AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Renewable Integration Study: Stage 1 report

April 2020

Enabling secure operation of the NEM with very high penetrations of renewable energy

Important notice

PURPOSE

AEMO publishes this Stage 1 report from its Renewable Integration Study to outline:

- System security limits that affect how much wind and solar PV generation can operate at any one time, and what the limits are NEM-wide and for individual regions.
- How close NEM regions are to these security limits now, and how close they are expected to be by 2025.
- Actions that can overcome these barriers so the system can operate securely with higher penetrations of wind and solar generation.

It is published as part of AEMO's responsibilities under section 49(2) of the National Electricity Law.

DISCLAIMER

ACKNOWLEDGEMENTS – EXTERNAL ADVISORY PANEL

AEMO convened a panel of industry stakeholders to provide expert feedback on this report prior to publication, and their contributions were valuable in shaping an earlier draft of this report. AEMO acknowledges their inputs and thanks them for their insights and expert review, noting that their inclusion here does not represent endorsement of this report:

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VERSION CONTROL

Version	Release date	Changes
1	30/4/2020	Initial release

Executive summary

The Renewable Integration Study (RIS) is the first stage of a multi-year plan to maintain system security in a future National Electricity Market (NEM) with a high share of renewable resources. AEMO's findings and the actions in this report reflect both its day-to-day experience operating the NEM power system, and the results of extensive RIS modelling and analysis.

In its *Integrated System Plan* (ISP), AEMO identifies futures for the NEM that maximise consumer benefits at the lowest system cost, while meeting reliability, security, and emissions expectations. Under every ISP scenario, the NEM's least-cost future features large increases in renewable generation – utility wind and solar connected to the grid and distributed solar photovoltaics (DPV) installed by households and businesses – with dispatchable generators, large-scale and distributed energy storage, demand side participation, and sector coupling (such as with gas and transport).

This Stage 1 RIS report takes the ISP's projections as given and investigates in detail the challenges in the short term, to 2025, of maintaining power system security while operating this resource mix at very high instantaneous penetrations[1] of wind and solar generation. It recommends actions and reforms needed to keep operating the NEM securely, now and as the power system transitions. AEMO looks forward to engaging with stakeholders to refine and progress the recommended actions, including assessing the potential roles of both existing and emerging technologies.

With this report, AEMO aims to provide foundational engineering perspectives for the ISP, Energy Security Board (ESB), industry, market institutions, and policy-makers. The RIS's technical perspectives will ideally inform future investments, regulations, and market designs to securely operate the NEM power system with very high instantaneous penetrations of wind and solar generation.

In summary, this Stage 1 RIS analysis finds that, in the next five years:

- The NEM power system will continue its significant transformation to world-leading levels of renewable generation. This will test the boundaries of system security and current operational experience.
- If the recommended actions <u>are</u> taken to address the regional and NEM-wide challenges identified, the NEM could be operated securely with up to 75% instantaneous penetration of wind and solar[2].
- If, however, the recommended actions <u>are not</u> taken, the identified operational limits will constrain the maximum instantaneous penetration of wind and solar to between 50% and 60% in the NEM.

Beyond 2025, AEMO has not identified any insurmountable reasons why the NEM cannot operate securely at even higher levels of instantaneous wind and solar penetration, especially with ongoing technological advancement worldwide.

Given the pace and complexity of change in the NEM, the RIS highlights the need for flexible market and regulatory frameworks that can adapt swiftly and effectively as the power system evolves.

[1] Instantaneous penetration of wind and solar is the half-hourly proportion of underlying demand that is met by wind and solar resources.

[2] In recommending actions and highlighting positive potential outcomes, AEMO does not underestimate the extent of work that will be required to successfully adapt the NEM. This includes the ongoing need for system limits that at times constrain the output of various generation sources. This study also identified a number of uncharted operating conditions emerging in the NEM by 2025. AEMO will continue investigation and analysis to identify and address additional limits and barriers that emerge.

While this report builds on international approaches[3] to operating power systems with high penetrations of wind and solar generation, it recognises Australia's unique challenges and identifies opportunities for Australia to continue developing world-leading expertise. The goal is to identify opportunities to break down barriers and maximise value for consumers from the NEM's growing renewable fleet.

The instantaneous penetration of wind and solar energy that can operate on the system at any time varies depending on system conditions. The main limits to instantaneous penetration of wind and solar are network congestion, system curtailment, and participant spill[4].

This report and its appendices explore system curtailment limits that impact wind and solar instantaneous penetration in the NEM power system, specifically:

- Limits that affect how much wind and solar PV generation can operate at any one time, and what the limits are NEM-wide and for individual regions.
- How close NEM regions are to these limits now, and how close they are expected to be by 2025.
- Actions that can overcome these barriers so the system can operate securely with higher penetrations of wind and solar generation.

Limits related to network congestion and participant spill, and other important areas, are out of scope for the RIS, because they are being studied or managed elsewhere and/or do not relate to a system curtailment limit on renewables. Subjects out of scope for this study include:

- Assessing adequacy of firm supplies of energy and storage to meet demand. This is being considered in AEMO's ISP, *Electricity Statement of Opportunities* (ESOO), Energy Adequacy Assessment Projection (EAAP), Medium Term Projected Assessment of System Adequacy (MT PASA) processes, and the Retailer Reliability Obligation (RRO).
- Assessing system limitations at the local, sub-regional level, including generator connection issues. This is being addressed in other projects, such as AEMO's work managing challenges in the West Murray area[5].
- Changing requirements for voltage control. These are being considered as part of the ISP and other ongoing AEMO and network service provider (NSP) network planning activities.
- Ensuring the power system can restart following a black system event. This is being considered as part of AEMO's system restart work.

Stage 1 of the RIS was established to be a technical analysis of system security limits NEM-wide and for NEM regions. While it identifies recommended actions that would meet the system's technical needs, it does not investigate the costs of proposed actions or all the specific mechanisms that could be implemented. These questions will be explored further as part of future work and other workstreams such as the ISP and the ESB's and Australian Energy Market Commission's (AEMC's) market reform processes.

This study has not considered the impact the COVID-19 coronavirus may have on supply or demand in the forecast horizon. This situation is rapidly evolving, and the consequences for the NEM are uncertain.

Western Australia's South West Interconnected System (SWIS) will experience similar challenges as the NEM as its penetration of wind and solar generation increases. While the unique characteristics of the SWIS will see challenges evolve in different ways, common approaches may be taken to resolving the issues. The RIS findings will support AEMO's ability to transition through challenges in the SWIS and contribute to ongoing electricity reform processes in Western Australia[6].

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[3] AEMO's October 2019 RIS report on how Australia compares with other international power systems is at https://www.aemo.com.au/energy-systems/Major-publications/Renewable-Integration-Study-RIS.

[4] Network congestion is when the network is not capable of securely transporting the output from one or several wind or solar resources.
System curtailment is when renewables are limited due to a need to maintain minimum levels of essential system services for system security.
Participant spill is when renewable generation removes itself from the market (self-curtails) due to market signals.

[5] At https://aemo.com.au/-/media/files/electricity/nem/network_connections/west-murray/transforming-australias-energy-system--west-murray.pdf?la=en&hash=ED13D8375B1E37626EEAFC86C59622EE.

[6] For more information, see https://www.wa.gov.au/organisation/energy-policy-wa/energy-transformation-strategy.

The changing NEM, now and in 2025

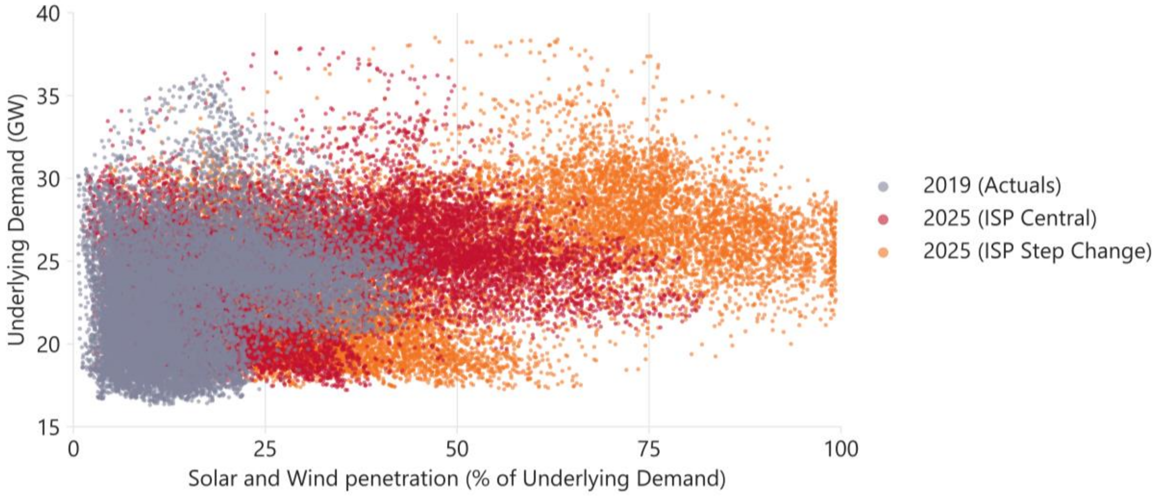
The NEM power system already has 17 gigawatts (GW) of wind and solar capacity installed[7]. Parts of the NEM have among the world's highest levels of wind and solar, including one of the highest levels of residential solar PV[8].

By 2025, the NEM is expected to have transformed even further. AEMO's Draft 2020 ISP forecasts, in its Central scenario[9], that by 2025 there will be 27 GW of wind and solar – both utility solar and DPV – generation capacity in the NEM.

Figure 1 shows actual wind and solar penetration in the NEM for each half-hour period in 2019 (historical data which includes all lost energy). The 2025 projections indicate the potential instantaneous penetration by 2025 under the ISP's Central and Step Change generation builds (these forecasts include lost energy from network congestion, but do not include system curtailment or participant spill).

This figure highlights significant forecast growth in the maximum potential instantaneous penetration of wind and solar, from just under 50% in 2019 to over 75% in the Central and 100% in the Step Change scenario. This report explores the extent to which these outcomes might be achievable from a system security perspective, and the actions needed to enable them.

Figure 1 Instantaneous penetration of wind and solar generation, actual in 2019 and forecast for 2025 under ISP Central and Step Change generation builds



Note: Penetration on this graph represent NEM half-hourly wind and solar generation divided by the underlying demand which includes demand response, energy storage, and coupled sectors such as gas and the electrification of transport.

Identifying and quantifying existing and emerging limits, and actions to manage them

As the penetration of wind and solar on the system increases, operation of the system becomes significantly more complex. The power system is being operated closer to its known limits more frequently, with increasingly variable and uncertain supply and demand, and declines in system strength and inertia.

The knowledge, tools, and market frameworks of the past are becoming less effective, and operators must adapt processes and tools, and train operators to be able to keep the system of the future secure.

The key system security challenges[10] that are being, and will need to be, addressed as wind and solar generation penetration continues to rise across all NEM regions are summarised in Table 1. The table also contains a summary of recommended actions to address identified limits.

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[7] The NEM power system's underlying demand (total demand met from all sources, including distributed resources) ranges from 16 to 35 GW.

[8] See https://www.aemo.com.au/energy-systems/electricity/national-electricity-market-nem/system-operations/future-grid/renewable-integration-study.

[9] Central and other 2020 ISP scenario assumptions are at https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/scenarios-inputs-assumptions-methodologies-and-guidelines.

[10] For definitions of terms used in this study, see AEMO's *Power System Requirements* paper, at https://www.aemo.com.au/energy-systems/electricity/national-electricity-market-nem/system-operations/future-grid.

The actions in this report aim to keep the power system secure and address known barriers to operating the NEM power system with higher levels of instantaneous wind and solar generation to 2025, based on existing proven technologies. Australia is already pioneering testing of new technologies to solve some of the challenges posed, and AEMO is committed to collaborating and exploring the role of newer technologies in efficiently and securely managing the power system with high penetrations of wind and solar generation.

In this report and the appendices, the challenges are addressed in detail under five focus areas:

- Challenges for **secure system operation** with increasing uncertainty and complexity (Chapter 2).
- Managing the system impact of the NEM's world-leading and growing levels of **distributed solar PV** (Chapter 3 and Appendix A).
- Managing **frequency** (Chapter 4 and Appendix B).
- Maintaining **system strength** (Chapter 5).
- Keeping balance in a system in which energy supply is increasingly **variable and uncertain** (Chapter 6 and Appendix C).

Table 1 summarises the challenges and actions (including timing and status) from the end of each of chapters 2-6. Figure 2 summarises the actions on a timeline.

Table 1 Managing power system requirements – summary of key challenges and actions

	Key challenges	Actions	Timing	Status
System operability **Ability to operate the power system within security and reliability standards**	**An increasing penetration of wind and solar operating in the system is pushing the system to minimum limits**. The existing dispatch process for the NEM was not designed for managing minimum conditions (particularly managing the commitment of synchronous units, to maintain minimum levels of inertia and system strength). The current reliance on operators to balance factors and intervene is sub-optimal as system variability, uncertainty, and complexity increase. Without effective and standardised operational process, tools, and training to schedule system strength and inertia services, the risk of human error grows and the level of intervention becomes increasingly unsustainable. Further, the market design needs to adapt so all essential security and reliability services are provided efficiently, when required, and without operator intervention. Given the pace and complexity of change in the NEM, there is a need for flexible market and regulatory frameworks (particularly technical standards and frameworks for sourcing system services) that can adapt swiftly and effectively as: • Understanding of the changing power system evolves. • Requirements for system services change. • Technology evolves.	**2.1** AEMO to identify and evaluate standard operational process, control room tools, and operator training to operationalise intervention (directions/instructions) for system strength and inertia services under the current framework.	2020	In progress
		2.2 AEMO to redevelop existing scheduling systems (Pre Dispatch [PD] and Short Term [ST] PASA) to better account for system needs, including: • Availability of essential system services, including inertia, system strength, and ramping requirements. • Catering for cross-regional sharing of reserves. • Better modelling of new technologies, including variable renewable energy (VRE), batteries, and distributed energy resources (DER – including demand response and virtual power plants [VPPs]).	2020-22	In progress
		2.3 Consistent with the outcomes of this study, the ESB considers that security constrained economic dispatch of energy-only is, by itself, no longer sufficient to maintain system security. The ESB considers that new system services need to be established and remunerated and an ahead market is required to ensure system security going forward[A]. As part of its post-2025 market design program, the ESB is assessing market mechanisms that increase certainty around system dispatch of energy and essential system services (inertia, system strength, minimum synchronous units, operating reserves, and flexibility) as real time approaches. The ESB will recommend a high level design to the COAG Energy Council by end of 2020 for implementation by 2025.	2020-25	In progress
	The growth in wind and solar is increasing the complexity of the system. This creates challenges for existing tools and processes used for system security analysis and assessment. Tools and processes used to model the system, assess outages, and measure system performance are becoming increasingly computationally complex and more costly in time and resources.	**2.4** AEMO to develop a detailed proposal outlining requirements, timing, and method to achieve specified NEM high-speed monitoring (phasor measurement units) to cover more points, allowing better visibility of performance of the system, and help operators to understand the changing power system.	2020	In progress
		2.5 AEMO to collaborate with industry and other world-leading power system operators to develop new operational capability, allowing better analysis of complex security phenomena and optimisation for a power system with world-leading levels of renewable generation (inverter-based, variable and decentralised), storage, and demand side participation.	2020-25	In progress

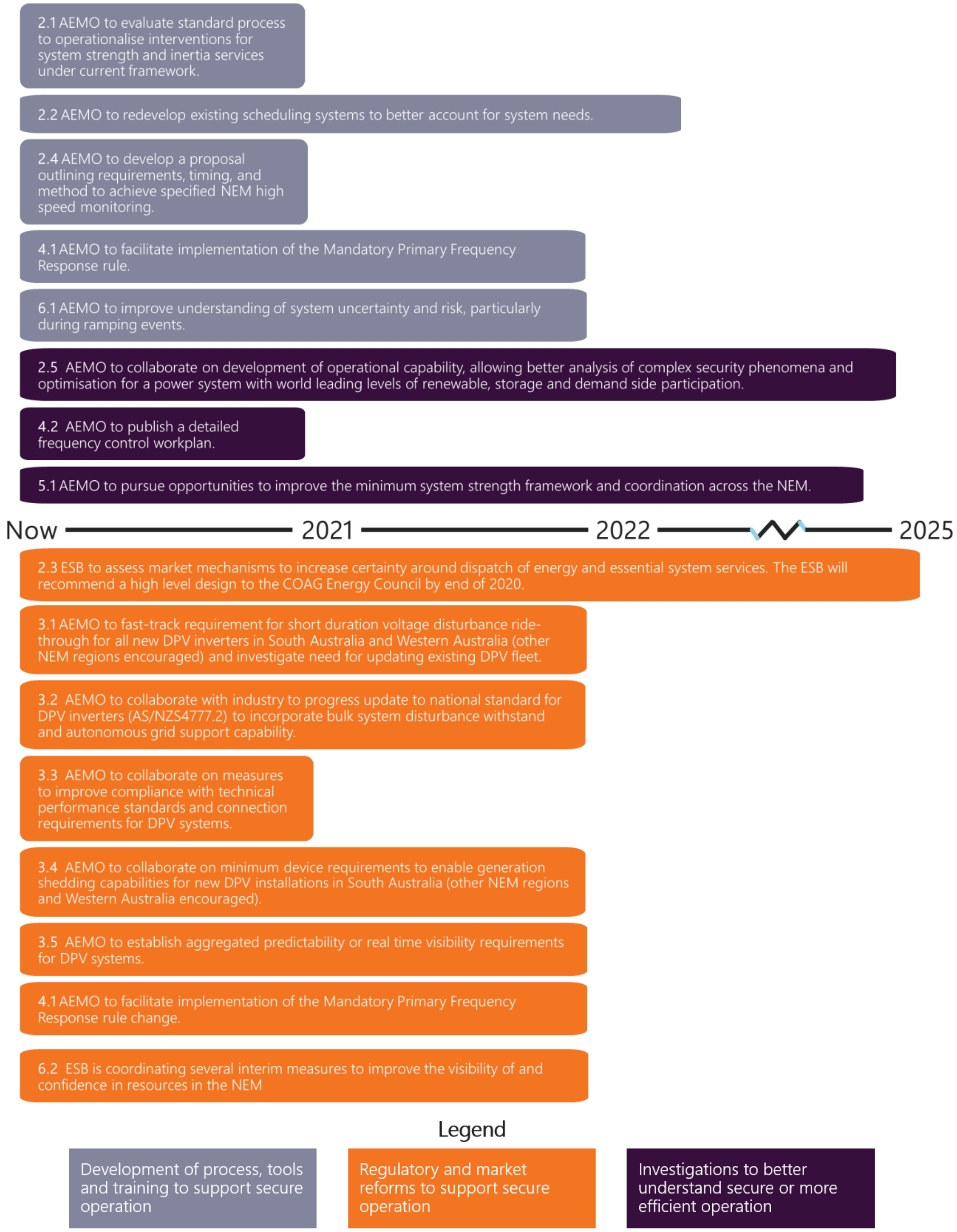
	Key challenges	Actions	Timing	Status
Integration of distributed solar PV (DPV) **Balancing increasing levels of small, distributed generation with power system requirements**	**The aggregate performance of the DPV fleet is becoming increasingly critical as penetrations increase.** Without action, the largest regional and NEM contingency sizes will increase due to DPV disconnection in response to major system disturbances.	**3.1** AEMO to fast-track requirement for short duration voltage disturbance ride-through for all new DPV inverters in South Australia (and Western Australia, with other NEM regions encouraged) and investigate need for updating existing DPV fleet to comply with fast-tracked short duration voltage disturbance ride-through requirement.	2020-21	In progress
		3.2 AEMO to collaborate with industry, through Standards Australia committee, to progress update to national standard for DPV inverters (AS/NZS4777.2) to incorporate bulk system disturbance withstand and autonomous grid support capability.	2020-22	In progress
	Governance structures for the setting of DER technical performance standards, and enforcement of these standards, are inadequate. Currently there is: • No formal pathway to ensure power system security and other industry requirements are accounted for within technical standards set by consensus. • Inconsistent compliance with technical performance standards across the DPV fleet today and a lack of clarity around enforcement.	**3.3** AEMO to collaborate with the ESB, Australian Energy Regulator (AER), AEMC, and industry to: • Submit a rule change establishing the setting of minimum technical standards for DER in the NEM (with similar reforms to be proposed for Western Australia's SWIS) covering aspects including power system security, communication, interoperability, and cyber security requirements. • Develop measures to improve compliance with new and existing technical performance standards and connection requirements for DPV systems, individual DER devices, and aggregations in the NEM (and SWIS).	2020	New
	System dispatchability is decreasing as invisible and uncontrolled DPV increases to levels not experienced elsewhere globally. In 2019, South Australia operated for a period where 64% of the region's demand was supplied by DPV; by 2025, all mainland NEM regions could be operating above 50% at times.	**3.4** AEMO to collaborate with industry to: • Mandate minimum device level requirements to enable generation shedding capabilities for new DPV installations in South Australia (other NEM regions and Western Australia encouraged). • Establish regulatory arrangements for how distribution NSPs (DNSPs) and aggregators could implement this as soon as possible. • Investigate the need for updating the existing DPV fleet to comply with regional generation shedding requirements.	2020-21	New
		3.5 AEMO to collaborate with DNSPs to establish aggregated predictability or real-time visibility requirements for DPV systems available for curtailment, and consistent real-time SCADA visibility for all new commercial scale (> 100 kilowatt [kW]) systems.	2020-21	New

	Key challenges	Actions	Timing	Status
Frequency management **Ability to set and maintain system frequency within acceptable limits**	**There has been a decline in the primary frequency response (PFR) provided by generation in the NEM**. This has reduced the power system's resilience to events at a time when events are becoming more complex and less predictable. It has also resulted in a lack of effective control of frequency in the NEM under normal operating conditions. A lack of consistency and certainty of PFR delivery from generation has impacted AEMO's ability to effectively model and plan the system, understand the cause of power system incidents, and design emergency frequency control schemes.	**4.1** AEMO to facilitate implementation of the Mandatory Primary Frequency Response rule. The requirement for near-universal PFR enablement across the generation fleet should be part of any future regulatory framework as an important part of maintaining and strengthening system resilience.	2020-21	In progress
	NEM inertia levels could drop by 35%. Historically, NEM mainland inertia has never been below 68,000 megawatt seconds (MWs). By 2025, inertia could drop to as low as 45,000 MWs. This will increase the required volume and/or speed of frequency sensitive reserve following a contingency event, and the power system will operate in configurations where the system dynamics are different to those experienced today. **DPV behaviour, inverter-based resources (IBR) behaviour, and run-back schemes are making the system more complex.** These emerging issues will further exacerbate post-contingent outcomes for credible and non-credible events. Non-credible contingencies are expected to result in higher rate of change of frequency (RoCoF), the effect of which is not yet fully understood for the NEM.	**4.2** AEMO to publish a detailed frequency control workplan covering tasks and timeframes to: • Revise ancillary service arrangements to ensure the required speed and volume of PFR match the size of the Largest Credible Risk (LCR) and Frequency Operating Standard (FOS) containment requirements for the range of expected future operating conditions. • Investigate the introduction of a system inertia safety net for the mainland NEM, under system intact conditions. This minimum level safety net should be progressively revised as operational experience is built and additional measures are put in place to ensure system security. Investigation should include specifying the initial value and how the safety net will be maintained. • Investigate the effect of higher RoCoF on DPV, utility-scale generation, switched reserve providers, and protection relays used in various network functions. The result of this investigation will be a recommended system RoCoF limit, or set of RoCoF limits, in addition to existing generator ride-though requirements. Investigation should include assessment of the adequacy of Emergency Frequency Control Schemes (EFCS), including Under Frequency Load Shedding (UFLS), under decreasing levels of inertia. • Continue investigation into DPV penetration into UFLS load blocks. • Apply appropriate limits to the total proportion of switched reserve. This is needed to ensure there is a minimum amount of dynamic frequency control. • Investigate appropriate regional contingency frequency control ancillary services (FCAS) requirements, particularly for South Australia and Queensland. • Update AEMO's existing system frequency model to be able to predict post-contingent frequency outcomes based on generating unit dispatch. Development of this model will benefit from the capture of high-speed generator output and network quantities on a routine or ongoing basis.	2020	New

	Key challenges	Actions	Timing	Status
Stable voltage waveform (system strength) **Ability to maintain the voltage amplitude, waveform and phase angle under system normal and contingent conditions within specifications**	**The NEM is at the international forefront of managing issues associated with low system strength;** AEMO has so far declared system strength gaps and worked with local transmission NSPs (TNSPs) to address shortfalls in South Australia, Tasmania, Victoria, and Queensland. Localised system strength challenges are also creating increasing hurdles for generators seeking to connect in weaker parts of the grid.	**5.1** AEMO to pursue opportunities to improve the minimum system strength framework and improve system strength coordination across the NEM, including: • AEMO to contribute latest findings and insights into ongoing ESB and AEMC reviews of system strength frameworks. • Following conclusion of the AEMC's investigation into system strength frameworks in the NEM, AEMO to assess the need for changes to the System Strength Requirements Methodology and System Strength Impact Assessment Guidelines. • AEMO to progress planned actions (see Section 5.3.3) as part of the Final 2020 ISP.	2020	In progress
Resource adequacy (managing variability and uncertainty) **A sufficient portfolio of energy resources to balance supply and demand in every 5-minute interval**	**The magnitude of peak ramps (upward/downward fluctuations in supply/demand) is forecast to increase by 50%** over the next five years as a result of increasing wind and solar penetration. Operators need to ensure there is adequate system flexibility to cover increased variability across all times.	*AEMO is investigating redeveloping its PASA systems (PD and ST) to better account for system ramping requirements. See recommendation 2.2.*		In progress
	There is a limit to the accuracy of deterministic forecasts of expected ramps, even using current best practice approaches. Forecasting limitations increase uncertainty and the need for greater ramping reserves.	**6.1** AEMO to improve understanding of system uncertainty and risk, particularly during ramping events, by exploring: • Trialling and implementing a ramping forecast and classification prototype. • Deploying additional weather observation infrastructure that is fit for purpose for the energy industry.	2020-21	New
	Ensuring sufficient flexible system resources are available to enable increased variability at times of high wind and solar penetration will become increasingly challenging. Times characterised by low interconnector headroom (spare capacity) or 'cold' offline plant will be particularly difficult to manage.	*The ESB is exploring options for explicitly valuing flexibility and incorporating this into scheduling and dispatch mechanisms. See recommendation 2.3.*		In progress
		6.2 Improve the reliability of information provided by participants (loads, and scheduled and semi-scheduled generation) to support security-constrained dispatch. The ESB is coordinating several interim measures to improve the visibility of and confidence in resources in the NEM, to ensure security can be maintained while new market arrangements are developed[B].	2020-21	In progress

A. See http://www.coagenergycouncil.gov.au/sites/prod.energycouncil/files/ESB%20Post2025%20Directions%20Paper.pdf.
B. For more information on interim security measures, see http://www.coagenergycouncil.gov.au/interim-security-measures.

Figure 2 Timeline of actions identified in this RIS



Maintaining a secure NEM and maximising the potential of wind and solar

Figure 3 shows the changing system conditions in the NEM from 2019 to 2025 (as in Figure 1). These are overlaid with the system limits identified[11] in this study which, if not addressed, will create barriers to the proportion of wind and solar PV generation that can securely operate at any one time.

To read Figure 3:

- Grey dots show the actual instantaneous penetration of wind and solar generation in the NEM in 2019. Red dots show the forecast instantaneous penetration of wind and solar generation in the NEM in 2025 under the Draft 2020 ISP Central generation build; orange dots show the forecast instantaneous penetration of wind and solar generation in 2025 under the Draft 2020 ISP Step Change generation build.
- Zone A indicates where managing variability and uncertainty will become increasingly challenging.
- Zone B indicates where inertia and system strength limits impact secure operation; the diagonal dotted lines in Zone B indicate the approximate staged progression of these limits that AEMO will seek out to 2025, as sufficient operational experience is obtained, and necessary frequency management reforms are progressed.
- Zone C is an aggregation of the current minimum online synchronous generation required to meet the minimum synchronous unit combinations for system strength in each region.
- White bubbles with numbered actions (see Table 1) give an indication of the levels of wind and solar penetration at which they would be needed:
  - Operational actions (2.1-2.5) – these are already required and are progressing in some instances, and will require further development to securely operate the system at higher penetrations.
  - DPV actions (3.1-3.5) – these are already required in some states such as South Australia where the penetrations are very high, and will be required in other states as penetration in those states increases.
  - Frequency actions (4.1-4.2) – actions are required to be completed to progressively test the system at lower levels of online inertia into Zone B.
  - System strength action (5.1) – this is required to ensure coordination of system strength sources across the NEM and enable system operation at very high penetrations in Zones B and C.
  - Variability and uncertainty actions (6.1-6.2) – these are required as penetrations of variable and uncertain energy sources increase from Zone A onwards.

If recommended actions are not taken to address the regional and NEM-wide technical challenges identified in this study, the identified operational limits will bind and constrain the output of wind and solar resources. This would limit their maximum contribution at any time in the NEM to between 50% and 60% of total generation.

If recommended actions are taken, the NEM could potentially be operated securely out to the beginning of Zone C by 2025, with up to 75% of total generation coming from wind and solar resources at any time[12].

Operation in Zone C, with up to as high as 100% of wind and solar generation operating securely at times, is theoretically achievable in future. This would, however, require more advanced methods of system operation, coupled with provision of essential system services to ensure adequate system flexibility, frequency, and voltage management.

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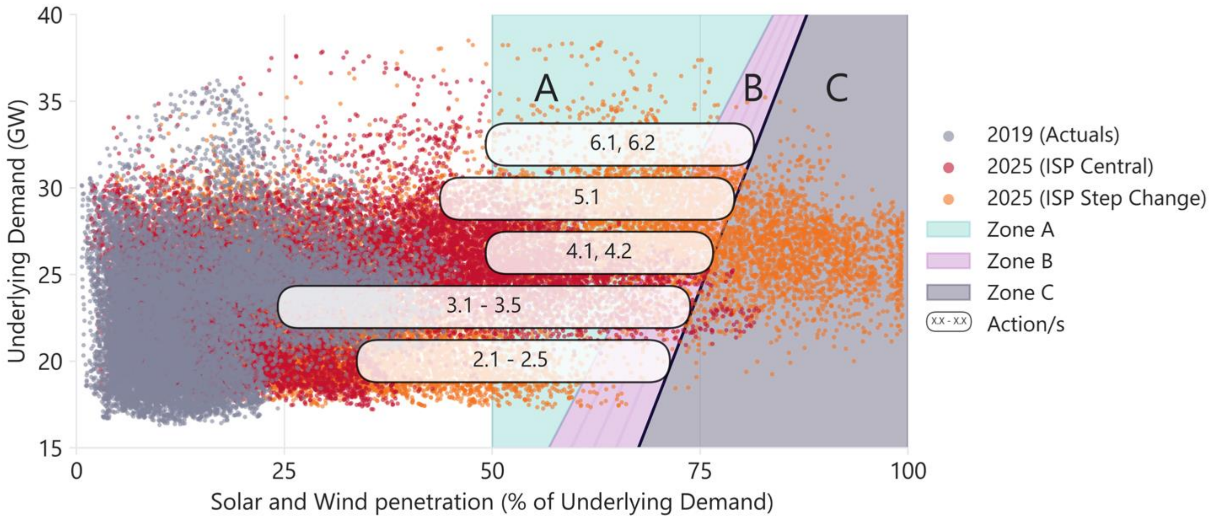
[11] The zones in this figure are indicative only and have been aggregated up from regional limits (Queensland, New South Wales, South Australia, Tasmania, Victoria).

[12] This study also identified a number of uncharted operating conditions emerging in the NEM by 2025. AEMO will continue investigation and analysis to identify and address additional limits and barriers that emerge.

Figure 3 Summary of identified system limits and remedial actions, overlaid on instantaneous penetration of wind and solar generation, actual in 2019 and forecast for 2025 under ISP Central and Step Change generation builds



Note: Penetration values on this graph represent non-overlapping half-hourly wind and solar generation divided by total underlying demand across the NEM during the same half-hours. Actual 2019 penetration includes all curtailment; 2025 projections only include network congestion.

Next steps

In recommending actions and highlighting positive potential outcomes, AEMO does not underestimate the extent of work that will be required to successfully adapt the NEM.

This Stage 1 RIS has been a large undertaking and explored several critical power system security questions in detail; however, its scope has been bound by the assumptions outlined throughout the report and appendices. There are also several areas for further study arising as a result of the RIS findings. This means there is a need for continued efforts on several fronts to build on these Stage 1 findings.

In addition, the NEM power system and market dynamics evolve daily, and a large body of work is already underway across many organisations to explore different changes in the power system and energy markets.

Given the high level of complexity and inter-relatedness of power system security challenges, AEMO sees a need to facilitate greater clarity among stakeholders regarding the priority focus as the generation mix transitions.

Key next steps following the publication of this report include:

- An open and transparent stakeholder engagement process to discuss the findings and actions arising from this report and priority focus areas for the future.
- Exploring the findings and insights from this work with regulatory bodies and policy-makers to help inform ongoing reform processes. Given the pace and complexity of change in the NEM, the RIS highlights the need for flexible market and regulatory frameworks that can adapt swiftly and effectively as our understanding of the changing power system evolves.
- Incorporating relevant findings as part of the Final 2020 ISP.
- Undertaking identified actions to address limits.
- Scoping and commencing areas of further study, including but not limited to the resilience of a high renewable future system to complex system events, and a study of the latest advancements in inverter technology.
- Building on the Stage 1 RIS findings and subsequent stakeholder engagement, developing (by Q2 2021) a roadmap for the secure transition to higher penetrations of wind and solar in the NEM, including key study areas, actions, and reforms.

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1. Introduction

1.1 Why AEMO is doing the Renewable Integration Study (RIS)

The Renewable Integration Study (RIS) is the first stage of a multi-year plan to support a secure National Electricity Market (NEM) with high penetration of renewable resources.

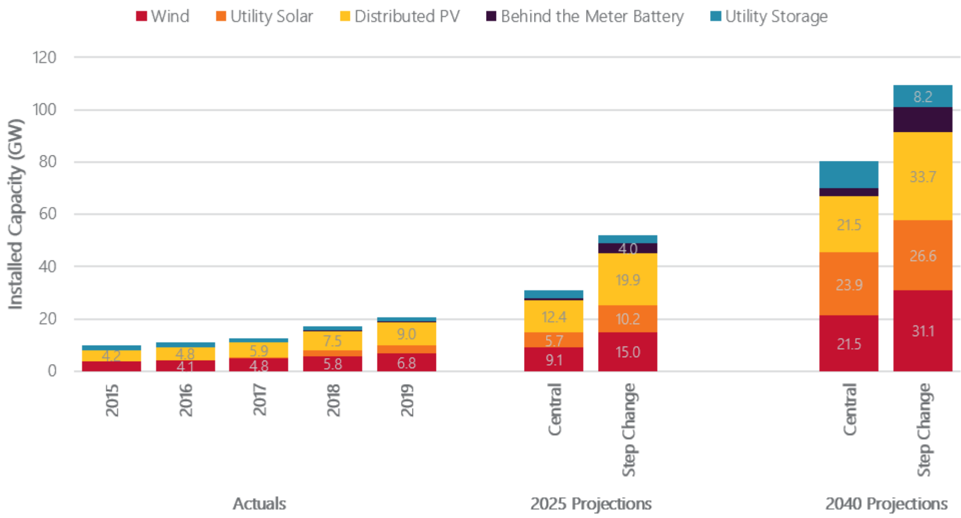
AEMO's recent international review[13] showed that parts of Australia are already experiencing some of the highest levels of wind and solar generation in the world, including one of the highest levels of small (residential) distributed solar photovoltaic (DPV) systems.

Under all scenarios in the Draft 2020 *Integrated System Plan* (ISP)[14], the NEM's least-cost future will see continuing increases in renewable generation – both utility-scale wind and solar connected to the grid, and DPV.

Stage 1 of the RIS has primarily based its analysis on the year 2025 of the Central scenario generation build in the Draft 2020 ISP. This projects that wind and solar generation capacity in the NEM will increase from 17 gigawatts (GW) in 2019[15] to 27 GW in 2025, as shown in Figure 4 below.

The ISP's Central scenario renewable generation build forecast is conservative in comparison to the Step Change scenario. If the generation build in the NEM develops according to the Step Change scenario, the observations in this study would be accelerated.

Figure 4 Installed wind and solar capacity in the NEM for 2019, with 2025 and 2040 forecasts from the Draft 2020 ISP Central and Step Change generation builds



Solar is split into the capacity of utility solar farms and the capacity of DPV systems, installed behind the meter on residential and commercial consumer premises. Behind the meter battery includes both projected virtual power plants (VPPs) and passive batteries projected by the ISP. Utility storage includes both utility-scale battery and pumped hydro.

13 AEMO, *RIS International Review*, October 2019, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Future-Energy-Systems/2019/AEMO-RIS-International-Review-Oct-19.pdf.

14 At https://www.aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp.

15 Throughout this report, the year refers to the financial year ending – for example, 2019 means the 2018-19 financial year.

The instantaneous penetration of wind and solar energy that can operate on the system at any time varies depending on system conditions, the main limits and hence causes of lost energy are:

- **Network congestion** – is when the network isn't capable of securely transporting the output from one or several resources. This could bind when the network is fully intact or during network outages.
- **System curtailment** – is when providers of essential system services are required to be online, which limits the output from renewables. For example, certain generators may be required to be kept online to provide inertia, frequency control ancillary services (FCAS), system strength, voltage control, or flexibility, and as a result the output from wind or solar resources are curtailed.
- **Participant spill** – is when participants reduce output due to market signals. For example, this could be due to low or negative energy spot prices or high real time FCAS prices which create opportunity or liabilities.

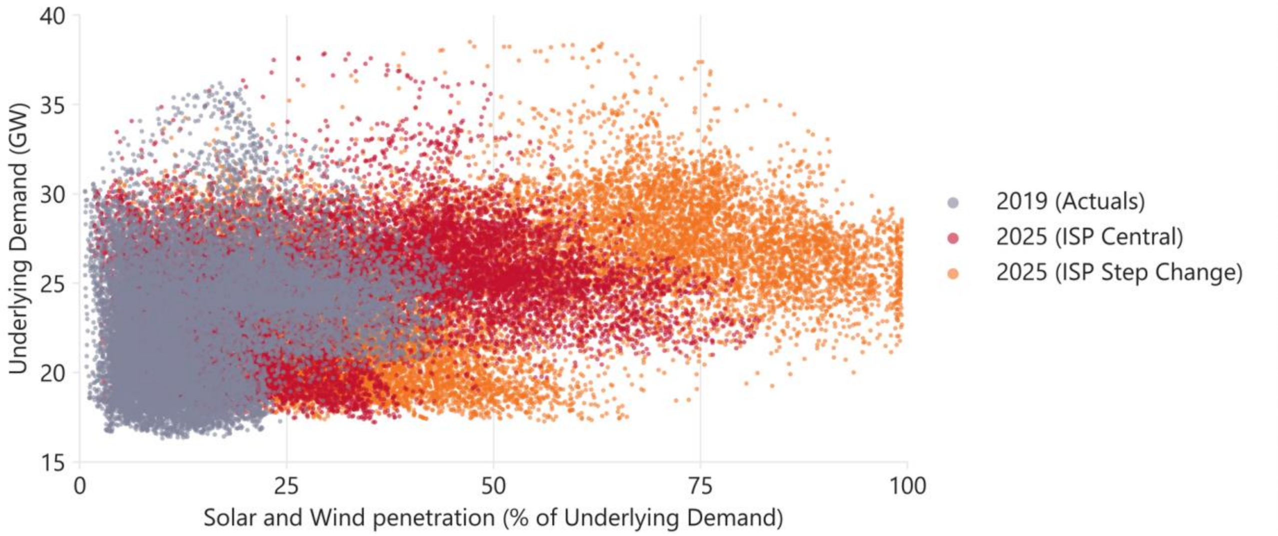
The RIS Stage 1 focuses on system curtailment related to system security.

Figure 5 shows:

- Actual instantaneous (half-hourly) penetration of wind and solar generation in the NEM in 2019. This uses historical data, and accounts fully for all renewable limits.
- Projected instantaneous penetration of wind and solar generation by 2025, under the ISP's Central and Step Change generation builds. These forecasts account only for projected network congestion and do not consider system curtailment or participant spill.

This figure highlights significant forecast growth in the maximum potential instantaneous penetration of wind and solar, from just under 50% in 2019 to well over 75% at times under the 2025 Central generation build and up to 100% under the Step Change generation build.

Figure 5 Instantaneous penetration of wind and solar generation, actual in 2019 and forecast for 2025 under ISP Central and Step Change generation builds



Note: Penetration on this graph represent NEM half-hourly wind and solar generation divided by the underlying demand, which includes demand response, energy storage, and coupled sectors such as electrification of gas and transport. Actual 2019 penetration includes all lost energy; 2025 projections include network congestion but do not include system curtailment or participant spill.

This report explores the extent to which these outcomes might be achievable from a security perspective, and the actions needed to enable them.

The findings from the RIS are being incorporated into AEMO's Final 2020 ISP, ensuring the ISP presents a future power system that will be operable.

More broadly, this report aims to provide foundational engineering perspectives to industry, the Energy Security Board (ESB), market institutions, and policy-makers to support their consideration of future investments, regulations, and market designs.

The South West Interconnected System (SWIS) in Western Australia will experience similar challenges as the penetration of wind and solar generation increases. While the unique characteristics of the SWIS will see challenges evolve in different ways, common approaches may be taken to resolving the issues. The RIS findings will support AEMO's ability to transition through challenges in the SWIS and contribute to ongoing electricity reform processes in Western Australia[16].

1.2 How the RIS scope was developed

Maintaining power system security and reliability necessitates that the physical requirements of the power system are satisfied at all times. In simple terms, this means ensuring:

- Resource adequacy – having a sufficient overall portfolio of energy resources to continuously achieve the real-time balancing of electricity supply and demand.
- Frequency management – the ability to set and maintain system frequency within acceptable limits.
- Stable voltage waveform (system strength) – the ability to maintain the voltage waveform and phase angle at all locations in the power system under system normal and contingent conditions.

In addition, several pre-requisites must be satisfied to enable power system operators to satisfy the power system's physical requirements. AEMO's *Power System Requirements* reference paper presented an overview of these physical requirements and operational pre-requisites[17].

Given the increasing levels of wind and solar generation projected to connect to the NEM under all future ISP scenarios, as outlined in Section 1.1, the RIS has been scoped to explore the particular impacts of increasing levels of wind and solar generation on power system requirements. This included exploring the impacts of the following key drivers:

1. Increasing wind and solar generation online, because its inverter-based characteristics change the way the power system responds to disturbances, and it drives increasing variability and uncertainty into balancing of supply and demand.
2. Increasing DPV generation online, operated by households and businesses behind the meter, that is neither visible nor controllable by operators.
3. Fewer synchronous units online, as renewable generation displaces synchronous generation and with it the essential system services provided by them (inertia, system strength, and operating reserve).

Figure 6 illustrates how some of these system requirements and wind and solar characteristics apply across different operability timeframes.

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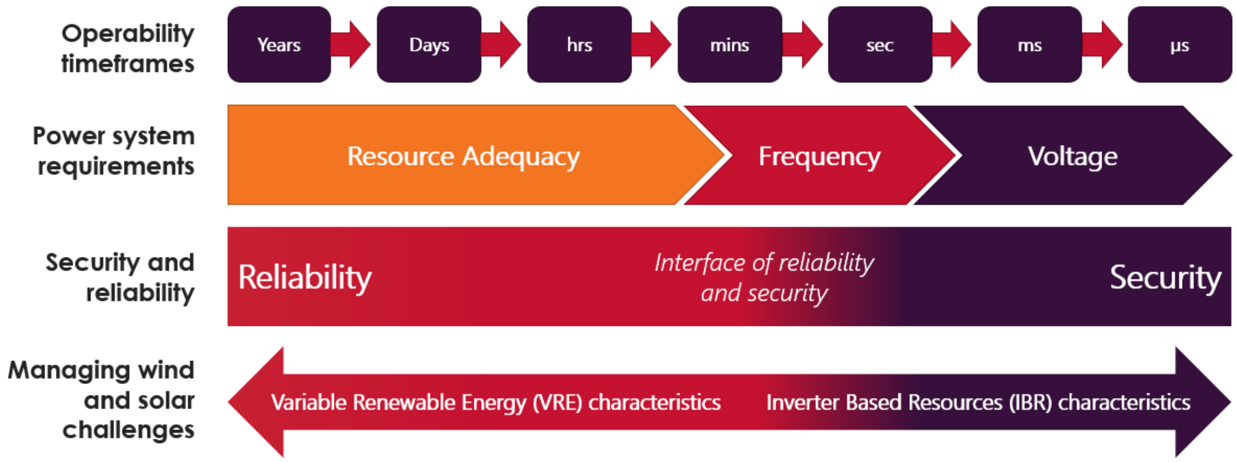
[16] For more information, see https://www.wa.gov.au/organisation/energy-policy-wa/energy-transformation-strategy.

[17] At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf.

Figure 6 System requirements and wind and solar characteristics across different operability timeframes



To maximise the value of the RIS to all stakeholders, AEMO considered the following factors when scoping RIS Stage 1:

- Reviewing leading international experience in wind and solar integration – this culminated in the RIS International Review published in October 2019[18].
- Where possible, prioritising the study of power system phenomena most likely to need managing in order to operate the NEM at high penetrations of wind and solar generation.
- Prioritising areas of study that expand the available analysis on operating a high renewable NEM, noting the volume of previous or concurrent investigations in the NEM[19].
- Using the projected generation builds under Draft 2020 ISP scenarios developed in consultation with industry.
- Choosing a target year for detailed analysis that strikes a reasonable balance between having the potential for very high periods of wind and solar generation and not being too far into the future. AEMO chose 2025 as the horizon for this study because it is far enough to provide insights into future operating patterns, and close enough for system conditions to be forecast with greater confidence based on existing mechanisms and technologies.

Stage 1 of the RIS was established to be a technical analysis of system security limits NEM-wide and for NEM regions. While it identifies recommended actions that would meet the system's technical needs, it does not investigate the costs of proposed actions or all the specific mechanisms that could be implemented. These questions will be explored further as part of future work and other workstreams such as the ISP and the ESB's and Australian Energy Market Commission's (AEMC's) market reform processes.

1.3 Stage 1 scope

Table 2 gives an overview of the study areas AEMO identified as priorities for Stage 1 of the RIS, and the approach AEMO has applied in exploring them.

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[18] AEMO, *RIS International Review*, October 2019, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Future-Energy-Systems/2019/AEMO-RIS-International-Review-Oct-19.pdf.

[19] See Chapter 9 in this report for relevant AEMO publications into the changing generation mix.

Table 2 Overview of RIS approach to studying impacts of increasing wind and solar penetration in the NEM on power system requirements and operational pre-requisites

Area of study	RIS approach	Further detail
System operability – predictability and dispatchability Ability to forecast upcoming power system conditions, have confidence in how the system will perform, and sufficient controls to manage dispatch and configure power system services to maintain system security and reliability	• Assessed how increasing wind and solar are impacting operability of the system, including the challenges of managing increasing uncertainty and interventions.	Chapter 2
Integration of distributed solar PV (DPV) Balancing increasing levels of small, distributed PV with power system requirements	• Surveyed issues identified by distribution network service providers (DNSPs) as levels of DPV increase. • Assessed bulk system limits for actual and 2025 projections of DPV penetration in each NEM region.	Chapter 3 and Appendix A
Frequency management Ability to set and maintain system frequency within acceptable limits	• Assessed potential changes in online system inertia under a range of plausible future dispatch configurations • Analysed frequency control outcomes for different combinations of inertia, primary frequency response, load relief, and secondary risks.	Chapter 4 and Appendix B
Stable voltage waveform (system strength) Ability to maintain the voltage waveform and phase angle under system normal and contingent conditions	• Compared historical synchronous machine dispatch against potential 2025 dispatch outcomes. • Summarised parallel system strength work programs assessing emerging fault level shortfalls, minimum synchronous machine requirements, and local stability challenges for wind and solar.	Chapter 5
Resource adequacy A sufficient overall portfolio of energy resources to continuously achieve the real-time balancing of supply and demand	• Conducted statistical analysis of historical system variability and forecast uncertainty. • Created 2025 synthetic data set using projected generation build and a spatial weather model. • Conducted statistical analysis of future variability and sensitivities on the system's flexibility to accommodate this.	Chapter 6 and Appendix C

There are also several technical areas of high importance that are not being studied in the RIS, because AEMO understands they are being evaluated in other programs of work and they do not relate to a system curtailment limits on renewables during normal operating conditions. These include:

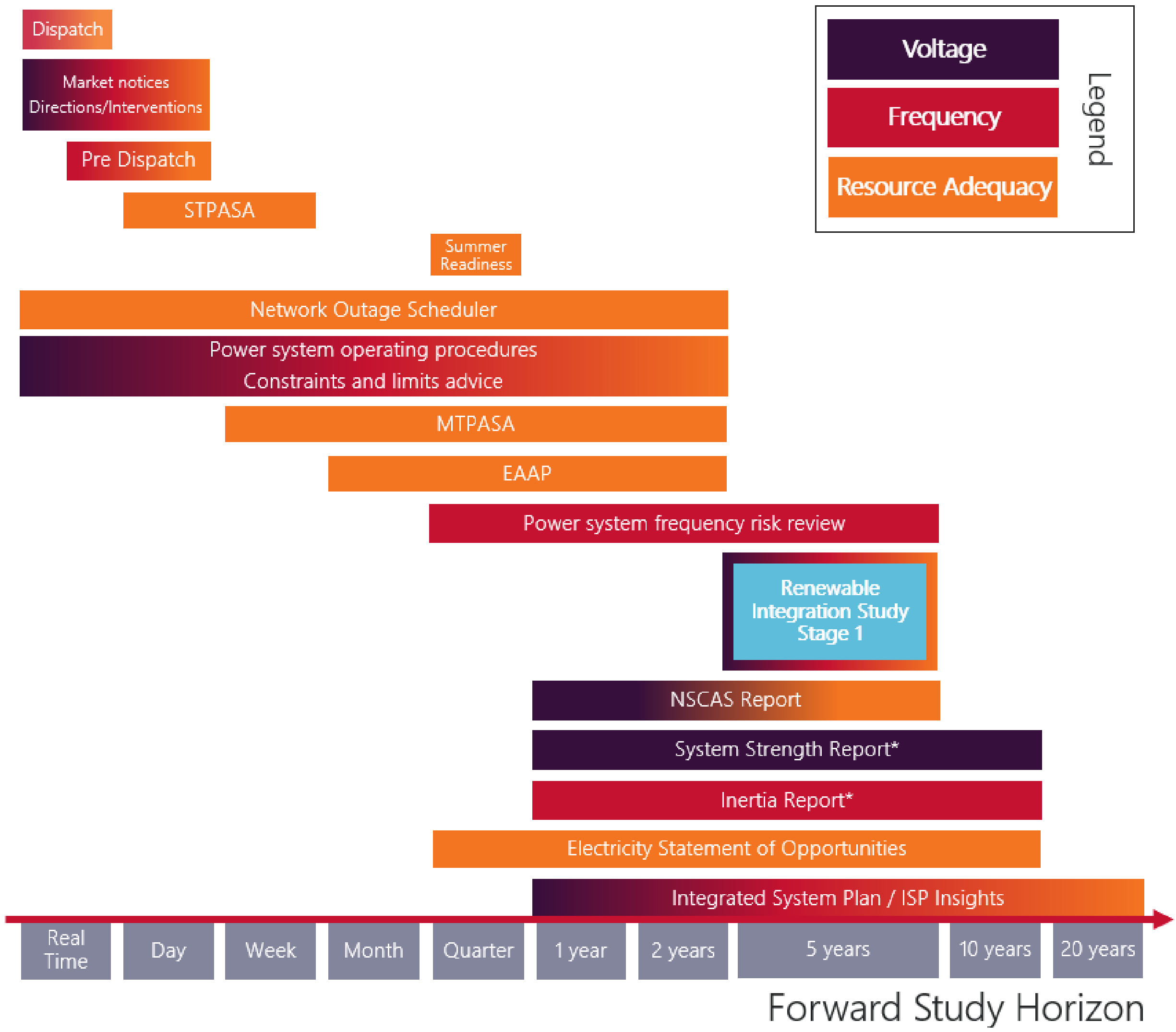
- More traditional power system limits and stability analyses[20] – given their extensive coverage in the ISP, network planning processes, and generation connection studies, it was assumed that these traditional limits would be manageable through existing processes, and would not pose regional or NEM-wide limits to the penetration of wind and solar generation.
- Assessing system limitations at the local, sub-regional level, such as generator connection issues – these are being, or will be, addressed in other projects and publications.

[20] Traditional system limits that will continue to be assessed and managed via other processes include thermal limits, voltage stability, transient and oscillatory stability, and local voltage management (management of pre and post contingent bus voltages).

- Assessing adequate firm supplies of energy to meet demand such that the NEM Reliability Standard[21] is met – this is considered in AEMO's ISP and *Electricity Statement of Opportunities*.
- Ensuring the power system can restart following a black system event – this is considered as part of AEMO's system restart work.

Figure 7 provides an overview of where the RIS Stage 1 report sits in relation to other AEMO NEM-wide planning publications, broken down by study horizon[22] and approximate areas of technical coverage. For further detail on these reports, refer to Chapter 9.

Figure 7 RIS Stage 1 report in relation to other AEMO planning publications



* Part of Draft ISP Rules (at http://coagenergycouncil.gov.au/publications/consultation-draft-isp-rules).
Acronyms: ST PASA: Short term projected assessment of supply adequacy; MT PASA: Medium term projected assessment of supply adequacy; NSCAS: Network Support and Control Ancillary Services Report

[21] The Reliability Standard, from the AEMC's Reliability Panel, specifies that expected unserved energy (energy that cannot be supplied to meet consumer demand because there is not enough available generation capacity, demand response, or network capability) should not exceed 0.002% of total energy consumption in any NEM region in any financial year.

[22] Study horizon refers to the period that is studied.

1.4 Report structure

The RIS Stage 1 report is presented as follows:

- Chapter 2 outlines the practical, day-to-day challenges and limits of operating a power system securely and efficiently, now and looking ahead to 2025.
- Chapters 3-6 summarise – in key areas of study – the challenges and barriers identified to how much wind and solar PV generation can operate at any one time, NEM-wide and in individual regions, and discuss how close NEM regions are to system limits now, and how close they are expected to be by 2025. Each chapter ends with a summary of recommended actions. Full analysis of three major areas of study are presented in detailed appendices, published separately to this document:
  - Appendix A. High penetrations of distributed solar PV.
  - Appendix B. Frequency control.
  - Appendix C. Managing variability and uncertainty.
- Chapter 7 summarises the changing system conditions to 2025 studied in this analysis, the key limits identified, and how recommended actions could see the NEM potentially operate securely in the next five years with up to 75% of total generation coming from wind and solar resources at any time.
- Chapter 8 considers next steps – specifically, consultation on this report and how its findings feed the 2020 ISP for the NEM.
- Chapter 9 lists additional related resources.

2. System operation

As outlined in chapters 3 to 6, increasingly variable and uncertain supply and demand, and declines in system strength and inertia, have moved the system to its limits, reducing its resiliency and increasing the risk to the system for complex events. The knowledge and tools operators have used in the past to operate the system securely are now less effective and need to be adapted.

For example, intervention by AEMO has always been a part of operating a secure NEM, but where it was used rarely in the past as a last resort to manage specific issues on the grid, it has now become commonplace, especially in regions with higher shares of renewable generation (South Australia, Tasmania, and Victoria). This RIS analysis projects that under the current market design the need for interventions to address system security requirements will grow across all NEM regions.

Successfully managing the system's increased uncertainty and operational complexity will require different approaches and better co-ordination of all resources. The existing dispatch process for the NEM was not designed for these new conditions, and the current reliance on operators to balance factors and intervene is sub-optimal and unsustainable.

To manage the system of the future efficiently, operators will require:

- Improvements to existing frameworks, giving operators increased certainty around system conditions that converge as real time approaches.
- Access to new and better sources of information to understand the changing system complexity.
- New operational processes, training, and tools to design and manage an increasingly complex system.

As the entity responsible for operation of the NEM, AEMO is committed to ensuring the system can operate securely, reliably, and efficiently with increasing penetrations of wind and solar resources.

This chapter:

- Summarises AEMO's understanding and experience of operating the current power system.
- Highlights the current challenges and actions that have been taken to adapt the system to securely operate regions of the NEM with world-leading levels of renewables.
- Explores the actions required to accommodate the projected penetration of wind and solar across the NEM, and ensure operational processes, tools and market reforms are in place for the continued secure operation of the grid.

This chapter is a precursor to the remaining chapters of the report, which study the specifics of the changing system and actions needed to manage these evolving system conditions.

2.1 How operators understand the power system

Power systems are among the world's largest machines and are made up of billions of components. The behaviour of a power system is highly complex, as it is defined by the aggregate behaviour of the network, the users (generators and loads), and the physical environment in which they operate.

To understand the behaviour of the power system, operators use a combination of approaches:

- **Operational experience** – using empirically derived evidence to understand and learn from the real system. The power system is continuously changing as users interact, and this experience is invaluable when running a power system. Some ways operators gain experience are through:
  - **Continuous monitoring** – continually monitoring the physical system to understand its behaviour and taking actions to keep the system secure. For example, following a system event, operators conduct detailed analysis to assess the performance of the system and feed information back to calibrate and improve operational processes and tools.
  - **Commissioning and testing** – making sure new equipment is tested and checked before it is connected to the system (for example, factory acceptance tests at time of manufacture, or on-site tests at time of commissioning). Equipment is then introduced in a safe way to minimise the risk to the system and allow operators to gain experience about the performance of new equipment. For example, when generators are first connected, they are not permitted to operate at full output immediately, but first go through a series of hold point tests to ensure any unforeseen performance issues can be safely managed.
  - **System testing** – carried out by operators where necessary, to test the response of the system in a controlled way. Historically this has not often been done. First, the need has been low, mainly because the basic performance characteristics of the system and components (load and generation) have not changed. Now, the system composition is changing rapidly as it moves to higher IBR and lower synchronous machines; for example, IBR work significantly differently to plant installed say 10 years ago. Second, system testing can affect sensitive customers and be disruptive to market operation. Examples of system testing include:
    - **Disturbance tests** – disturbances can be applied to the system to observe behaviour; for example, tests carried out recently in West Murray to understand the interaction of wind and solar plant involved a set of controlled tests, switching in/out reactive support plant and/or transmission lines to confirm the accuracy of simulation models in predicting complex power system phenomena, often involving interactions of multiple plant.
    - **Black start testing** – historically, generator black start tests in the NEM have been restricted to testing the capability of System Restart Ancillary Services (SRAS) sources. More comprehensive testing, involving several generating systems and network equipment, is currently being considered. Such tests validate restart plans, and allow critical responses to be tested, which might not be practical to account for in the simulation model (such as the interdependencies which impacted SRAS sources in South Australia during the 2016 black system).

  As the system transitions to new operational configurations with increasing wind and solar and decreasing conventional generation online, it will be important to test these new operational configurations in a way which minimises both the risk to system and the impact on market operation. The RIS International Review noted that a world leader in wind integration, EirGrid in Ireland, has taken a similar approach to the progressive increase in inverter-based resources (IBR) and reduction in synchronous generation[23].
- **System modelling** – using data and software packages to create models that can predict the behaviour of the system without physically interacting with or changing the system itself. This has the advantage that operators need not rely on experiencing events to understand how the system will respond, but, like all models, the results are only as good as the inputs, assumptions and methodologies. Operators use several different types of models to predict the behaviour of the system:
  - Techno-economic models allow operators to assess market outcomes and are used to plan the system over varying time horizons.

[23] See p. 4, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Future-Energy-Systems/2019/AEMO-RIS-International-Review-Oct-19.pdf.

– Demand models are used to predict the demand profile of the system for operation and planning timeframes.
– Weather models are used to forecast the weather and hence the influence it may have through weather-dependent generation or impact on the physical system.
– Power system security models are typically built and run to assess the security of the system to disturbances on the system.

2.2 How the NEM power system is securely operated

AEMO currently operates the NEM power system within defined limits using a security-constrained dispatch engine – the National Electricity Market Dispatch Engine (NEMDE)[24].

To ensure a dispatch configuration will operate within the technical envelope of the power system, limits are assessed ahead of time (using power system security models) and converted into a series of mathematical constraint equations[25]. These constraints are fed into NEMDE and must be satisfied as part of each generation dispatch decision[26].

The NEMDE central dispatch algorithm uses a linear programming model to find the optimal dispatch solution, by minimising the total cost of the dispatched resources while maintaining a secure operating system. Table 3 summarises how NEMDE calculates results for dispatch and pre-dispatch[27].

Table 3 Dispatch and pre-dispatch

	Pre-dispatch	Dispatch
Run frequency	30-minute	5-minute
Resolution and timeframe	30-minute resolution out to the following trading day	5-minute resolution for the next five minutes
Purpose	• Provides market (including energy and FCAS) information to participants to allow them to make informed decisions. • Provides AEMO with information to allow it to fulfil its duties in relation to system reliability and security, in accordance with the NER.	Used to run the market. Provides instructions to generators (and scheduled loads) on how much to produce (or consume), subject to a security constrained process.

NEMDE is set up to ensure the system remains operating within its physical limits. Historically, these limits have mainly been associated with keeping the system within its **maximum** physical limits, including loading on the network and interchange between regions. It achieves this by providing instructions on the amount of energy provided from each scheduled generator and the maximum amount of energy provided from each semi--scheduled generator.

As the generation mix has changed, new emerging limits are predominantly associated with operating near the system's **minimum** physical limits. Examples include synchronous unit requirements to maintain fault levels, inertia requirements, operating reserves, and limits associated with low levels of operational demand.

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[24] NEMDE is a central computer system that takes bid information, demand forecasts, network constraint information, and other information as input variables, and every five minutes determines market spot prices and which combination of generators should be dispatched to meet demand for the next 5-minute period at the least cost.

[25] In the case of thermal constraint equations only, there is a facility which can develop these constraint equations automatically in close to real time based on current system conditions. This is currently only used when there are no appropriate constraints in the library.

[26] See https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/system-operations/power-system-operation/power-system-operating-procedures.

[27] A 5-minute pre-dispatch schedule is also produced at a 5-minute resolution for an hour ahead, although this process is not currently required in the National Electricity Rules (NER).

The system has not been designed to cater for these new minimum limits, and it may not be efficient to define them, or possible to do so under the current rules. These minimums could be achieved by constraining off generators that erode a particular essential system service, which would have the effect of keeping online more expensive generators, to meet the minimum power system requirements.

Without constraints to stipulate these limits, the NEMDE process cannot automatically keep the system above these minimum levels. Instead, AEMO's control room must monitor these limits and intervene in the dispatch process to avoid the limits being breached. AEMO has a range of intervention mechanisms which it can use to manage system security and reliability. These include[28].

- **Direction** – taking action as contemplated by NER clause 4.8.9(a) or section 116 of the National Electricity Law, in relation to scheduled plant or a market generating unit.
- **Instruction** – taking some other action contemplated by NER clause 4.8.9(a) or section 116 of the National Electricity Law.
- **Reliability and Emergency Reserve Trader (RERT)** – activating emergency reserve contracts procured under NER clause 3.20 where required to meet the reliability standard[29].

While intervention mechanisms have always been a part of operating a secure NEM, historically their use has been low, with intervention used as a last resort to manage specific issues on the grid. An intervention should only arise if there is a failure in the market to deliver the necessary power system outcome. Frequent interventions being needed for the same issue would imply an enduring market failure.

As Section 2.3 outlines, however, intervention is now commonplace in parts of the NEM and is expected to be required more frequently in more NEM regions over the next five years.

2.3 Challenges to system operation

This section identifies key challenges that are currently facing system operators in the NEM. Subsequent chapters in this RIS explore the challenges in detail and propose interim and longer-term actions to remedy these challenges.

2.3.1 Increased variability and uncertainty

Variability and uncertainty in power system operation is increasing, because of:

- The inherent variability and uncertainty of fuel availability for weather-driven wind and solar generators, and displacement of online conventional generation, which was traditionally used to accommodate variability and uncertainty in the system. See the case study at the end of Section 2.4, Chapter 6, and Appendix C for further detail.
- Uncertainty in pre-dispatch schedules, as they vary from period to period. This variability depends on factors including how participants respond to market information and assessments of expected conditions or changes to underlying physical plant conditions. For example, as generation assets age they become less reliable, which may increase variability due to plant conditions.
- Changing system behaviour with the adoption of new technology, including distributed energy resources (DER) (see 'Increasing decentralisation' below for more details).

This growing variability and uncertainty make it harder for operators to pre-empt upcoming conditions and system configurations. Traditional snapshot-based security analysis, to ensure the right mix of resources is available when needed, is increasingly challenging. This is illustrated in the case study at the end of Section 2.4.

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[28] These and other operating procedures are outlined in AEMO, Power System Security Guidelines, SO_OP_3715, at https://www.aemo.com.au/energy-systems/electricity/national-electricity-market-nem/system-operations/power-system-operation/power-system-operating-procedures.

[29] Current RERT Guidelines (2019) are at https://www.aemc.gov.au/market-reviews-advice/review-reliability-and-emergency-reserve-trader-guidelines-2019.

2.3.2 Reduced synchronous sources

As outlined in Chapter 4 and Chapter 5, the number of online synchronous generators is being displaced by increasing penetrations of IBR, without compensation for the loss of synchronous services. As a result, system strength[30] and inertia have reduced, and the system is reaching the bounds of known stability limits.

AEMO declares a shortfall in a region if the provision of the system service (inertia or system strength) is projected to be less than the required level for a period of time. System strength and inertia shortfall assessments are published annually. If AEMO declares a shortfall, transmission network service providers (TNSPs) are required to make the relevant services available[31].

Table 4 lists NEM regions where system strength and inertia shortfalls are currently declared, with relevant interim and longer-term management actions. Directions for system strength are discussed in more detail in Section 2.4.

Table 4 Current inertia and system strength shortfalls in the NEM

Region	Issues	Interim management plan	Long-term management plan
South Australia	Regional fault level shortfall declared in October 2017.	Directions for system strength. Since July 2017, directions have been in place 17% of the time.	Installation of high inertia synchronous condensers by ElectraNet as South Australian TNSP by 2021[A].
	Regional inertia shortfall declared in December 2018.	Directions for inertia and FCAS required under credible risk of islanding.	
Victoria	Inertia and fault level shortfalls in West Murray declared in 2019.	Hold points on NW Victoria generation to manage stability until system strength remediation is complete[B].	Under study by AEMO as Victorian Jurisdictional planner.
Tasmania	Regional inertia and fault level shortfalls declared in November 2019.	TasNetworks has negotiated the provision of inertia network services and system strength services under contract from a provider within the Tasmanian region offering suitable synchronous condenser capabilities.	
Queensland	System strength shortfall declared in North Queensland in April 2020.	Constraints for system strength are currently implemented, requiring minimum synchronous unit combinations and curtailing wind and solar under certain conditions.	Under study by Powerlink, as the local TNSP, with system strength services to be implemented by 31 August 2021.

A. See https://www.electranet.com.au/what-we-do/projects/power-system-strength/.
B. See case study on increasing IBR in north-west Victoria at the end of Section 2.4.

Projecting shortfalls is a difficult process, because it is highly dependent on the behaviour of generators in the energy market, which can change much faster than shortfalls can be declared and addressed.

Even if a shortfall is accurately projected, there are additional challenges:

- There is a lag between when a shortfall is identified and when it can be remediated. In the interim, before solutions are contracted, temporary solutions – including additional use of directions – may be required to manage the system.
- Under current market arrangements, these resources may not be dispatched efficiently:
  - An operational tool and market mechanism are needed to schedule these services.
  - Further co-ordination between markets is required where multiple providers are capable of providing several services (such as energy, FCAS, and inertia services).

[30] For more information about system strength, see AEMO, System Strength: *System Strength in the NEM Explained*, March 2020, at https://aemo.com.au/-/media/files/electricity/nem/system-strength-explained.pdf?la=en.

[31] See NER clause 5.20B.3 and 5.20B.4.

2.3.3 Increasing decentralisation

Due to the growth in DPV generation over the last decade, the NEM generation mix is becoming increasingly decentralised, with some regions at world-leading levels of penetration[32]. Today this is mostly comprised of individually small passive devices co-located with customer loads. As penetrations continue to increase, this passive fleet is having a growing aggregated impact on system operation, as a result of:

- An increasingly large component of generation not currently being subject to the same performance requirements as utility-scale generation, in terms of its ability to supportively respond to small fluctuations, as well as the ability to withstand the range of larger, plausible bulk system disturbances.
- An increasingly large source of generation that is not visible to operators and cannot be curtailed (even under emergency conditions), reducing the operational levers available to AEMO to securely manage the supply demand balance at any given time.

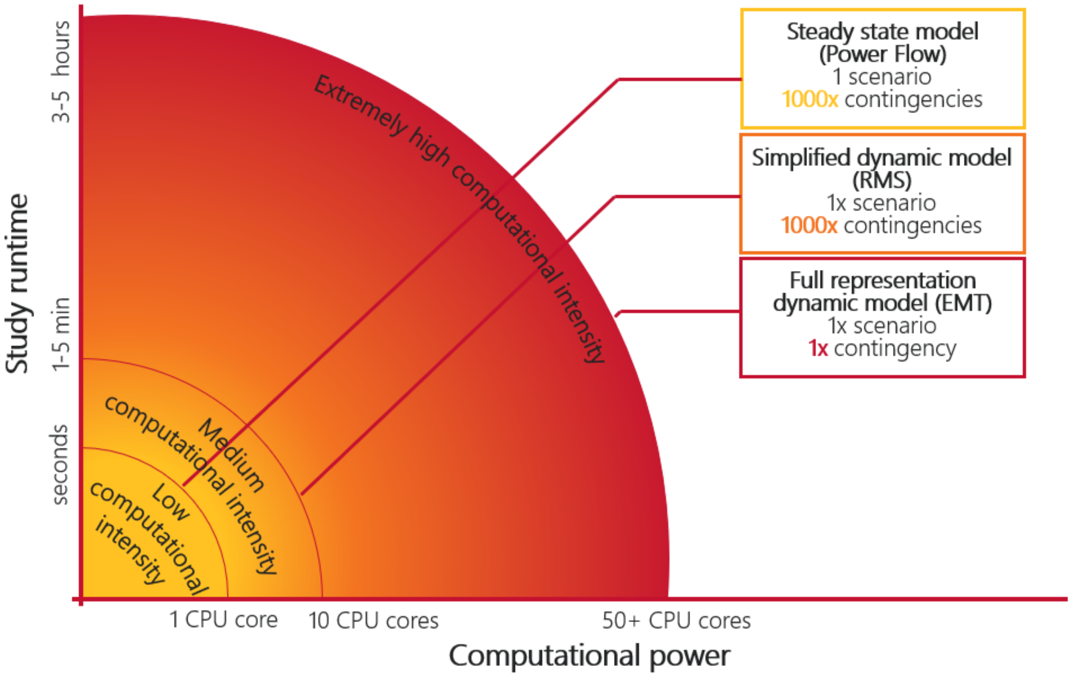
Operational challenges associated with increasing shares of DPV generation in the power system are discussed in Chapter 3 of this report and Appendix A.

2.3.4 Increasing complexity for security analysis

Operators need to analyse emerging system conditions associated with high IBR and low synchronous generation, including reduced system strength and inertia. Conventional models, referred to as root-mean square (RMS) models, provide good accuracy for simulating most of the traditional security challenges. Some emerging inverter-based performance requires more detailed electromagnetic transient (EMT) models to assess the stability of these systems.

EMT studies require more complex models, which increases the computational burden and time taken to run them, as shown in Figure 8. For example, running a single contingency in an EMT study takes thousands of times longer than a single contingency in an RMS dynamic study, with 50 times the computing resources[33].

Figure 8 Computational complexity between modelling simulations for the NEM



[32] AEMO, *RIS International Review*, October 2019, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Future-Energy-Systems/2019/AEMO-RIS-International-Review-Oct-19.pdf.

[33] Note simulation run times are variable and are highly dependent on model development, complexity and the software/methodology used to run. These estimates are based on the current tools used by AEMO, noting full system EMT models are early in their deployment.

The power system is made up of many components, which vary in age and condition. As a result, components are continuously being maintained, replaced, and extended. Secure system operation requires careful planning and assessment of outages and their impact on the rest of the network. Outages can be planned, at short or long notice, or unplanned.

The complexity of assessing and scheduling planned outages is increasing:

- In recent years, in line with summer readiness plans, additional effort has been made to schedule planned maintenance and project work for transmission and generation assets outside of summer months[34]. This has left less time in the year to schedule and complete commissioning, maintenance, and project work, making the scheduling process more difficult. There is also an increased chance of multiple outages being planned for the same time, which can lead to the deferral or cancellation of some outages, delaying planned maintenance or having other flow-on impacts on the operation of network and generation assets.
- Assessing and scheduling outages is even more complex in areas of low system strength or inertia:
  - Historically, most outages did not materially affect the dynamic stability of the system, so they did not require a high level of detailed assessment before they began. With an increasing number of areas being identified with low system strength or inertia, an increasing number of outages require more detailed, complex, and time-intensive assessment before commencement.
  - To maintain acceptable levels of system stability in these areas, there are typically additional limitations on the number of concurrent outages (for both network equipment and generation) that can occur, which creates further scheduling difficulty.
  - AEMO may apply additional limits and temporary constraints to existing generation in these areas for the duration of outages to help maintain stability in a specific area. For example, in West Murray, studies showed that under some outage conditions, existing generation in this region would need to be reduced to maintain power system voltages, currents and frequency, line flows, and fault levels within designated limits[35].

2.4 Operating the NEM with high wind and solar penetration

As the system continues to change rapidly, there is a need to reconsider various aspects of system design and operational tools to ensure operational processes, tools, and market reforms are in place for the continued secure operation of the grid.

Successfully managing a power system with increased operational complexity will need more efficient co-ordination of all resources. This will require better information-sharing across operators and participants, and reduced uncertainty where possible so the right resources can be scheduled at the right time in an efficient way.

To manage the system of the future efficiently, operators will require:

- Improvement to existing frameworks that give operators increased certainty around system conditions that converge as real time approaches.
- Access to new and better sources of information to understand the changing system complexity.
- New operational processes, tools, and operator training to manage the changing system complexity.

This section provides examples of measures being used to keep the NEM operating securely now:

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[34] The summer operational period spans from November to March (inclusive). In summer, the power system must manage additional risk as it responds to high consumer energy demand, increasing periods of high temperatures, and climatic events including bushfires and storms. To get the best capacity from networks over this period, outages (including generation and transmission equipment) are minimised, where this does not increase any risk to future reliability of equipment or present a safety issue. See AEMO's Summer Readiness 2019-20 plan, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/System-Operations/Summer-2019-20-Readiness-Plan.pdf.

[35] For example, in north-west Victoria, for generators connected to network assets undergoing maintenance there may be periods where they are curtailed to manage system security. See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Congestion-Information/2019/Planned-outages-in-the-North-Western-VIC-and-South-West-NSW-transmission-network-industry-communique.pdf.

- Some measures, such as inclusion of the Forecast Uncertainty Measure (FUM) to account for uncertainty in reserve assessment, provide examples of long-term enhancements to operating the system under changing conditions.
- Other measures, such as the use of directions to manage system strength and inertia shortfalls, are examples of interim solutions, which are necessary for secure system operation but are also inefficient and distortionary and may not provide proper valuation of the service.

As the 31 January 2020 case study at the end of this section shows, the real-time workload for operators to keep the system secure and balance interdependent factors is a critical and growing challenge. The case study also raises the issue of how efficiently interdependent or competing system issues are managed, given current processes to determine when to commit and withdraw services are still largely manual. While contracts and the compensation framework for directions provide some mechanism to value system services, they do not necessarily deliver the most efficient dispatch of those services, especially where those system services are provided in conjunction with the delivery of energy.

2.4.1 Reserve assessment

AEMO conducts reserve assessments ahead of real time[36] and declares Lack of Reserve (LOR) conditions when projections indicate the risk of involuntary load interruption, that is, conditions where there is not enough supply to meet demand. There are different LOR levels that indicate a progression of severity from LOR1 to LOR3, where LOR3 indicates involuntary load interruption[37].

LOR declarations have the following objectives:

- Provide information to market participants on the expected level of short-term capacity reserve. Market participants can then respond to this information by voluntarily withdrawing outages or committing additional capacity to the market, where possible.
- For the LOR2 level, provide a benchmark for AEMO to intervene in the market to commit extra capacity.

A key enhancement to the reserve assessment process was inclusion of the FUM. AEMO identified how the process could be improved by accounting for uncertainty, then implemented the FUM into its systems for use in determining LOR levels[38] following a rule change by the AEMC in December 2017 to update the reserve assessment framework.

The FUM introduced a risk-based approach to reserve assessment, and incorporates several variable factors including:

- Temperature forecast.
- Solar irradiance forecast.
- Forecast output of semi-scheduled (wind and solar) generating units.
- Current demand forecast error for forecast lead times below 24 hours.
- Current supply mix by fuel type (coal, gas or hydro).

Incorporating the FUM into reserve calculations allows a more accurate assessment of required reserves needed to manage uncertainty and maintain reliability. This in turn places AEMO in a better position to be able to foresee the range of probable events and inform the market.

[36] Every day, AEMO publishes the Pre-Dispatch Projected Assessment of System Adequacy (PD PASA) for the following day, and the Short-Term Projected Assessment of System Adequacy (ST PASA) looking two to seven days ahead. The LOR assessment horizon is from the current time to the end of the period covered by the most recently published ST PASA.

[37] See AEMO's Reserve Level Declaration Guidelines for more information, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power_System_Ops/Reserve-Level-Declaration-Guidelines.pdf.

[38] The FUM was implemented in AEMOs production systems in February 2018.

Other improvements to reserve assessment tools and processes have also been identified, so they continue to serve the NEM now and in a future dominated by new technologies. Some current design features of the reserve assessment process that are undergoing investigation include:

- The study period is currently assessed as a whole, rather than time-sequentially.
- Each NEM region is currently assessed as a separate study region. The reserves available in each study region are determined after meeting supply demand balance in other regions.
- The (currently simplistic) modelling of energy limited plant, and the optimisation of battery storage (for example including intra-daily cycling), can be improved.
- Currently modelling does not include:
  - Required power system services including inertia, system strength, levels of ramping capability, and FCAS requirements.
  - Pricing information.
  - Modelling power system security under additional conditions (such as minimum demand).

If variability and uncertainty increase with increasing penetrations of wind and solar (as projected in Chapter 6), LOR declarations may be required more often, potentially increasing the need for market intervention if suitable responses are not forthcoming from the market.

2.4.2 AEMO intervention event

An AEMO intervention event is where AEMO intervenes in the market by issuing a direction or instruction or exercising RERT for the purposes of power system security and reliability, as mentioned in Section 2.2. The 31 January 2020 case study at the end of this section details an example where directions, instructions, and RERT were needed to manage the power system.

Recently, intervention events have become more frequent in parts of the NEM, particularly in areas with higher wind and solar generation[39].

Figure 9 shows the increasing frequency of directions (one type of intervention event) and the increasing volume of hours in which operators are managing directions in the NEM. The figure shows both the historical number of hours (column) where generators are directed[40], and the number of directions issued (value above column), in each financial year from 2014-15 to the current financial year (to date).

In 2019-20 to date, 65 of the 229 directions occurred due to the separation event between South Australia and Victoria from 31 January to 17 February 2020 (see case study below). Because the data provided for 2019-20 is incomplete (current as of 5 March 2020), the final figure for the financial year will be larger.

Longer-term solutions are needed to identify system strength and inertia requirements and schedule the relevant services, to address the root cause of the observed increase in directions.

A reduction in directions is beneficial, because they distort the market and investment signals and are also a time and labour-intensive process for AEMO.

As noted in Section 2.3.2, even if a shortfall for system strength or inertia is accurately projected, if the remediation involves contracting with a service provider, this does not remove the need for intervention to instruct contracted service providers when required.

Based on the current market framework and projected resource mix of the draft 2020 ISP Central scenario, the requirement for interventions will increase across the NEM out to 2025 as instantaneous penetrations of wind and solar generation grow.

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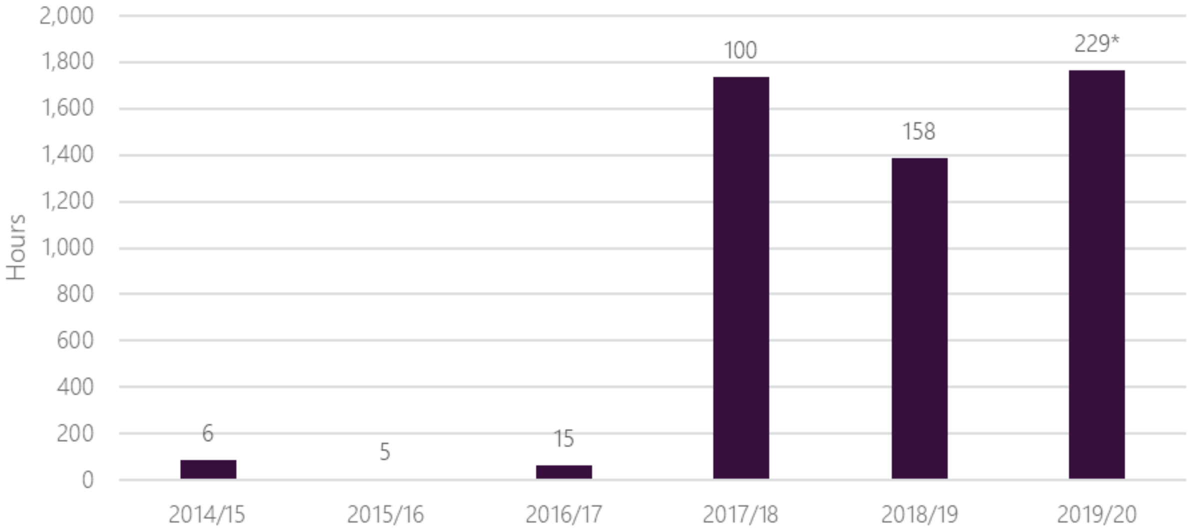
[39] AEMO's Quarterly Energy Dynamics (QED) reports show the increasing proportion of time that units are being directed in South Australia and Victoria and the increasing cost of these directions. This is particularly evident in the 2019 Q4 QED (pg. 25), at https://aemo.com.au/-/media/files/major-publications/qed/2019/qed-q4-2019.pdf?la=en&hash=A46E0A510AE9F127B0A991B312C54460. For more information on trends in directions, see AEMO's Quarterly Energy Dynamics reports, at https://aemo.com.au/energy-systems/major-publications/quarterly-energy-dynamics-qed.

[40] The number of hours represents the period of time a direction was effective in the NEM.

Figure 9 Historical number of directions and duration, 2015-20



*Incomplete year; data current at 5 March 2020.
Note: values above each column represent number of directions issued.

Case study | South Australia – Victoria separation | 31 January to 17 February 2020

The day of separation – 31 January 2020 – was characterised by extreme temperatures across several NEM regions. A high-pressure system over the Tasman Sea, combined with an approaching cold front, resulted in north to north-west winds and very hot humid conditions across south-east Australia. Thunderstorms were forecast to develop over western and central Victoria during the afternoon, with the risk of severe thunderstorms bringing damaging winds and heavy rain.

Tight supply-demand: there was high demand across the NEM on the day. In particular, Victoria reached a maximum of 9,667 megawatts (MW – the thirteenth-highest on record) and New South Wales reached 13,190 MW (forty-seventh-highest on record).

At 12:41, AEMO issued a forecast LOR level 1 condition in Victoria for the period 15:00 to 17:00. At 13:47, this was updated to a forecast LOR 2 condition. This means there was a tightening of electricity supply reserves, so that there was enough supply to meet forecast demand in Victoria, but supply could be disrupted if a large incident occurred.

Variability and uncertainty: four different phenomena led to deviations between forecast and actual generation across several sites throughout the day. These all occurred before the separation event and continued into the afternoon:

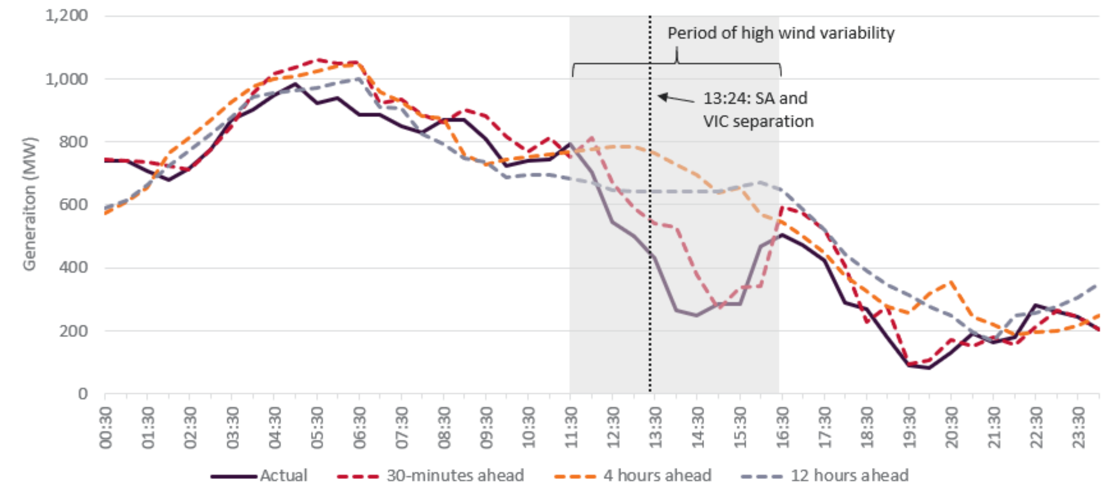
- High temperatures causing de-rating of wind farms.
- Variable and gusty conditions causing high wind speed shutdown in some locations, and insufficient wind to generate in other locations.
- A network outage requiring disconnection of some wind generation.

Accurate forecasting of generation is essential to AEMO's assessments of system adequacy, particularly on extreme days such as this, where reserve margins are low and renewable penetrations are significant. When rain showers and thunderstorms are prominent, as on this day, winds can behave in a manner that is not readily forecastable by global weather models, which are key inputs to energy forecasts with longer lead times (greater than an hour), leading to differences between forecast and actual generation.

Forecasts closer to real time (within one hour) lag actual generation throughout the day, as shown in Figure A, so are not good predictors of future variability.

Further information on integration of weather information into power forecasts is available in Appendix C.

Figure A Victoria semi-scheduled wind, pre-dispatch target vs actual generation



Separation event: at approximately 13:24, the collapse of several steel transmission towers on the Moorabool – Mortlake and Moorabool – Haunted Gully 500 kilovolt (kV) lines resulted in the tripping of these lines and the separation of South Australia from Victoria.

Managing the system on the day: manual intervention and additional monitoring by the control room and support staff was required:

- **Manual management of wind farm availability (reliability)** – a doubling of dedicated staff was required to manage the power system. The additional staff were required to actively identify wind sites at risk of de-rating, monitor output from the sites, and contact plant operators for updated information if significant deviations between actual output and expected availability occurred.
- **Reliability and Emergency Reserve Trader (RERT)**[41] – AEMO dispatched up to 185 MW of RERT in Victoria and 134 MW in New South Wales between 15:30 and 21:30, involving activation of 15 contracts across both states, with five of the contracts requiring pre-activation. An additional two contracts in New South Wales and one contract in Victoria were pre-activated, but not activated in response to the LOR2 conditions.
- **Other** – AEMO issued one direction to keep non-scheduled wind farms offline to control flows on the Heywood (Victoria – South Australia) interconnector.

Subsequent management of separation: in the 17 days following 31 January, while South Australia was operating as an extended island[42], significant manual intervention was required by the control room. The interventions included[43]:

- **System strength (security)** – AEMO issued 18 directions[44] for synchronous generators to remain synchronised in South Australia. This meant AEMO was intervening in the market 100% of the time between 1 February 2020 and 17 February 2020.
- **FCAS** – AEMO issued 25 directions for the provision of FCAS in South Australia – 15 directions to generators to be synchronised to provide reserve, and 10 directions of batteries to 0 MW output and a specified state of charge so they could provide raise and lower reserve and allow operators to re-secure the system within 30 minutes in the event of a contingency.
- **Reliability** – AEMO issued two directions for generators in order to service essential loads in the area.
- **Other** – AEMO issued 25 directions to semi-scheduled and non-scheduled wind farms to disconnect or reduce MW output (usually 0 MW).

[41] RERT is an intervention mechanism under the NER that allows AEMO to contract for emergency reserves such as generation or demand response that are not otherwise available in the market, as a safety net in the event that a critical shortfall in reserves is forecast.

[42] The South Australia extended island consisted of the South Australia region and the elements of the Victorian network east of the Tarrone and Mortlake substation, including the Alcoa Portland Smelter (APD).

[43] Some directions were issued for both system strength and FCAS. A total of 65 directions was issued between 31 January 2020 and 17 February 2020.

[44] One direction was issued at 21:00 on 31 January 2020, after the separation event.

This event demonstrates the large volume of manual work that was undertaken by the operators to maintain the system in a secure operating state. It also raises questions about the efficiency of scheduling system services using a manual process, particularly where there are many participants who can provide an array of services. In a manual process, it takes longer than it would with an automated tool to assess which participants can provide a particular service, subject to technical requirements and the services they are already providing, and assess how to procure that service at the lowest cost.

In this case study, generally synchronous generators were directed on, batteries were directed to hold a state of charge (with 0 MW output), and wind was directed down or off. To manage future operating scenarios with even higher penetrations of wind and solar resources (and potentially more participants), new operating tools, processes, and market changes will be needed to automate and manage the decision-making and scheduling process to efficiently source the required system services and ascribe a market value to them.

As noted in Section 2.3.2, this raises a challenge around how interdependent or competing system issues are managed, given that current processes to determine when to commit and withdraw services are still largely manual. While contracts and the compensation framework for directions provide some mechanism to value system services, they do not necessarily deliver the most efficient scheduling of those services, especially where those system services are provided in conjunction with the delivery of energy or other services.

2.4.3 New constraints to manage IBR

Historically, a common remediation measure used to manage system security was to limit the maximum active power (megawatt) output of synchronous generators. However, some instability limits of IBR are not related to the plant's megawatt output, but to the number of inverters connected, represented by the plant's aggregate megavolt amperes (MVA) rating. This emerging instability limit cannot be directly managed by the current NEM dispatch process and associated constraint equations, because the existing process is not capable of directly managing the number of inverters connected to the system.

Case study | Increasing IBR in West Murray

North-West Victoria's West Murray area has attracted significant investment in inverter-based solar and wind generation because of its quality solar and wind resources, but it is a remote and electrically weak part of the grid.

In 2019, AEMO undertook detailed power system studies which indicated that five solar farms in north-west Victoria **exhibited sustained voltage oscillations,** which exceeded allowable stability limits, following a credible contingency under system intact conditions. The analysis showed that **a reduction in the number of online inverters at these five farms reduced the magnitude of voltage oscillations.** However, reducing only the total megawatt output of each solar farm, while maintaining all inverters online, was not effective.

In September 2019, to maintain power system security, AEMO limited the number of online inverters at the five farms. **Approvals for new generators due for commissioning or registration in the area were also postponed** until new operating parameters could be verified, approved, and implemented. (These constraints were successfully resolved at the time of writing.)

This case study also underlines the need for advanced simulation capability, so issues are captured early, limiting the impact to the system, markets, and investments.

Full study details at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Network_Connections/Power-System-Limitations-December.pdf. More about the announced lifting of constraints in April 2020 is at https://www.aemo.com.au/news/constraints-lifted-for-west-murray-solar-farms.

2.5 Actions to support system operation

Specific actions related to system operation are listed in Table 5. Where actions also address other challenges identified in this study, cross-references are provided. The table notes where actions are already underway, and which are new actions from the RIS Stage 1.

Table 5 Challenges and actions – system operation

Key challenges	Actions	Timing	Status
An increasing penetration of wind and solar operating in the system is pushing the system to minimum limits. The existing dispatch process for the NEM was not designed for managing minimum conditions (particularly managing the commitment of synchronous units to maintain minimum levels of inertia and system strength). The current reliance on operators to balance factors and intervene is sub-optimal as system variability, uncertainty, and complexity increases. Without effective and standardised operational process, tools, and training to schedule system strength and inertia services, the risk of human error grows, and the level of intervention becomes increasingly unsustainable. Further, the market design needs to adapt so all essential security and reliability services are provided efficiently, when required, and without operator intervention. Given the pace and complexity of change in the NEM, there is a need for flexible regulatory frameworks (particularly technical standards and frameworks for sourcing system services) that can adapt swiftly and effectively as: • Understanding of the changing power system evolves. • Requirements for system services change. • Technology evolves.	**2.1** AEMO to identify and evaluate standard operational process, control room tools, and operator training to operationalise intervention (directions/instructions) for system strength and inertia services under the current framework.	2020	In progress
	2.2 AEMO to redevelop existing scheduling systems (Pre-Dispatch [PD] and Short Term [ST] PASA) to better account for system needs, including: • Availability of essential system services, including inertia, system strength, and ramping requirements. • Catering for cross-regional sharing of reserves. • Better modelling of new technologies, including VRE, batteries and DER (including demand response and VPPs).	2020-22	In progress
	2.3 Consistent with the outcomes of this study, the ESB considers that security constrained economic dispatch of energy-only is, by itself, no longer sufficient to maintain system security. The ESB considers that new system services need to be established and remunerated and an ahead market is required to ensure system security going forward[A]. As part of its post-2025 market design program, the ESB is assessing market mechanisms that increase certainty around system dispatch of energy and essential system services (inertia, system strength, minimum synchronous units, operating reserves, and flexibility) as real time approaches. The ESB will recommend a high level design to the COAG Energy Council by end of 2020 for implementation by 2025.	2020-25	In progress
The growth in wind and solar is increasing the complexity of the system. This creates challenges for existing tools and processes used for system security analysis and assessment. Tools and processes used to model the system, assess outages, and measure system performance are becoming increasingly computationally complex and more costly in time and resources.	**2.4** AEMO to develop a detailed proposal outlining requirements, timing, and method to achieve specified NEM high-speed monitoring (phasor measurement units) to cover more points, allowing better visibility of performance of the system, and help operators to understand the changing power system.	2020	In progress
	2.5 AEMO to collaborate with industry and other world-leading power system operators to develop new operational capability, allowing better analysis of complex security phenomena and optimisation for a power system with world-leading levels of renewable generation (inverter-based, variable and decentralised), storage, and demand side participation.	2020-25	In progress

A. A. See http://www.coagenergycouncil.gov.au/sites/prod.energycouncil/files/ESB%20Post2025%20Directions%20Paper.pdf.

3. Distributed solar PV

Australia has experienced strong growth in DPV generation over the last decade, with parts of the NEM now at world-leading levels. AEMO expects this growth to continue over the next decade. Most DPV systems in the NEM today operate in a passive manner – they are not subject to the same performance requirements as large-scale sources and are not visible or controllable by distribution network service providers (DNSPs) or AEMO, even under emergency conditions.

DNSPs have begun to experience technical challenges associated with increasing passive DPV penetration, and have started to implement measures to improve hosting capacity.

At the bulk system level, the aggregated passive DPV fleet is impacting AEMO's ability to securely operate the South Australian region today, through:

- Increasing contingency sizes, associated with the potential mass disconnection of DPV systems following plausible bulk system disturbances, eventually becoming unmanageably large, especially for regions of the NEM that may operate as islands under some conditions.
- Ongoing reduction in the daytime system load profile, first impacting availability of the stable load blocks necessary for the effective operation of critical emergency mechanisms in the daytime, and eventually to the point of insufficient load to support minimum synchronous generation levels.

Under current DPV growth projections, without action, growing passive DPV generation will also impact system operation in other NEM regions by 2025.

AEMO's full analysis relating to the implications of increasing levels of DPV is in Appendix A.

DPV generation already exceeds the largest scheduled generator in the NEM today. There is already 9 GW of DPV installed in the NEM today; by 2025, this is projected to increase to 12 GW in the Central scenario and 19 GW in the Step Change scenario.

Given the already high levels across the NEM, and expected growth into the future, this part of the RIS considers the power system challenges associated with increasing levels of passive DPV generation. Better integrating this fleet with the needs of the power system, through improved performance standards and minimum levels of curtailability, will help to address some of these challenges.

Other forms of DER – such as storage and electric vehicle charging, and demand response – can also assist by 'soaking up' excess DPV generation in the daytime, but could also create their own system challenges if not harnessed effectively. AEMO's DER Program is considering the range of market and technical enablers for the secure and efficient integration of DER within our energy systems[45]. The ISP projections for these technologies, as outlined in Section 1.1, have been included in the analysis.

[45] For more information on AEMO's DER Program and the different workstreams, see https://www.aemo.com.au/initiatives/major-programs/nem-distributed-energy-resources-der-program.

3.1 Increasing distributed solar PV

The *RIS International Review* identified a typical trajectory of system limits as the share of passive DPV increases[46]. Limitations first arise within the distribution network as penetrations increase or concentrating in certain areas, eventually impacting the transmission-distribution interface as these penetrations grow. As this growth continues and DPV generation becomes significant at the bulk system level, the inability to see and actively manage the DPV fleet impacts almost all core duties of the system operator in some way – including system balancing, power system stability, and recovery and restoration following major system events.

NEM regions are at different points along this trajectory today. By 2025, AEMO expects all regions to have moved significantly along this path as penetrations increase. Table 6 compares the maximum instantaneous penetrations of DPV generation today against 2025 projections. In 2019, South Australia operated for a period where 64% of regional demand was met by DPV generation. By 2025, this could reach as high as 85%. Other mainland NEM regions could be regularly operating close to or above 50% instantaneous penetration.

Table 6 Historical (2019) and projected (2025) maximum instantaneous penetration of DPV

Maximum instantaneous DPV penetration (%)	Historical (2019)	Projected (2025, ISP scenario)	
	Actual	Central	Step Change
South Australia	64	68	85
Victoria	31	45	66
Queensland	30	45	57
New South Wales	21	33	48
Tasmania	12	14	21

AEMO has an ongoing program of work to better understand the implications of increasing levels of passive DPV generation on the power system, with a current focus on South Australia[47]. Lessons from this work have informed key actions to maintain system security in this region in the short term, and actions to better integrate the DPV fleet with the future power system operation in other regions.

3.2 Impacts on the distribution network

Distribution networks in the NEM are beginning to experience challenges associated with increasing penetrations of passive DPV generation. To gain a better understanding of this, AEMO surveyed DNSP planning documents and engaged with DNSPs over a series of workshops in June 2019. Table 7 summarises issues that have begun to emerge within each DNSP franchise area.

While all DNSPs have started to experience voltage management challenges in their low voltage (LV) networks, the extent of DPV integration challenges is highly location-specific, depending on the size and location of PV clusters relative to physical network characteristics and load. Currently, South Australia and Queensland are experiencing the most significant challenges due to their high DPV penetration levels, exacerbated by these areas also having generally lower network capacity and higher impedance.

DNSPs are implementing a range of measures to improve DPV hosting capacity within their networks:

[46] At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Future-Energy-Systems/2019/AEMO-RIS-International-Review-Oct-19.pdf.

[47] For further information see, https://aemo.com.au/initiatives/major-programs/nem-distributed-energy-resources-der-program/operations

- **Network strategies** – remediating and reconfiguring network assets, and augmenting network capacity and flexibility to securely manage increasing DPV generation in the daytime, while still accommodating the ramp in demand at the end of the day.
- **Behind-the-meter strategies** – reconfiguring settings or limiting export from DPV systems and activating other DER in the LV network, such as loads and storage devices, to 'soak up' excess DPV generation in the daytime.
- DNSPs' ability to efficiently integrate DPV generation within their networks is severely hampered by a **lack of visibility of the LV network**. Most are undertaking measures to improve visibility of locations with higher penetrations.

Table 7 Summary of DPV integration issues experienced by DNSPs

Level		Issue	SA	QLD		VIC					NSW/ACT				TAS
			SA Power Networks	Energex	Ergon Energy	CitiPower	Powercor	United Energy	AusNet Services	Jemena	Ausgrid	Evoenergy	Endeavour Energy	Essential Energy	Tas Networks
Behind meter	Customer premises	Over voltage complaints	●	●	●	●	●	●	●	●	●	●	●	●	●
		DPV inverter settings	●	●		●	●	●	●	●	●	●		●	●
		Under voltage	●	●	●	●			●				●		
		Other power quality	●	●				●		●	●	●			
LV	LV feeder	Voltage regulation	●	●	●	●	●	●	●	●	●	●	●	●	●
		Phase balance	●	●	●		●	●	●	●	●	●		●	●
		Thermal capacity	●	●	●	●	●	●	●	●		●			●
	Distribution substation transformer	Tap setting	●	●	●	●	●	●	●	●	●	●	●		●
		Thermal capacity	●	●	●	●	●	●	●	●		●			
MV	Zone substation feeder	Voltage regulation	●	●	●				●						
		Thermal capacity	●	●										●	
	Zone substation transformer	Tap range	●		●				●		●	●	●		
		Voltage set point	●		●			●	●		●	●	●		
HV	Sub trans. transformer	Voltage set point	●						●		●		●		
Protection		Low background fault level	●									●			
		Fault discrimination		●								●			

● indicates the DNSP has started to experience the issue in parts of their network or planning for it to arise under current DPV projections. It does not provide any indication of materiality across the DNSP's network.
Source: AEMO analysis of DNSP 2019 Annual Planning Reports, workshops with DNSPs in June 2019.

From the bulk system perspective, AEMO expects the growth in regional DPV generation to continue as uptake continues to grow, and DNSPs implement such measures.

3.3 Impacts on the bulk system

Increasing levels of passive DPV generation have started to impact AEMO's ability to securely operate the South Australian power system today, and are beginning to impact operation in other NEM regions. Appendix A sets out the different bulk system challenges associated with increasing DPV generation and presents a high-level overview of how these challenges could impact each NEM region by 2025.

Figure 10 shows, for each NEM region:

- Actual DPV penetration against underlying demand each half-hour in 2019.
- Projected DPV penetration against underlying demand for each half-hour in 2025, under the ISP Central and Step Change scenarios.

- Overlaid on each plot are zones reflective of the different operating conditions under which challenges associated with increasing levels of DPV generation online might arise.[48]

All NEM regions are projected to be frequently operating with significantly higher penetrations DPV generation than today. Further analysis is required to better understand the operational implications of this transition for each region, but the charts do present a preliminary indication for the operational challenges that may emerge by 2025.

The zones in Figure 10 indicate the following:

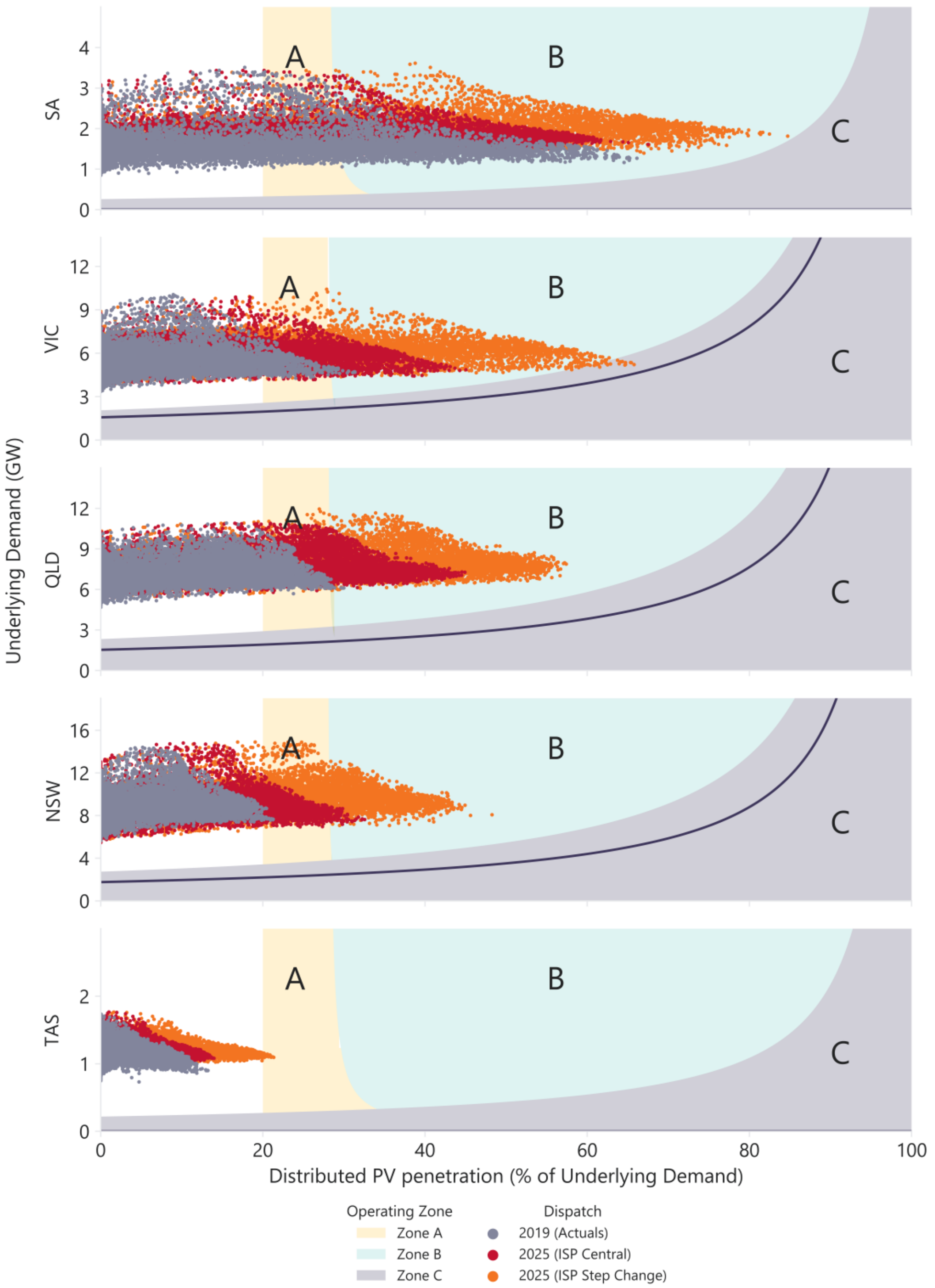
- **Zone A: DPV generation begins to impact the system load profile**, potentially resulting in challenges associated with:
  - The effectiveness of emergency mechanisms (such as Under Frequency Load Shedding [UFLS] and system restart), due to the reduced availability of stable load blocks in the daytime.
  - Transmission network voltage control, due to reduced load in locations within the transmission network with large clusters of DPV generation.
  - Managing the net load variability associated with increasing ramps in DPV generation at the start and the end of the day, and cloud movements impacting significant PV clusters at the sub-regional level.
- **Zone B: the potential mass disconnection of DPV begins to impact the effectiveness of contingency management practices.** Loss of DPV generation might exceed potential load disconnection following plausible transmission disturbances. If coincident with the loss of other generation, this could result in a contingency exceeding the largest credible risk in the region today. Eventually, without action, as DPV penetration continues to increase, contingency sizes may become unmanageably large, especially for regions of the NEM that may operate as an island under some conditions.
- **Zone C: operational demand has reduced to such a point that there is insufficient load to support minimum synchronous generation requirements** for the provision of the system strength, inertia, frequency control, and voltage management services necessary for secure system operation under credible risk of separation or islanded conditions in 2025. New South Wales, Queensland, and Victoria will also have a hard limit to DPV generation under normal operation (the black line).

Zones have been defined based on AEMO's analysis to date of the system challenges associated with increasing DPV generation in the South Australian region, including UFLS adequacy in the daytime, system security implications of DPV disconnection, and minimum load requirements during islanded conditions. This has highlighted the need to plan and implement operational strategies to manage these impacts in the short term.

As part of this, urgent changes to improve the performance of DPV fleet in response to disturbances, improved compliance with standards, and a level of real-time visibility and curtailability of the DPV fleet will all assist with managing these challenges in South Australia. Over the next five years, other NEM regions are projected to enter similar operating zones as South Australia today. Based on the South Australian experience, implementing these changes for new DPV systems nationally, in anticipation of high penetration in other regions, would assist with securely integrating the future DPV fleet with the needs of the power system.

[48] More detailed limits are provided and overlaid in Figure XX in Appendix A.

Figure 10 Projected penetrations of DPV to 2025 under Draft 2020 ISP Central and Step Change generation builds, with indicative limits



3.4 Actions to support integration of distributed solar PV

Actions to support increasing DPV uptake are listed in Table 8. The table notes where actions are already underway, and which are new actions from the RIS Stage 1.

In the absence of such reforms, AEMO will increasingly need to recommend hard regional hosting capacity limits for passive DPV, which may necessitate moratoriums on new DPV installations or costly retrofit of existing DPV.

Table 8 Challenges and actions – distributed solar PV

Key challenges	Actions	Timing	Status
The aggregate performance of the DPV fleet is becoming increasingly critical as penetrations increase. Without action, the largest regional and NEM contingency sizes will increase due to DPV disconnection in response to major system disturbances.	**3.1** AEMO to fast-track requirement for short duration voltage disturbance ride-through for all new DPV inverters in South Australia (and Western Australia, with other NEM regions encouraged) and investigate need for updating existing DPV fleet to comply with fast-tracked short duration voltage disturbance ride-through requirement.	2020-21	In progress
	3.2 AEMO to collaborate with industry, through Standards Australia committee, to progress update to national standard for DPV inverters (AS/NZS4777.2) to incorporate bulk system disturbance withstand and autonomous grid support capability.	2020-22	In progress
Governance structures for the setting of DER technical performance standards, and enforcement of these standards, are inadequate. Currently there is: • No formal pathway to ensure power system security and other industry requirements are accounted for within technical standards set by consensus. • Inconsistent compliance with technical performance standards across the DPV fleet today and a lack of clarity around enforcement.	**3.3** AEMO to collaborate with the ESB, Australian Energy Regulator (AER), AEMC, and industry to: • Submit a rule change establishing the setting of minimum technical standards for DER in the NEM (with similar reforms to be proposed for Western Australia's SWIS) covering aspects including power system security, communication, interoperability, and cyber security requirements. • Develop measures to improve compliance with new and existing technical performance standards and connection requirements for DPV systems, individual DER devices, and aggregations in the NEM (and SWIS).	2020	New
System dispatchability is decreasing as invisible and uncontrolled DPV increases to levels not experienced elsewhere globally. In 2019, South Australia operated for a period where 64% of the region's demand was supplied by DPV; by 2025, all mainland NEM regions could be operating above 50% at times.	**3.4** AEMO to collaborate with industry to: • Mandate minimum device level requirements to enable generation shedding capabilities for new DPV installations in South Australia (other NEM regions and Western Australia encouraged). • Establish regulatory arrangements for how DNSPs and aggregators could implement this as soon as possible. • Investigate the need for updating the existing DPV fleet to comply with regional generation shedding requirements[A].	2020-21	New
	3.5 AEMO to collaborate with DNSPs to establish aggregated predictability or real-time visibility requirements for DPV systems available for curtailment, and consistent real-time SCADA visibility for all new commercial scale (> 100 kilowatt [kW]) systems.	2020-21	New

A. For the purposes of maintaining adequate levers for secure system operation in abnormal operating conditions during high DPV generation periods, AEMO's work to date has found:

- Generation shedding capability as a "back-stop" measure is essential; it is required in addition to ongoing investment in storage and development of distributed markets for daily efficient market operation.
- When it is required, the necessary change in the supply-demand balance could be very large and increasing as DPV generation continues to grow.
- Harnessing load and storage flexibility may reduce the amount of DPV generation shedding necessary. However, given uncertainties in the availability of this flexibility in real time, this does not remove the need for the generation shedding capability to be available in the first place

4. Managing frequency

The contingency FCAS[49] markets are responsible for ensuring the amount of frequency sensitive reserve available can manage the trip of a single generating unit.

Since the introduction of the FCAS markets, the increase in the size of the largest generating unit – coupled with a decline in system inertia[50] and load relief – has changed the physical parameters underpinning reserve management. The level of inertia is projected to decline further out to 2025. Under the projected condition, more and/or faster frequency sensitive reserve will be needed.

No large power system currently operates without synchronous inertia, and a minimum level of synchronous inertia will be needed in 2025. A staged approach to operating at lower inertia is recommended, to progressively manage the expansion in the operating envelope of the system. This will allow the system frequency control design to be adapted to the changing system, with capacity built in advance of the requirement becoming evident on the system.

4.1 Changing system conditions

Since the introduction of FCAS markets in 2001, a number of parameters fundamental to frequency control have changed, and are projected to change further.

The largest generating unit, which is the risk managed through raise contingency FCAS, has increased from 660 MW to a typical value of 750 MW. At the same time, system inertia has been declining, and this decline is expected to continue. Load relief[51], which dynamically supports frequency control, has also reduced, having a comparable effect to the decline in inertia.

Over the same period, there has been a decline in the Primary Frequency Response (PFR)[52] provided by generation in the NEM[53]. This has reduced the power system's resilience to events and resulted in a lack of effective control of frequency in the NEM under normal operating conditions. A lack of consistency and certainty of PFR delivery from generation has impacted AEMO's ability to effectively model and plan the system, understand the cause of power system incidents, and design Emergency Frequency Control Schemes (EFCS). The implementation of the Mandatory Primary Frequency Response rule change is currently underway to address this issue[54].

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[49] More information on how FCAS markets relate to power system requirements is at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf.

[50] System inertia is provided by the aggregate rotating mass from rotating machines that are directly coupled to the grid. Inertial response acts to reduce the Rate of Change of Frequency (RoCoF) following a disturbance. Under low RoCoF conditions, PFR has more time to respond.

[51] Load relief is the change in load that occurs when system frequency changes. It results from the motor component of the load, which draws less power when frequency is lower and more power when frequency is higher. As more motor load is connected through electronic interfaces, this beneficial system property is declining.

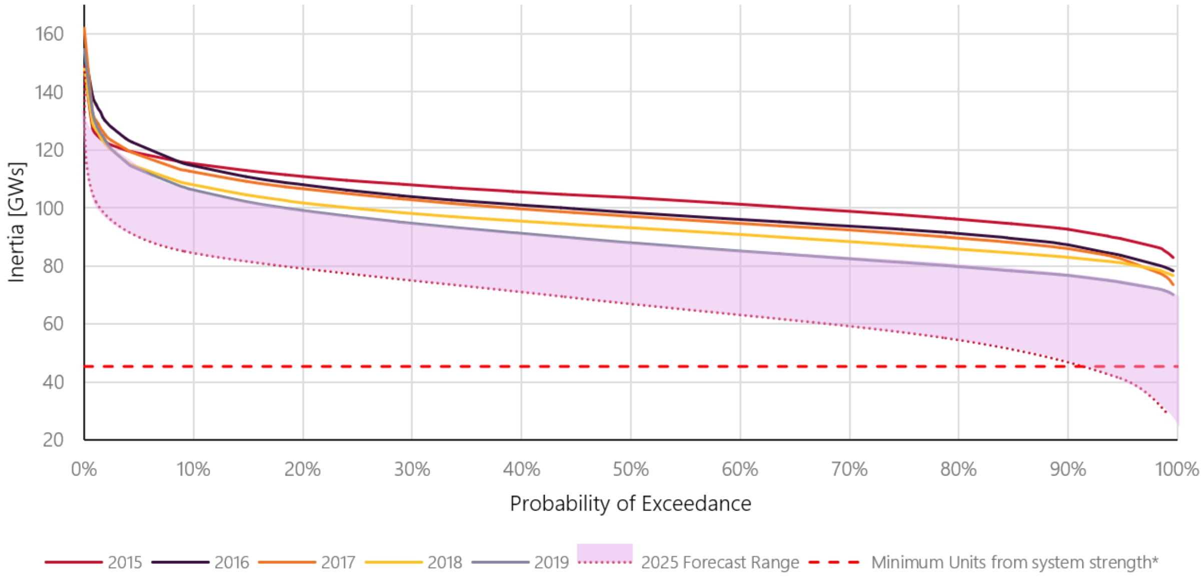
[52] PFR is when a generator measures the local frequency and adjusts its active power output in response. PFR is automatic; it is not driven by a centralised system of control and begins immediately after a frequency change beyond a specified level is detected.

[53] See https://www.aemc.gov.au/sites/default/files/2019-08/Rule%20Change%20Proposal%20-%20Mandatory%20Frequency%20Response.pdf.

[54] See https://www.aemc.gov.au/sites/default/files/2019-08/Rule%20Change%20Proposal%20-%20Mandatory%20Frequency%20Response.pdf.

Figure 11 shows declining NEM mainland inertia since 2015, and the projected future inertia range from dispatch models out to 2025[55].

Figure 11 Inertia duration curves – historical (actual) and future range (forecast) of NEM mainland inertia



4.2 Changing requirements for frequency sensitive reserve

AEMO has recently changed the load relief factor assumed when setting contingency FCAS procurement volumes[56] in response to the changing system, resulting in increased FCAS procurement. The forecast reduction in inertia out to 2025, combined with the decline in load relief, will mean that more, and/or faster, frequency sensitive reserve will be needed to ensure the Frequency Operating Standard (FOS) continues to be met for all credible events. The FOS containment requirement has been met for all historical credible contingencies.

Figure 12 shows the modelled 6-second reserve requirement[57] across the historical and projected inertia range. The expected level of inertia available from minimum synchronous unit combinations for system strength is also shown, along with the static reserve requirement[58].

The reserve requirement curve is weighted towards the responsiveness of the large thermal FCAS-providing generators, to represent all PFR in the NEM. This is illustrative of the required increase of frequency sensitive reserve at a base speed of provision, but in practice this will vary depending on the aggregate PFR capability of the units dispatched.

The accumulation of changes to inertia, load relief, and risk size has meant that support from PFR delivered in addition to that procured through the FCAS markets, along with response at speeds greater than set by the Market Ancillary Service Specification (MASS)[59], have played an increasing part in reducing the frequency excursions for historical events.

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[55] The forecast range indicates the range of forecast modelling output using a range of market dispatch assumptions out to 2025. The minimum extremity of this range is from the Draft 2020 ISP Short Run Marginal Cost modelling, which can be expected to give a conservatively low inertia forecast. The Minimum Units line represents the minimum inertia expected to be maintained through system strength requirements

[56] See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Ancillary_Services/Frequency-and-time-error-reports/2019/Update-on-Contingency-FCAS-Aug-2019.pdf.

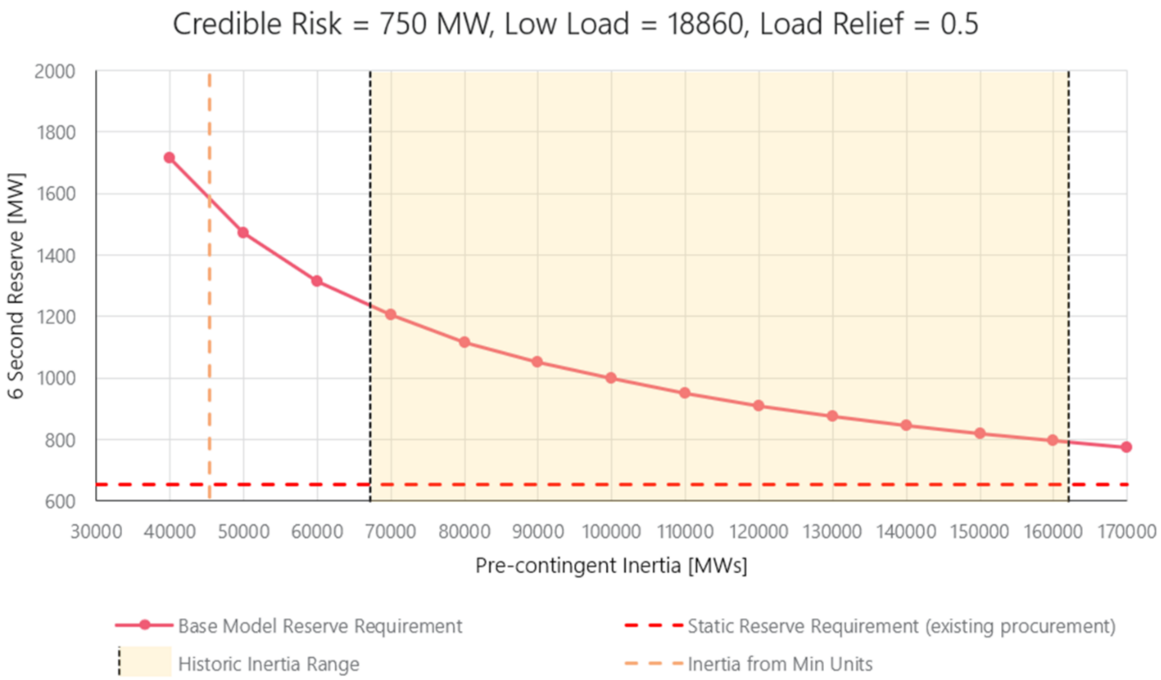
[57] Modelling methodology and assumptions provided in Appendix B.

[58] The static reserve requirement is the amount of active power required to replace the amount tripped less the expected load relief. This is the amount of 6-second reserve currently procured through the FCAS market under normal conditions.

[59] At https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/system-operations/ancillary-services/market-ancillary-services-specification-and-fcas-verification-tool.

Additional detail on frequency management for credible events is given in Appendix B4.

Figure 12 The 6-second reserve requirement for credible events (NEM mainland)



4.3 Fast Frequency Response (FFR)

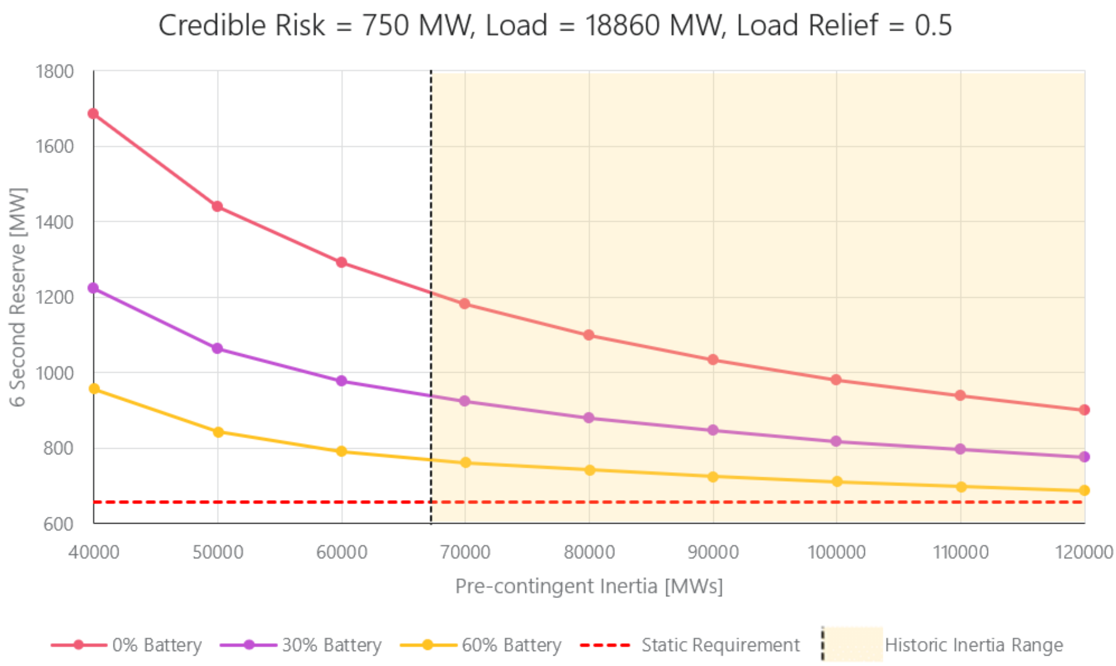
The speed of frequency response is a continuum across technologies and individual plants. Some reserve providers, such as batteries and switched reserve[60], can provide rapid responses in the order of hundreds of milliseconds, often termed Fast Frequency Response (FFR).

This speed of response is particularly effective at reducing the frequency sensitive reserve required at low inertia. As the use of these technologies increases, there are system impacts beyond reserve management to be considered to effectively integrate them into the power system.

An example of the impact of faster reserve is given in Figure 13. More information on different types of frequency sensitive reserve is provided in Appendix B4.8.

[60] Switched FCAS providers are generally large or aggregated loads that can be partially or fully switched off in response to low frequency events.

Figure 13 Reserve requirement with increasing proportions of faster reserve



4.4 Managing new types of risk

DER behaviour, utility-scale IBR behaviour, and run-back schemes are making the system more complex. These emerging issues are expected to further exacerbate Rate of Change of Frequency (RoCoF) and worsen post-contingent outcomes for credible and non-credible events. Additional detail on frequency management for non-credible events is given in Appendix B5.

The consideration of secondary risks, such as the coincidental trip of DER that may occur alongside the trip of the largest generating unit, will be important in setting frequency sensitive reserve requirements as the potential impact of these risks grow. Additional detail on secondary risks is given in Appendix B4.9.

4.5 Managing the transition to lower inertia

No large power system currently operates without synchronous inertia, and a minimum level of synchronous inertia will be needed in 2025. A staged approach to operating at lower inertia is recommended to progressively manage the expansion in the operating envelope of the system. This will allow the system frequency control design to be adapted to the changing system, with capacity built in advance of the requirement becoming evident on the system.

The proposed minimum inertia safety net for system intact would operate in parallel with the existing regional requirements that are in place when there is a credible risk of islanding, or a region has been islanded. The existing and proposed inertia limits are given in Table 9.

Additional detail on managing the transition to low inertia is given in Appendix B6.

Table 9 Existing and proposed inertia limits

<table>
<tr><th>System condition</th><th>Managed event</th><th>Inertia requirements</th></tr>
<tr><td>System intact</td><td>Credible trip of Largest Credible Risk (single unit)</td><td>Mainland: This report recommends investigating the implementation of an initial minimum inertia safety net within range of the historical minimum inertia level in the mainland, with staged reduction towards a minimum inertia available thorough system strength requirements (45,350 MWs).
Tasmania: Minimum threshold level of inertia, or secure level of inertia is always applicable.</td></tr>
<tr><td>System intact</td><td>Non-credible separation event</td><td>Regional inertia and reserve levels to survive non-credible separations not generally defined. These types of events are subject to periodic review through the Power System Frequency Risk Review (PSFRR).</td></tr>
<tr><td>System intact</td><td>Credible or protected risk of separation</td><td>Defined as Minimum threshold level of inertia, calculated as per the Inertia Requirements and Shortfalls Methodology.
Current values:<table><tr><td>Queensland</td><td>12,800 MWs</td></tr><tr><td>New South Wales</td><td>10,000 MWs</td></tr><tr><td>Victoria</td><td>12,600 MWs</td></tr><tr><td>South Australia</td><td>4,400 MWs</td></tr><tr><td>Tasmania</td><td>3,200 MWs</td></tr></table></td></tr>
<tr><td>Islanded region following separation</td><td>Credible trip of Largest Credible Risk within islanded region</td><td>Defined as Secure operating level of inertia calculated as per the Inertia Requirements and Shortfalls Methodology.
Current values:<table><tr><td>Queensland</td><td>16,000 MWs</td></tr><tr><td>New South Wales</td><td>12,500 MWs</td></tr><tr><td>Victoria</td><td>15,400 MWs</td></tr><tr><td>South Australia</td><td>6,000 MWs</td></tr><tr><td>Tasmania</td><td>3,800 MWs</td></tr></table></td></tr>
</table>

4.6 Actions to support frequency management

Actions related to frequency are listed in Table 10. The table notes where actions are already underway, and which are new actions from the RIS Stage 1. Further details regarding these actions can be found in Appendix B.

Table 10 Challenges and actions – frequency

Key challenges	Actions	Timing	Status
There has been a decline in the PFR provided by generation in the NEM. This has reduced the power system's resilience to events at a time when events are becoming more complex and less predictable. It has also resulted in a lack of effective control of frequency in the NEM under normal operating conditions. A lack of consistency and certainty of PFR delivery from generation has impacted AEMO's ability to effectively model and plan the system, understand the cause of power system incidents, and design emergency frequency control schemes.	**4.1** AEMO to facilitate implementation of the Mandatory Primary Frequency Response rule change. The requirement for near-universal PFR enablement across the generation fleet should be part of any future regulatory framework as an important part of maintaining and strengthening system resilience.	2020-21	In progress
NEM inertia levels could drop by 35%. Historically, NEM mainland inertia has never been below 68,000 MWs. By 2025, inertia could drop to as low as 45,000 MWs. This will increase the required volume and/or speed of frequency sensitive reserve following a contingency event, and the power system will operate in configurations where the system dynamics are different to those experienced today. **DPV behaviour, IBR behaviour, and run-back schemes are making the system more complex.** These emerging issues will further exacerbate post-contingent outcomes for credible and non-credible events. Non-credible contingencies are expected to result in higher RoCoF, the effect of which is not yet fully understood for the NEM.	**4.2** AEMO to publish a detailed frequency control workplan covering tasks and timeframes to: • Revise ancillary service arrangements to ensure the required speed and volume of PFR match the size of the LCR and FOS containment requirements for the range of expected future operating conditions • Investigate the introduction of a system inertia safety net for the mainland NEM, under system intact conditions. This minimum level safety net should be progressively revised as operational experience is built and additional measures are put in place to ensure system security. Investigation should include specifying the initial value and how the safety net will be maintained. • Investigate the effect of higher RoCoF on DPV, utility-scale generation, switched reserve providers, and protection relays used in various network functions. The result of this investigation will be a recommended system RoCoF limit, or set of RoCoF limits, in addition to existing generator ride-though requirements. Investigation should include assessment of the adequacy of EFCS, including UFLS, under decreasing levels of inertia. • Continue investigation into DPV penetration into UFLS load blocks. • Apply appropriate limits to the total proportion of switched reserve. This is needed to ensure there is a minimum amount of dynamic frequency control. • Investigate appropriate regional contingency FCAS requirements, particularly for South Australia and Queensland. • Update AEMO's existing system frequency model to be able to predict post-contingent frequency outcomes based on generating unit dispatch. Development of this model will benefit from the capture of high-speed generator output and network quantities on a routine or ongoing basis.	2020	New

5. System strength

The NEM is at the international forefront of managing issues associated with low system strength, and AEMO and local NSPs are adapting to operating in these low system strength conditions. These changes create uncertainty about how the system could perform under certain operating scenarios.

AEMO has so far declared system strength gaps and worked with local TNSPs to address low system strength in South Australia, Tasmania, Victoria, and Queensland. AEMO has been pioneering new analytical techniques to simulate the complex interactions between IBR in areas with low system strength.

By 2025, this study forecasts that all NEM regions will be operating more often with a combination of low numbers of synchronous machines and high levels of IBR online, both of which reduce available system strength.

System strength is a complex concept, and an area of emerging understanding internationally[61]. Definitions vary across jurisdictions, and continue to evolve as the international power system community's collective understanding of power system phenomena continues to grow.

AEMO sees system strength as the ability of the power system to maintain and control the voltage waveform at any given location in the power system, both during steady state operation and following a disturbance. System strength can be related to the available fault current at a specified location in the power system, with higher fault current indicating higher system strength with greater ability to maintain the voltage waveform[62].

5.1 Current regulations

One of the key findings of AEMO's international review[63] was that Australia is at the forefront of challenges in connecting wind and solar generation in areas with low system strength, and therefore has had to implement world-leading regulations in response. The regulations can be broken into two categories:

- **Bulk power system** – to support the system during periods of low synchronous generation, new regulatory obligations were established in the NEM to ensure minimum fault levels.
  - AEMO is required to determine the fault level requirements across the NEM and identify whether a fault level shortfall is likely to exist now or in the future. The projected fault levels for each node are listed in the Draft 2020 ISP[64]. The *System Strength Requirements Methodology* defines the process AEMO must apply to determine the system strength requirement at each node[65].

[61] AEMO, *RIS International Review*, October 2019, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Future-Energy-Systems/2019/AEMO-RIS-International-Review-Oct-19.pdf.

[62] For more information, see AEMO, System Strength: *System Strength in the NEM Explained*, March 2020, at https://aemo.com.au/-/media/files/electricity/nem/system-strength-explained.pdf?la=en.

[63] At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Future-Energy-Systems/2019/AEMO-RIS-International-Review-Oct-19.pdf.

[64] See https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/isp/2019/draft-2020-isp-appendices.pdf?la=en.

[65] At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/System-Security-Market-Frameworks-Review/2018/System_Strength_Requirements_Methodology_PUBLISHED.pdf.

- The local TNSP is required to provide system strength services to meet the minimum three phase fault levels at relevant fault level nodes if AEMO has declared a shortfall.
- Based on the regulatory obligations, to date AEMO has already declared system strength gaps at fault level nodes in South Australia, Tasmania, Victoria, and Queensland[66]. Detailed EMT studies are also being used to refine the minimum unit combinations of synchronous generators for operating the current system. The studies have determined a minimum of four synchronous units for South Australia and five for Victoria to maintain sufficient system strength[67].

- **Generator obligations** – some of Australia's best wind and solar energy resources are in lightly interconnected parts of the network with low system strength[68]. An area of the grid is generally considered to have low system strength if the short circuit ratio (SCR) drops below three[69].
  - In 2017, the AEMC established some of the first regulations to ensure new generator connections in areas with low system strength do not adversely impact stable operation of the NEM[70].
  - In parallel, AEMO has been pioneering new analytical techniques to simulate the complex interactions between IBR in these areas[71].
  - Generators connecting in these areas with low system strength conditions are required to demonstrate that they do not adversely impact system operation. This is already being seen for projects located a long way from synchronous generating units.

5.2 Changes to system strength

Figure 14 shows the projected change on the operation of existing synchronous generation in NEM regions, as levels of supply from wind and solar (including DPV) generation sources increase. Synchronous generation (in gigawatts) is plotted against the wind and solar (in gigawatts) online for:

- Actual dispatch outcomes in 2019 (coloured dots), which include all system constraints.
- 2025 projections (grey dots), which indicate the potential instantaneous penetration by 2025 under the ISP's Central generation build (similar to the projections in Figure 5 in Section 1.1). Forecasts include lost energy from network congestion, but do not include system curtailment or participant spill).
- The numbers of large synchronous generators online are taken from the minimum combinations list set out in the transfer limit advice[70], and are highlighted by the different coloured dots.
- The solid red line represents the aggregate current minimum stable operating levels of the lowest combinations of synchronous generators in that region[70]. (Zone C in Figures 1, 3, and 20 is the summation of all NEM regions.)

As Figure 14 shows, NEM regions other than South Australia had little experience in 2019 operating with very low numbers of large synchronous generators online. By 2025, however, there could be enough wind and solar IBR operating in these regions to regularly push the system into very unfamiliar territory, including periods with:

- Low number of large synchronous machines online (decreasing the region's underlying system strength).
- Very high levels of IBR online (decreasing the system strength in the vicinity of these resources).
- Both low numbers of large synchronous machines and high IBR online.

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[66] See https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/system-operations/system-security-market-frameworks-review.

[67] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/congestion-information/transfer-limit-advice-system-strength.pdf?la=en.

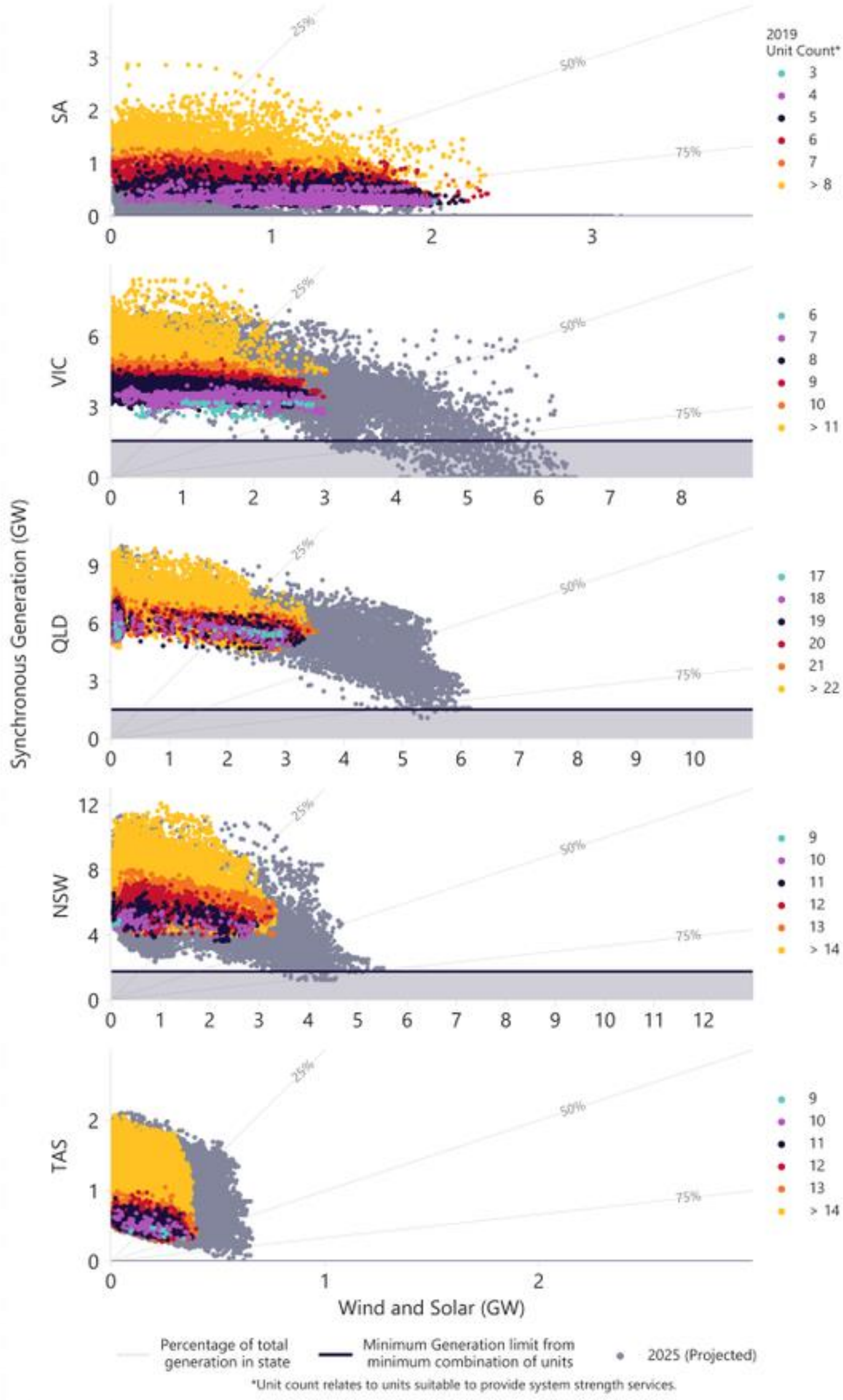
[68] 2018 ISP, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/ISP/2018/Integrated-System-Plan-2018_final.pdf.

[69] Y Zhang, S Huang, J Schmall, J Conto, J Billo, E Rehman, "Evaluating System Strength for Large-Scale Wind Plant Integration", PES General Meeting | Conference & Exposition, 2014 IEEE.

[70] See https://www.aemc.gov.au/rule-changes/managing-power-system-fault-levels.

[71] AEMO, *System Strength Impact Assessment Guidelines*, at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/System-Strength-Impact-Assessment-Guidelines.

Figure 14 Regional synchronous generation plotted against wind and solar generation, 2019 actual and 2025 Draft 2020 ISP Central generation build (GW)



Note: Actual 2019 generation includes all lost energy; 2025 projections only include network congestion.

5.3 Managing system strength

Minimum fault levels can be managed through a combination of solutions:

- Synchronous generation that is online.
- Generation that operates in synchronous condenser mode.
- Synchronous condensers.
- Control system tuning.
- New network.

The location of these solutions is important, because system strength is a relatively localised phenomenon.

5.3.1 Managing minimum fault levels in planning

As noted in Section 5.1, the minimum fault level obligations in the NEM are designed to ensure that potential future shortfalls in fault level are identified in advance, and the relevant TNSP is responsible for ensuring sufficient resources are available to fill the gap.

Forecasting emerging system strength shortfalls within a planning horizon relies on good information about factors that are near impossible to predict reliably over an extended period. These factors include:

- Synchronous generating system withdrawals or changes in operating regimes.
- The location, size, and capabilities of IBR.
- Operational patterns of embedded generation and DER.
- Changes in networks and dispatch patterns.

System strength can change rapidly as network operations vary and generators react to economic and structural changes in, and affecting, the NEM. New generation technology such as solar farms can be proposed, built, and commissioned within 18 months, with immediate impacts on the dispatch patterns of synchronous generation, invalidating AEMO's longer-term forecasts.

For these reasons, AEMO reviews its assumptions annually and seeks to be proactive and innovative in its planning for system strength. Considering these challenges, AEMO forecasts fault levels at the fault level nodes hourly, using ISP market modelling scenario outcomes to assess the statistical likelihood of different fault levels under a variety of conditions and dispatch outcomes, including the impact of network augmentations and outage conditions.

Failure to predict a shortfall with sufficient advance notice for the TNSP to procure an efficient system strength service would necessitate interventions (directions) as an interim measure.

In South Australia, the declared shortfall led to ElectraNet procuring four synchronous condensers[72]. Chapter 2 describes how, until the installation of these synchronous condensers, AEMO has been forced to intervene and commit synchronous generation, leading to a large workload for AEMO's control room and a high volume of market directions.

In Tasmania, the declaration of a fault level shortfall is leading TasNetworks to contract with existing generators for the provision of fault level by operating in synchronous condenser mode. AEMO is currently working with TasNetworks to implement a procedure by which the contracted synchronous condensers can be enabled efficiently by AEMO when required. Part of this process will be determining how much of the process can be automated, to minimise the workload for AEMO's control room as far as possible.

Shortfalls have also been declared in remote parts of the grid in Victoria (Red Cliffs) and Queensland (Ross), which are currently being investigated by the regional TNSPs. Considering the projections in Figure 14, fault levels will likely decline at some key nodes across the NEM over the coming decade. If these lead to a TNSP

[72] The first two units are scheduled to be installed by the end of 2020.

contracting with a synchronous generator (rather than a synchronous condenser) for system strength services, similar to current efforts in Tasmania, consideration needs to be given on how to efficiently instruct these contracted services ahead of time and reduce additional monitoring and intervention by AEMO's control room.

5.3.2 Managing minimum fault levels in operations

As noted in Chapter 2, the increasing prevalence of interventions in the NEM is already challenging AEMO's secure operation of the system. Any increase in the scale or complexity of interventions in future (for example, managing unit commitment decisions across multiple regions) will make it more difficult.

Further, if multiple concurrent unit commitment decisions must be regularly made by AEMO's control room, the limitations of how much optimisation can occur raises the question of whether the most efficient outcome is being achieved for consumers. As noted in Chapter 2, even after units are contracted to provide system strength, this will reduce the amount of directions (and associated direction compensation process[73]), but AEMO will still need an ahead process to instruct units to provide system strength services ahead of time to keep the system secure.

5.3.3 System strength for new generator connections

The rapid scale and pace of IBR connections in remote areas of the NEM is resulting in unprecedented technical issues impacting grid performance and operational stability. The nature, extent, and causes of these issues are only becoming apparent with the advanced and very detailed modelling capability that is now essential for technical assessments in weak areas of the grid.

Some areas have continued to attract significant investment in grid-scale solar and wind generation, despite being remote and electrically weak parts of the NEM. Put simply, the transmission infrastructure is insufficient to allow full access to all the generation that is seeking to connect. Transmission infrastructure investments to progressively address these issues have been identified, but will take a number of years to proceed through regulatory approval processes, procurement, and construction.

AEMO's Final 2020 ISP[74] and subsequent System Strength reports will seek to improve system strength coordination across the NEM by:

- Improving the transparency of system strength across the grid.
- Promoting the development of scale-efficient renewable energy zones (REZs) that are designed for the connection of IBR.
- Presenting evidence that coordinated system strength services can deliver positive net market benefits.
- Outlining an efficient strategy for the coordinated delivery of system strength services.

5.4 Actions to support system strength

Actions related to system strength are listed in Table 11.

[73] AEMO Direction Compensation Recovery Process, at https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/data-nem/settlements-data/direction-compensation-recovery.

[74] AEMO published the Draft 2020 ISP in December 2019. The Final 2020 ISP is expected to be published in mid-2020. https://aemo.com.au/en/energy-systems/major-publications/integrated-system-plan-isp

Table 11 Challenges and actions – system strength

Key challenges	Actions	Timing	Status
The NEM is at the international forefront of managing issues associated with low system strength; AEMO has so far declared system strength gaps and worked with local TNSPs to address shortfalls in South Australia, Tasmania, Victoria, and Queensland. Localised system strength challenges are also creating increasing hurdles for generators seeking to connect in weaker parts of the grid.	**5.1** AEMO to pursue opportunities to improve the minimum system strength framework and improve system strength coordination across the NEM, including: • AEMO to contribute latest findings and insights into ongoing ESB and AEMC reviews of system strength frameworks. • Following conclusion of the AEMC's investigation into system strength frameworks in the NEM, AEMO to assess the need for changes to the System Strength Requirements Methodology and System Strength Impact Assessment Guidelines. • AEMO to progress planned actions (see Section 5.3.3) as part of the Final 2020 ISP.	2020	In progress

6. Variability and uncertainty

This study indicates that variability and uncertainty driven by weather-dependent resources will keep increasing to 2025. This increase is occurring on both the supply and the demand side (due to increased utility wind and solar generation and the increased uptake of DPV).

To effectively integrate higher levels of variable renewable energy (VRE) while maintaining a secure and reliable grid, the system needs access to adequate sources of flexibility that can respond to the constantly varying supply-demand balance, as well as headroom to cover uncertainty.

While there is an increasing need for system flexibility under higher penetrations of VRE, there may be less flexibility available when required in some regions of the NEM, due, for example, to synchronous generation retirements, or displacement of online synchronous generation during high VRE periods.

These are complex new operating conditions. It is important to explore operational and market enhancements that can help reduce uncertainty, fully utilise available system flexibility, and manage the risks to secure supply.

AEMO's full analysis relating to variability, uncertainty, and fleet flexibility is in Appendix C.

Historically, both demand and supply were relatively predictable. Today, as more VRE like wind and solar generation is integrated into the grid, both supply and demand are more variable and harder to predict. This increased variability and uncertainty changes the behaviour of the system, and operators need new controls to keep the system operating reliably and securely.

6.1 Increase in variability

The magnitude and frequency of large ramps[75] in VRE across the NEM is increasing. This means there will be larger and more frequent fluctuations in generation that will need to be managed to maintain the supply-demand balance.

Figure 15 shows the growth in the top 1% of hourly VRE ramps in each NEM region during 2015-19 and that projected for 2025 under the Draft 2020 ISP Central generation build[76]. It highlights the aggregate ramp across all renewable generation (white line), and the top ramps that occurred for each individual technology type (coloured bars)[77].

[75] A ramp is an upward or downward fluctuation in supply or demand over a defined time interval. VRE ramps refer to the net change in wind, utility solar, and DPV. Ramps are used in this report to represent variability in the system.

[76] See Appendix C for further details on the methodology used to produce the variability and uncertainty analysis.

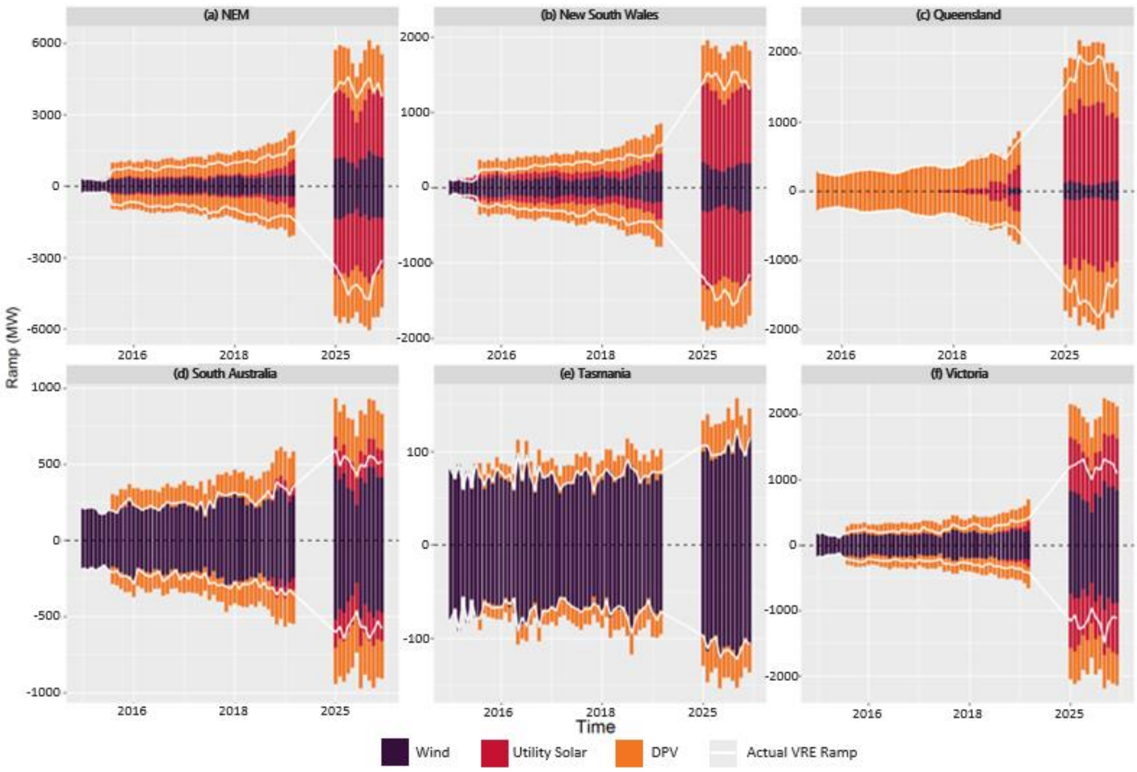
[77] Note that the largest 1% ramp across different technologies is not likely to occur simultaneously. Stacked together they represent the top 1% theoretical ramp for a region if all VRE types had their 99th percentile ramp simultaneously.

For example, panel (a) in Figure 15 shows that:

- Historically[78], the 1% largest downward VRE ramp in the NEM in one hour was -1.4 GW.
- By 2025, the largest equivalent VRE ramp in the NEM is projected to be -4.5 GW and could reach a maximum of -5.8 GW.

As the installed capacity of VRE grows, so does the magnitude of ramps and the potential for them to impact system operation. Figure 15 also shows that although ramps are increasing in magnitude, these increases are smaller than the growth in installed capacity. This is most evident for regions with a greater diversity between VRE technologies (that is between wind, utility solar, and DPV) and greater geographic distribution of the same VRE technology.

Figure 15 NEM monthly top 1% of largest hourly ramps in VRE, actual 2015-19 and projected in 2025 under Draft 2020 ISP Central generation build



The magnitude of hourly **net demand**[79] ramps is projected to increase significantly out to 2025, with variability in VRE outpacing underlying demand as the main driver of these ramps.

The net demand curves in Figure 16 highlight the increased **system flexibility** that will be required to respond to both expected and unexpected changes in supply and demand.

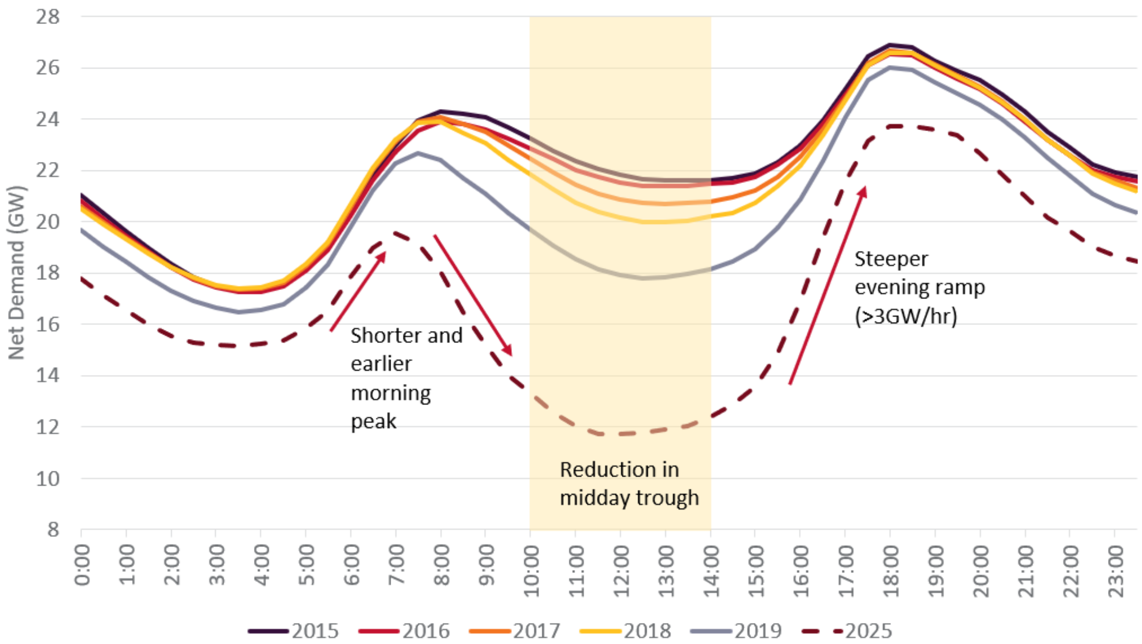
The "duck curve" in Figure 16 has become familiar in the industry, with net demand falling in the middle of the day and rising quickly in the evening. This figure highlights that in 2025 – compared to the experience of 2015-19 – evening ramps will be much larger than experienced historically, due to increased penetrations of wind and solar.

[78] The historical study period for this variability analysis is between January 2015 and April 2019.

[79] Net demand is underlying demand net of VRE generation, that is, the demand that must be met by scheduled generation sources and not by wind or solar (including utility solar and DPV).

While the diurnal solar pattern is well represented by these average net demand curves, net demand variability that occurs over shorter timeframes must also be considered, particularly when driven by less predictable weather patterns, such as fast-moving clouds and wind gusts.

Figure 16 NEM average winter net demand curves, actual 2015-19 and projected in 2025 under Draft 2020 ISP Central generation build



6.2 Increase in uncertainty

As VRE becomes more prevalent, AEMO must be able to manage the unpredictability associated with weather to operate the system securely.

Variable events, such as changes in wind or cloud movements, are challenging to forecast accurately over both short and longer forecasting horizons. Technological development and innovation have resulted in significant improvements in weather forecast accuracy, however the level of accuracy and precision achievable by best practice weather forecasts can still lead to significant challenges in predicting VRE output and variability in the power system.

Figure 17 shows some of the challenges in forecasting wind and solar. It highlights that:

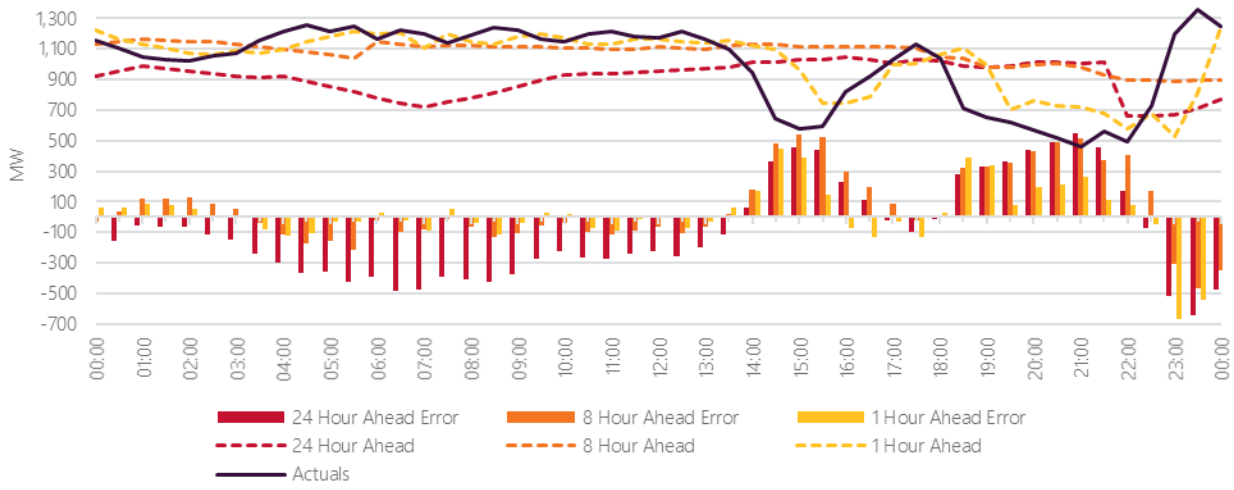
- The 24-hour and 8-hour ahead forecasts showed minimal prediction of the ramping event. These forecasts rely on global numeric weather prediction models (NWPs), and on this particular day the local effects of a prefrontal trough and a large band of precipitation were not well resolved by the NWP. This resulted in an increase in forecast inaccuracies during the ramping periods.
- While the 1-hour ahead forecast improves closer to real time as more up-to-date information is incorporated, the persistent component of these forecasts means they tend to lag actual real time generation[80]. Recent wind and solar output gives a good indication of the level of future output (close to real time), but it does not give a reliable indication future variability. The 1-hour ahead forecast gives a reasonable indication of future output when variability is low (see Figure 17, 00:00 to 13:00), however is not actually predicting the variability. When variability is high (see Figure 17, 14:00 to 00:00), the performance of the model erodes and there is a higher margin of uncertainty.

[80] As shown in Figure 17, the 1-hour ahead forecast (yellow trace) has a similar shape to actual generation (purple trace), however it is offset (shifted to the right) by one hour.

Failure to forecast these large changes in VRE (and subsequent net demand requirements) will become increasingly operationally difficult. There is a need to improve the performance of weather forecasting and power forecasting models, or develop new dedicated operational tools, to appropriately manage and communicate uncertainty under variable or extreme weather conditions.

Flexible resources are also needed, to cover the residual uncertainty that cannot be addressed by forecasting improvements and variability that is characteristic of wind and solar resources.

Figure 17 Wind forecast v actuals, Monday 18 December 2017



6.3 Changes to system flexibility

As VRE penetration increases, the system needs to operate more **flexibly** to accommodate increases in variability and uncertainty. As the composition of the system changes (including plant, network, and behavioural changes), the capability of the system to respond to ramping requirements will also change. Key areas include:

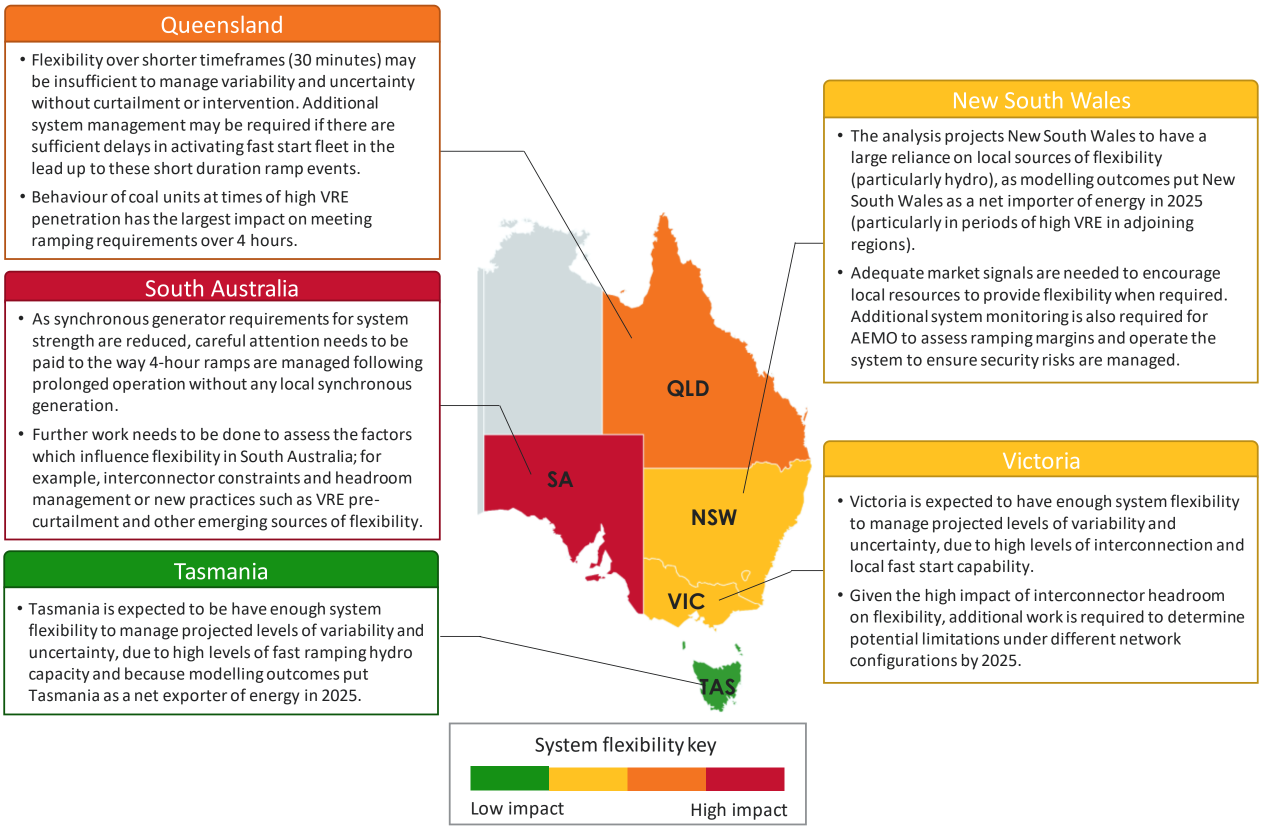
- Continued growth in wind and solar generation (including DPV).
- Conventional generation retirement.
- Displacement of online conventional generation, during periods of high VRE penetration.
- Development of other technologies, including batteries.
- Strengthening interconnection between regions and sub-regions.
- Participant learning and operational experience under high VRE penetrations.

To accommodate the transformation to a system dominated by VRE, a range of flexible resources must be utilised and planned ahead of time, so the right mix of resources is available when needed, to meet ramping requirements that vary across different timescales.

Market participants operate their portfolios to manage risk and will endeavour to cover their exposure to pricing and operational impacts from variable and uncertain conditions. However, as a system operator, it is incumbent on AEMO to maintain power system security, and as such to monitor and manage any security risks to the system. To assess the ramping requirements and capability of the system to respond across different timeframes, new operational tools and processes will be required. Appropriate regulatory frameworks should also be considered to ensure market signals align with this system need.

Figure 18 highlights the key findings from AEMO's analysis of system flexibility across 30-minute, 1-hour, and 4-hour timeframes in the NEM in 2025. This analysis shows that by 2025, in the absence of enhanced operational tools and regulatory frameworks, a degree of VRE curtailment or market intervention may be required to maintain adequate system flexibility across all timeframes.

Figure 18 Summary of regional system flexibility to cover projected 30-minute, 1-hour, and 4-hour ramps in 2025



6.4 Actions to manage variability and uncertainty

Actions related to variability and uncertainty are listed in Table 12. Where actions also address other challenges identified in this study, cross-references are provided. The table notes where actions are already underway, and which are new actions from the RIS Stage 1.

Table 12 Actions – variability and uncertainty

Key challenges	Actions	Timing	Status
The magnitude of peak ramps (upward/downward fluctuations in supply/demand) is forecast to increase by 50% over the next five years as a result of increasing wind and solar penetration. Operators need to ensure there is adequate system flexibility to cover increased variability across all times.	*AEMO is investigating redeveloping its PASA systems (PD and ST) to better account for system ramping requirements. See action 2.2.*		In progress
There is a limit to the accuracy of deterministic forecasts of expected ramps, even using current best practice approaches. Forecasting limitations increase uncertainty and the need for greater ramping reserves.	**6.1** AEMO to improve understanding of system uncertainty and risk, particularly during ramping events, by exploring: • Trialling and implementing a ramping forecast and classification prototype. • Deployment of additional weather observation infrastructure that is fit for purpose for the energy industry.	2020-2021	New
Ensuring sufficient flexible system resources are available to enable increased variability at times of high wind and solar penetration will become increasingly challenging. Times characterised by low interconnector headroom (spare capacity) or 'cold' offline plant will be particularly difficult to manage.	*The ESB is exploring options for explicitly valuing flexibility and incorporating this into scheduling and dispatch mechanisms. See action 2.3.*		In progress
	6.2 Improve the reliability of information provided by participants (loads, and scheduled and semi-scheduled generation) to support security-constrained dispatch. The ESB is coordinating several interim measures to improve the visibility of and confidence in resources in the NEM, to ensure security can be maintained while new market arrangements are developed[A].	2020-21	In progress

A. For more information on interim security measures, see http://www.coagenergycouncil.gov.au/interim-security-measures.

7. Maintaining security and maximising the potential of wind and solar in the NEM

This Stage 1 RIS analysis finds that, in the next five years:

- The NEM power system will continue its significant transformation to world-leading levels of renewable generation. This will test the boundaries of system security and current operational experience.
- If the recommended actions are taken to address the regional and NEM-wide challenges identified, the NEM could be operated securely with up to 75% instantaneous penetration of wind and solar[81].
- If, however, the recommended actions are not taken, the identified operational limits will constrain the maximum instantaneous penetration of wind and solar to between 50% and 60% in the NEM.

Looking beyond 2025, AEMO has not identified any insurmountable reasons why the NEM cannot operate securely at even higher levels of wind and solar generation, especially with ongoing technological advancement worldwide.

Given the pace and complexity of change in the NEM, the RIS highlights the need for flexible market and regulatory frameworks that can adapt swiftly and effectively as the power system evolves.

7.1 Summary of challenges and actions

This Stage 1 RIS analysis provides a window into what might be involved in operating the NEM power system at very high penetrations of wind and solar generation by 2025. It identifies several current and emerging challenges to system operation driven by the changing generation mix, including:

- The system being pushed toward minimum limits that challenge the existing dispatch process.
- Increasing complexity of the system, creating challenges for existing tools and processes used for system security analysis and assessment.
- Decreasing system dispatchability as invisible and uncontrolled DPV increases to levels not experienced elsewhere globally, and increasing dependence on the aggregate performance of the DPV fleet.

[81] In recommending actions and highlighting positive potential outcomes, AEMO does not underestimate the extent of work that will be required to successfully adapt the NEM. This includes the ongoing need for system limits that at times constrain the output of various generation sources. This study also identified a number of uncharted operating conditions emerging in the NEM by 2025. AEMO will continue investigation and analysis to identify and address additional limits and barriers that emerge.

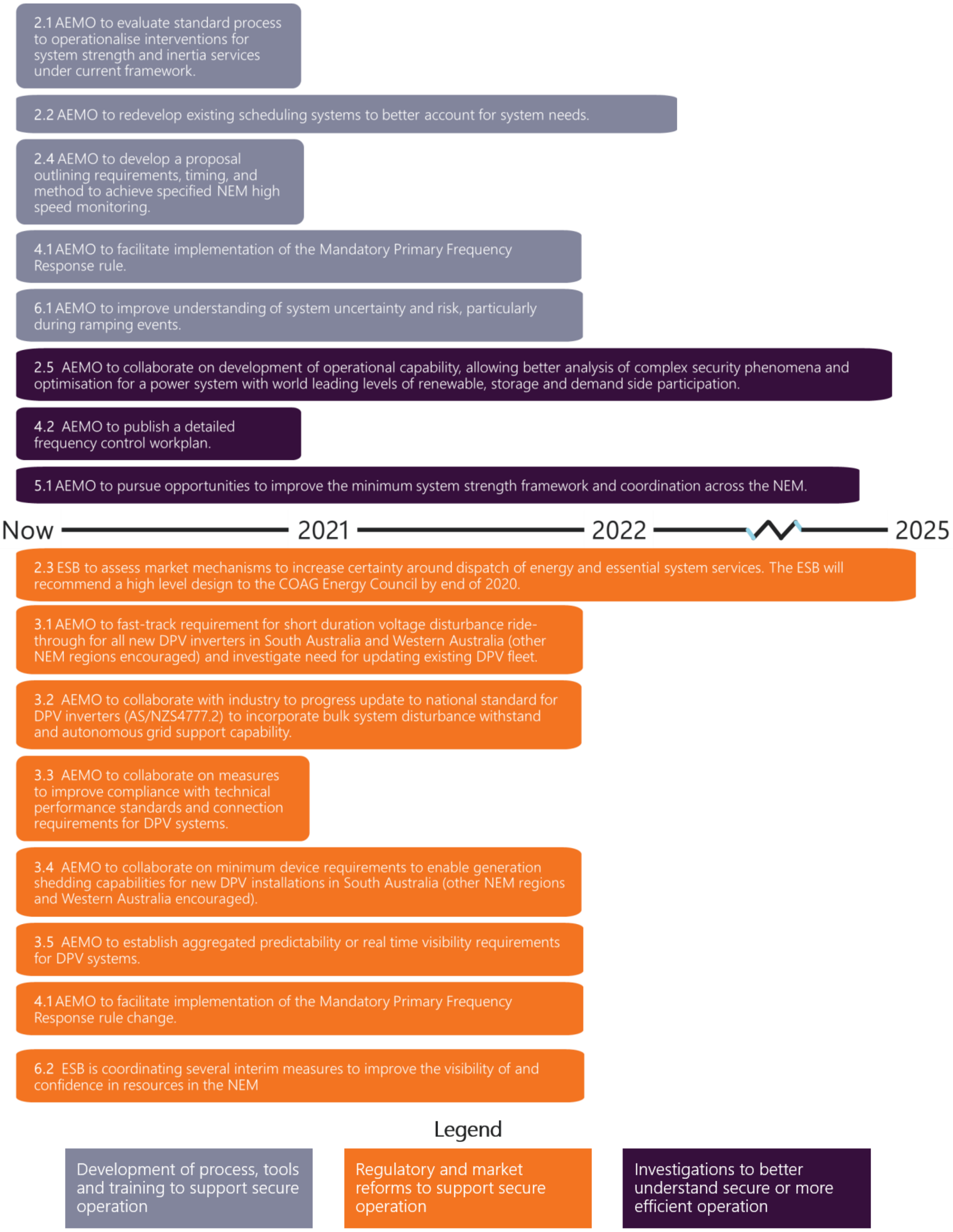
- A decline in the PFR provided by generation in the NEM. This has reduced the power system's resilience to events at a time when events are becoming more complex and less predictable.
- NEM inertia levels dropping, potentially by 35%. This will increase the required volume and/or speed of frequency sensitive reserve following a contingency event, and means the power system will operate in configurations where system dynamics are different to those experienced today.
- The behaviour of IBR and DPV and run-back schemes making the system more complex. These emerging issues will further exacerbate post-contingent outcomes for credible and non-credible events.
- The NEM being at the international forefront of managing issues associated with low system strength, with localised system strength challenges creating increasing hurdles for generators seeking to connect in weaker parts of the grid.
- The magnitude of peak ramps (upward/downward fluctuations in supply/demand) being forecast to increase by 50% over the next five years as a result of increasing wind and solar penetration. Ensuring sufficient flexible system resources are available to enable increased variability at times of high wind and solar penetration will become increasingly challenging.

This Stage 1 RIS details a range of actions to manage the challenges identified. These actions can be broadly categorised into:

- Development of processes, tools, and training to support **secure** operation.
- Regulatory and market reforms to support **secure** operation.
- Investigations to better understand **secure** or **more efficient** operation.

Figure 19 shows a summary of these actions and their relative timing. Further details on each action are at the end of Chapters 2-6, and in Table 1 in the Executive Summary.

Figure 19 Timeline of actions identified in the RIS



7.2 Operating the NEM at very high penetrations of wind and solar

Figure 20 visually represents the changing system conditions in the NEM from 2019 to 2025. These are overlaid with the system limits identified[82] in this study which, if not addressed, will create barriers to the proportion of wind and solar PV generation that can securely operate at any one time.

To read Figure 20:

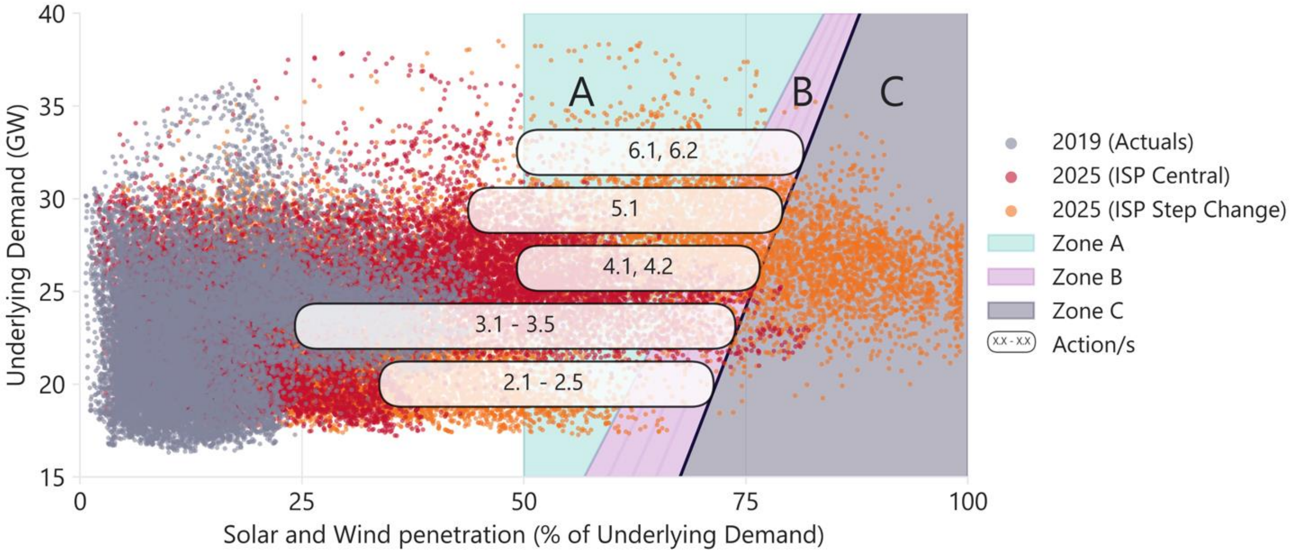
- **Grey dots** show the **actual instantaneous penetration of wind and solar generation in the NEM in 2019**.
- **Red dots** show the **forecast instantaneous penetration of wind and solar generation in the NEM in 2025 under the Draft 2020 ISP Central generation build**.
- **Orange dots** show the **forecast instantaneous penetration** of wind and solar generation **in 2025 under the Draft 2020 ISP Step Change generation build**.

As instantaneous penetration of wind and solar generation is forecast to continue growing towards 2025, and to more frequently exceed 50%:

- **Zone A indicates where managing variability and uncertainty will become increasingly challenging.** To ensure power system is secure at penetrations in this zone, variability and uncertainty will have to be balanced with the available flexibility at NEM-wide, regional, and sub-regional levels.
- **Zone B indicates where inertia and system strength limits impact secure operation. The diagonal dotted lines indicate the approximate staged progression of these limits** that AEMO will seek out to 2025, as sufficient operational experience is obtained and necessary frequency management reforms are progressed. These technical requirements need to be met at regional and sub-regional levels.
- **Zone C is an aggregation of the current minimum online synchronous generation required** to meet the minimum synchronous unit combinations for system strength in each region. These technical requirements need to be met at regional and sub-regional levels.
- **White bubbles with numbered actions (see Figure 19 above)** give an indication of the levels of wind and solar penetration at which they would be needed:
  - **Operational actions** (2.1-2.4) – these are already required and are progressing in some instances and these will require further development to securely operate the system at higher penetrations.
  - **DPV actions** (3.1-3.5) – these are already required in some states such as South Australia where the penetrations are very high and will be required in other states as penetration in those states increase.
  - **Frequency actions** (4.1-4.2) – these must be completed to progressively test the system at lower levels of online inertia in zone B.
  - **System strength action** (5.1) – this is required to ensure coordination of system strength sources across the NEM and enable system operation at very high penetrations in zone B and C.
  - **Variability and uncertainty actions** (6.1-6.5) – these are required as penetrations of variable and uncertain energy sources increase from zone A onwards.

[82] The zones in this figure are indicative only and have been aggregated up from regional limits (Queensland, New South Wales, South Australia, Tasmania, and Victoria).

Figure 20 Summary of identified system limits and remedial actions, overlaid on instantaneous penetration of wind and solar generation, actual in 2019 and forecast for 2025 under ISP Central and Step Change generation builds



Note: Penetration values on this graph represent non-overlapping half-hourly wind and solar generation divided by total underlying demand across the NEM during the same half-hours. Actual 2019 penetration includes all curtailment; 2025 projections only include network congestion.

If recommended pre-emptive actions are taken to address the regional and NEM-wide technical challenges identified in this study, the NEM could potentially be operated securely out to the beginning of Zone C by 2025, with up to 75% of total generation coming from wind and solar resources at any time.

If recommended pre-emptive actions are not taken, the identified operational limits will bind. This would constrain the output of wind and solar resources, limiting their maximum contribution at any time in the NEM to between 50% and 60% of total generation.

Operation in Zone C, with up to as high as 100% of wind and solar generation operating securely at times, is theoretically achievable in the future. This would, however, require more advanced methods of system operation coupled with provision of essential system services to ensure adequate system flexibility, frequency, and voltage management.

8. Next steps

AEMO's overarching objective is for the RIS to become an action plan that supports the secure transition of the NEM power system. In recommending actions and highlighting positive potential outcomes, AEMO does not underestimate the extent of work that will be required to successfully adapt the NEM.

Key next steps following the publication of this report include:

- An open and transparent stakeholder engagement process to discuss the findings and actions arising from this report and priority focus areas for the future.
- Exploring the findings and insights from this work with regulatory bodies and policy-makers to help inform ongoing reform processes.
- Incorporating relevant findings as part of the Final 2020 ISP.
- Undertaking identified actions to address limits.
- Scoping and commencing areas of further study, including but not limited to the resilience of a high renewable future system to complex system events, and a study of the latest advancements in inverter technology.
- Building on the Stage 1 RIS findings and subsequent stakeholder engagement, developing (by Q2 2021) a roadmap for the secure transition to higher penetrations of wind and solar in the NEM, including key study areas, actions, and reforms.

8.1 Managing the transition

As the system transitions to new operational configurations with increasing wind and solar and decreasing conventional generation online, it will be important to test these new operational configurations in a way which minimises both the risk to system and the impact on market operation.

This could take the form of setting transitional safety nets in each region of the NEM to operating with combinations of fewer synchronous machines and increasing levels of IBR. A progressive approach could then be taken to lowering these safety nets as improved operating practices and new technology demonstrate – under a sufficient combination of operating conditions – that the system can be operated securely with combinations of fewer synchronous machines and increasing levels of IBR.

The RIS International Review noted that EirGrid in Ireland has taken a similar approach to the progressive increase in inverter-based resources (IBR) and reduction in synchronous generation[83].

8.2 Future work

This Stage 1 RIS has been a large undertaking and explored several critical power system security questions in detail; however, its scope has been focused on the areas outlined in Section 1.3, and by the assumptions

[83] See p. 4, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Future-Energy-Systems/2019/AEMO-RIS-International-Review-Oct-19.pdf.

outlined throughout the report and appendices. There are also several areas for further study arising as a result of the RIS findings. This means there is a need for continued efforts on several fronts to build on these Stage 1 findings. In addition, the power system and market dynamics evolve daily, and there is a large body of work already underway across many organisations in the NEM to explore different changes in the power system and energy markets.

Given the high level of complexity and inter-relatedness of power system security challenges, AEMO sees a need to facilitate greater clarity among stakeholders on the priority focus as the generation mix transitions.

An integrated roadmap of priority security activities will be essential to ensure that the available resources of NEM stakeholders are allocated in the most effective way to support a rapid system transition that serves the long-term interests of consumers. AEMO will publish such a roadmap by Q2 2021, including priority future study areas, actions, reforms, and details of how AEMO will test and relax any transitional safety nets as new operational configurations are progressively experienced.

Beyond this roadmap, AEMO identifies the importance of future study including (but not limited to) the resilience of a high renewable future system to complex system events, and a study of the latest advancements in inverter technology.

8.3 Implications for the *Integrated System Plan*

In its ISP, AEMO identifies a future for the NEM that maximises consumer benefits, at the lowest system cost, while meeting reliability, security, and emissions expectations. Under every ISP scenario, the NEM's least-cost future features large increases in renewable generation – utility wind and solar connected to the grid and distributed solar photovoltaics (DPV) installed by households and businesses – as well as increases in demand side participation, energy storage, and sector coupling (such as with gas and transport).

The RIS is a technical investigation which identifies the challenges and requirements of the power system in 2025. These challenges and requirements will be extrapolated and considered in the ISP, and where practical, the impacts will be included in the cost benefit assessment. Looking beyond 2025, AEMO has not identified insurmountable technical reasons why the NEM cannot operate at even higher levels of wind and solar generation in the longer term.

The 2020 ISP builds from the requirements and limits identified in the RIS as it considers the operability of the NEM out to 2040. Further, the 2020 ISP will:

- Present an efficient and robust roadmap for the evolution of the NEM power system.
- Prioritise the development of renewable energy zones (REZs) to improve coordination of generation and transmission investment.
- Demonstrate how the power system can be operated with high penetrations of VRE.
- Deliver a robust plan that prepares the power system for climate change.
- Project inertia across the NEM against regional requirements and develop an efficient strategy to meet those requirements.
- Economically assess different options to deliver system strength in REZs and across the wider grid.
- Analyse the impact of DER on power system limits and present a series of recommendations to enable ongoing investment in DER.

Each of the NEM system limits for 2025 identified in the RIS and discussed in this Stage 1 report is being considered as part of the 2020 ISP analysis. Beyond 2025, a number of the limits identified in the RIS can be generalised and considered in longer-term ISP projections.

The 2020 ISP will consider the requirements and recommendations identified in the RIS. The drivers of benefits for many of the projects that will be actioned through the ISP must be robust to the challenges identified in the RIS. The outputs of the RIS will continue to inform and build on the ISP, according to its two-yearly timeframes.

8.4 Stakeholder engagement

The findings of this report have far-reaching implications for the energy sector in Australia, and highlight that industry needs to collaboratively address the collective challenges of operating the NEM now and in the coming years. AEMO looks forward to an open and transparent stakeholder engagement process, to:

- Communicate the results and key insights to interested stakeholders.
- Enable stakeholders to ask questions and receive clarification and additional information from AEMO about the methodology and results of the study.
- Promote discussion regarding the actions arising from this report and priority focus areas for the future.
- Explore the findings and insights from this work with regulatory bodies and policy-makers to help inform ongoing reform processes.
- Leverage stakeholder feedback and perspectives to help shape a roadmap for the secure transition to higher penetrations of wind and solar in the NEM, including priority study areas, actions, and reforms.

The consultation process for the RIS Stage 1 report began in February 2020, with input from a small panel of technical experts who provided feedback on a draft of this summary report[84].

The next step of the engagement plan includes consultation with a broad range of stakeholders through a variety of formats, as outlined in Table 13. Given current COVID-19 restrictions, AEMO is exploring a variety of engagement options to maximise the value to all stakeholders. Stakeholder feedback and suggestions on other approaches are welcome.

Table 13 RIS engagement activities and timeline

Engagement activity	Objectives	Timeline
Webinar(s) • Recordings will be published on the RIS website.	Inform stakeholders of the results and key insights.	May 2020
Videoconference workshops • Workshops will be broken-down into discrete topics and/or industry groups to keep attendee numbers at each workshop small enough to enable meaningful discussion and debate. • AEMO welcomes feedback and suggestions from stakeholders regarding the workshop topics and structure they'd like to see.	Consult with stakeholders – open dialogue and discussion regarding matters of most interest, including but not limited to: • Discussion and clarification about the methodology and results of the study. • Discussion regarding the actions arising from this report and priority focus areas for the future. • Exploring the relevance of findings and insights to ongoing reform processes.	May-June 2020
Written submissions • AEMO welcomes submissions from stakeholders wishing to provide formal written feedback, concerns, or suggestions regarding the RIS Stage 1 report or priority focus areas for the future.	Consult with stakeholders – allow opportunities for formal written responses from stakeholders regarding the RIS Stage 1 report or future activities.	June 2020

Information on the RIS, supplementary resources, and links to other related projects are available on the AEMO website[85].

For further information, feedback or suggestions on engagement activities, and lodgement of written submissions, please contact AEMO's Future Energy Systems team at FutureEnergy@aemo.com.au.

[84] Advisory panel members are listed on pages 2 and 3.

[85] At https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/Future-Energy-Systems/Renewable-Integration-Study.

9. Reference resources

AEMO has published other reports into the changing generation mix. A shortlist of relevant publications is provided in Table 14.

Table 14 Relevant AEMO publications

Publication	Notes and location	Publication date
Regular NEM-wide planning documents		
Integrated System Plan (ISP)	Prepared every two years to forecast a wide spectrum of interconnected infrastructure and energy development scenarios and plans including transmission, generation, gas pipelines and distributed energy resources. At https://www.aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp.	2018 ISP – July 2018 2020 ISP – draft December 2019
ISP Insights	Published as required to provide a deep technical dive into select technologies or projects and their potential impact on future NEM development. At https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp.	NA
Electricity Statement of Opportunities (ESOO)	Provides forecasts and analysis of technical and market data for the NEM for the next 10 years. At https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/forecasting-and-reliability/nem-electricity-statement-of-opportunities-esoo.	NA
Energy Adequacy Assessment Projection (EAAP)	Quantifies the impact of potential energy constraints on expected levels of unserved energy in the NEM for the next two years. At https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/forecasting-and-reliability/energy-adequacy-assessment-projection-eaap.	NA
Short term and Medium Term Projected Assessment of System Adequacy (ST PASA & MT PASA)	Provides information on peak load forecasts, total available generation capacity, demand-side management capacity, any identified capacity shortfall of ancillary services, transmission outages, any security problems, fuel supply and logistics and any facility testing. MT PASA is published weekly for each week in the next two years. ST PASA is published 2-hourly for each half hour for the next six trading days. At https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/data-nem/market-management-system-mms-data/projected-assessment-of-system-adequacy-pasa.	NA
Network Support and Control Ancillary Services Report (NSCAS)	Assesses any requirements for NSCAS for network loading, voltage control, and transient and oscillatory stability ancillary services over the next five years that are not currently being addressed by NSPs. At https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/system-operations/ancillary-services/network-support-and-control-ancillary-services-procedures-and-guidelines.	NA
Summer Readiness report	Provides information on AEMO's preparations for the forthcoming summer period, designed to minimise the risk of customer supply disruption in the NEM. At https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/system-operations/summer-operations-report.	NA
Publications related to power system operation and renewables		

Publication	Notes and location	Publication date
RIS International Review: Maintaining Power System Security with High Penetrations of Wind and Solar Generation – International insights for Australia	At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Future-Energy-Systems/2019/AEMO-RIS-International-Review-Oct-19.pdf.	October 2019
Renewable Integration Study	At https://www.aemo.com.au/energy-systems/Major-publications/Renewable-Integration-Study-RIS.	June 2019
WA Renewable Integration report	At https://www.aemo.com.au/Electricity/Wholesale-Electricity-Market-WEM/Security-and-reliability/Integrating-utility-scale-renewables .	March 2019
Distributed Energy Resources (DER) Program	Full program details at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program.	April 2019
Power System Requirements paper	At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf.	May 2018
International Review of Frequency Control Adaptation	At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2016/FPSS---International-Review-of-Frequency-Control.pdf.	October 2016
Technical Integration of DER	At https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Improving-DER-Capability.	April 2019
International Review of Opportunities to Activate DER	At https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols.	October 2019
International Review of PV Feed-in Management	At https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols.	October 2019
System Strength: System Strength in the NEM Explained	At https://aemo.com.au/-/media/files/electricity/nem/system-strength-explained.pdf?la=en.	March 2020
System Strength Impact Assessment Guidelines	At http://aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/System-Security-Market-Frameworks-Review/2018/System_Strength_Impact_Assessment_Guidelines_PUBLISHED.pdf.	July 2018
System Strength Requirements Methodology	At http://aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/System-Security-Market-Frameworks-Review/2018/System_Strength_Requirements_Methodology_PUBLISHED.pdf.	July 2018
Inertia Requirements Methodology	At http://aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/System-Security-Market-Frameworks-Review/2018/Inertia_Requirements_Methodology_PUBLISHED.pdf.	June 2018
ISP Insights - Building power system resilience with pumped hydro energy storage	At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/ISP/2019/ISP-Insights---Building-power-system-resilience-with-pumped-hydro-energy-storage.pdf.	July 2019
Rule Change Proposal - Generator Technical Requirements	At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2017/AEMO-GTR-RCP-110817.pdf. Details of the AEMC's final Rule determination, plus consultation papers and AEMO submissions are at https://www.aemc.gov.au/rule-changes/generator-technical-performance-standards.	August 2017

Publication	Notes and location	Publication date
Working Paper - Fast Frequency Response in the NEM	At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2017/FFR-Working-Paper---Final.pdf.	August 2017
Technology Capabilities for Fast Frequency Response	At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2017/2017-03-10-GE-FFR-Advisory-Report-Final---2017-3-9.pdf.	March 2017
Visibility of DER	At https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/FPSSP-Reports-and-Analysis.	January 2017
Update to renewable energy integration in South Australia	At https://www.aemo.com.au/-/media/Files/PDF/Joint-AEMO-ElectraNet-Report_19-February-2016.pdf.	February 2016
South Australian Wind Study Report	At https://www.aemo.com.au/-/media/Files/PDF/2015_SAWSR.pdf.	October 2015
Renewable Energy Integration in South Australia	At https://www.aemo.com.au/-/media/Files/PDF/Renewable_Energy_Integration_in_South_Australia_AEMO_Electranet_Report_Oct_2014.pdf.	October 2014
Wind Turbine Plant Capabilities Report	At https://www.aemo.com.au/-/media/Files/PDF/Wind_Turbine_Plant_Capabilities_Report.pdf .	2013
Wind Integration Studies Report	At https://www.aemo.com.au/-/media/Files/PDF/Integrating-Renewable-Energy--Wind-Integration-Studies-Report-2013pdf.pdf.	2013
100 Per Cent Renewables Study	At https://www.environment.gov.au/system/files/resources/d67797b7-d563-427f-84eb-c3bb69e34073/files/100-percent-renewables-study-modelling-outcomes-report.pdf.	2013

A1. Technical appendices

All these appendices, providing detail on the analysis, limits and actions identified, are published separately and are available at https://www.aemo.com.au/energy-systems/Major-publications/Renewable-Integration-Study-RIS:

- **Appendix A. Distributed solar PV.**
- **Appendix B. Frequency control.**
- **Appendix C. Variability and uncertainty.**

Abbreviations

Abbreviation	Term in full
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
CEC	Clean Energy Council
CER	Clean Energy Regulator
CPU	Central Processing Units
DAPR	Distribution Annual Planning Report
DER	Distributed energy resources
DNSP	Distribution Network Service Provider
DPV	Distributed photovoltaics
EAAP	Energy Adequacy Assessment Projection
EFCS	Emergency Frequency Control Scheme
ENA	Energy Networks Australia
ESB	Energy Security Board
EMT	Electromagnetic transient
ESOO	Electricity Statement of Opportunity
FCAS	Frequency Control Ancillary Services
FOS	Frequency Operating Standard
FUM	Forecast Uncertainty Measure
GPS	Generator Performance Standards
GW	Gigawatts
IBR	Inverter-based resources
ISP	Integrated System Plan
LCR	Largest Credible Risk
LOR	Lack of Reserve
MASS	Market Ancillary Service Specification
MT PASA	Medium Term Projected Assessment of System Adequacy

Abbreviation	Term in full
MVA / MVAr	Megavolt amperes / Megavolt amperes reactive
MW	Megawatts
MWs	Megawatt seconds
NCAS	Network Control Ancillary Services
NEM	National Energy Market
NEMDE	National Energy Market Dispatch Engine
NER	National Energy Rules
NMAS	Non-Market Ancillary Services
NSP	Network Service Provider
NWP	Numeric weather predictions
OEM	Original Equipment Manufacturer
PASA	Projected Assessment of System Adequacy
PFR	Primary Frequency Response
PV	Photovoltaic
QED	Quarterly Energy Dynamics
RERT	Reliability and Emergency Reserve Trader
REZ	Renewable Energy Zone
RIS	Renewable Integration Study
RIT-T	Regulatory Investment Test for Transmission
RoCoF	Rate of Change of Frequency
RTDS	Real-time dynamic simulator
ST PASA	Short Term Projected Assessment of System Adequacy
SWIS	South West Interconnected System
TAS	Tasmania
TNSP	Transmission Network Service Provider
UFLS	Under Frequency Load Shedding
VRE	Variable renewable energy