testing as many of the cranking paths as practicable is the best method to identify deficiencies in both black start sources and plans.

- CAISO noted that the relatively high frequency of testing which occurs in some sub-regions has resulted in identification and resolution of operational problems that could not have been reasonably foreseen, along with a development of strong communication and camaraderie between external parties that will likely improve trust and performance in a real event.
- ERCOT noted that through testing, every year new defects are found in the performance of black start units. They noted tests rarely succeed the first time, with multiple tests usually required (even if the test was previously successful last year).
- AEMO WA noted that increased frequency of testing has seen black start units move from rarely meeting restart requirements when tested to almost always being able to restart first time every time.
- Energinet noted the following challenges when undertaking testing:
  - Black start network testing often has technical issues related to conducting such a test next to a live network, including voltage induction of parallel lines, correct operation of synchronisation equipment and coordination challenges of interlocks in substations.
  - Larger thermal units have complex auxiliary systems, which may be supplied from multiple sources during a restart test, resulting in multiple frequencies to manage. This can result in challenges in synchronising across these frequencies internally to the plant.
  - Line commutated converter (LCC) HVDC interconnectors have minimum power requirements and can immediately inject when unblocked. This sudden injection can result in reverse power tripping in generators; hence generators must be dispatched at higher loads to prevent this.
  - Frequency control in general in large thermal units is challenging, and adjustments were almost always required to the governor settings to achieve satisfactory performance.

Furthermore, many ISOs/TSOs recognised that although there is great value in performance of network re-energisation testing, depending on the topology and interconnectivity of the network, securing sufficient outages to perform testing at a time and cost that is acceptable to all parties remains a major challenge.

3 Adaptation of future system restart plans

3.1 Anticipated changes

The need for ISOs/TSOs to revise their system restoration frameworks will be primarily driven by the increasing complexity of both generation and load technologies. As IBR continue to displace traditional synchronous generation, and as load profiles evolve due to DER, inverter-based loads (IBL) and electrification trends, several aspects of current restoration planning, procurement and operationalisation will require reconsideration. The table below outlines key anticipated changes in the power system, a description of their technical implications, and corresponding considerations for adapting system restoration strategies in high-IBR environments.

Table 1 Summary of anticipated changes and implications for system restoration strategies

Anticipated change	Detailed description	Implications for system restoration approach
Increased share of IBR	Most IBR lack sizeable inherent inertia and fault current compared to synchronous machines, affecting frequency and voltage control during early stages of black start and subsequent restoration stages. In addition, many IBR exhibit control susceptibilities and instability mechanisms when operating with a low number of online synchronous machines.	The increasing reliance on IBR and the parallel reduction in online synchronous generators requires restoration frameworks to evolve beyond MW-based procurement. System operators must plan for low-inertia and low-fault-current conditions. Restoration planning should explicitly account for limitations in traditional black start units and build confidence in IBR technologies through testing and standardisation of the expected performance.
Reduction in the number of online synchronous generators	Results in a reduced number of synchronous generators available both as black start sources and as larger units that would traditionally be brought online during later stages of restoration to provide voltage and frequency control and supply additional MW for progressive network energisation and load restoration.	Same as above.
Evolving load behaviour (DER, IBL, and industrial loads)	Includes high DER penetration (e.g., DPV) and growth in large-scale inverter-based or industrial loads such as data centres and electrolysers. These loads can be highly variable, unpredictable, or distorted, and DER may produce net export during daylight. Large load steps or inrushes may destabilise a weak grid.	Restart plans must account for the unpredictable and dynamic behaviour of DER and IBL. DER may disconnect or destabilise the system due to inappropriate protection settings or net export during light load conditions. IBL may introduce harmonics, flicker, and exhibit poor fault response, potentially failing to ride through even a single disturbance, thereby compromising stability in weak network conditions. Procurement frameworks should incentivise stable and predictable load, including controllable industrial demand. Enhanced visibility, control, and forecasting of load performance are essential, and new standards may be required to define acceptable behaviour of large loads during system restoration.
Greater deployment of GFM inverters	Provides new restoration capabilities but introduces coordination challenges, particularly when operating under current-limited conditions. Operating in these conditions can alter inverter behaviour and may compromise the intended operation of conventional protection systems.	Technology-neutral participation frameworks and pilot demonstrations are essential. GFM inverter capabilities must be harmonised and validated to ensure coordinated operation and stable performance. Operational limits such as current saturation, and interaction with other GFM and GFL inverters, must be well understood.
More complex control behaviours of IBR and IBL	Requires high-fidelity modelling to accurately capture system interactions and dynamics under restoration scenarios.	Detailed EMT and scenario-based studies are necessary. Traditional steady-state or simplified dynamic analyses are insufficient to assess complex IBR–IBL interactions during restoration. Accurate modelling of protection systems is also essential, as new restoration configurations may alter fault levels, timing, and coordination dependencies.
Changing network	Restoration under low system strength or IBR-based sources alters network behaviour,	Restoration plans must explicitly consider the readiness of network components. This includes potential re-tuning of

Anticipated change	Detailed description	Implications for system restoration approach
requirements under high-IBR conditions	including voltage profiles, protection coordination, and energisation transients. Traditional approaches for network control may no longer be valid.	reactive power support devices, verification of relay settings, and energisation studies to avoid temporary overvoltages due to increasing risk of resonance in IBR dominated restoration.
Energy limitations of new black start technologies	Some IBR restart sources such as BESS may have limited energy availability due to state-of-charge (SoC), making them unsuitable for prolonged restoration without coordination.	Restoration frameworks must consider the duration for which restart sources can provide energy, not just their instantaneous MW capacity. This may necessitate hybridisation of sources (e.g., BESS + solar), SoC management strategies, or sequential energisation to avoid exhausting limited energy reserves during critical phases.

However, the rate at which these changes will need to occur will be different depending on the specifics of the jurisdictions; in particular, if traditional restart sources are not likely to be displaced. For example, consider two jurisdictional examples, being CAISO and AEMO NEM:

- Both regions are seeing IBR-based solar resources deployed at a rapid rate.
- CAISO's solar generators are largely transmission-connected and visible and controllable to the transmission and system operators.
- AEMO NEM also has large amounts of transmission-connected IBR solar, but even more distribution-connected rooftop PV that is invisible and uncontrollable to the system operator (and much of which is operating to outdated standards).
- CAISO has large amounts of gas and hydroelectric units, which are fast and flexible enough to complement the energy profile from variable renewable sources. Hence, these gas and hydroelectric units – and any black start capability they bring – are likely to remain a feature of the power system for the foreseeable future.
- AEMO NEM has modest amounts of gas and hydro across its system but may still have reliance on coal restart resources in some sub-networks.
- CAISO is strongly interconnected to other regions, with 48 interconnectors to other systems.
- AEMO NEM operates as an island (effectively two synchronous islands), and regions within the island may have only a single AC interconnector to one another.

Although both systems are strongly adopting renewable energy technologies, the CAISO system may not need to radically change to system restart principles in the near future (primarily being top-down restoration from interconnectors, with gas and hydro bottom-up restoration alternatives). Indeed, the role of IBR technology may even be bypassed during restart, should conditions allow.

Conversely, AEMO must rapidly evolve its restart plan to cover the imminent closure or reduced operation of many of its thermal generators and cater for unprecedented amounts of rooftop PV undermining daytime load required for restoration island stabilisation. Fundamentally the NEM must find ways to adopt the increasingly dominant IBR sources as potential primary black start units (or at least, restoration support services) as they continue to displace traditional restart sources.

The following section outlines a series of practical improvement opportunities that directly address the challenges identified above, with a focus on implementation and design flexibility.

3.2 Improvement opportunities

As power systems around the world experience increasing shares of IBR, evolving load types, and the retirement of conventional synchronous generation, system restoration frameworks must adapt to a new set of operational realities. The following improvement areas highlight opportunities to better leverage emerging technologies, address capability gaps, and define a target state for future system restoration practices.

3.2.1 Move beyond megawatt-based procurement

Traditional restoration frameworks typically focus on procuring megawatt quantities from restart-capable sources. However, in high-IBR systems, megawatts alone are not a sufficient indicator of restoration viability. Additional technical attributes such as inertia (real or synthetic), fault current quality, ability to run at zero export, control stability under weak grid conditions, and parallel start-up compatibility are critical to successful restoration.

Recommendation 3.2.1: Define performance-based criteria for restoration services that account for these broader system needs. Avoid over-simplified procurement based solely on active power capacity.

3.2.2 Remove participation barriers for emerging technologies

Current procurement frameworks may unintentionally exclude advanced but energy-limited technologies, such as GFM batteries, due to rigid requirements like extended fuel or energy storage duration (e.g. 'must be capable of running at maximum output for 24 hours'). Units such as GFM batteries may be well suited to initiate fast restoration of auxiliaries, provide balancing or voltage control services, or support other start-up units with minimal energy usage, shortening overall restoration times.

Recommendation 3.2.2: Reassess minimum technical requirements for black start participation. Where suitable, enable limited-duration units to fulfil specific support roles in a modular restoration plan.

3.2.3 Recognise the importance of load in restoration planning

The availability of stable, controllable load is important to maintain system stability during restoration, particularly for generation types sensitive to minimum export conditions (e.g., paralleled synchronous units or TTHL technologies). However, in some jurisdictions, there is insufficient or highly variable load during daylight hours due to large amounts of embedded generation (e.g., rooftop PV). Hence in these jurisdictions, the explicit inclusion of load as part of restoration plans would be highly beneficial.

Recommendation 3.2.3: Actively procure suitable industrial or demand-side loads as restoration resources. Address regulatory or commercial barriers that prevent controlled load from being integrated into restoration frameworks.

3.2.4 Enable modular restoration using diverse and partial-capability units

In regions where sufficient traditional restart options are no longer available, solutions may need to consider a modular approach. Rather than relying on a single black start unit, restoration can increasingly be approached as a coordinated effort between complementary services, e.g.:

- primary black start sources (e.g. small gas turbine),
- auxiliary energisation units (e.g. wind turbines),
- reactive support (e.g. STATCOMs),
- grid-forming stabilisation (e.g. GFM BESS), and/or

- energy buffers (e.g. GFM or GFL BESS).

In this way, shortcomings of one unit or technology type can be compensated by another technology type (and vice-versa), allowing hybrid restoration services to be developed.

Recommendation 3.2.4: Create flexible frameworks that allow multiple sources, each with partial capabilities, to work in coordination. Based on regional factors, procurement of interconnectors may be explored as a potential viable restoration point if sufficient safety and synchronisation controls exist.

3.2.5 Deliver early, clear, and technology-neutral signals to industry

OEMs are attempting to develop technology to be used in multiple, disparate markets, adding to complexity and cost. To ensure future-capable equipment is being developed today, system operators must provide early and, where possible, standardised guidance to manufacturers and project developers. This includes clear, non-technology-specific technical requirements and expectations for restart performance.

Recommendation 3.2.5: Establish standardised, internationally aligned performance requirements for restart services and communicate them well in advance of tender cycles. This supports cost-effective design and testing by OEMs.

3.2.6 Ensure proportional risk and incentive structures

To encourage the development of new projects in a power system, investment certainty is required. Outdated requirements, excessive liabilities, unclear expectations, or poorly designed penalties can discourage otherwise capable technologies from participating in restoration procurement.

Recommendation 3.2.6: Ensure the commercial terms for restoration services are proportionate to risk and compliance obligations. Consider revising remuneration structures where appropriate to attract diverse participants.

3.2.7 Expand physical testing and validation into the network

Practical plant and network testing remains a cornerstone of restoration assurance. Anecdotally, multiple jurisdictions have discovered critical issues only through full-scale testing that would not have emerged in simulations. Testing should not stop at the connection point, but extend into the network where restoration actions will be applied.

Recommendation 3.2.7:

- Conduct live energisation trials beyond the point of connection, ideally up to the next planned restart unit, in particular involving one or more IBR.
- Require re-testing when key equipment is replaced, even if it is a “like-for-like” substitution.
- Establish mechanisms for technical and commercial remediation of issues found during testing.

3.2.8 Improve modelling scope, methods, and assumptions

As system restoration increasingly involves IBR, distribution-level DER, and new protection paradigms, traditional Root Mean Square (RMS) or steady-state models are insufficient, as they do not adequately represent controllers and protection mechanisms which could have a material impact on plant performance [8]. Hence, EMT-based simulation, incorporating waveform-level control logic and protection devices, is essential.

Recommendation 3.2.8:

- Model restoration pathways beyond the next busbar, ideally to cover major load centres and parallel start-up units.
- Mandate EMT-based analysis for deterministic evaluation of all restoration services, including integrated protection behaviour and DER reconnection dynamics.

3.2.9 Address communications and operational readiness

Nearly all those surveyed reported that many generation sources in their jurisdiction are now remotely controlled and/or dependent on public communication networks for control. This may even include potential black start sources. Depending on their location within the cranking path, such generators may be crucial to supply services to the restoring system, yet following a widespread collapse, these networks may be compromised or unavailable, leaving the generator uncontrollable.

Recommendation 3.2.9: Require physical presence or local control capability at restart plants following an event. Establish alternative communications or fallback mechanisms to ensure continued operability.

3.2.10 Account for the role of DER and emerging large loads

High penetration of DPV can present a risk during restoration, especially if it reconnects en masse and destabilises generator load balance. Similarly, large IBL such as data centres can cause fast, unpredictable ramps and significant inrush effects.

Recommendation 3.2.10:

- Develop explicit treatment strategies for DER in restoration plans. This includes consideration of their behaviour under restoration conditions, such as unintended reconnection, anti-islanding settings, and their effect on minimum load availability in high-DPV regions.
- Establish clear performance criteria for large industrial or IBL loads used during early restoration, including their voltage/frequency tolerance, protection behaviour, and ability to support or hinder the stability of restoration islands.

4 Methodology framework

To apply the recommended improvements described in section 3 across different jurisdictions and system conditions, a flexible and system-neutral methodology framework is required.

Table 2 below sets out a framework for developing a system restart plan for jurisdictions that are forecasting increases in IBR penetration to a level where traditional synchronous machine black start sources are likely to be displaced and/or load characteristics are changing to an extent that traditional black start sources may struggle to maintain stability.

These are the core principles underpinning this framework:

- Increased IBR penetration generally requires more detailed information and analysis to understand both unit and system performance and hence accurately develop restart plans.
- The different characteristics of what IBR can provide to the system mean that both network and load performance must also be considered during restoration plan development.
- A broader set of services may be required to achieve the same system capability as previously maintained, hence commercial mechanisms must be expanded to consider procurement beyond black start sources alone.
- The industry is necessarily conservative in relying on new and unproven technologies for low-probability, high-impact scenarios such as system restart, so there must be local, proven real-world trials and demonstrations in place before it will be widely accepted.

Table 2 Methodology framework principles

Objective and scope
• Define the purpose of the black start plan and the expected outcomes. • Ensure alignment with broader system resilience, security, and operational integrity goals.
Regulatory and compliance requirements
• Ensure the plan developed will be aligned with overarching government regulations and local grid code requirements (if applicable to system restoration). • Incorporate future-proofing provisions to enable participation of new technologies.
System restart technical requirements
• Establish technical criteria for system restoration, including generator and network capabilities that will not preclude IBR technology from participating in the restoration process, yet still ensures a high standard of restart capability. • Include diversity requirements that consider and manage the variable output from VRE sources. • Review and update minimum technical performance requirements across all relevant asset types, including generators (synchronous and IBR), large loads (including inverter-based), and network components, to ensure they support robust system restoration and are suited to emerging system conditions, such as renewable energy zone development or inverter-dominant areas. • Define performance expectations for GFM-capable resources intended for black start or restoration support, including their ability to establish stable islands, provide the necessary stabilising functions, and manage voltage and frequency autonomously under weak grid conditions.
Data provision and modelling requirements
• Define what technical, modelling and process information is required from potential black start sources, network owners, and next-start generators*. • Update any modelling or information provision standards such that the necessary authority to collect the increased detailed information required is in place.

- Ensure system operators can perform simulation studies and independently reproduce extreme operating conditions relevant to system restoration, validated against real system events or staged restoration testing.
- Ensure sufficient real-time visibility and modelling of large loads and DER-rich feeders to support accurate simulation and operational decision-making during restart.

Commercial viability

- Broaden procurement to include restoration support services (e.g., network energisation, stabilising loads).
- Ensure:
  - fair compensation for different service types, and
  - contractual mechanisms for long-term investment in restart capabilities.

System analysis

- Identify the most capable black start sources, supporting services and restart pathways through detailed simulation and planning studies that can adequately capture performance of protection and control systems in a weak grid.
- Identify and model the dynamic performance of large industrial loads, data centres, and DER-rich distributed loads, particularly those with inverter-based interfaces, and assess their suitability as stabilising or controllable restart blocks, including definition of pre-conditions for energisation.
- Consider the availability and robustness of both sources and the network in formulating viable plans.

Operational planning

- Develop step-by-step, executable restart plans.
- Include fallback pathways, alternative sources, and dependency contingencies.
- Ensure procedures are actionable even under partial observability.
- Incorporate parallel restoration paths (e.g. top-down and bottom-up), where viable, including interconnectors, or regional sub-networks. Ensure synchronisation and coordination points are clearly defined, studied and tested.

Testing and validation

- Develop pilot test plans to demonstrate the capability of IBR black start and support services to reliably deliver restart capability in the given jurisdiction.
- Require GFM-capable plant to demonstrate the ability to energise dead networks and maintain stable operation and allow correct operation of protectively relays through real-world or staged system restoration testing.
- Ensure frequent, regular testing of restart sources is mandated that attempts to mimic the conditions likely to exist during a real system restart event. Ideally, such testing should include the re-energisation of network elements between the unit and its next-start generator*, followed by re-energisation of the next-start generator's* auxiliaries.

Communication and staffing protocols

- Require adequate staffing of restart resources such that there are no dependencies on remote key personnel that may be uncontactable during a supply disruption.
- Require communication and control systems of participating elements to have redundancy and no dependency on public systems which may be unavailable during a real restart event.
- Regularly practice drills with a focus on communication and coordination between all parties involved.

Continuous improvement

- Regularly review and update restart plans, testing plans, and technical requirements based on lessons learned from past incidents, testing outcomes and technological advancements.

* "Next-start generator" is a term borrowed from ERCOT which refers to the next generator to be energised.

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Appendices

Summary of system restoration requirements

ISO/TSO-specific findings of note

The following summarises noteworthy differences between the jurisdictions evaluated.

- NESO and AEMO NEM had some form of "restore X amount by Y hours" overarching restoration target for supply capacity.
  - AEMO NEM had the most specific MW-time restoration targets, while other jurisdictions using this approach had far more flexibility.
- Maximum restoration time for primary restoration units to start up and be ready to commence switching varied from 30 minutes to six hours.
  - **N.B.**, to be considered for a contract, not necessarily as a rigid commencement time for the main restart plan.
- EirGrid have a requirement to procure *whatever is necessary* to be able to restore the system (pending regulatory approval), and NESO noted while there is no set regulatory limit on procurement, they are still required to implement the most economical solution.
- The requirements of some transmission operators (TOs) in the CAISO jurisdiction disallow BESS and variable IBR from participating as a primary black starter by virtue of extended energy storage requirements (up to 48 hours).
  - HVDC interconnectors also cannot tender for system restoration due to non-compliance with the NERC definitions of black start.
  - CAISO noted that the substantial BESS capacity could be used as a controllable load during restart if the need arises.
- CAISO forecasts no issues with system restoration during periods of high solar irradiance, as the majority of their solar plant is large, transmission-connected and controllable. There is also an abundance of BESS and native load which can be used for stabilisation purposes.
- No restrictions in ERCOT requirements were identified that would restrict IBR technology to tender for restoration, however there would need to be waivers put in place by ERCOT to avoid extended energy storage requirements, and consideration of IBR participating in restart is an ongoing area of investigation.
- Provision of restoration services in ERCOT are heavily reliant on physical testing of equipment, including their ability to energise a portion of the network and energise the largest motor auxiliary of the next unit to be started.
  - Testing of availability is undertaken quarterly with penalties for non-compliance.
  - Testing of physical restoration of load may be considered.

- ERCOT had explicit restoration service staffing requirements, either needing the station to be staffed 24/7, or the correct staff to be on site within 1 hour (maximum) of a blackout event.
- ERCOT noted that testing seldom passed the first time, even if the provider was previously successful.
- Energinet routinely perform testing of the black start unit's capability to both energise a portion of the transmission network and energise the next-start generator's auxiliaries (similar to ERCOT).
- AEMO and Energinet strongly rely on deterministic and detailed EMT modelling to develop their system restart plans and to select their black start sources.
- EU regulations have a provision to consider a 'Significant Grid User' (SGU) to be factored into the restoration plan. This could be a generator or a load, and if identified, the ISO/TSO is obliged to consider their restoration in their plan.
  - While jurisdictions reviewed did not identify such SGUs in their plans, EirGrid has an additional provision to prioritise the restoration of load areas where the lack of supply could result in a 'significant risk'.
- EU jurisdictions generally allow the use of interconnectors as part of system restart.
- NERC requirements *technically* allow load to be considered in the restoration plan in terms of "*the Load needed to stabilize generation and frequency, and provide voltage control*", however this does not appear to be used in practice.
- NESO are seeking to enable new restart technologies to participate in system restart, largely due to the retirement of traditional sources. Interconnectors and non-synchronous technologies are explicitly considered for restoration tenders. However, it is noteworthy that a recent tender for wind-based system restart resulted in no contracts being awarded for a primary restoration service, but did allow for wind to provide an energy 'top-up' service.
- NESO have requirements for fault current and inertia provision from their contracted restoration units, recognising that a restoration MW is not the same as a system normal MW.
- NESO have developed plans that allow simultaneous top-down and bottom-up restoration, with bottom-up restoration using a variety of distribution islands to band together to form a viable restoration service.
- The most common restart testing requirement was to re-energise a unit that has been disconnected from external supply, and restore up its point of connection. ERCOT and NESO may use extended network and load energisation as part of the test process. AEMO too may use extended network testing, but this seldom occurs in practice.
- AEMO NEM and AEMO WA have immediate needs to address high levels of DPV in their system which are eroding the availability and stability of distribution-connected load.

North American Reliability Council (NERC)

NERC requirements form the basis of most requirements adopted by the ISOs/TSOs in North America. CAISO and ERCOT requirements fall under the NERC area of control. Black start planning and testing falls under requirements set by NERC in EOP-005-3 [9]. These requirements are generally quite broad and speak more the need to have requirements and plans in place more so than dictating the precise nature and amount of black start services required. Hence, it falls to the ISOs and TOs to develop more detailed standards as required.

NERC defines:

- the aim of black start as "ensure plans, Facilities, and personnel are prepared to enable System restoration from Blackstart Resources to ensure reliability is maintained during restoration and priority is placed on restoring the Interconnection", and
- a black start resource as "a generating unit(s) and its associated set of equipment which has the ability to be started without support from the System or is designed to remain energized without connection to the remainder of the System, with the ability to energize a bus, meeting the Transmission Operator's restoration plan needs for Real and Reactive Power capability, frequency and voltage control, and that has been included in the Transmission Operator's restoration plan". [10]

There are some notable obligations that must be considered by ISOs/TSOs within this high-level requirement:

- Loads: "The restoration plan shall include: … Operating Processes to restore Loads required to restore the System, such as station service for substations, units to be restarted or stabilized, the Load needed to stabilize generation and frequency and provide voltage control."
  - The ability to explicitly consider the use of load for stability and technical envelope maintenance purposes during restart is a noteworthy requirement that provides an important tool in maintaining restoration islands.
- Modelling: "Each Transmission Operator shall verify through analysis of actual events, a combination of steady state and dynamic simulations, or testing that its restoration plan accomplishes its intended function. This shall be completed at least once every five years. Such analysis, simulations or testing shall verify:
  - The capability of Blackstart Resources to meet the Real and Reactive Power requirements of the Cranking Paths and the dynamic capability to supply initial Loads.
  - The location and magnitude of Loads required to control voltages and frequency within acceptable operating limits.
  - The capability of generating resources required to control voltages and frequency within acceptable operating limits."

  Again, it is seen that the role of load must be considered in system restoration, albeit from a simulation perspective. The requirement does not dictate a particular domain of simulation to be used (e.g., PDT/RMS or EMT), only that both dynamic and static steady-state studies must be completed.
- Testing**:** "Each Transmission Operator shall have Blackstart Resource testing requirements to verify that each Blackstart Resource is capable of meeting the requirements of its restoration plan. These Blackstart Resource testing requirements shall include:
  - The frequency of testing such that each Blackstart Resource is tested at least once every three calendar years.
  - A list of required tests including:
    - The ability to start the unit when isolated with no support from the [bulk energy system] or when designed to remain energized without connection to the remainder of the System.

- The ability to energize a bus. If it is not possible to energize a bus during the test, the testing entity must affirm that the unit has the capability to energize a bus such as verifying that the breaker close coil relay can be energized with the voltage and frequency monitor controls disconnected from the synchronizing circuits."

This sets out the minimum that ISOs/TSOs must ensure restart providers must meet across North America, being a physical restart test without external supply at least once every three years, and closing onto a dead bus should network arrangements/conditions allow.

Hence the NERC requirements form the base on which CAISO and ERCOT requirements are built.

Californian Independent System Operator (CAISO)

The responsibility for developing and maintaining black start capability within the CAISO region has been delegated to the individual TOs that make up the region, rather than CAISO itself. Instead, CAISO provides a coordination function between the TOs. The TOs are responsible for defining requirements for functional behaviour, procurement and testing of the black start units (consistent with NERC EOP-005-003). There is no overarching restart target identified for the region (e.g., X% of load restored within Y hours) – best effort applies.

Generally, system restoration in the CAISO region is expected to be a top-down process, as there are 48 interconnections between regions and both generation and load RAS always armed to prevent a collapse of the entire region. However, should a total blackout occur, black start units are procured in each TO's sub-region and would be used for a bottom-up restoration. Although interconnectors are not procured, they are assumed available (given the large quantity).

While TOs are responsible for contracting with black start providers through a competitive process, CAISO can and does procure some black start units under regulatory contracts in cases where the generation unit is also owned by the TO company. It is noted that there are likely many more restart capable sources available than what is tendered, as reportedly, becoming a restart source comes with compliance obligations with which some generators do not or cannot comply.

CAISO does not perform any dynamic modelling of the restart process, and instead delegates this obligation to the TOs, who are required to do so to confirm the validity of their plans. It is noted that at least one TO relies on PDT (PSLF) rather than EMT studies.

CAISO currently does not have any concerns in maintaining black start capability, even with increased IBR penetration. There are ample hydro and gas units available well into the future, a large amount of underlying load always available, 12 GW of battery storage connected which could be used as a controllable load (with plans to quadruple this in the near future), and most variable IBR is large-scale and controllable, rather than rooftop PV. Sourcing sufficient stable load simply isn't an issue currently or for the foreseeable future.

> **N.B.** CAISO does not currently have any preference for GFL or GFM installations of IBR, due to the generation mix still containing a large portion of synchronous machines, and the extensive interconnection to other regions.

A key lesson learned from system restart testing of plant was that regular testing both unmasks issues that were not foreseen in the re-energisation of equipment, and importantly, builds camaraderie between all parties involved if conducted frequently and with a common purpose.

A tender was run in 2021 for a sub-region within CAISO [11] [12] which highlighted the following considerations for those wanting to become a black start source:

- At the highest level, procurement criteria include being technically feasible, financially reasonable, and being reliable. However, quantitative metrics were not provided.
- There are no explicit limitations on technology that can participate in black start, so long as those sources can meet the selection criteria [13]. However, this criterion is generally synchronous-centric and has a requirement for extended operation at maximum output (12 to 48 hours) which would likely exclude most BESS or variable IBR from participating.
- Locational diversity was explicitly considered, with potentially a second unit not procured as it did not allow for the locational diversity from the first unit.
- HVDC links were confirmed to be ineligible as they do not meet the NERC definition of a black start source.
- Pricing for restart must be based on actual costs and is managed through FERC, and contracts are generally multi-year with exit provisions, although CAISO will also procure sources through regulatory contracts where the source is owned by the local TO.

Technical requirements in “ISO Tariff – Appendix D” [14] included:

- a “minimum number of starts” being required, clarified to be three attempts in the Technical Variables and Criteria report,
- an agreed load pickup range,
- a startup time of 10 minutes (**N.B.**, not necessarily ready to energise the network) and an ability maintain output for 12 hours,
- sufficient reactive power control to keep system voltage within emergency voltage limits, and
- staffing levels which accord with Good Utility Practice.

A local TO Southern California Edison (SCE) had further selection requirements [15] for the Los Angeles Basin Region. These included:

- meeting the NERC definition of a black start source,
- the ability to meet minimum continuous running time of 48 hours,
- the ability to energize a dead transmission bus within three hours (i.e., switching begins), including further consideration of the speed at which a resource could re-energise the 220 kV loop,
- the flexibility to energise other nearby generators and allow them to restart,
- resource longevity (requiring up to 10 years of service),
- the overall cost of the service,
- the ability to meet fault impedance requirements of the restoration path (**N.B.** this suggests that protection requirements may explicitly be considered as part of SCE’s plan development),
- the flexibility of the generator protection relays to withstand conditions during system restart (i.e., no false tripping),
- ability to provide PSLF models of the plant (notably PDT/RMS domain rather than EMT domain), and

- conformance with the additional NERC standards:
  - Correct protection relay settings (PRC 19-2 and 25-1),
  - Cybersecurity protocols (CIP 008-2 and 008-3), and
  - Communication (COM-001).

There was little information on testing requirements available outside of those published in NERC EOP-005-003. However, it was noted in discussions with CAISO that:

- conformance with the ability to provide a black start service largely falls on the service provider to demonstrate, with the CAISO ultimately responsible for signing off on performance,
- testing was generally conducted yearly for each contracted service, and
- regular testing built of a sense of camaraderie between the various parties involved.

Electricity Reliability Council of Texas (ERCOT)

From discussions with staff, it is understood that the restoration plan development and modelling process is strictly confidential, hence details in this space are limited. However, it was noted that ERCOT processes comply to the same high-level requirements set out by NERC in EOP-005-003. The following black start unit requirements are from Chapter 3 [16] and Chapter 8 [17] of the ERCOT Nodal Protocols, and are in addition to the NERC requirements.

- Each Generation Resource providing black start service must meet the requirements specified in the NERC Reliability Standards and the Operating Guides.
- Resources are contracted for three years at a time, at which point they need to re-bid.
  - Black start resources can be swapped out mid-term if requested and connected to the same cranking paths as the previous resource.
- Where purchased fuel is used, backup fuel must be available to run the unit for 72 hours at maximum output throughout the contract period.
  - This can be waived if ERCOT deem it allowable.
- For a resource to be determined capable of providing black start capability:
  - There must be redundancy in communications and control paths.
  - It must be verified as passing the basic starting, line energising, load-carrying, and next start tests.
- Any limitations regarding weather extremes on the performance of the black start unit must be clearly stated. This is an area of strong focus.
- A requirement for locational diversity exists, inferred from Section 3.14.2(6) where ERCOT shall periodically determine and review the location and number of Black Start Resources required.
- ERCOT RFP documents [18] indicate that:
  - Unit restart time must be less than six hours (an upper limit, with lower values considered more favourably).

  - Once the point of connections is energised, pre-determined switching actions need to occur within one hour.
  - Site must be staffed 24/7 or the necessary staff can be on site within one hour of event reasonably indicating that a system wide blackout has occurred.

ERCOT has a strong reliance on physical testing of both units and networks to confirm the validity of its black start plans, more so than any other jurisdiction surveyed. The following outlines the mandatory testing requirements of ERCOT which help ensure that their restart plan is fit for purpose.

ERCOT performs four tests (basic startup, line energising, load carrying, and next start tests) before the annual certification of the black start resource. Prior to January 1 of each year, all existing and prospective black start resources must meet the qualification for all four tests; otherwise, ERCOT decertifies the black start resource. For example, all four test qualifications must be fulfilled by December 31, 2024 if the resource wants to provide the black start service starting January 1, 2025.

- Basic startup testing:
  - Testing must be completed yearly before 1 July to qualify for the following year.
  - Failure to pass within two months of the first test may see the device deregistered. ERCOT may limit the number of retests.
  - Units must be capable of supplying only their auxiliaries or no load for 30 minutes.
  - Special attention is paid to the operation of overflux, OEL and UEL protection relays, with verification from ERCOT required.
- Line energising testing:
  - Testing must be completed once every three years.
  - Must include basic testing plus energising of line(s) along the cranking path such that the unit "…demonstrates the Black Start Resource's ability to energize enough transmission to deliver to the Loads the Resource's output that ERCOT's restoration plan requires…"
  - Soft-starting of the line is allowed.
- Load carrying test:
  - Testing must be completed every four calendar years.
  - It includes basic and line-energising tests, plus supplying a pre-arranged load such that the unit "…demonstrate the Black Start Resource's capability to supply the required Load, while maintaining voltage and frequency for at least 30 minutes…"
- Next-start resource test:
  - Testing must be completed every four calendar years.
  - It includes the above tests plus: "…[demonstrate the] ability of a Black Start Resource to start up the next start unit's largest required motor while continuing to remain stable and control voltage and frequency shall be tested…". To pass the test:

        - "The potential Black Start Resource must start the next start unit (as determined by ERCOT), or start the next start unit's largest required motor and satisfied the next start unit's minimum startup Load requirements" OR
        - "The Resource Entity shall demonstrate to the satisfaction of ERCOT through simulation studies conducted by the Resource Entity or a qualified third party, that the potential Black Start Resource is capable of starting the next start unit's largest required motor while meeting the next start unit's minimum startup Load requirements."
        - "If a physical test is performed, the Black Start Resource must remain stable (in both voltage and frequency) and controlling voltage for 30 minutes."
- ERCOT may perform unannounced basic startup testing during the contract period.
    - There is an additional quarterly "black start resource availability test" which requires the unit to start and run at minimum output for at least four settlement intervals at very short (two hours) notice to demonstrate availability. Black start resource may start the generator on its own during the quarter, and operate at the minimum operating level or higher for one hour or longer to replace the black start resource availability test.
- Back-up fuel-switching tes tis required once every two years unless the 72-hour back-up fuel requirement is waived by ERCOT.

ERCOT also encourages testing compliance with penalties for failure for the quarterly black start resource availability test:

- If a test is failed once, there will be zero availability payments until the next test succeeds (to be completed within 10 business days unless ERCOT agrees with a later date).
- If failed twice, there will be no more future payments and previous payments since the last successful test or real-time operation will be clawed back.
- If the unit fails in a real black start event, all future payments will be cancelled, previous payments since the last successful test or real-time operation will be clawed back, and the unit will be decertified.

In discussion with staff, it was noted that:

- Despite their rigorous testing regime, defects in the black start sources were found every year. Tests rarely succeeded the first time, with multiple re-tests required. This was even if they were previously successful.
    - This is a particularly important point for consideration, as there is no substitution for real world operations.
- ERCOT's dynamic simulation testing beyond next-start testing is still being matured, and simulations are more focused on determining and confirming restart timeframes based on operational probabilities.

EirGrid

EirGrid operate under the jurisdiction of the EU, and as such are subject to many of the requirements set across broader Europe (which like NERC reliability standards, focuses more to the concepts and broad compliance requirements, rather than detailed standards to maintain). It is from these EU standards that EirGrid are obliged to develop and maintain a restoration plan [19].

Further to the EU requirements, it was noted that under Statutory Instrument SI445/2000 [20], EirGrid as ISO/TSO are mandated to procure whatever services are necessary to ensure grid security. However, it is understood through discussions that effectively all possible restart-capable devices are procured, and there are no options left for a competitive process to be used. This will reportedly change in the future if more restart-capable devices become available.

EirGrid have published their Restoration Plan Design [21] which, in addition to section OC.4.7 of their grid code [22], outlines much of their requirements and drivers for system restoration across Ireland. The primary objective of restart is noted to be: "Achieve restoration of continuous supply to all consumers as quickly and as safely as possible with minimum adverse consequences", with supplementary objectives of preventing plant damage, maintaining normal shutdown conditions, conserving station supplies, restoration of dispatchable generators quickly, and restoration of customers/locations where loss of supply has the "highest risk". Determination of the highest risk loads is done by distribution system operators, and generally targets critical national infrastructure.

Further to these objectives, there are quantitative targets defined in the Restoration Plan Design which set expectations for all parties to work towards, should the conditions on the day allow. From a base assumption that all generators, network, communications and IT are available after a system black, these include:

- EirGrid to have an action plan ready 30 minutes after the situation has been ascertained,
- black start stations to be up and stable within one hour of the action plan being developed,
  - other primary target generators external supply to be restored within two hours,
- load of restart pathway subsystems to be restored within four hours,
- resynchronisation of sub-subsystems within six hours, and
- all HV transmission re-energised within 12 hours.

The plan design requires restart to be considered from both top-down and bottom-up approaches to allow maximum flexibility for scenarios where there has been only a partial blackout (i.e. a sub-region of the island has collapsed) or the entire island has collapsed. It generally focuses on the use of synchronous generators as the primary black start sources, with a notable carve-out that the East-West Interconnector (EWIC) from England is specifically considered as a restart source which can be used for top-down restoration. Through discussions it was understood that the use of the interconnector for top-down restoration is a general preference, where conditions allow. It is also noteworthy that wind farms are specifically required to shut down (and stay off) as a first step in the restart plan, due to implications of voltage and frequency swings from their variable nature. No requirements that would be likely to exclude batteries from participating in restart were noted.

An inherited requirement from the EU standards is the concept of a "Significant Grid User" (SGU), which may be either a generator or a load. If any such SGU is identified by the relevant ISO/TSO, they must be specifically considered within the restoration plan as to how they can be restored promptly following a supply interruption. No such SGUs were identified in the EirGrid jurisdiction, but it is noteworthy that should a need arise, there are specific abilities to consider their needs during restart.

Limited commentary is provided on the requirements which apply to black start sources. It was noted in discussions that there are currently 20 black start sources contracted across the four regions. Despite this, fuel/technology diversity is considered, as gas turbines and interconnectors also form part of the mix. A timing requirement applies, defined as: "*Following the issue of a blackout signal (referred to as a blue alert signal in* *the agreement) the black start unit or units at the black start station must be started up to energise the system up to their connection point in accordance with its black start plan within the contracted black start time of 60 minutes*".

In terms of the network restoration rebuild planning, there were several technical requirements outlined that may be of interest to other ISON members when considering their own restart plans:

- Stability is always prioritised over speed.
- The four sub-regions are to be restarted in parallel following a system-wide blackout.
- It is preferable to have many moderately loaded machines rather than few highly loaded machines.
- Network stations are broken into priority 1 and 2, with priority 1 (on the black start path) to be staffed within 30 minutes, and priority 2 stations within 60 minutes.
- Soft energisation of cranking paths is allowed if technically feasible.
- Frequency is to be kept at 50 hertz (Hz) or higher.
  - Automatic Frequency Regulation systems should be turned off.
  - Only a single unit should remain in isochronous (only) with others in setpoint or droop.
  - Following each load pickup, the isochronous unit should return to a midpoint output.
  - When picking up load, the loss of the largest generator must be considered.
- The target voltage for the network should be roughly 0.9 per unit (pu).
- Transformer taps should present the largest number of turns upon energisation from the HV to minimise inrush.
- Energise only one circuit of double-circuit paths to minimise line charging and increase current flow for fault discrimination.
- Avoid energisation of any HV line with an unloaded transformer at the far end.
- All telecommunications should be through dedicated comms networks, not public networks.

System restart testing is mandated through the EU requirements. EirGrid in Section 10.5.7 of its grid code [22] have further defined two types of testing: Unit Tests and Station Tests.

- A Station Test refers to a complete disconnection of the generating station from the power system and witnessing the ability of the station to return to service without any external supply.
  - This is to be done at least once every three years.
- A Unit Test refers to testing of a single black start unit within a station and does not require the entire station to be disconnected from the grid. This is a functional test of the unit's ability to restart and energise up to its point of connection.
  - This is to be done every year.

Tests may be required with as little as sevend ays advance notice, and are evaluated based on the speed of the unit to return to service:

- Generators that energise to their point of connection within 60 minutes of loss of supply are considered acceptable.
- Generators that energise to their point of connection within 60 to 120 minutes of loss of supply will incur a partial penalty (loss of payment for 30 days).
- Generators that take longer than 120 minutes to energise to their point of connection will be considered as a failed source, and incur loss of payment for 90 days.

Finally, it was a requirement under OC.9.5.4 that EirGrid must issue a blackout state at least once a year for training and testing of all staff and parties.

Energinet

Energinet operates under the jurisdiction of the EU, and as such are subject to many of the requirements set across broader Europe. Requirements are further supplemented by the Danish electricity regulations.

Energinet's principle of design for their system restart plan is to develop viable bottom-up restart pathways for each synchronous island of their system (of which there are two) to cater for a worst-case scenario. Top-down restoration would be used in practice should there be available interconnectors to other viable power systems, with bottom-up resources being simultaneously deployed. There were no overarching targets for broader system restoration noted (e.g., percentage of system, system restoration within a given time, etc.).

- The current planning design predominantly focuses on the use of synchronous machines as the primary black start unit for bottom-up restoration due to the need to meet the energy requirements.
- It allows for IBR devices such as wind and solar plants to reconnect relatively early in the restoration process as a support service, providing bulk MW, voltage or frequency control, but not as a primary black starter:
  - Further work is ongoing to consider the need to "cap" output from such variable energy sources during restoration to minimise energy fluctuations on the system.
  - Such support services would not be contracted; it is an expectation that if the unit is above 25 MW and available that it would assist in system restoration, but Energinet is currently unaware of the preparedness of the IBR and their operator. This is a focus area for future work.
- Synchronous condensers are brought online for system support services (inertia and voltage control), and HVDC with VSC for voltage control:
  - The HVDC VSC Mega Volt-Amperes Reactive (MVAr) capacity in Energinet's area is roughly the same as the synchronous condenser capacity.
  - The HVDC converters are operated in STATCOM mode if the remote end TSO is not ready/able to energize the whole link.
- The amount of transmission-connected BESS is currently insufficient to play a meaningful role in system restoration; however, this may change as projects come online.

Energinet's definition and requirements of black start units are based on standard connection requirements [23], EU requirements [24] and tender documentation [25]. With strong reference to these standards, the following requirements on black start generators were defined:

- Generation facilities are not required to have black start capability – it is an optional service.

- Power-generating facilities with black start capability must be capable of starting from shutdown without any external electrical energy supply and within a time frame set by Energinet.
  - This timeframe is nominally within two hours, although up to nine hours may be acceptable if the unit is steam-based and cold prior to the event.
- The generating unit must be connected to a 150/60 kV or higher voltage substation (132/50 kV in the eastern synchronous area).
- The unit must be capable of performing at least two start-up procedures within a 24-hour period, supplying at least 30 MW for at least 12 hours after each start-up. If the unit can supply more energy than 30 MW, Energinet may increase this requirement.
- Energy reserves must be sufficient to supply at least 30 MW for 24 hours. Reliance on the public gas network is allowed.
  - This may be a limiting factor in the participation of variable energy source IBR and BESS, however it was noted in discussions that historical analysis has shown a combination of a wind and solar farms tendering together may have sufficient energy available to be available for black start services almost all year round.
    - Energinet performed analysis which showed that due to the geographical distribution of large offshore wind farms, the average availability of 30 MW for 24 hours was equivalent to a large coal power plant, when considering the start up time and failure rates during operation. Similar conclusions were made for onshore wind and solar farms.
- The unit must be capable of accommodating 10 MW load step increases, and 20 MW load step reductions.
- The black start unit must have enough reactive power capability to restore the connecting network and auxiliaries of at least two other power stations. At a minimum however, the unit must be able to supply 50 MVAr and absorb 20 MVAr through continuous dynamic voltage regulation to be considered.
  - If the unit is a new provider, live testing must also occur.
  - Soft energisation is allowable.
- Frequency control capability requirements include:
  - Being able to synchronise within the frequency limits set out in point (a) of Article 13(1) and the voltage limits set out in Article 16(2), requiring an extended ability to withstand frequency excursions.
  - No deadbands around the target 50 Hz frequency, and capable of adjusting the static frequency by 2 to 12%.
  - Operating in LFSM-O and LFSM-U, as specified in point (c) of paragraph 2 and Article 13(2).
  - Controlling frequency in case of overfrequency and underfrequency within the whole active power output range between minimum regulating level and maximum capacity as well as at house-load level.
  - Being capable of parallel operation of a several power-generating facilities within one island.

- Being in continental Europe, interconnectors can be readily (and preferentially) used for top-down system restoration purposes. Sufficient safety mechanisms are in place to prevent a continent-wide collapse of the power system (i.e., intentional breakpoints).
  - Energinet report that the use of VSC HVDC interconnectors for restart is readily considered and tested.
- Note that once selected as a black start provider, the unit is obliged to substantially increase its physical site security given it is now forms a critical portion of the power system.

Energinet uses EMT modelling to evaluate potential bottom-up black start source capability, with an aim to confirm that the chosen black start source is capable of re-energising both a portion of the network and restarting the next-start generator's auxiliary loads.

- Although EMT model data is collected during the generator connection process, including representations of the generator protection relays, additional specific modelling requirements are outlined in Section 5 of [26] for black start tender units to be compatible with Energinet's black start studies.
- Network protection relays are not yet explicitly included in the EMT models used for black start planning. This is considered an area of future expansion. Today, fault curves generated from EMT studies are provided to protection relay experts for commentary and issue identification.
- While EMT modelling currently only evaluates a black start unit's ability for energisation of the next-start unit auxiliary loads and connecting network, consideration is being given to extend EMT modelling to broader system restoration.

The load-destabilising effect of DER / distributed solar in the distribution network is of general concern to Energinet but has not yet reached a level where specific actions need to be taken. Supplying of stable load is achieved through use of the distribution network (i.e., no transmission-connected load is required for stabilising services – although large district heating loads could be used) and is the responsibly of the distribution system operator to ensure the requested load is available. It is noteworthy that Energinet have a very strong and collaborative relationship with their DSOs and routinely engage in detailed joint planning to tackle issues such as this.

Testing of black start units is achieved through a three-stage process:

- Testing of the auxiliary power unit (e.g., diesel generator) of the black start unit.
  - Tested seven times a year.
- A complete disconnection of the black start station from the broader system power system to test its ability to re-energise (i.e., restore voltage) up to its point of connection. This may include demonstration of additional capabilities such as being able to manipulate frequency setpoints.
  - Tested once a year.
- Testing that the black start unit can energise both a portion of the transmission system connecting to the next-start unit, and energise the next-start units auxiliaries.
  - May also include the energisation of load should appropriate load be available, and resynchronisation with the broader grid.
  - Tested once every four years (largely due to the effort required to coordinate between parties and secure the necessary outages and resources).

Furthermore, Energinet shared the following practical challenges when undertaking testing:

- Black start network testing often has technical issues related to conducting such a test next to a live network, including voltage induction of parallel lines, correct operation of synchronisation equipment and coordination challenges of interlocks in substations.
- Larger thermal units have complex auxiliary systems, which may be supplied from multiple sources during a restart test, resulting in multiple frequencies to manage. This can result in challenges in synchronising between these subsystems internally to the plant.
- LCC HVDC interconnectors have minimum power requirements and can immediately inject when unblocked. This sudden injection can result in reverse power tripping in generators; hence generators must be dispatched at higher loads to prevent this.
- Frequency control in general in large thermal units is challenging, and adjustments were almost always required to the governor settings to achieve satisfactory performance.

Selection of black start service providers is achieved through a competitive tender process.

- Three-year contracts are used, although Energinet noted a general desire to increase the contract length to give greater certainty to all parties, but this was limited by legislation.
- Energinet considers a procured unit to be available 24/7 for restoration services. If it is determined within a contract period that this has not occurred, financial penalties will apply.

Additional system restoration concerns for Energinet were reported as:

- General unknown performance of IBR technology, with the potential to undermine system restart if not proven capable and stable for extreme operational cases.
- A general shift to remote plant operation with a subsequent overreliance on public telecommunication networks by generator operators, who are assuming that the public communications systems will be available during a black start event for unit control.
- Uncertainty as to whether the balancing tools used by the control room will operate as expected during a black start event.

National Energy System Operator (NESO)

NESO was previously under the jurisdiction of the EU and required to follow the same overarching requirements as EirGrid and Energinet. Following Brexit, they have undertaken a program to update their system restart standards and plans.

NESO has a clear target for overall system restoration, defined in [27] as: "*This new Electricity System Restoration Standard will require NGESO to have sufficient capability and arrangements in place to restore 100% of Great Britain's electricity demand within 5 days. It should be implemented regionally, with an interim target of 60% of regional demand to be restored within 24 hours. The Electricity System Restoration Standard will reduce restoration time across Great Britain and ensure a consistent approach across all regions*." It was noted in discussions that this target does not impose financial limitations on what can be procured, such that engineering judgement can be used to determine what is needed. It was further noted that the market is working reasonably well, and any suspected abuse of market power is quickly investigated by authorities.

A black start strategy published [28] provides additional context on the efforts currently underway in NESO to modernise and make system restoration more flexible. Specifically, there was a recognition of the diminishing pool of "full" service providers, hence the need to consider combined services to source capability across multiple sites and technologies (including interconnectors for top-down restoration). Plans for simultaneous top-down and bottom-up restoration are considered by NESO. In meeting the target, only generators can be procured, not other equipment or loads.

NESO have published extensive work on its “Distributed ReStart” program, which looks to leverage many smaller restart-capable generators in the distribution network to initiate a distributed bottom-up restart process through careful coordination of distribution islands. There are requirements published by NESO on requirements for the various different types of generators that can participate in this bottom-up approach, which can be found in the tender documents for recent procurement rounds, such as a recent tender for the Northern Region [29].

> **N.B.** In the UK context “Distributed Energy Resources” or DER may include small thermal units such as gas-fired turbines and diesel units, where in many other jurisdictions, DER is a term largely used for unscheduled inverter-based resources such as rooftop PV.

Assessment criteria for generators are split into different generator categories, such as Primary Restart Generators, Top-Up Generators, Anchor Generators, and Distributed Restart Top-Up Generators. Assessment of potential resources to participate in restart generally include the following common elements (example of a Primary Restoration Service Provider requirement in parenthesis):

- complexity of the generator’s connection to the network,
- the time to start and connect to the network (less than two hours),
- the service availability over a nominated period (greater than 80%),
- the presence of control systems that can regulate voltage and frequency (required),
- the maximum power output of the unit, including the maximum block loading size it can withstand (greater than 10 MW),
- the reactive power delivery capability of the unknit (greater than 50 MVAr leading),
- the ability of the unit to provide supply for extended periods (greater than 10 hours),
- the ability of any supporting auxiliary units to maintain the primary unit (greater than 72 hours),
- able to deliver multiple attempts at restart (greater than three times),
- the ability to provide inertia to the system (greater than 400 Mega Volt-Amperes per second [MVA.s]),
- the ability to provide material fault current,
- whether it provides material contribution to system stability, and
- the impact of the service on the overall restoration time.

Depending on the category of generator to be considered, different quantitative standards apply. It is noteworthy <u>that fault current provision and inertia contributions are required from restoration sources</u> – a technical consideration not noted in other jurisdictions evaluated.

Further to the individual unit capability, diversity requirements are also considered when procuring sources. Tender award notices [30] stated that units were selected from “multiple and diverse technology types” without going into detail. The UK grid is divided into sub-regions for restart [31], indicating that geographical diversity is considered in developing a holistic restart plan.

Testing requirements are outlined in draft contracts [29] and operating protocols, and require the unit to both energise its point of connection and a portion of the network to resynchronise with the remaining system, i.e.,: "*the ESR Service Provider to energise from dead a local busbar, a circuit(s), a transformer(s) and a remote busbar and then synchronise onto a live busbar that is already synchronised to the National Electricity Transmission System*". There are a variety of tests (with some similar to the requirements outlined in EU standards) that must be completed at different intervals:

- A unit test can be as frequent as every year, which includes a partial station shutdown, a unit restoration from its auxiliaries and synchronisation with the power system.
- A capability assessment (defined in OC5.7.2 [32]) or station test is to be completed once every three years, which includes a complete disconnect of the station and all its units from the power system followed by restoration and synchronisation of a unit to the power system.

In evaluating and awarding contracts, both the technical and commercial criteria are weighted at 50% each. In previous NESO restart paradigms, it was noted that the commercial criteria counted significantly more than the technical criteria when evaluating the viability of a service. This indicates a key change in approach and understanding from NESO to a more engineering-focused solution. Contracts are offered as five-year periods [33].

A tender was recently completed to determine whether wind power can provide system restart services to NESO, which was open to both on-shore and off-shore providers [34]. Many of the requirements for both service capability and testing were the same as those applied to a Primary Restoration Service Provider described previously. However, it is notable that after evaluation of submissions, no primary service contracts were awarded to wind service providers [35].

Modelling of potential system restart sources and consequently the restart plan development is completed using a combination of PowerFactory RMS models and PSCAD EMT models. A guidance document available [36] to aid tenderers in providing the required information. Notably, the modelling of protection of devices is required, with the guidance document requiring models to: "…*contain all the relevant protection functions applicable to the technology being modelled to ensure an adequate user system response to disturbances on the transmission system*."

Australian Energy Market Operator (AEMO) – Western Australia

AEMO operates the main WA grid (the South-West Interconnected System [SWIS] independently of the eastern National Electricity Market (NEM), with no interconnection between them and with separate rules, procedures and regulatory responsibilities.

AEMO WA has relatively simple and clear system restart standards [37], restart procedures [38], and rules [39] (Section 3.7) regarding how system restart is to be managed and associated procurement requirements.

At a high level, "*AEMO must use its reasonable endeavours to ensure the SWIS is restarted and restored in the event of a system shutdown or major supply disruption*". Specific timing and restoration level requirements are not provided. Throughout the standards and procedures, the terminology used generally indicates a synchronous machine paradigm is considered for restart, but (subject to consultation requirements), AEMO itself is responsible for setting and amending the standard and procedures within broad market rules, which would allow consideration of IBR technology. Within the Wholesale Electricity Market Rules, AEMO may alter the standard as needed to cater for "any other matters that AEMO determines are necessary to ensure the

SWIS is restarted in the event of a system shutdown or major supply disruption". This may include real operational changes in the network or hazards identified.

Participating black start sources are required to meet specified technical requirements including:

- be energised up to its point of connection and ready for network switching within 60 minutes of being called upon,
- be at least 50 MW or greater, and stable for 10 MW block loading and 5 MW induction motor loads,
- have sufficient on-site fuel storage for at least 14 hours of operation at nominal power,
- have ability for at least three restart attempts (if non-TTHL),
- have stable operation in both isochronous and droop mode operation,
- regulate output (MW and MVAr) stably in the absence of any other sources and be capable of altering terminal voltages by at least ±5%,
- restart a portion of the network and energise a transformer of at least 490 Mega Volt-Amperes (MVA) in size,
- consume sufficient MVAr to offset long-distance line charging,
- be staffed 24/7, or if not, be under remote control of AEMO,
- have air pollution waivers in place,
- have backups available for critical starting equipment, and
- be stable at no load for extended periods of time.

Variations of the above apply for TTHL sources, including modified requirements such that TTHL units are to be at their point of connection within 30 minutes, and are stable at 0 MW sent-out (i.e., house load) for extended periods.

In developing its restart plan, AEMO must consider the following aspects:

- In sourcing and procurement, consideration of electrical, geographical and technology diversity to minimise any single points of failure.
- Consideration of flexibility and complexity of network pathways, simplicity in reaching other generators, and the proximity to stable load.
- Consideration of priority restoration of any sensitive loads on the network.
- Mandatory collaboration with network operators on identifying viable network paths and limitations for system restart.
- Changes that should be made to the network equipment to support system restart pathways, with set timeframes for implementation and testing.

The standard also notes that site selection is an optimisation of many factors, not simply meeting one criterion for the sake of meeting that criteria. Availability and reliability of both the restart unit and the connecting network are factored into procurement choices.

Testing of the black start sources needs to be completed every six months, which at a minimum will include energisation to its point of connection but may also require partial energisation of the network if deemed necessary and if conditions allow (this reportedly seldom occurs in practice). Network operators are obliged to actively participate in the network testing component.

> **N.B.** AEMO noted that the relatively recent increase in testing frequency to six months has led to increased success in plant meeting its system restart requirements across all providers.

Sub-networks for procurement are defined by physical characteristics of the network, including the number and strength of transmission corridors, the distance between generation centres, how much load or generation is within a geographical region, and the location of synchronisation facilities.

Modelling and development of the system restart plan is conducted through transient studies, and restart provider applicants are required to furnish additional detailed information at application to ensure the model of their equipment is sufficiently detailed for restart studies.

Procurement of services is undertaken through a competitive tender, with a requirement that potential providers are obliged to cover costs for adequacy testing and any potential network augmentation required to enable the service to successfully reach into the network and be useful.

Note that the SWIS has extremely high penetration of rooftop PV and other IBR equipment. While there is no specific regulation of how periods of high IBR penetration (from both controlled and uncontrolled sources) should be treated in terms of restart, AEMO reports that it is an area of deep concern for the SWIS both in terms of maintaining restoration island security (i.e. sourcing sufficient load) and the general unknown performance of DPV. To counter this, AEMO have pre-identified feeders within the distribution network likely to host little or no DPV such that stable load can be found during daylight hours.

Although there appear to be large industrial loads available to aid with sufficient stabilising load, concerns have been raised regarding the sensitivity of such loads to voltage dips and variations, with many industrial loads tripping offline for minor voltage variations during system normal conditions. Voltage variations during restart conditions are likely to be far more severe and hence may be more likely to result in these loads tripping offline.

Australian Energy Market Operator (AEMO) – National Electricity Market

As noted above, Australia's east coast grid (NEM) operates independently of AEMO WA, with no interconnection and with separate rules, procedures and regulatory responsibilities.

AEMO is bound to meet the System Restart Standard [40], set by the Australian Energy Market Commission's Reliability Panel [41]. The standard (currently under review) sets out the following elements that AEMO must consider when both procuring system restart sources and developing its system restart plan:

- The aggregate reliability of the services for each sub-network must exceed 90%, except for Tasmania where it must exceed 95%.
  - This includes consideration of the individual service availability and black start performance, and reliability of the transmission network elements connecting to the restart sources.
  - Two sub-networks have additional procurement requirements for specified areas within their boundaries, with lower allowable reliability figures.
- Sub-networks may be defined by AEMO based on the electrical properties of the network, including the amount of generation and load, electrical distance between generation centres within a region of the NEM).

- Restoration timeframes are defined for each sub-network based on a MW and time target to be met

Figure 1 **Restoration target extract from the AEMC's system restart standard (as at August 2025, currently under review)**

1. Electrical Sub-Network[4]	2. Level of Restoration (MW)	3. Restoration time[5] (hours)	4. Required Aggregate Reliability
Queensland	1650	4	90%
New South Wales	1500	2.0	90%
Victoria	1100	3.0	90%
South Australia	330	2.5	90%
Tasmania	300	2.5	95%

  - The MW target refers to the potential supply capacity (generation and transmission) to be restored, not the amount of load to be restored.
  - The amount of potential supply in column 2 must be restorable within the timeframe outlined in column 3.
  - This is a procurement target, not an operational target.
- Diversity of services must be considered, with regard to:
  - Electrical aspects, where reliance on a singular part of the network for all sources is disallowed.
  - Geographical aspects, where there must be a diversity in location of where system restart sources are located to account for the impact of geographical events such as natural disasters.
  - Energy sources, again to consider the failure of any single energy supply source.
    - Notably, the standard does not include specific duration requirements for energy supply (e.g., must be capable of operating at nominal output for X hours) – however this would have to be considered in relation to achieving the overall targets.
- Units to restart a region can exist outside the region to be restarted, however they can only ever be procured for one region (no doubling up).

AEMO also produces the System Restart Ancillary Services (SRAS) Guidelines [42], which outlines more on how the process of evaluating and procuring system restart services must occur.

- AEMO considers procurement of two kinds of service for system restart:
  - Black Start Services, which are plant which can start without reliance on the power system whatsoever, and
  - Restoration Support Services, which are plant that can aid in the restoration of the power system based on their capabilities and strategic location.
- Black start services must be able to start without drawing supply or TTHL, operate at zero export for an extended period, close onto a deenergised busbar, provide voltage and frequency control, energise a portion of the network, provide fault current sufficient for protection to work, and operate stably.

- Restoration support services must be able to provide one of voltage/reactive power control capability, frequency control capability, stabilising load, and fault current capability. Self-start capability is welcome, but not necessary provided the service can be energised by a black start service.

  N.B. Although stabilising load is a potential restoration support service, AEMO reports challenges in procuring it, as it may not contribute to reaching the MW-time restoration target as currently formulated based on energising generation capacity. This is an area of active investigation for AEMO as rooftop PV continues to undermine available load during daylight hours, potentially delaying restart where the minimum active power requirements of large black starting synchronous machines cannot be met in some solar-rich regions.

- Testing of contracted sources is also defined in the SRAS Guidelines:
  - Testing must occur at least once per year, and within 20 business days of a period of maintenance or alteration to the restart equipment or restart network components.
    - Notice as short as five business days may be given.
  - Additionally, a new restart provider, a new restart path, significant changes to the plant or network, a previously unsuccessful test, changes to the switching sequence at the network owner request may trigger a restart test to occur.
  - A black start test must entail as a minimum:
    - isolating the unit from the power system and the unit starting without external supply (or tripping to house load),
    - maintaining zero export for at least 30 minutes,
    - altering both its voltage (±5%) and frequency (±0.5Hz) to demonstrate controllability,
    - energising its transformers up to the point of connection and closing on a dead busbar, and
    - energisation of the network to verify capability is a *possibility* as defined under the National Electricity Rules (NER) clause 4.3.6 (b), but is seldom enacted in practice.
  - If there is evidence from testing that the service will not be effective, AEMO has the right to terminate the agreement.
- Modelling requirements and objectives are set out in the SRAS Guideline:
  - At a high level, the objective is to verify the capacity of the proposed service to start and supply auxiliaries of other power stations, assist the stable energisation of generation and transmission and pick-up of Stabilising Load Blocks, facilitating a restoration of the Minimum Restart Path and consequently to achieve the standard.
  - Studies conducted include steady state studies, transient load-generation studies, transient overvoltage studies, and network fault studies. Such modelling is undertaken in the EMT domain, with:
    - highly detailed models of black start providers, including all relevant generator protection relay models, and site-specific models for any IBR,
    - geometric line models for the network and transformers with equipment specific saturation profiles,

- network protection relays (particularly transformer differential relays) with site-specific settings, and
- large induction motor load models, and general load models.

AEMO primarily plans for a bottom-up restoration as a worst-case scenario. While operationally an interconnector from another region may be available to facilitate a top-down restoration (as was the case for South Australia in 2016), interconnectors are not considered for procurement.

Procurement of sources is a competitive process for each of the subregions. Contracts are generally multi-year with extensions available, however long-term (e.g. 10-year) contracts can be considered to provide investment certainty for new generators who may be willing to include system restoration capability.