AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Integrating Utility-scale Renewables and Distributed Energy Resources in the SWIS

March 2019

Important notice

PURPOSE

AEMO has prepared this report to provide information and recommendations to the Western Australian Public Utilities Office about the security of the South West Interconnected System (SWIS), using information available to AEMO as at the date of publication.

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Executive summary

The South West Interconnected System (SWIS) through the Wholesale Electricity Market (WEM) provides approximately 18 million megawatt hours (MWh) of electricity each year to more than 1.1 million households and businesses, and incorporates 102,000 kilometres of transmission and distribution lines. It is geographically isolated, with no interconnections to other transmission systems.

The peak demand in 2017-18 in the SWIS was 3,616 megawatts (MW) with an average demand of around 2,000 MW and a minimum operational demand[1] of around 1,200 MW.

The SWIS is experiencing continued rapid growth of both utility-scale renewable resources and distributed energy resources (DER). There is now more than 1,000 MW of rooftop photovoltaic (PV) DER installed behind the meter (on consumers' premises) in the distribution networks. As the levels of installed DER grow, the minimum operational demand in the SWIS will decline.

Recent studies performed by AEMO to determine the operational limits of the SWIS have determined:

1. Without changes to accommodate new technologies, voltage in the SWIS cannot be controlled within technical limits as the level of minimum operational demand approaches 700 MW. AEMO's current forecasts of rooftop PV DER growth indicate that minimum operational demand will reach 700 MW between 2022 and 2024, depending on the PV DER installation rate and load growth and taking into account day-to-day variability in weather and load conditions.
2. System security risks are emerging now as the increase in large-scale renewable generation displaces the dispatchable thermal generators that presently provide all system security services such as inertia, frequency control, system strength, and voltage control.
3. Technical standards and regulatory and market constructs require carefully designed but urgent change, to implement or incentivise new technologies in the SWIS such as synchronous compensation, energy storage, and increased inverter capabilities. These changes will support the management of power system security and effectively integrate renewable generation and DER in a way that facilitates efficient utilisation of existing and future electricity sources.

Collectively, rooftop PV DER is the largest energy source in the SWIS, significantly reducing emissions and directly contributing to reduce energy bills for the proprietors. AEMO's 2018 *WEM Electricity Statement of Opportunities* (ESOO)[2] forecast that installed rooftop PV DER will more than double by mid-2028, to 2,400 MW.

A recent study[3] by AEMO and CSIRO confirmed that renewables are now the lowest-cost form of new built generation. Reflecting that economic reality:

- All new utility-scale generation in the SWIS for the last five years has been renewable.
- All 790 MW of new large-scale generation forecast by AEMO to connect to the SWIS by 2021 is expected to be renewable.

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[1] Operational demand is demand served by registered scheduled and non-scheduled market generators. It does not include demand served by DER.

[2] Available at https://www.aemo.com.au/-/media/Files/Electricity/WEM/Planning_and_Forecasting/ESOO/2018/2018-WEM-ESOO-Report.pdf.

[3] Graham, P.W., Hayward, J, Foster, J., Story, O.1 and Havas, L., CSIRO and AEMO, *GenCost 2018*, December 2018, available at https://www.csiro.au/en/News/News-releases/2018/Annual-update-finds-renewables-are-cheapest-new-build-power.

The existing 1,000 MW of rooftop PV DER can already serve over 45% of the instantaneous demand in the SWIS at times of low demand, yet it is not centrally monitored or controlled, and does not respond autonomously to contribute to the secure operation of the system.

Analysis of some recent power system incidents in the National Electricity Market (NEM) has found evidence that significant amounts of DER (as much as 40% of distributed PV generation in a region) can disconnect or cease operation for a period of minutes following large power system disturbance. Extrapolating forward to larger installed capacities, this could translate to the loss of generation far exceeding existing credible contingency sizes, putting the power system in an unsecure operating state in the absence of additional frequency control reserves. AEMO is engaging with industry on improving DER performance standards to improve disturbance withstand capability and will publish a report on this shortly. AEMO is also working with NEM distribution network service providers, including Western Power in the SWIS, to update capabilities covered by the Australian inverter standard AS/NZS 4777 and ensure required capabilities are enabled in network connection processes.

As DER penetration grows, the islanded nature of the SWIS means that at times of high DER output and low demand, the remaining grid load will be insufficient for any other generation to control voltage across the system. Provision of a frequency reference, and system strength and frequency control capabilities, will be at critically low levels, so that credible events will create significant risk of cascading failures across the SWIS. If future rooftop PV DER installations continue to use the predominant technologies presently installed and remain uncontrolled, the SWIS will become inoperable under its present operating parameters.

Actions can be taken to overcome these challenges and allow DER to be used to improve the security and reliability of the system. AEMO recommends the urgent incorporation of new technologies in the grid such as energy storage systems and synchronous condensers, together with the adoption of updated inverter standards combined with market and regulatory changes. These changes should be designed to support and incentivise a secure, clean, cost-effective power system.

The rapid addition of renewables and DER in the SWIS mirrors experience in the NEM[4], particularly in South Australia, where large amounts of renewables were added as fossil-fuelled generators retired. The primary difference from the NEM is that the SWIS is electrically isolated, and has no support for security or ancillary services from a neighbouring region as a backstop. From a system perspective, this increases the urgency of updating the technologies within the system and complementary market changes to ensure that there are appropriate resources necessary for secure and reliable operation in a cost-effective manner, while supporting the achievement of emissions reduction targets.

AEMO's operating experience in the NEM and WEM is not unique. Other jurisdictions experiencing large renewable growth, such as Ireland, California, Texas, and the United Kingdom, have all encountered similar challenges to the integration of new generation technologies. Hawaii presents the best comparison for the SWIS, due to its islanded nature. Recognising the system impacts of increasing penetration of rooftop PV DER, Hawaii (along with California) developed its own inverter standards to include advanced functionality. These system requirements were reflected in the 2018 revision to the IEEE 1547 standard for DER connection following an extensive four-year cross-industry collaboration in the US, addressing both local distribution and bulk system needs. Other grids around the world have also demonstrated the value of proactive technical, market, and regulatory changes to accommodate the changing resource mix[5].

Distributed, non-synchronous resources are technically able to provide essential services to the power system. Technical standards and market arrangements need to be designed to incentivise this capability, cognisant of the fact that these resources may provide these services in different ways.

Appropriate market changes can also facilitate new revenue streams for existing generators that historically provided such essential services as a by-product of their energy production, and promote more efficient

[4] AEMO, *AEMO Observations: Operational and market challenges to reliability and security in the NEM*, March 2018, available at https://www.aemo.com.au/-/media/Files/Media_Centre/2018/AEMO-observations.pdf.

[5] International Energy Agency (IEA), Getting Wind and Sun onto the Grid: a Manual for Policy Makers, 2017, available at https://www.iea.org/publications/insights/insightpublications/Getting_Wind_and_Sun.pdf.

arrangements across the full range of resources for the provision of energy, capacity, and system security services.

The WEM Reform Program encompasses changes that are critical to AEMO's ability to manage an effective response to DER penetration and utility-scale variable renewable generation. Implementing a system planning function for the SWIS, similar to the NEM, will provide a mechanism to model future developments and identify development pathways to facilitate the changing energy transition. Adding mechanisms for DER integration as part of the reform's detailed design will further improve the reform program to deliver optimal outcomes for electricity consumers, industry participants, investors and the operation of the SWIS.

Changes to accomplish the least cost integration of renewables and DER to facilitate a smooth industry transition must be in place no later than Q4 2020.

AEMO acknowledges the short timeframe, but again notes the urgency of the system challenges and recognises that it will take time to both implement and adopt the necessary rule changes and updates to Australian Standards. Timely implementation of reforms in response to the challenges posed by DER and increased penetration of utility-scale renewables is important and will ensure that future investment decisions in the SWIS to ensure ongoing security of supply and reliability are governed by an appropriate regulatory framework.

It is also important to note that any capital investment in response to these challenges will itself take time to implement, from project inception to project commissioning, which further accentuates the importance of a robust and timely policy response to provide regulatory clarity for the future investments to occur.

AEMO specifically recommends the actions in Table 1 below, to address the challenges and harness the opportunities presented by the rapid and continuing increase of rooftop PV DER and utility-scale renewable generation in the SWIS.

Table 1 Recommendations for the integration of DER and utility scale renewables

	Recommendations
1.	<u>Update inverter standards to include advanced capabilities and implement within distribution connection requirements</u> AEMO to work with Western Power to progress amendments to AS/NZS 4777.2 for the grid connection of DER via inverters, integrating recent improvements to IEEE 1547-2018 and other recently published international equivalent standards. This will include autonomous grid support including frequency and voltage disturbance ride-through and regulation from the inverters. AEMO is already engaging with: • Energy Networks Australia and distribution network service providers nationally on local distribution and bulk system level needs and the adoption of advanced inverter capability within distribution connection requirements. • The Clean Energy Council and manufacturers on transition to any new requirements and compliance. AEMO will work with Western Power on the development and implementation of new requirements in the inverter standard for the SWIS by end of 2019.
2.	<u>Energy Storage in the SWIS</u> AEMO to determine the requirement for energy storage installations for system security purposes in the SWIS and work with the Economic Regulation Authority, Western Power, government, and industry to: • Enable the registration, connection, and operation of energy storage systems in the SWIS through regulatory reform and rule changes by end of 2019. • Propose a funding scheme or process to establish energy storage projects to commence installation during 2020.
3.	<u>System security technologies</u> AEMO to complete a detailed technical, economic and regulatory evaluation that includes: • Identifying the optimal locations and technical requirements for the deployment of synchronous condensers or other applicable technologies in the SWIS to manage system strength and inertia to required levels. • Cost of meeting the requirements. • Regulatory changes required to enable implementation at the least cost.

	Recommendations
4.	WEM Reform Program additional scope and focus The Government's WEM Reform Program must be completed on or ahead of the current schedule, with additional dedicated resources if required. Scheduled to go live in October 2022 (with some changes implemented in 2020), the Government's WEM Reform Program will provide some of the fundamental changes that are necessary to facilitate the energy transition, such as co-optimised energy and essential grid support services[6] dispatch and improved generator performance standard arrangements. Additional scoping of the objectives and timelines of the reform program is necessary to include mechanisms for DER integration in the detailed design in a timely manner.
5.	Integrated System Planning is required Confer a function for long-term integrated system planning on AEMO by the end of 2019. AEMO to deliver a SWIS strategic integrated development plan, based on sound engineering and economics and with key input from Western Power, which can facilitate an orderly energy system transition under a range of scenarios – plan to be delivered by July 2020.
6.	DER Roadmap Develop a DER Roadmap that identifies the funding and resources requirements, and the technical, operational, and regulatory changes, that are necessary to trial, implement, and incentivise the use of DER by distribution utilities and AEMO to reduce costs and provide value to owners of these systems and the market.
7.	Distribution System Operator and Distribution Market Operator functions are required AEMO to work with Western Power and the PUO and develop recommendations for the development of distribution system operation and distribution market operator functionality to facilitate the optimised real-time integration of distributed resources to support system security, reliability, and economic efficiency.

[6] Electricity can be considered as an amalgam of services and functions that provide physical outcomes, for example, the economic supply of heating, cooling and lighting and also frequency, voltage, and inertia control. Co-optimisation is concerned with simultaneous optimising the trade-offs between these services and functions to create a sustainable, least cost balance between these services and functions.

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Glossary

This report uses terms and common abbreviations as set out in the following table.

Table 2 Glossary

Term	Meaning
AEMO	Australian Energy Market Operator
DC	Direct current
Demand • Operational demand • Underlying demand	Operational demand is the demand met by scheduled and non-scheduled generation in the WEM, excluding DER such as rooftop PV systems. It includes the effect of network losses. Underlying demand is the total demand for electricity and is met by all generation devices in the SWIS including DER such as rooftop PV systems.
DER	Distributed energy resources
Frequency • Over frequency • Under frequency	For alternating current (AC) electricity, the number of cycles occurring in each second, measured in Hertz (Hz). Power system frequency is controlled by the constant balancing of electricity supply and demand. Table 2.1 of the Technical Rules specifies the Frequency Operating Standards applied in the South West Interconnected System (SWIS). Over frequency and under frequency represent unsecure operating states where frequency is outside the normal range (49.8 to 50.2 Hz), where there is insufficient load to cover generation (over frequency) or where this is insufficient generation to meet load (under frequency). AEMO uses essential services to ensure that the SWIS operates within the normal frequency bands and to restore the SWIS to the normal frequency bands within the target recovery time following a contingency event.
Inertia	Inertia is the rapid and automatic suppression of rapid frequency deviations, slowing the rate of change of frequency through a rapid change in generation levels. A lack of inertia in the network can present risks to system security. At present, inertia is predominantly provided by synchronous generators in the SWIS.
Inverter	Electrical apparatus to change DC into AC. Distributed generation is generally inverter connected.
kV	Kilo-volt (1,000 Volts)
MW	Megawatt (1,000,000 watts)
NEM	National Electricity Market
Non-synchronous generation	Non-synchronous generation (also referred to as asynchronous generation) includes wind farms, solar PV generators, and batteries that export power to the grid. They do not have moving parts rotating in synchronism with the grid frequency, but instead are interfaced to the power system via power electronic converters (refer to "power electronic converters") which electronically replicate grid frequency.
Operational demand	See "Demand"
Power electronic converters (PECs)	Power electronic converters include rectifiers and inverters which convert alternating current to direct current and vice versa, respectively. Utility-scale wind generation is connected to the grid with complex converters whereas rooftop solar is connected to the grid with inverters (refer to "inverter").
PV	Photovoltaic
Reliability (Power system Reliability)	Ability of the system to supply adequate power to satisfy consumer demand, allowing for credible generation and transmission network contingencies.

Term	Meaning
Security (Power system security)	To be secure, the power system must operate within defined technical limits and to return within those technical limits after a disruptive event occurs, such as the disconnection of a major power system element (such as a power station, major powerline or major industrial load).
SWIS	South West Interconnected System
Synchronous generation	Directly connected to the power system and rotates in synchronism with grid frequency. Thermal (coal, gas) and hydro (water) driven power turbines are typically synchronous generators.
System strength	System strength is an umbrella term that refers to a suite of interrelated factors which together contribute to power system stability. It reflects the sensitivity of power system variables to disturbance, and indicates inherent local system robustness, with respect to properties other than inertia. System strength affects the stability and dynamics of generating systems' control systems, and the ability of the power system to both remain stable under normal conditions and return to steady-state conditions following a disturbance. For more detail on system strength, refer to https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2016/AEMO-Fact-Sheet-System-Strength-Final-20.pdf.
UFLS	Under frequency load shedding
Underlying demand	See "Demand"
Voltage	The electrical force or electric potential between two points that gives rise to the flow of electricity.
Voltage Control	Voltage control in the power system acts to maintain voltages at different points in the network within acceptable ranges during normal operation, and to enable recovery to acceptable levels following a disturbance.
WEM	Wholesale Electricity Market

1. Introduction

1.1 Purpose

This report:

- Informs the Public Utilities Office (PUO) of the outcomes of recent studies conducted by AEMO to determine the operational limits of the South West Interconnected System (SWIS).
- Demonstrates how the SWIS could be affected from a market and system perspective if changes are not urgently made to address system security challenges emerging now and in the short to medium term.
- Recommends changes and further initiatives to efficiently integrate and utilise new technologies, distributed energy resources (DER), and utility-scale renewable resources to improve power system security, reliability, and market outcomes in the SWIS.

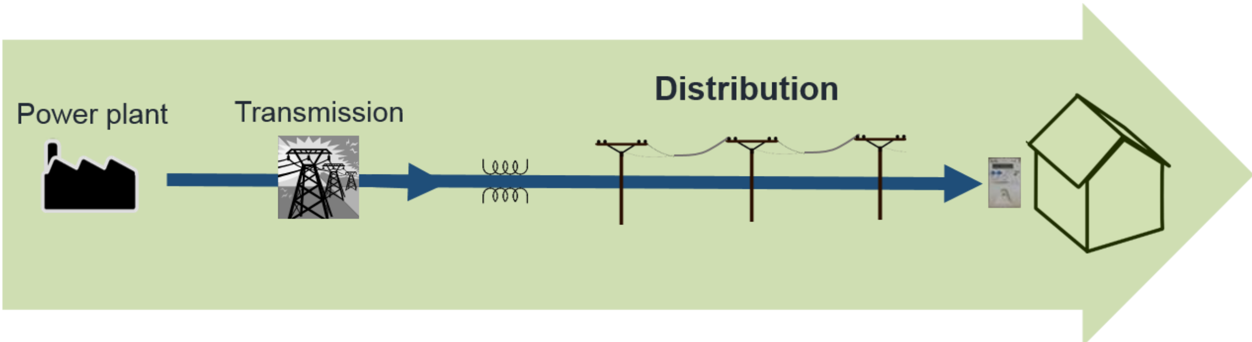
AEMO's studies highlight a need for immediate steps to implement standards for inverters, and reform regulatory and market frameworks, to efficiently accommodate the continuing growth in both DER and utility-scale renewable generation in the SWIS.

1.2 Background and context

1.2.1 The traditional power system

Up to a decade ago, the SWIS consisted largely of dispatchable synchronous generation delivering power to consumers via transmission and distribution networks designed and built for one-directional power flow. In the past, the primary focus for development of the SWIS was the ability of network and generation assets to meet peak demand periods, typically the middle of hot summer days, with minimum demand occurring in the middle of the night.

Figure 1 The traditional electricity system



The present WEM and SWIS regulatory framework, including the market and system rules and technical standards, was designed to ensure efficiency and secure operation of this resource mix.

As with all markets and power systems across the world at that time, these synchronous alternating current generators had specific inherent characteristics that were critical for secure power system operation and grid support. Specifically, they provide a power system with the following essential services[7][8]:

- Inertia – large masses of rotating machinery that provide a degree of resistance to change as a consequence of disturbances.
- System strength – synchronous alternating current machines produce large short-circuit fault currents, the necessary response to maintain constant power output during a fault-related drop in voltage.
- Voltage control – synchronous alternating current machines absorb and generate reactive power needed to control voltage levels.
- Frequency control – ability to automatically vary rotational speed in response to variations in demand.
- Dispatchability – able to be dispatched and output raised or lowered as needed within ramp limits of the units.

Due to their abundance, traditional electricity system market designs had no need to incentivise, or products to commoditise, these characteristics as a service. The services did not need to be separately valued by the market, as they were provided by design in the process of energy generation.

Integrating the first few percentage points of variable renewable (non-synchronous) energy generation, such as wind and solar photovoltaic (PV) generation, in the generation mix poses few challenges for most power systems[9] – as has been the case in the SWIS. This is because all power systems have technical requirements that accommodate variability and uncertainty of power demand.

However, beyond a certain critical mass of non-synchronous machines, power systems will experience a reduction in their capability to remain stable through higher levels of variability. This typically requires increasing adaptations to market, regulatory, and technical frameworks to manage generation with different characteristics.

The most important issue that presents in the transformation from the traditional electricity system (designed around thermal synchronous generation) to a power system incorporating a large proportion of cleaner renewable energy sources is the inherent absence of market incentives, technical standards, or regulatory requirements for the essential grid support services listed above.

While other proven technologies can provide the essential properties that synchronous generation traditionally provided, these technologies in the SWIS will require planning, investment in enhanced and robust communication systems, and control linkages between large numbers of distributed devices to maintain system security[10].

1.2.2 A cleaner, more adaptive SWIS

Advances in PV technology, various financial incentives, and targets to reduce emissions have supported installations of utility-scale wind and solar, as well as DER in the form of rooftop PV systems. Many households and businesses have been able to install their own generation to meet their load and export the excess energy to the grid. In the SWIS, whole areas of the distribution network now export energy to the rest of the grid during daylight hours, meaning that some distribution feeders act as net generators during some parts of the day.

This has many positive outcomes for consumers, including reduced energy bills and reduced carbon emissions in generating the amount of electricity required to meet demand.

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[7] AEMO's *Power System Requirements reference paper*, published March 2018, provides some detail on these essential properties. See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf. A short summary of these requirements as relevant to the SWIS is provided in Appendix A1.

[8] Ancillary services are defined in the WEM Rules for the purpose of delivering essential services.

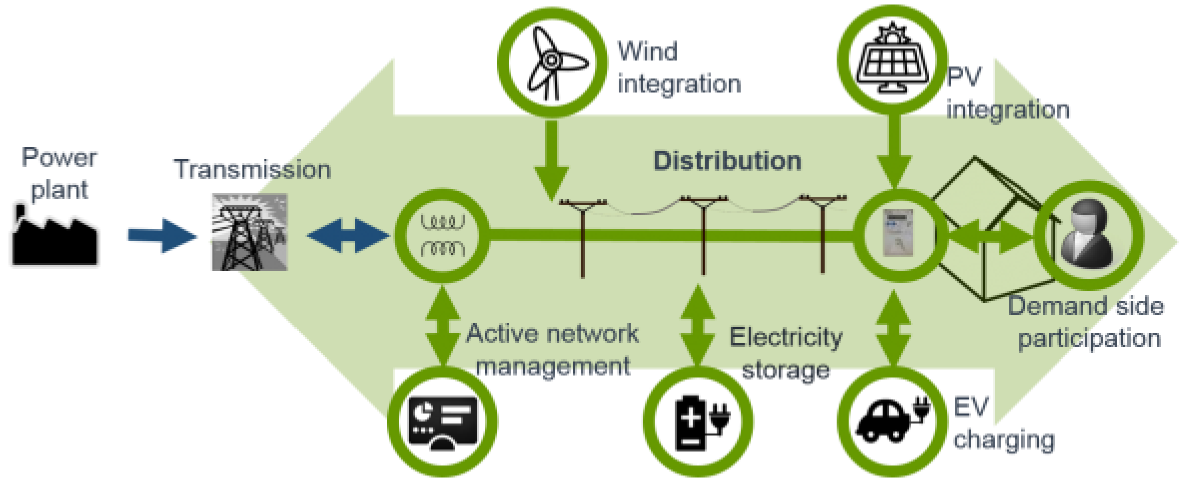
[9] See https://www.iea.org/topics/renewables/systemintegration/.

[10] AEMO, *Power System Requirements reference paper*, March 2018, p.15.

While the maximum demand level remains relatively flat, the incorporation of increasing utility-scale renewables and DER presents significant challenges to the management of system security as minimum operational demand levels decrease and shift to daylight hours. The SWIS must be able to respond to larger, more diverse, and less predictable demand variations, including the increasing afternoon ramp as output from rooftop PV DER decreases, while maintaining the essential characteristics that allow the system to ride through and respond to system faults.

An evolved electricity system with the integration of renewable generation and DER is illustrated in Figure 2.

Figure 2 The evolved electricity system



In the evolved electricity system, electricity can flow in a bi-directional manner, that is, flowing to consumers connected to the distribution network, or from the distribution network to the transmission network when generation from DER sources connected to the distribution exceeds customer demand in specific suburbs or substations. This is often referred to as reverse power flow (because it is reverse to the traditional direction of power flow).

In the SWIS, the introduction of significant volumes of variable renewable inverter-connected generators means traditional thermal synchronous generation is being displaced, due to the cheaper running costs of renewable generation. Renewable technologies that generate direct current energy and connect to the system via inverters do not inherently provide all the previously unvalued yet essential system support services with the characteristics provided by synchronous generators[11].

This transformation introduces new and substantial complexities into the operation of the SWIS and the markets, under regulatory and market frameworks that, for the most part, still contemplate a traditional power system.

Technical standards, markets, and regulatory frameworks require change to ensure the secure, reliable, and cost-effective integration of clean energy technologies in the evolving SWIS.

The growth in the penetration of DER and utility-scale renewable generation has resulted in circumstances where the available supply of existing ancillary services in the SWIS has been challenged. In the last 10 years, AEMO has not needed to use back-up load following ancillary services (LFAS), but since October 2018 back-up LFAS has been required to be enabled on four occasions (on three different days) for system security, due to weather conditions causing high volatility of wind and/or fluctuations in rooftop solar PV generation.

[11] While renewable energy technologies can provide some ancillary services, the characteristics of synchronous generation facilities with respect to their rotational mass and greater degree of dispatchability make synchronous generation a more capable source of ancillary services.

Modelling undertaken as part of the Wholesale Electricity Market (WEM) Reform Program has indicated that the existing 72 megawatts (MW) of primary LFAS will be insufficient to satisfy the system security requirements of the SWIS, which is clear evidence that change is required.

1.2.3 The SWIS is an islanded power system

The SWIS has specific unique characteristics differentiating it from the east coast National Electricity Market (NEM) and other larger power systems around the world. The SWIS is an electrically islanded single system that cannot transfer generation and ancillary (or system support) services to or from neighbouring electrical systems. The power system in Hawaii presents a comparable case study in this respect.

The SWIS must stand alone, requiring it to be more secure and reliable than a power system with interconnections to other transmission systems such as South Australia, Ireland, Germany, California, and Norway. The SWIS must have enough generation to meet peak period demand, even when it is not windy and the sun is not shining, and also retain enough reserve generation to cover for unplanned outages.

In this context, it is more important in the SWIS that high penetration and growth of DER and utility-scale renewable generation are well planned in an integrated manner, with the appropriate technical standards, regulatory frameworks, and market incentives to allow AEMO to manage the resources on the grid and in the distribution networks securely, reliably, and cost-effectively.

1.2.4 Defining DER

There is no universally agreed and applied definition of DER. In this report, AEMO uses the term DER to refer to resources that either produce electricity, store electricity, or manage consumption, and reside within the distribution system, including resources that sit behind the customer meter.

DER presents in two categories – passive and active.

Passive DER

Passive DER are essentially 'set and forget' installations which may have some local independent control for use by the owner. Almost all DER presently installed are passive solar PV. There are no active smart controllers that respond to price or other parameters; if the sun is shining, the systems generate.

Provided their existence, size, and location are known, this makes their output relatively predictable, subject to inevitable changes and approximations in weather forecasting. AEMO has developed specific solar forecasting tools and methodologies to determine the approximate output of distributed solar PV across the SWIS.

Active DER

Active DER systems incorporate smart controllers that can respond to parameters such as price, or directly to control signals for system security purposes. Typical examples are smart controllers for residential or industrial batteries and demand response installations that are co-ordinated by and connected to an aggregator or retailer with many other active DER installations.

There are presently no frameworks in place for the visibility and integration of active DER systems into the distribution network systems or the market systems. Cyber security concerns must also be appropriately addressed as the active DER sector develops.

Current and potential examples of these resources include:

- Demand response.
  - Demand response comprises consumer devices, such as smart pool pumps and thermostats, that act to reduce or increase their electricity demand in response to an "event". For industrial consumers, demand response also refers to actions that reduce demand by shutting off processes or reverting to local generation. An event can be a request for action from a system operator, network provider,

retailer, and/or third party (for example, a load aggregator). This can be considered as active DER which is controllable.

- Behind-the-meter fixed resources at the consumer premises.
  - Behind-the-meter fixed resources at the consumer premises are generally installed as a "set and forget" configuration, and include rooftop PV capacity. This can be considered as passive DER, which, in the form installed in the SWIS, is not able to be controlled outside of the premises in which it is installed. In the future this may include the charging of electric vehicles behind the meter[12].
- Virtual Power Plants (VPP).
  - VPPs are aggregations using technology platforms to control multiple active DER sites so they can participate in the electricity market or provide network services at scale.
- Microgrids.
  - Microgrids are separate systems, typically within a contiguous geographic area, that can operate independently of the main system for a defined period of time. Microgrids can be used to both withdraw and inject power into the grid.
- Community solar and community storage.
  - Community solar and community storage are large-scale solar and storage installations where ownership can be shared among various participants who may not have contiguous load.
- Common infrastructure such as electric vehicles charging stations.

There are many different forms of DER with new and varying business models that can provide a range of grid, essential, emergency reserves, and network support services. Unlocking these new value streams in addition to the consumers' services must be supported by markets and competition to support the investment choices delivering the best value.

[12] AEMO's 2018 *WEM Electricity Statement of Opportunities* (ESOO) (page 31) concluded that electric vehicles would have negligible impact on operational demand, representing only 1.5% of total operational demand in the 2027-28 financial year. It was not expected that electric vehicles would be used as a source of electricity supply for the household.

2. AEMO analysis

2.1 Methodology

AEMO conducted preliminary analysis[13] to determine the indicative limits (under current market and regulatory settings) at which the SWIS will likely be exposed to unacceptable power system security risks.

The preliminary analysis indicates that – although a number of limits are expected to influence the minimum amount of synchronous generation required to be online – in the absence of any other means to provide voltage control, inertia, and system strength, the first limit expected to be breached is related to voltage control.

2.1.1 Determining threshold level of demand to sustain voltage control

The first part of the analysis was to determine the level of operational demand to sustain sufficient synchronous generation online to maintain the control of system voltage. This was done by ascertaining the means by which AEMO would manage reactive power on the network under various system operating scenarios and determining the point at which controlling voltage would be compromised. Appendix 0 provides a detailed description of the methodology used by AEMO to determine the threshold level of operational demand and synchronous generation.

This analysis concluded that at or below an operational demand of 700 MW, the control of voltage on the network (due to the inadequate absorption of reactive power) would be compromised. This analysis looked at the various combinations of synchronous generation connected to the network (online and offline), ramp rate considerations, transmission lines in service, and the minimum generating thresholds of the generation fleet in the SWIS.

2.1.2 Determining market implications

AEMO constructed a preliminary simulation model of dispatch in the WEM to forecast expected market outcomes, due to the trajectory of minimum demand and the combination of generation that would be dispatched through the market to service the threshold level of operational demand determined in the first part of the analysis.

The modelling approach took the balancing merit order outcome for October 2018 and created a simulated balancing merit order outcome for each successive month of October 2019 to 2028. The model incorporated growth in DER, consumer load, and transmission-connected renewables in each of these future years. October was chosen because it has emerged as the most challenging month for system security due to its high solar irradiance and the incidence of lower load due to milder weather.

The model assumed two scenarios for DER growth over this period:

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[13] The analysis was undertaken as a consequence of AEMO's existing obligations under the WEM Rules. More sophisticated and expansive analysis (and a broader range of inputs) is warranted to determine the impact of DER on the power system and market outcomes. AEMO's capacity to undertake this further analysis will be dependent on any expanded scope of functions and requirements it receives under the WEM Rules to provide AEMO the mandate to undertake this analysis and to recover the costs of activities performed in relation to these expanded functions and requirements.

- PV forecast from AEMO's 2018 *WEM Electricity Statement of Opportunities* (ESOO)[14]: DER installed each year from 2019 to 2028 (where the average rate of growth of solar PV per year is 150 MW per year over this period).
- As a sensitivity, an additional persistence PV forecast: DER installed at 200 MW per year, based on the 2018 growth rate of PV installation.

The model also assumed:

- No change in generation bidding behaviour and no major changes to current policy settings such as the network connections framework. These are simplifying assumptions not reflective of AEMO's assessment of future likelihoods.
- Load grows at an average of 1.65% per year and renewable projects enter production in accordance with Table 3 in Section 2.2.2 of this report.
- No additional renewable projects over and above those identified in Table 3 connect to the SWIS over the period between 2018 and 2028.

2.1.3 Determining the year in which DER growth forecast to cause breach of system security threshold

The final part of the analysis was to determine the date at which SWIS operational demand would breach the system security threshold of 700 MW.

In evaluating when system security risks are projected to arise, AEMO considered and modelled day-to-day variability in the forecasts. The incidence of future system security risks was determined based on analysis that calculated operational demand in every half-hour interval from 2019 to 2030, based on the following key inputs:

- Historical SWIS demand data[15].
- Historical rooftop solar PV generation capacity factor data[16].
- Persistence PV forecast: DER installed at 200 MW per year from 2019 to 2030, based on the 2018 growth rate of PV installation.
- 2018 ESOO load growth forecasts: month-by-month projections of expected load growth out to 2030.

The modelling approach calculated the underlying load (the sum of operational demand and rooftop solar generation) in each demand reference year, then applied a load growth rate based on the ESOO forecasts. Rooftop PV generation in each interval in a year was determined by applying ESOO forecasts of PV installed capacity to historical capacity factor data. The operational demand forecast was then calculated by subtracting rooftop PV generation from underlying load. To consider variability in forecast of load and solar generation patterns, this process was applied to multiple demand and solar reference years.

2.2 Additional system characteristics influencing system security

2.2.1 System inertia

AEMO has undertaken analysis to investigate system inertia, particularly in response to larger generator contingencies (greater than 300 MW). Inertia levels have been identified in the order of 8,000 megawatt seconds (MWs)[17], which can be provided by a level of synchronous generation output slightly lower than the

[14] Available at https://www.aemo.com.au/-/media/Files/Electricity/WEM/Planning_and_Forecasting/ESOO/2018/2018-WEM-ESOO-Report.pdf.

[15] AEMO, Market Data Western Australia – Balancing Market Summary. Available at http://data.wa.aemo.com.au/#balancing-summary.

[16] PV capacity factor data is the same as that used in the 2018 ESOO. The 2018 ESOO capacity factor data was developed based on the output of rooftop PV systems sampled across the SWIS, and comparisons to irradiance values from the Bureau of Meteorology (BOM). Regression analysis was applied to produce a historical SWIS rooftop PV capacity factor trace.

[17] Megawatt seconds is a measure of the amount of kinetic energy in the grid.

700 MW identified for voltage control, for the minimum frequency level that can be reached before under frequency load shedding (UFLS) will be required.

However, this is strongly dependent on the size of the largest contingency relative to the system size at the time. A number of indicative studies indicate that the loss of a much smaller unit, around 150 MW output, can be tolerated down to even lower levels of inertia without impacting system security (possibly of the order of 100-200 MW lower). This is dependent on what generators are online, as well as the available primary frequency response.

As current indications are that the voltage control limit will be the first limiting factor, further studies are planned to detail the inertia requirements of the SWIS.

However, it should be noted that the size of the maximum contingency may need to be managed by constraining down generation at lower loading to ensure the system can respond to the contingency.

2.2.2 Changes in the generation mix and load

Based on AEMO's analysis, Figure 3 shows the expected growth in DER and utility-scale renewables and the resulting net demand. As more DER is installed, minimum demand is likely to continue to reduce, and continue to occur during the day as has been the case in recent years.

Figure 3 Expected profile of minimum demand, DER capacity (in the form of solar PV) and new utility-scale renewable installed capacity, based on the persistence PV installation forecast

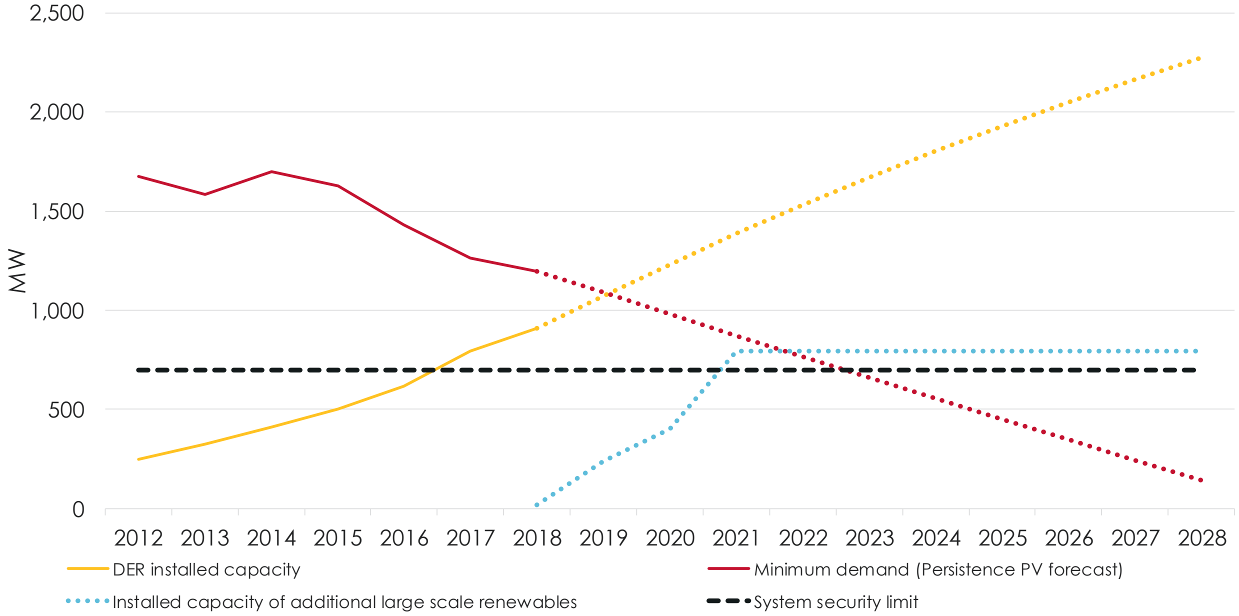


Figure 3 shows the minimum operational demand and DER capacity. In 2022 the level of minimum operational demand will potentially breach the system security threshold of 700 MW. In this year, DER will potentially supply 62% of underlying demand in the Trading Interval with the maximum DER penetration.

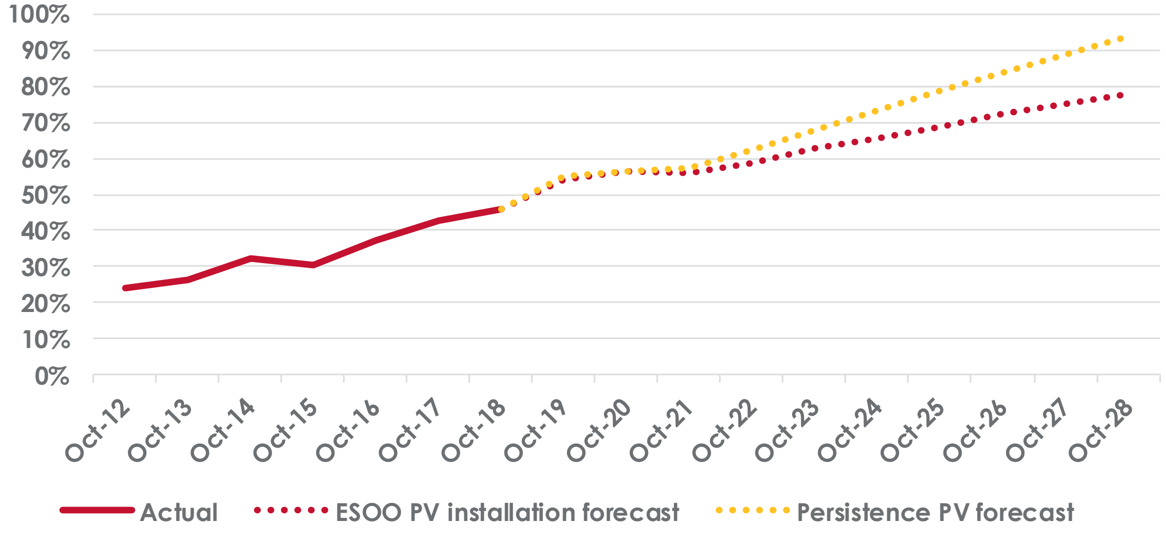
Most importantly, the differentiator between rooftop PV DER and utility-scale solar installations is the extent of individual facility control. In the absence of revised technology standards and communication systems, rooftop PV DER cannot be curtailed easily or quickly without also disconnecting the loads they are connected to.

The proportion of energy supplied from renewable sources is expected to increase significantly in respect of the maximum penetration intervals. This will reach high levels by world standards. To ensure secure operation, Ireland's system operator EirGrid currently imposes an instantaneous 65% limit on the contribution of non-synchronous generation (mostly wind)[18], up from a previous limit of 50%. This higher limit was developed as part of EirGrid's DS3 program, a major ongoing study undertaken since 2011 to identify the Irish system's non-synchronous generation limits and develop system service products to enable greater integration of renewables.

In 2018, the SWIS experienced periods above 40% of non-synchronous generation in a Trading Interval[19] (see Figure 4). AEMO's analysis projects that the SWIS will potentially reach an instantaneous non-synchronous generation level of 65% in 2024 (or 2023 under the persistence PV forecast scenario).

However, the key distinctions between the SWIS and the EirGrid, namely the higher level of rooftop PV penetration in the SWIS and the lack of interconnectivity of the SWIS to another electricity grid, are considerations in the sustainable level of instantaneous non-synchronous generation penetration. In the absence of an appropriate suite of technologies to support the provision of essential power system services from renewable generation and DER, the options for ensuring the secure operation of the SWIS as higher levels of renewable generation are achieved are limited. Either a greater proportion of synchronous generation will need to be online at all times to provide essential system services, or significant network investment will be required.

Figure 4 Maximum instantaneous penetration of variable renewable energy (rooftop PV systems and utility scale renewables) in a trading interval in October



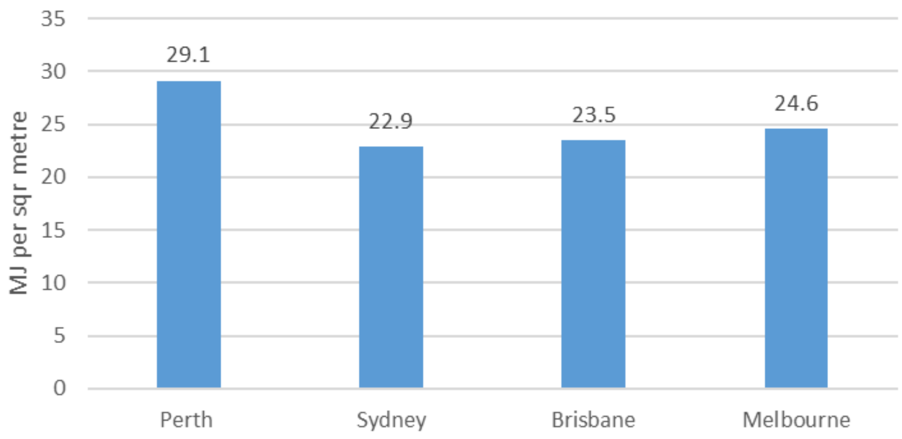
High solar irradiation and uptake of rooftop solar PV

The SWIS has an excellent solar irradiation resource, making it a particularly attractive location for the installation of solar PV. Perth has a January monthly average solar irradiance of 29.1 MJ per m^2 which is 27% greater than that of Sydney, 24% greater than Brisbane, and 18% greater than Melbourne (see Figure 5).

[18] Eirgrid Group, media release, "Eirgrid Group achieves record level of variable renewable energy on Irish electricity system", 13 April 2018. Available at http://www.eirgridgroup.com/newsroom/record-renewable-energy-o/index.xml. The increase to an instantaneous 65% limit was implemented after a five-month trial by EirGrid Group.

[19] Instantaneous penetration of non-synchronous generation was calculated on an end-of-interval basis in the current analysis. The maximum instantaneous penetration of non-synchronous generation may reach 65% within a Trading Interval before 2023.

Figure 5 Perth's comparative solar irradiance



In 2018, approximately 200 MW of new rooftop PV systems was installed, representing an increase in total rooftop PV capacity in the SWIS of around 24% in the last 12 months.

AEMO forecasts rooftop PV capacity in the SWIS to increase 165% from 913 MW in 2017-18 to 2,419 MW in 2027-28 under the high case of the 2018 WEM ESOO[20].

In parallel with the growth of new renewable generation, the traditional generation fleet in the SWIS is aging, particularly coal-fired generation. The four oldest coal-fired power stations units (854 MW in total) consist of two units that are 35 years old and two units that are 40 years old.

It is expected that at least some of these older SWIS coal-fired power units will cease operations during the 2020s as they approach their nominal 50-year design life coupled with decreased revenues from reduced energy dispatch and higher maintenance costs due to increased ramping and cycling.

This will potentially have implications for the ability of the system to maintain stable frequency and voltage unless alternate technologies through specific technical standards, markets, or regulatory frameworks to enhance the SWIS and manage secure grid operation are put in place.

Analysis of cheapest generation options

Analysis undertaken by AEMO and the CSIRO in the NEM for the inaugural *GenCost 2018* report[21], which analysed energy generation costs for new power plants in Australia from 2020 to 2050, found that new-build solar and wind technologies are the lowest-cost form of generation. This remained the case even when solar and wind firmed with energy storage of up to six hours were considered, and climate policy risks were taken into account. The data and information provided in the GenCost report was used by AEMO as the basis for broader consultation on inputs and assumptions for use in key forecasting and planning publications, such as the 2018 Integrated System Plan (ISP) for the NEM.

AEMO published the inaugural ISP for the NEM in July 2018[22]. The ISP analysis confirmed that the generation mix was changing, characterised by a growing proportion of supply from renewable energy sources and non-synchronous generation, and from DER (primarily rooftop solar PV)[23]. It also indicated that, based on projected costs, the least-cost transition pathway to achieving economic replacement investment is to replace retiring coal generation with a portfolio of utility-scale renewable generation, energy storage, DER, flexible thermal capacity, and targeted investment in transmission.

[20] See https://www.aemo.com.au/-/media/Files/Electricity/WEM/Planning_and_Forecasting/ESOO/2018/2018-WEM-ESOO-Report.pdf.

[21] Graham, P.W., Hayward, J, Foster, J., Story, O.1 and Havas, L., CSIRO and AEMO, *GenCost 2018*, December 2018, available at https://www.csiro.au/en/News/News-releases/2018/Annual-update-finds-renewables-are-cheapest-new-build-power.

[22] See https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Integrated-System-Plan.

[23] AEMO, 2018 ISP, pp.4-6.

This approach will not only minimise overall cost, but also support consumer value by making better use of existing plant, DER, lower fuel and operating costs of variable renewable generation, and operating risk.

Proposed renewable generation in the SWIS

The proposed and likely renewable generation and PV DER installations planned to occur in the SWIS in the next three years are shown below in Table 3. A total of 1,267 MW is projected to be installed.

Table 3 Expected increase in rooftop solar PV and renewable generation in the SWIS between 2018 and 2021

Source*	Scale (MW)	Year
Rooftop and commercial solar PV**	477	Cumulative including 2017-18 to 2020-21
Northam solar farm	10	2018
Greenough River solar farm expansion	30	2020
Badgingarra wind farm	130	2019
Merredin solar farm	100	2019
Warradarge wind farm	180	2020
Yandin wind farm	210	2020
Other wind or solar farm(s)	130	2020-21
Total	1,267	

* The utility-scale renewable projects in Table 3 are those that have either signed a network connection contract (including Generator Interim Access) with Western Power or are being developed by a Market Participant that is a retailer in the SWIS.
** From 2018 WEM ESOO.

2.3 Conclusions from the analysis

A widespread shift from large synchronous and dispatchable (coal and gas) generation to non-synchronous and variable renewable generation resources, under the present operational and market frameworks, will be felt in terms of lower levels of inertia and reduced voltage control capability, and other challenges such as decreasing system strength, increasing variability, and more rapid changes in frequency during normal operation and following single and multiple contingency events (as shown in the following chapter).

Maintaining power system security and reliability of supply in these conditions will necessitate more frequent and deeper interventions under the current frameworks, particularly at times of low demand. Preliminary analysis undertaken by AEMO for the purposes of this report projects that, without urgent action to accommodate the forecast changes to the generation mix, the SWIS will face an increasing threat to system security and a progressive and rapid deterioration in the function of the market.

Key findings

Assuming no changes to the present technical standards and the WEM regulatory regime, and renewable generation and DER growth as forecast by AEMO, the key findings from the studies are:

1. At a minimum operational demand and synchronous generation level of less than 700 MW, voltage control is problematic resulting in unsecure operation and high likelihood of cascading failures on the system. The worst-case scenario is the real risk of a SWIS blackout due to cascading failure or widespread load shedding if no action is taken now to implement the technologies and regulatory reforms to support secure operation of DER and renewable generation technologies.
2. As the SWIS approaches a minimum operational demand level of 700 MW, it will become increasingly unstable, requiring increased frequency and extent of intervention by AEMO to maintain power system security by constraining off non-synchronous generation and constraining on synchronous

generation. Various forms of network investment to maintain system security will be required in addition to reforms to the ancillary services framework.

In addition, the studies concluded that, without investment[24] (for example, in alternative technology resources that can provide essential services) or change:

- By the early-2020s, the market and system would no longer be able to operate in an acceptable cost-effective, secure, and reliable manner.
- By 2023, the market would reach the wholesale market floor cap, resulting in distorted market signals.
- From 2022 to 2024, AEMO would have to, as a last resort after constraining off non-synchronous generation and constraining on synchronous generation, employ rotational load shedding to disconnect excess DER generation to preserve system security. Load shedding would be implemented by the distribution utility via UFLS schemes. The UFLS scheme configuration may need to be modified to enable discrimination between feeders that are net load blocks versus feeders that are net generators (exporting to the grid) due to high DER generation output relative to demand.
- UFLS schemes will need to be reviewed in the near future prior to the connection of new renewable generation between now and 2021 or risk exacerbating system collapse if the wrong (high DER output and net generator) distribution feeders are disconnected for a loss of generation contingency event.
- Inertia issues materialise at slightly below the 700 MW of synchronous plant generation limit, based on present plant capabilities and dispatch, although further work is required to determine the exact limit.

When considered separately, increases in non-synchronous generation and increases in DER penetration will stress the current technical and operational limits of the SWIS power system and will challenge the function of the market. In the absence of immediate reforms to technical standards, market and regulatory mechanisms, the effect of increases in non-synchronous generation and increases in DER penetration create untenable risks to system and market operation. These can include blackouts and distorted market signals as the consequence of the level of online synchronous generation trending below minimum required levels to provide the essential system security services.

While further analysis is required to conclusively determine specific values for various technical limits, a comparison to international benchmarks shows that penetrations in the SWIS are reaching levels that will result in significant challenges. Moreover, this analysis shows the need to look at the issue holistically; if issues with voltage control are resolved (for example, through the installation of additional network reactive devices), then inertia or system strength difficulties will soon become apparent. Ultimately, with insufficient levels of operational demand, there will not be enough demand remaining to enable sufficient levels of utility-scale synchronous generation to also provide the traditional WEM ancillary services and power system support services required to operate the SWIS.

AEMO considers that appropriate technical standards for inverters, and well-managed processes for integrated system planning, market and regulatory arrangements, need to be developed and implemented in the next 12-24 months, so the electricity system can continue to be provided with essential services for system security and the WEM can provide opportunities for consumers to benefit from their individual contributions to power system security and reliability.

[24] Under the existing regulation and market rule arrangements it is difficult to see how these investments would occur for essential services that presently are not renumerated. Potentially Western Power could put up a case that these alternative technologies are needed for power system security or AEMO could seek to source through the Dispatch Support Services framework; however particularly for previously undefined essential services this is an unproven approach and subject to Economic Regulation Authority approval.

3. Challenges posed by growth in DER and utility-scale renewables in the WEM

3.1 Security risks and market impacts from decreasing demand

3.1.1 Operational challenges

Increasing rooftop PV DER penetration has led to significant decreases in daytime demand, with system day minimum load levels falling year-on-year since 2014. Due to the reduced operational demand, less synchronous generation is online during daylight hours. The continued reduction in minimum demand levels poses an operational challenge, because system essential services[25] in the SWIS are currently being provided by synchronous generation to ensure system stability and security. In the present system and market arrangements, if operational demand falls below the minimum level of synchronous generation needed to provide the required levels of essential services, the power system will be in an unsecure operating state and vulnerable to blackouts.

Daytime minimum demand is currently at its lowest level since 2000. Figure 6 illustrates daytime minimum demand increasing with night-time minimums until 2014. It has since decreased rapidly, falling approximately 500 MW in four years, and falling below night-time minimums in 2016. The forecast minimum demand, based on AEMO's analysis, show night-time minimums increasing while daytime minimums continue to decrease. Based on modelled trajectories, the SWIS will breach the existing minimum level of operational demand (700 MW) required for system security between 2022 and 2024, depending on PV DER installation rate, load growth, and day-to-day variability in load and solar PV generation patterns.

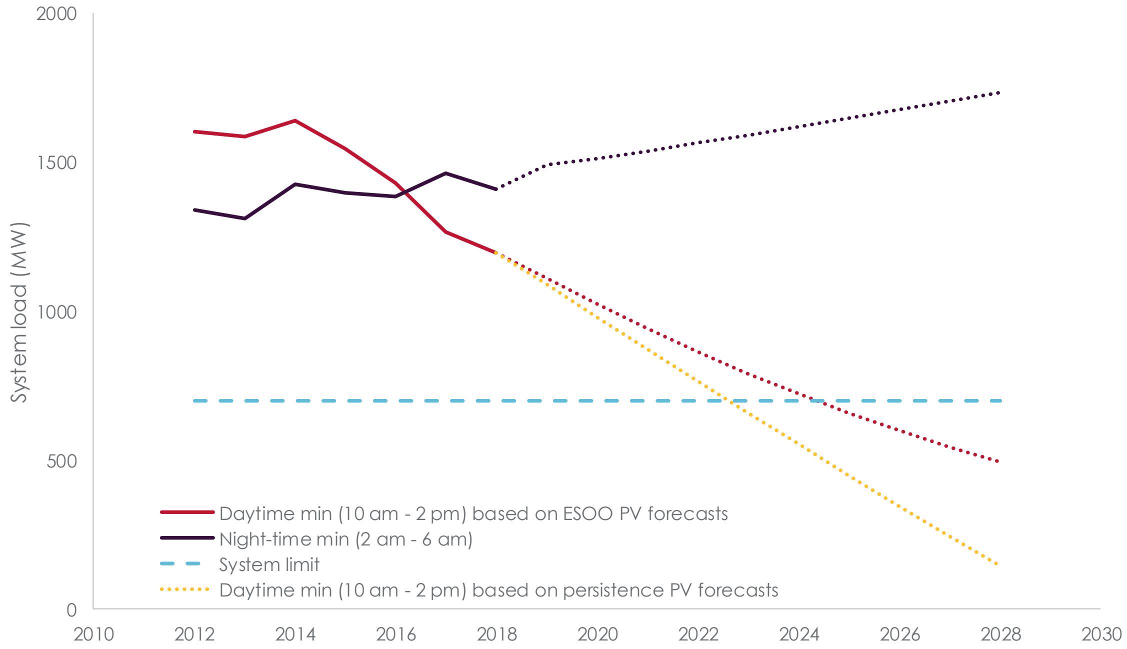
The relationship of reactive power, DER, and system security

Reactive power is required on the network to ensure power can be transported from where it is produced to where it is required. In addition, some loads require reactive power to function correctly. Reactive power has traditionally been provided by synchronous generators. However, it is also generated by the network elements themselves. A balance in the reactive power generated and that required is essential to manage voltages within limits. Voltages are required to be within equipment design limitations to prevent damage, or incorrect functioning of equipment. This may occur right through the system from the transmission network through to customer equipment. While frequency provides an indication of the balance between supply and demand in real power (MW) terms, voltage provides an indication of the balance between supply and demand of reactive power (MVAr). However, while frequency is a system wide measure of this balance, voltage is a more localised measure.

A heavily loaded network requires reactive power to be provided while a lightly loaded network will generate excess reactive power which needs to be absorbed or taken off the network to keep voltages within limits. The penetration of DER means that the SWIS is increasingly lightly loaded and this poses a threat to system security (voltage management) as the level of DER penetration increases.

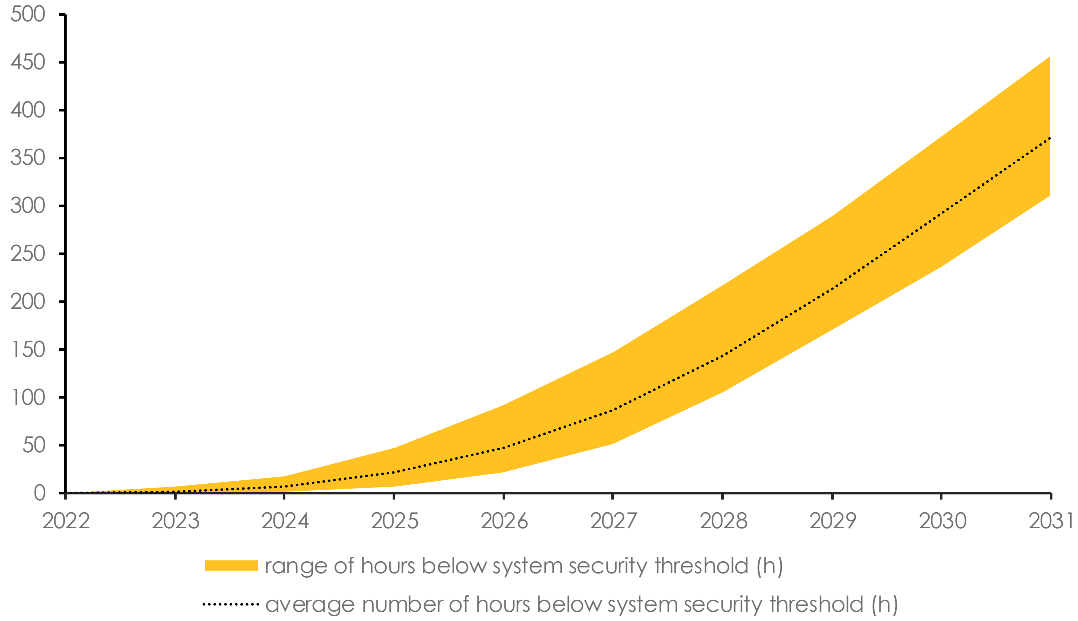
[25] Including resource adequacy and the management of frequency and voltage. System strength and inertia falls within these attributes.

Figure 6 Minimum demand (MW) in each calendar year, 2000-18



AEMO's forecasts that considered day-to-day variations in load and rooftop PV generation involved multiple simulations to account for forecast variability. Figure 7 shows the range of hours in a year where SWIS operational demand is projected to be below the 700 MW system security threshold. The dotted line represents the average across the simulated outcomes.

Figure 7 Range of hours in a calendar year where SWIS operational demand is below the system security threshold (persistence PV forecast)



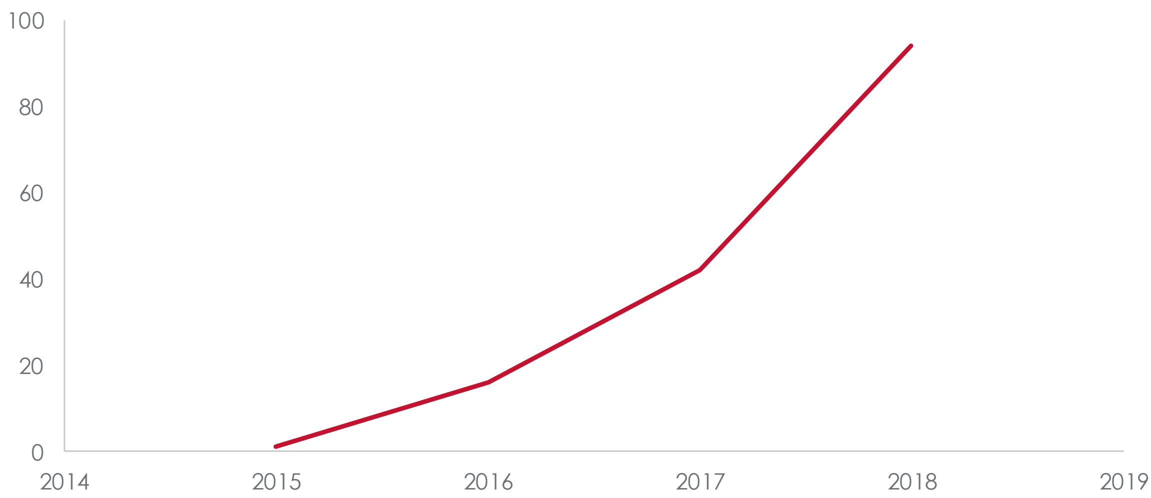
In as early as 2022, the system security threshold could be breached in up to 10 hours of the year; by the end of 2024, the system is unsecure in up to 50 hours; by the end of 2030, this number increases to 460 hours (more than 19 days) of the year. This reflects the escalation of challenges for the secure and reliable operation of the power system.

Under these circumstances, the first response would be to constrain off non-synchronous generation and constrain on synchronous generation to prevent system collapse. However, instances can arise, although they are rare, where a level of shedding of DER is required to maintain system security. If the entirety of the shortfall below the 700 MW system security threshold was required to be met by the shedding of DER (when the ability to constrain on synchronous generation is limited), 48,000 households would need to be disconnected. In 2022, up to 58,000 households may experience interrupted electricity supply for a DER shedding event; in 2025, this increases to 252,000 households[26]. The increase in the number of households subject to disconnection is a consequence of the reduction in operational demand.

Further, low operational demand is occurring more frequently during daylight hours. Figure 8 shows daily minimums now happen exponentially more often in the daytime, with the trend expected to continue in 2019 and beyond as DER penetration continues to rise.

Coupled with the trend of daytime minimums being lower than night-time minimums, the increased frequency of daytime minimums means there is increased probability of the system entering an unsecure operating state, due to demand falling below the minimum level of synchronous generation required for the provision of essential power system services. This highlights the importance of the reforms to the ancillary services framework currently underway as part of the WEM Reform Program with respect to the type, speed of response and duration of ancillary services to maintain system security.

Figure 8 Number of days where daytime minimum demand was the daily minimum, 2015-18



3.1.2 SWIS demand profiles

Power systems with high rooftop PV DER penetrations, where large amounts of solar generate during the daylight hours, are experiencing demand profiles referred to as the "duck curve", due to their shape.

The duck curve demand profile is more pronounced during low-load days, typically a sunny autumn or spring weekend day, when rooftop PV systems are at maximum production within the SWIS (shown in Figure 9 and Figure 10 below). The high output from larger utility-scale solar systems contributes to the operational challenges of managing low demand periods by tending to force out higher marginal cost synchronous plant as the result of competition to supply the remaining operational demand.

Over the last five years, the shape of the load curve on the minimum demand day has changed considerably. Prior to 2016, the duck curve effect was not observable during the minimum demand day. This changed in 2016, and since 2017 minimum annual demand has occurred during the daytime, both times in October.

[26] This analysis assumes rooftop PV grows at 200 MW per year, the rooftop PV installation is 5 kW, half of all residential customers have rooftop PV in the disconnected area, and midday residential demand is 0.4 kW per household. This results in an average household DER export of 2 kW during the middle of the day in the disconnected area.

The operational challenges posed by reducing minimum demand are:

1. High ramp rates (up and down), which at present are required to be managed by the dispatchable thermal generation fleet, may challenge the ramp rate capability of some units. This could be assisted or managed with energy storage.
2. The evening peak period is characterised by almost no solar generation, requiring a complete change of generation sources at this time, presenting challenges if the required generators are forced to switch off during the day in the absence of any storage.
3. The penetration of rooftop PV DER cannot be curtailed by Western Power or AEMO without turning it off altogether by disconnecting a distribution feeder or substations, also disconnecting the load it is connected to.
4. Due to the islanded nature of the SWIS, in the absence of large-scale energy storage, there is no load to have generators running and synchronised on standby ready for the evening ramp and peak as the PV DER drops away.

To illustrate these challenges, three key operating zones are shown on the duck curves in Figure 9 and Figure 10:

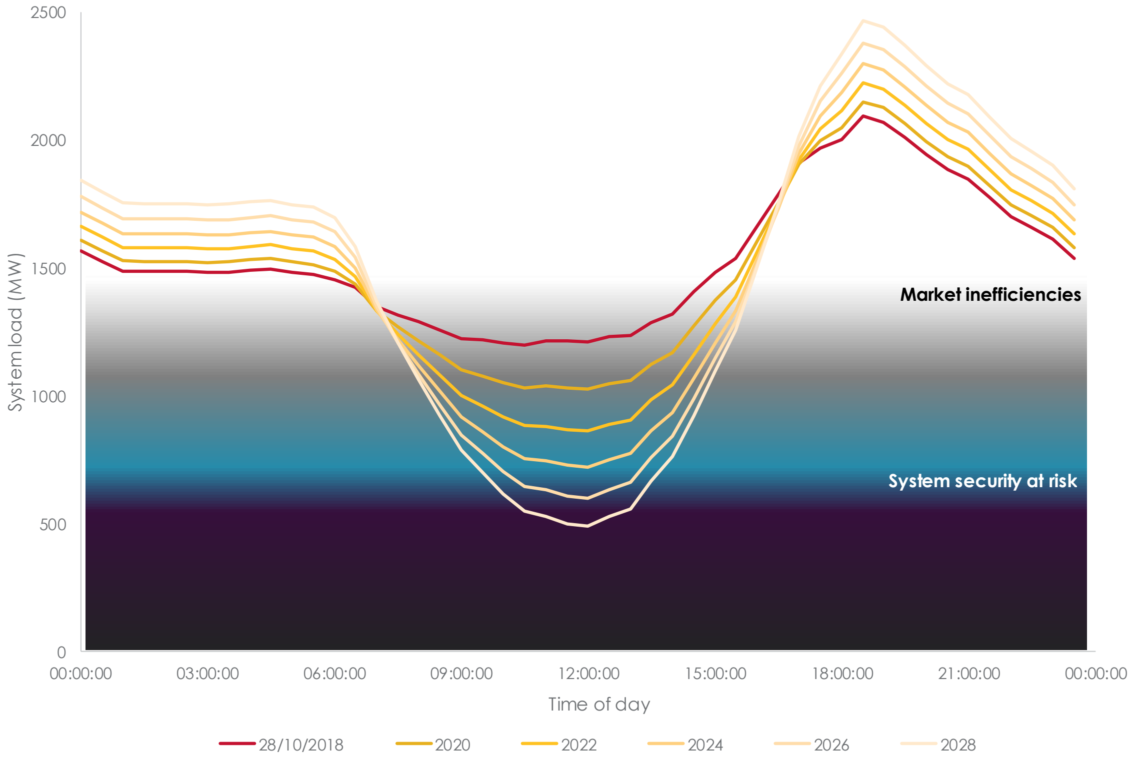
- Market inefficiencies – grey zone:
  - Baseload plant was designed for relatively steady operation and not for the fast ramping or cycling[27], which is becoming a feature of a power system with greater variability on both the demand and supply side. Baseload generation (mainly coal units) have a minimum generation limit below which they cannot generate. Baseload units are, by design, not built to ramp up or down quickly during the day or cycle on and off, as this will cause mechanical and thermal stress to their equipment in the long run, and compromise cost efficiency and reliability in their operation. To avoid going below their minimum generation limit, or where ramping will be significant, baseload units may choose to shut down operation and then restart in a few days' time. However, there are start-up efficiency and reliability impacts from this cycling.
  - The combination of all these issues is represented by the grey zone, and is expected to increase costs for existing generators that would be expected to eventually be passed on to consumers. Furthermore, while the SWIS has a relatively high proportion of gas peaking plant that provide relatively fast ramping without compromising equipment efficiency, peaking plant are higher cost than baseload coal-fired and combined cycle gas plant. The grey zone would be expected to become larger with increasing levels of utility-scale renewables as renewables have close to zero marginal cost and hence tend to bid lower than fossil-fuelled generators.
  - To ensure system security, the market would be more reliant on ancillary services that are contracted or tendered in contrast to real-time dispatch (while the WEM Reform Program will co-optimise energy and ancillary services, it is not anticipated that all ancillary services will be co-optimised).
- Market inefficiencies – blue zone:
  - Synchronous machines (mainly fossil-fuelled plants) that are connected to the power system provide kinetic energy in the form of inertia (known as stored energy) and system strength, and also assist with voltage control. These characteristics enable the power system to withstand disturbances and contingencies, and to maintain frequency and the voltage within the required acceptable range dictated by the technical standards. The blue zone shows the potential limitations of minimum inertia and voltage control that is required within the SWIS at low-load periods and may require AEMO to constrain off non-synchronous (that is, inverter-connected) generators if the price has not already fallen below their bid price, noting that generator unit quantities needed to provide existing ancillary services are required, under the WEM Rules, to bid that capacity at the market floor price.

[27] Consequently, baseload is not readily dispatchable.

- Under the present wholesale market arrangements, those generators constrained off would generally be paid as if they were still running, which results in additional cost to the market. There are many factors that impact the maximum amount of non-synchronous generation that can be accommodated by the power system, including the type and characteristics of the online thermal generation and operational demand. Where these non-synchronous limits are reached, AEMO must constrain off utility-scale non-synchronous generation.

- System security risks – black zone (<700 MW[28]):
  - Power system operation below the blue zone is presently unsustainable, characterised by a greater exposure to system security and reliability issues such as blackouts in the event of multiple or large contingency events that would necessitate load shedding to maintain system security. This limit would occur when the DER has reached such a high level that, even after AEMO has dispatched off all controllable utility-scale non-synchronous generation (either due to the market price falling below non-synchronous generation bid price or AEMO directing this plant off), there is insufficient demand on the system to keep the required level of synchronous generation energised.
  - The lower the amount of synchronous generation providing essential services below the critical level, the higher the system security risk[29]. AEMO would then be faced with two scenarios, if urgent action is not taken, namely either to let the level of synchronous generation fall below the minimum level and hope there are no contingencies, or to instruct Western Power to trip off distribution feeders with high DER export[30]. AEMO would take the second action, as it must ensure that the system operates securely.

Figure 9 AEMO's analysis on the shape of the load curve on the minimum demand day, 2018 actuals forecast to 2028, based on ESOO PV forecasts

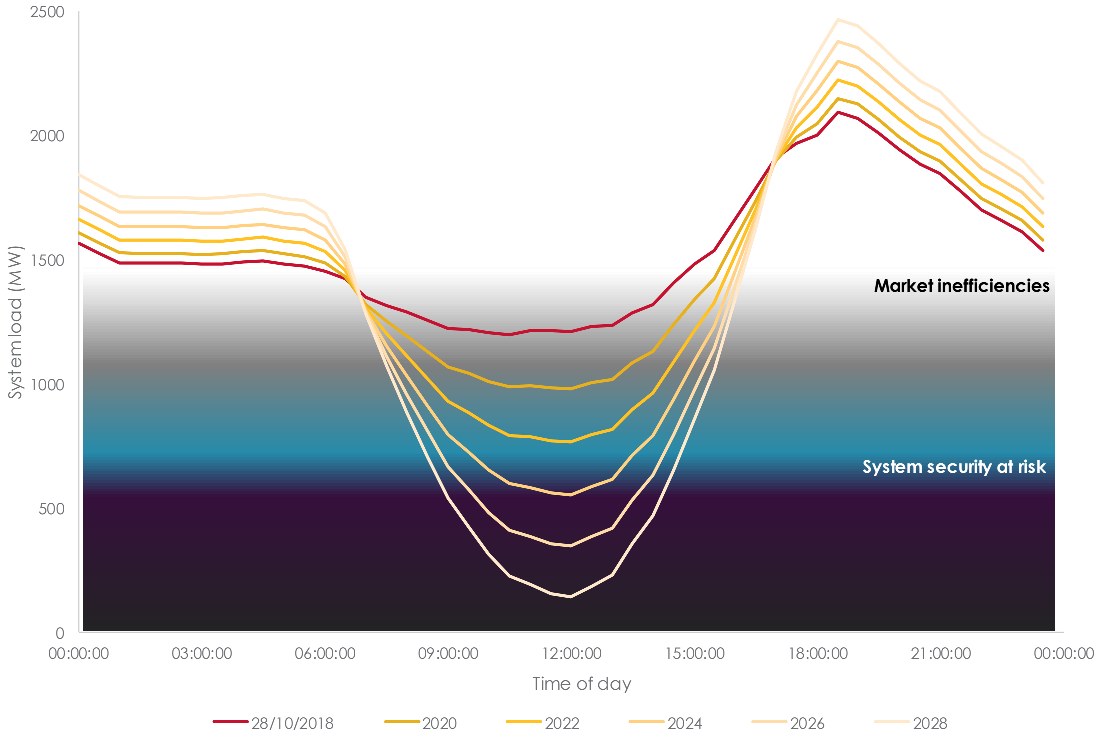


[28] The methodology of the system security threshold of 700 MW is outlined in Appendix 0.

[29] Ultimately, where DER output exceeds all underlying operational demand (that is, below the 0 MW line), frequency will rise and DER inverters would then reduce output. However, as this is not coordinated, and with no plant providing frequency control services, frequency swings would ultimately result in under frequency load shedding, and system blackout would likely result.

[30] Further consideration of regulatory instruments is required to ensure this is an option available to AEMO, noting these powers have been used where there is insufficient generation but not for excess generation.

Figure 10 AEMO's analysis on the shape of the load curve on the minimum demand day, 2018 actuals forecast to 2028, based on a persistence PV forecast



3.1.3 Increased frequency of intervention to maintain system security

The outcome of the reduction in operational demand is expected to result in rapid escalation in the proportion of trading intervals that have negative prices that are frequently and persistently below the short run marginal cost of synchronous generators.

The result of this is that synchronous generation will have no economic incentive to be online, and, if not remaining online for other reasons such as expectation of higher prices over the peak, will not provide the essential services required to sustain system security and reliability.

Therefore, AEMO will be required to intervene in the market for security purposes to ensure a required level of synchronous generation is dispatched, contrary to the dispatch outcome that would have otherwise occurred under balancing merit order (the market pricing mechanism).

This is evidence of partial market failure. Market failure occurs when the market is effectively sidelined or bypassed because price signals have become misaligned from system reliability/security requirements and the price of electricity does not reflect the true value of services directly or indirectly arising from its supply. In the instance of this market failure, a non-market process determines the supply of these direct and indirect services, because the price mechanism is unable to sustain their economic provision.

The frequency of this market intervention is expected to increase exponentially as operational demand continues to decrease. Directions in South Australia have led to an estimated direct cost of $20 million a year to market participants in South Australia; indirect costs in terms of opportunity costs for generators that are constrained off to preserve system security (that is, generators that do not provide essential services) could be as much as an order of magnitude higher.

Additional modelling is recommended to more accurately quantify the cost of the market implications of the necessary responses to DER and utility-scale renewables penetration.

Occurrence of system security risks

While October has been identified as the most challenging month in recent experience, it is important to note that risks to system security occur across all the months of autumn (September to November), and parts of late winter and early summer. AEMO's analysis indicates that the period between September and December consistently poses significant operational challenge, due to relatively low load and high PV generation.

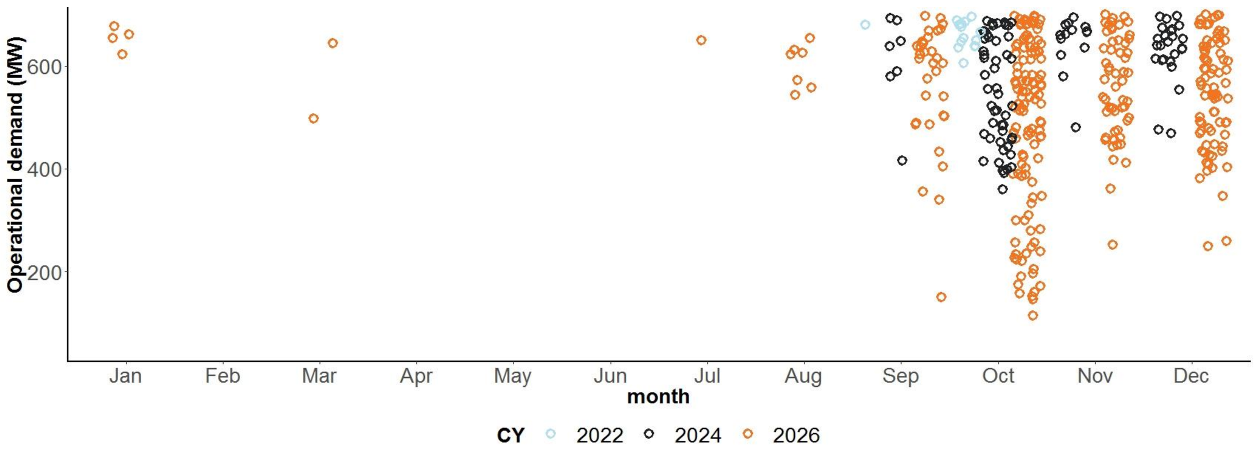
Operational challenges are also likely to be exacerbated by large variations in the spread and occurrence of system security risks. Any DER action plan must take into account, plan for, and be flexible enough to accommodate the fact that security risks of varying duration may occur at any time across more than four months a year.

Table 4 and Figure 11 show a possible distribution of system security breaches where operational demand was below the 700 MW threshold. Figure 11 shows the distribution of intervals, with every circle representing a 30-minute period with operational demand less than 700 MW.

Table 4 Indicative distributions of system security risks

Parameter	Possible distribution		
	2022	2024	2026
Months where risks occur	September-October	September-December	May occur throughout the year: Jan, Mar, Jul-Dec
Lowest operational demand	600 MW	350 MW	100 MW
Number of hours affected on the worst day	3 hours	6 hours	7 hours
Maximum number of households requiring disconnection	Up to 60,000	Up to 200,000	Up to 300,000
Total hours in the year below 700 MW threshold	10 hours	50 hours	150 hours

Figure 11 Indicative distribution of system security risks across a year: events in each month



The 700 MW system security threshold indicates the commencement of the black zone represented in Figure 9 and Figure 10 that depict AEMO's analysis on the shape of the load curve on the minimum demand day. Above the black zone in these figures is the blue zone. It is important to note that the extent of market intervention on the part of AEMO to constrain on synchronous generation to maintain system security will occur even when operational demand is above 700 MW, as indicated in the blue zone in these figures.

The consequence is that the frequency of AEMO intervention in the market is significantly greater than the analysis conducted on the black zone, which shows where potentially all generation operating in the SWIS in these instances is operating as a consequence of an instruction from AEMO, as opposed to the economic merit order.

3.1.4 Impact of ramping on coal units

Coal-fired generation units involve the interaction of many mechanical and thermodynamic processes, such as grinding mills, fuel conveyor systems, fuel injection, boilers, steam turbines, and cooling systems. These processes are designed to operate within fine engineering tolerances, and the operation of the coal-fired power station can be compromised by the failure of any singular system. The risks of the failure of any singular system is accentuated when the plant as a whole is operated in a manner contrary to its original design, such as when the plant is required to stop and start or ramp its output frequently over wide ranges.

AEMO analysed publicly available SCADA data, and found that changes in the behaviour of Synergy's coal fleet (as part of the Synergy portfolio that is the default provider of ancillary services in the SWIS) are already being observed. In calendar year 2018, Synergy coal fleet movements were higher than in any other year. Continued increases in coal fleet movements are likely to lead to additional maintenance requirements and a reduced economic return. As an example, Muja 5 experienced 11% more trading intervals that exhibited ramping in 2018 than was the case in 2014.

Synergy has advised AEMO that:

- If the Muja D facility's two 227 MW coal-fired units were two-shifted (stopped and started within a day) on an ongoing basis, which is expected to be the case in coming years, the maintenance cost of these units would increase approximately $8 million per year.
- If the minimum generation level is reduced below the existing level to enhance the flexibility of Muja D's dispatch, Synergy has undertaken preliminary analysis indicating that this would entail a significant capital expense, requiring an eight-week plant outage and a 12-month lead time for design and plant preparation. The required outage to undertake the required capital works could cost Synergy approximately $11 million[31] in foregone revenue.

Two-shifting coal-fired units also imposes operational risks that the plant will trip during the ramp-up process, or that the ramp-up process will be delayed for various mechanical or thermal reasons, such that the plant will not be fully online to meet the peak. Two-shifting is expected to become a common occurrence in future years as the growth of DER and utility-scale renewable generation continues.

Additional analysis of the incidence and implications of the ramping of Synergy's coal units as the default provider of ancillary services is shown in Appendix A2.

3.1.5 Variability of renewable generation in the SWIS

Generation output from a solar PV system changes based on cloud cover, sun angle, shading on the PV system, and to a lesser extent temperature. Rapid and increasing DER penetration has increased the significance of rooftop residential and commercial solar PV generation, and has made operational demand more exposed to transient weather conditions. The smaller geographic spread of rooftop solar PV in the SWIS (as opposed to the NEM which has multiple regions) means localised conditions such as cloud cover have a greater impact on overall PV generation.

Further, generation variability is cumulative across variable renewable generation technology types. Wind generation in the SWIS is currently difficult to forecast, and the impact of wind variability has increased with the installed capacity of wind from 500 MW to 630 MW[32] in 2019, and will increase even more when the forecast installation of wind capacity increases to 1,020 MW in 2021.

[31] Figure estimated by AEMO assuming a capacity factor of 60% and an average electricity price of $30 per MWh.

[32] Due to the addition of Badgingarra Wind Farm (130 MW) in early 2019.

Increasing variable renewable penetration means fluctuations in operational demand have become both more frequent and larger in size, introducing significant intra-day as well as inter-day variability. The changing and variable operational demand profile is already being seen in the SWIS.

Variability of renewable generation can be reduced and managed with energy storage technologies.

3.1.6 Under-frequency load shedding

AEMO has analysed substation electricity flows to determine the extent to which reverse power flows are evident at specific substations and associated feeders due to generation from DER exceeding customer demand.

In the circumstance of reverse power flows, certain substations are contributing to the total supply of generation in the system. This undermines the assumption that substations always act as loads, which has significance in the extreme case where targeted load shedding is required to address major generation disruptions in the transmission network.

UFLS is designed as a last resort option to maintain system security and prevent more widespread system collapse by shedding load to remove the imbalance between the demand and supply of electricity. However, the operation of the UFLS scheme is typically an automated response at the substation level to major generation disturbances in the transmission network that cannot be addressed by dispatching other forms of generation.

Paradoxically, reverse power flows are advantageous in the rare circumstance of major generation disturbances that cannot be addressed by the dispatch of alternative generation. However, the traditional design of the UFLS scheme can compound system security risks if a substation is disconnected in response to a major generation disturbance when the substation is actually exporting electricity to the transmission network.

Analysis of 2018 data found that several substations (which include multiple distribution feeders) in the SWIS are net exporters of energy during the day in the shoulder and early summer periods (particularly September to December). The occurrences of net export across the distribution system will only increase as more DER is installed.

UFLS schemes in the SWIS are implemented based on static settings using broad assumptions regarding the load distribution and profile on the distribution network. These static settings have been sufficient in the traditional one-way flow power systems, with UFLS operating by switching off distribution feeders that are importing electricity from the grid. In the evolved electricity system with bi-directional power flows, UFLS schemes based on static settings risk being quickly outdated.

The risk of major generation disturbance is greater as the extent of renewable penetration increases, due to lower inertia. Table 3 (in Section 2.2.2 of this report) shows the expected increase of the connection of 790 MW of additional renewable energy. As more intermittent non-scheduled generation comes online in similar geographic regions between now and 2021, as outlined in Table 3, the severity and magnitude of possible generation contingency events is likely to increase.

This highlights the importance of ensuring that UFLS schemes in the SWIS are appropriately configured. Managing these contingencies effectively to preserve system security may require updates to UFLS schemes to ensure distribution feeders that are net exporters remain connected to the grid. Some utilities, such as the operator of the Hawaiian electricity grid, Hawaii Electric Light, have installed dynamic UFLS, whereby the distribution feeders selected to the UFLS scheme change depending on their load.

3.1.7 System restart services

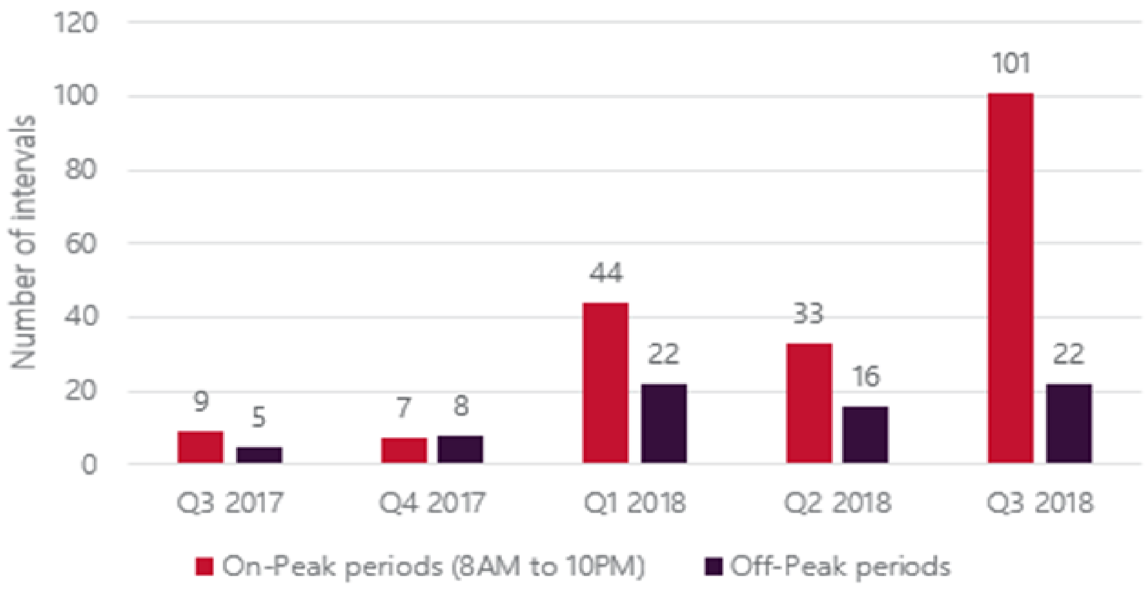
In the rare event that a system restart is required (for example following a black system event), large amounts of passive DER may inhibit restart, by reducing the stable load available to support the operation of synchronous generation units providing system restart services. As the amount of DER installed on the system increases, managing system restoration could become increasingly problematic.

An action plan for DER should support load management and enable reconnection of DER systems when the system is stable. Subject to the implementation of a DER Roadmap that incorporates DER controllability and DER provision of system support services, DER could even assist in providing energy and load management during a system restart.

3.2 Market implications of declining operational demand

Decreasing daytime minimum operational demand is resulting in decreasing daytime prices in the Balancing Market. Significant decreases in daytime pricing have emerged rapidly, and there have been negative average daytime prices in 2018 relative to 2017, as Figure 12 shows.

Figure 12 Increasing occurrence of negative trading intervals in the WEM in 2018



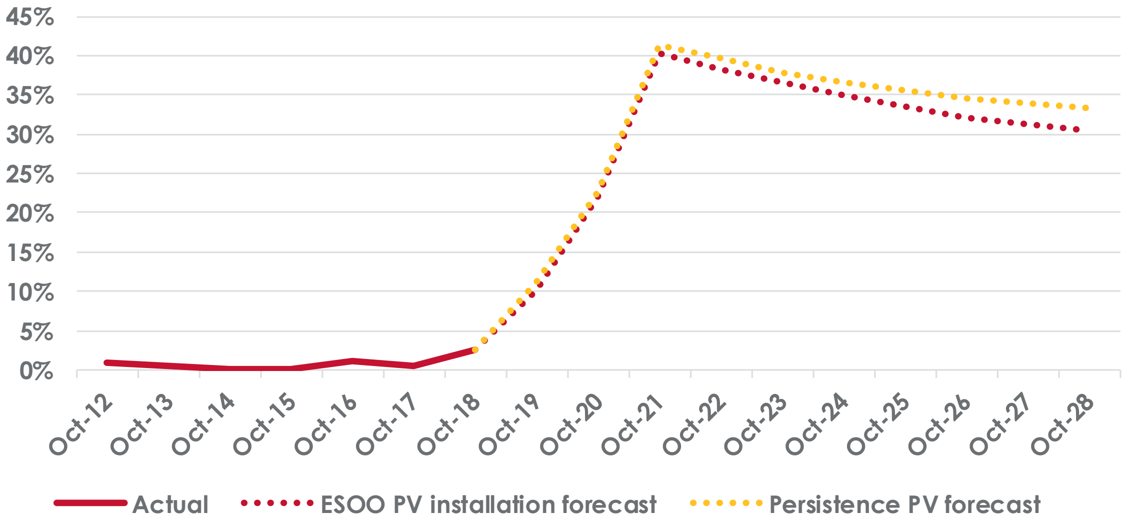
AEMO's modelling indicates the prospect of a significant increase in the incidence of negative prices. Some level of negative pricing in the electricity market is not atypical, but this analysis indicates the frequency of negative pricing will become pervasive.

Figure 13 shows a forecast increasing number of trading intervals with negative prices, increasing exponentially up to approximately 40% in the month of October 2021, after which it is projected to gradually begin decreasing, due to underlying load growth and no further installation of large-scale renewables.

A small number of trading intervals with negative prices is not atypical, nor injurious to the interests of the market or customers. However, the rapid increase and persistence negative price trading intervals shown by the AEMO analysis in Figure 13 will result in a distorted investment signal. When prices persist below short run marginal cost, this is likely to result in financial distress of market participants.

Furthermore, the anticipated level and persistence of negative prices is likely to result in synchronous generation ceasing to be dispatched for periods, and this will challenge the availability of essential services required to ensure system security and reliability, unless AEMO intervenes in the market.

Figure 13 Occurrence of negative trading intervals in the WEM



The extent of negative prices in the wholesale market, and the potential extreme volatility, is expected to have wide-ranging implications for both private sector and government-owned market participants. The Western Australian Government is expected to face implications of potentially uncontrolled DER penetration and large growth in renewable generation because it is responsible for incurring the financial implications of these issues through its ownership of Synergy and Western Power.

Synergy is currently the default provider of essential services in the SWIS under the WEM Rules. It is expected that the quantity of essential services, and the frequency of their deployment, will increase significantly as a consequence of the issues outlined in this report. This will result in costs being incurred by Synergy that might not be recovered under the current essential services framework, while also incurring the risk of negative pricing. The use of Synergy's generation fleet for essential services, and the two-shifting and additional ramping of its generation fleet, will also increase the maintenance costs that Synergy incurs and reduce the efficient operation of its generation fleet.

Synergy also pays residential customers for rooftop PV generation under the Renewable Energy Buy Back Scheme, at a price of $71.35 per megawatt hour (MWh). This is often higher than the wholesale market electricity price presently, and this may remain the case in coming years at times of high rooftop PV DER output. This will represent a financial burden for Synergy and a competitive disadvantage as its competitors can benefit from the potentially lower market prices when solar PV generation is in surplus, particularly in the case of competing for contestable customers.

3.3 Distribution network challenges

High penetration of DER has led to higher voltages in the distribution network. Existing network infrastructure was built to manage low voltages caused by maximum demand events, however, they are not as well equipped to manage high voltages.

The main mechanism to reduce voltages on most of the existing distribution network is the zone substation distribution transformer tap setting. At the distribution feeder level, increasing DER is causing localised voltage issues whereby the fixed tap on the distribution feeder transformers – designed to cater for the maximum voltage on a low demand day (and minimum voltage on a high demand day) – is being challenged by decreasing minimum demands.

During minimum demand periods:

- High voltage persists as the consequence of low load. Distribution transformers in several areas are at their lowest tap setting and cannot provide further voltage reduction.

- Reactive power flows on the transmission network increase and must be absorbed by synchronous generators, however, as few synchronous generators are online, these generators are approaching thermal limits in their ability to absorb reactive power.

Voltage control challenges have already begun to emerge in the SWIS, particularly during daytime minimum demand. On 28 October 2018, combined high levels of DER generation (766 MW) and low operational demand (1,324 MW) meant that the synchronous generators online were absorbing reactive power at levels close to their thermal limits.

Beyond these limits, generators will no longer be able to absorb more reactive power, and transmission voltages will drift up. If uncontrolled, there is a risk that voltages may reach unsecure levels that can cause consumer appliances to be damaged, lines to trip, or faults to occur, which could ultimately lead to a cascading system collapse.

Network operators are taking steps to manage the voltage effects of rooftop PV DER on the network, through the following measures:

- Ergon in Queensland is trialling distribution feeder transformer tap changers, which are more expensive than the existing manual tap changers[33]. Ergon has evaluated a list of solutions for varying levels of rooftop PV DER penetration.
- SA Power Networks (SAPN) in South Australia is extending the tap range of specific zone substation transformers and installing reactive plant on 11 kilovolt (kV) lines, alongside increased monitoring and control of the distribution network. SAPN is also applying a range of additional solutions for voltage control, including modifying connection standards to require new rooftop PV inverters to aid in managing local voltage. SAPN, as the distribution network operator, is also working with transmission network operator ElectraNet to manage DER impacts on voltage across both the transmission and distribution networks[34].
- In Victoria, a 500 KV line has been switched off at nights to keep the voltage in the required range. This approach is not sustainable, as it will lead to early failure of network assets. In the SWIS, the 330 KV line of Muja to Northern Terminal also has been switched off in some instances to manage reactive power and rising voltages.
- Western Power has a range of projects and initiatives to address the changing usage pattern of network infrastructure. Western Power is currently developing strategies to ensure suitable voltage control in the future.

3.3.1 Protection implications

Power systems, which automatically operate to isolate faulted equipment on the power system, were traditionally designed to accommodate power flow from generators to consumers. Protection systems have been designed and installed accordingly.

With the advent of DER, the SWIS is increasingly experiencing multi-directional power flows, due to consumers, traditionally treated as load, becoming generators from time to time. Existing protection systems will need to be enhanced to accommodate the new reality of network usage.

Additionally, DER and utility-scale non-synchronous generators may reduce the fault level and short circuit ratio, which are fundamental requirements for the protection system to operate correctly. This will require specification of appropriate fault current contribution for any batteries installed.

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[33] Ergon Energy Network, *Distribution Annual Planning Report 2018-19 to 2022-23*, 31 December 2018, p.158, available at https://www.ergon.com.au/__data/assets/pdf_file/0018/720234/Ergon-DAPR-2018.pdf.

[34] SA Power Networks, *Distribution Annual Planning Report 2017/18 – 2021/22*, 20 December 2017, p.23-24, available at https://www.sapowernetworks.com.au/data/3032/distribution-annual-planning-report-2017-18-2021-22/.

4. Integrating DER and utility-scale renewables into the SWIS

The challenges posed by DER and utility-scale renewables are by no means insurmountable. Technical solutions for these challenges exist today, and have been successfully deployed in a variety of power systems around the world.

These challenges require fit-for-purpose technical standards and regulatory frameworks. The market must be designed with the increasing levels of DER and utility-scale renewable energy in mind, based on the required technical and operational components to securely operate the SWIS.

AEMO's 2018 ISP[35] for the NEM identified that the least-cost alternative to replacing existing generators when they reach the end of their economic life is a combination of renewable resources (such as wind and solar), complemented by storage, transmission network augmentation, and gas plants. This combination of technologies is inherently more flexible than the present scenario, and will ensure the capability to optimise the real-time response to an increasing dynamic market and system environment.

4.1 Technical standards for DER inverters

High levels of PV DER in an islanded system have been experienced in Hawaii. In 2014, the Hawaii grid operator faced a similar scenario, where the penetration of PV DER was reducing the level of minimum demand towards the technical security limits of the system. The grid operator concluded that integrating PV DER into the system required inverters to participate in maintaining secure and reliable operations. As is the case in the SWIS, rooftop PV DER was not connected to a communications network, and the Hawaii studies concluded the cost of doing so was prohibitive.

In Hawaii, it was determined that the most timely and feasible way to enable PV inverters to support the grid was for them to autonomously respond to local conditions. As a result, the operator, in conjunction with the National Renewable Energy Laboratory (NREL) and the US Department of Energy (DOE), developed inverter technical standards for voltage and frequency disturbance ride-through and supportive response to local conditions.

California also undertook a similar exercise to Hawaii, mandating several smart inverter grid support functions to avoid the further build-up of legacy inverters, that were beginning to pose risks to grid operations and reliability.

Smart inverter requirements in Hawaii and California were integrated into a major revision of the IEEE 1547 standard for DER connection in April 2018, following an extensive four-year, cross-industry collaboration in the United States. IEEE 1547-2018 addresses both local distribution and bulk system needs, covering

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

interoperability and specific grid support functions, including voltage and frequency disturbance ride-through, voltage and frequency regulation, and communications and control capability.

Hawaii currently secures 33% of its electricity from rooftop solar PV, with a policy objective of sourcing 100% of its energy requirements from renewable sources by 2045[36]. California sourced almost 12% of the state's total electricity production from solar PV and solar thermal power plants in 2017, and its Renewable Portfolio Standard requires that 33% of California's electricity come from renewable resources by 2020, and 50% by 2030. Much of this is expected to come from solar power via PV facilities or solar thermal power facilities[37].

AEMO recommends that learnings from the Hawaii experience should be considered for implementation in the SWIS, with the potential adaptation of capabilities specified in the IEEE Std 1547-2018 standard to suit Australian conditions.

AEMO is conducting a broad program of work to progress with the implementation and delivery of improved performance from DER, particularly rooftop PV systems, across the NEM as well as the WEM. This will enable all new DER inverter installations to assist in maintaining operation during disturbances and supporting recovery by autonomously responding, enhancing stability in a disturbance.

The Australian Standard for inverter-connected DER (AS 4777) was amended in 2015, and does include some advanced capabilities. However, these capabilities are optional, and detailed implementation requirements are not specified. AEMO understands, via advice from the Clean Energy Council (CEC), that many currently available inverters can deliver this optional capability, and AEMO has been working with the Energy Networks Association (ENA) and distribution network service providers (DNSPs) to encourage the adoption of this capability (such as Volt-Var control) within distribution connection requirements.

AEMO is working with Western Power in the SWIS and other electricity market participants in the NEM to progress amendments to AS/NZ 4777.2-2015, learning from the IEEE 1547-2018 revision and other international equivalent standards, with any appropriate modifications for inverters in Australian networks in the near term.

4.2 The role of energy storage

Measures that increase demand during the day will be critical to continue to allow the ongoing adoption of PV DER. Behind-the-meter batteries at customer premises, if implemented with the correct controls and inverters, will bolster minimum demand during the battery charging cycle. Further, utility-scale batteries could help to absorb excess solar PV generation and represent an additional source of demand for generated electricity during the daytime period.

Together, both distributed and utility-scale batteries would assist in alleviating the system security challenges associated with low operation demand, that is, where load on the grid is insufficient to support a critical level of synchronous generation to be kept online and assist in ramping levels.

However, batteries are not expected to be the entire solution to the issues outlined in this report. Other complementary actions are recommended, and may include emergency PV feed-in management to curtail rooftop PV DER as a last resort measure.

AEMO's 2018 ISP[38] for the NEM indicated a growing need for energy storage over the next 20 years to increase the flexibility and reliability of supply. The analysis of the WEM and the SWIS in this report draws a similar conclusion over the 10-year period of the study horizon.

AEMO analysis using the WEM ESOO PV installation forecast has identified an average of 70 MW / 200 MWh of battery capacity installed per year from 2022 to defer the system security risks. In AEMO's sensitivity analysis using a persistence PV forecast, up to 150 MW / 600 MWh of battery capacity installed per year from

[36] Scientific American Energy and Environment News, 27 April 2018, available at https://www.scientificamerican.com/article/as-hawaii-aims-for-100-renewable-energy-other-states-watching-closely/.

[37] See https://en.wikipedia.org/wiki/Solar_power_in_California.

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

2022 would defer system security risks projected to occur. AEMO's analysis did not assess the optimal economic individual battery size but did assess the required total battery capacity from a system perspective.

4.3 Technologies to enhance system security

The transition to cleaner energy supply will result in the inevitable displacement of thermal fossil-fuelled generators which have traditionally contributed to the secure operation of the traditional power system by virtue of their synchronous characteristics. It is imperative that any transitional arrangements to integrate renewable generation provide mechanisms to implement the essential power system support services that will be required to maintain the secure and reliable operation of the SWIS.

AEMO will complete a detailed economic and technical analysis to specify the required general location, timing, and technical requirements for technologies such as synchronous condensers and batteries that can provide inertia, system strength, and ancillary services to the SWIS. It is anticipated that these technologies will complement advances in inverter technology as means to assist the flexibility and responsiveness that will be required to maintain system security.

4.4 The WEM Reform Program

The WEM Reform Program is a necessary foundation, but insufficient on its own, to address all the challenges posed by DER and utility-scale renewable penetration.

The existing scope of the WEM Reform Program represents a key part of the solution to meet some of the challenges and facilitate some of the solutions posed by DER and the increased connection of utility-scale variable renewable generation. Holistic changes are required to the framework for network connection and access and for market operation. DER-specific reforms must be aligned and integrated with the WEM Reform Program, and must be informed by a robust DER Roadmap.

The WEM Reform Program will be fundamental to managing and facilitating the uptake of transmission grid-connected renewable generation and DER. This is because the core reforms of the WEM Reform Program will enable better management of constraints and intermittency through:

- The co-optimisation of energy and essential services in real time.
- Increased automation and transparency in market dispatch processes, which is necessary to manage system reliability and security in a constrained grid and support an efficient market.
- Reduced reliance on, and cost of, essential services to manage forecasting uncertainty by dispatching energy more frequently and reducing the gate closure period.
- Essential services required to be explicitly defined, valued, and incentivised to keep the power system secure and reliable as it transforms.
- Provisions to enable the registration of large-scale batteries to participate in the market.
- Clarification of the responsibilities of Market Participants.
- Improvements in the way Generator Performance Standards are embodied and enacted.
- Consideration of an integrated system planning function (refer to Section 4.6).
- Clarifying the technical reliability and security standards for the operation of the power system, clearly assigning responsibility for satisfying those standards, and establishing robust governance mechanisms for their ongoing review.
  - These standards are currently under consideration in the PUO's network and market reform programs and are expected to lead to changes to the Electricity Network Access Code, Technical Rules, Network Quality and Reliability of Supply Code, and the WEM Rules. AEMO is supporting the PUO in this work.

- Specifying the services that Market Participants can provide to contribute to satisfaction of the reliability and security standards, and the markets or mechanisms through which those services are procured and valued.
  - The PUO has commenced this work under the WEM Reform Program and has engaged technical consultants to support this process. AEMO is supporting the PUO in this work.

By identifying and valuing newly specified essential services within a reformed framework, this would be expected to encourage existing generators to change their plant to be able to provide these services. This may include reducing minimum generation levels and increasing ramp rates to improve their flexibility. Similarly, new generators (whatever their type) will be incentivised to design their plant to provide these services[39].

These arrangements will also consider who would be most appropriate to pay for these services, such as a causer pays model for frequency control due to variable generator output, to further encourage Market Participants to optimise and improve plant performance to reduce overall system costs.

These arrangements may also provide an opportunity for the network operator to determine whether network investments could reduce the need for these system services at lower cost than a market or contracted service.

AEMO has been working with Western Power on new Generator Performance Standards required for the transforming power system, with the intention that these will be incorporated into an improved regulatory framework for these technical standards via the WEM Reforms.

The PUO's networks and market reform program provides an opportunity to advance these changes, although this work is generally being done without direct reference to the DER developments, and additional policy and implementation work explicitly on DER is required to more fully achieve the opportunities.

With network and market reform regulatory changes targeted for 2020 to support an implementation go-live date of 1 October 2022, it is critical that the PUO work is sufficiently prioritised and resourced. This will maximise the delivery of benefits without delaying the foundation WEM reforms needed to avoid the market and system impacts AEMO has forecast to occur in the early-2020s.

Additional complementary reforms to the WEM Reform Program to assist the integration of DER

The WEM Reform Program is necessary, but its present scope is insufficient to facilitate the integration of DER and utility-scale renewables. Additional reforms that complement the WEM Reform Program are required in the form of a DER-specific program of reforms, based on a DER Roadmap. These reforms include:

- Maximising the opportunities and incentives for end consumers with DER to offer those services and benefit from their contribution to satisfying the reliability and security standards. This will also be critical to provide AEMO with visibility and some control of the actions of end consumers with DER to assist in managing an increasingly variable power system. Measures to improve opportunities and incentives for end consumers may include (but are not limited to):
  - Changes to DER technical standards and communications standards.
  - Establishment of a dynamic DER register for the SWIS and/or the requirement for registration to apply at the time of network connection for all those resources for which visibility, predictability, and coordination is determined to be necessary.
  - Retail tariff reform.

[39] Non-synchronous generators and batteries can be designed to provide the vast majority of essential system services, as indicated by the ability of small-scale systems to operate without synchronous generation. In some cases, the services may not be identical to those provided by synchronous generators (for example, non-synchronous generators can provide synthetic inertia), however, if the essential services are defined appropriately, these differences can be accommodated efficiently without impacting system security and reliability.

– Development of Distribution System Operation (DSO) functionality as being considered in the joint ENA-AEMO Open Networks initiative[40] (refer to Section 4.5).

– Changes to the WEM Rules to allow 'multiple trading relationships', whereby an end consumer can benefit by offering services to the market via a third-party aggregator while retaining a relationship with their retailer.

– Changes to the WEM Rules to enable information gathered for the SWIS DER register to be included in AEMO's operational forecasting and planning processes.

– Changes to the *Electricity Industry (Metering) Code 2012* to accommodate DER so residential customers can trade their energy between themselves (peer-to-peer), either as part of embedded network or outside of an embedded network.

– AEMO to be conferred a function for long-term system planning function, including a requirement to develop an Integrated System Plan for the SWIS in conjunction with Western Power.

– Amending AEMO's existing functions to support actions it may or must take to accommodate DER as part of managing the operation of the power system and market.

– Amending the regulatory frameworks, and potentially regulatory architecture, for SWIS network connection and access, and power system and market operation to enable more efficient change processes and common change mechanisms.

Interim operational measures may be required during the reform process

If minimum load approaches levels that threaten power system security, AEMO will need to take direct action to ensure system security and plan the system in a way that mitigates these events. This could include intervention measures such as:

- Wide-ranging curtailment of variable renewable generators during the day to ensure minimum operational demand does not go below system critical thresholds.
- The procurement of additional backup essential services during periods of high variability.
- Instructing generators to stay online in order to absorb reactive power and manage voltage issues on the network.

These intervention methods would result in significant costs to the market, particularly as the frequency and quantum of intervention increases, such that rule changes[41] to provide improved investment signals may be considered. The optimal approach would also need to consider the relative merits of reinforcing the network, installing reactive compensation and incentivising generators to make reactive capability available to the network.

Eventually, even with the above measures, if DER continues to be installed and is not controllable, it will reach a point where there is insufficient other generation on the system to provide the necessary essential services to keep the system secure. AEMO may need to instruct Western Power to trip exporting distribution feeders (where the PV output exceeds the underlying demand) or take parts of the transmission network offline where redundancy is adequate to preserve system security without undue risk to supply reliability for customers[42].

However, these powers were designed for when there was insufficient system generation to meet demand, so the risks associated with such options need to be explored further. If AEMO does use these powers, tripping exporting feeders (rather than reducing down PV output) is a very blunt way of dealing with the issue, which has the consequence of blacking out areas of the network and interrupting customer load. A degree of capability to control output from the distribution network may be required, taking into account the risk of

[40] See https://www.aemo.com.au/-/media/Files/Electricity/NEM/DER/2018/OEN-Final.pdf.

[41] For example, constrained off payments being removed or reduced when occurring for system security reasons and examining causer pays arrangements.

[42] In accordance with Clause 3.6.6A of the WEM Rules and the Technical Rules. These instruments arguably need amendment to clarify this power to define 'disconnect' and facility in a consistent manner.

incorrect UFLS operation of tripping the wrong distribution feeders and substations that may occur when transmission-connected generation trips. The combination of these events could threaten system security.

It is clear that the challenges of the future of the transformation of the energy system and market outlined in this report will grow. It is critical that the framework governing how the market and the system is operated is reformed to enable these changes to be met at the lowest possible cost, and retain system security and reliability, while supporting the achievement of emission obligations.

4.5 Distribution System Operator and Distribution Market Operator Functionality

The increase in electricity supply from the distribution system and the implications outlined in this report support the case that this supply should be integrated and managed along with the wholesale market and the transmission system. This will necessitate the creation of Distribution System Operator (DSO) and Distribution Market Operator functionality in the SWIS.

Neither the WEM Rules or Technical Rules currently contemplate this capability. Recognising this, in mid-2018, AEMO commenced a process in partnership with ENA to consider how best to evolve network, system and market operations to better operate the grid and market in an environment of high DER to formulate a two-way system and marketplace. The joint ENA and AEMO Open Energy Network consultation began with the exploration of three frameworks for the co-ordination and optimisation of DER in the network:

- Single integrated platform (SIP): A unitary point of entry to the wholesale market for supply from the distribution system. AEMO, a regulated entity, would develop a single integrated platform along with Western Power. The platform would be managed by AEMO as part of its market and system responsibilities. The platform would use agreed standard interfaces to support participation in the integrated multidirectional market by retailers, aggregators, and VPP platform companies. Western Power would link to the platform as both a transmission and distribution network services provider, and would be responsible for providing information on local constraints.
- Two-step tiered platform: A layered distribution level platform interface operated by Western Power, whereby the Western Power platform would interface with the platforms operated by AEMO. Participants would communicate directly with the Western Power level platform on local constraint issues, and the distribution network would optimise these resources against local network constraints, based on bids from the aggregators servicing the area. Distribution networks would provide an aggregated view via the transmission connection point. AEMO would take this information and consider the overall system security and economic dispatch.
- Independent DSO optimises distribution level dispatch: An independent DSO that is separate from AEMO and Western Power would work with the Western Power to optimise the dispatch of the DER, based on local system constraints provided by Western Power. These aggregated bids would be provided to AEMO for incorporation into the wholesale market dispatch.

Over the course of the last six months, AEMO and the ENA have worked with industry to consider the appropriate model, engaging EA Tech to undertake a detailed Smart Grid Architecture Model (SGAM) for the three frameworks.

Stakeholder feedback on the initial consultation and functional specification workshops held across Australia in late 2018, and the outcomes of the SGAM modelling, have highlighted that the introduction of an additional party will introduce unnecessary cost and complexity – as it will require the cost of establishing a new organisation, creates risks in managing safety and reliability across multiple organisations, and introduces duplication and complexity of information flows particularly in a dynamic environment.

In addition, the feedback and SGAM analysis have identified two distinct roles that will need to be undertaken to enable effective co-ordinated operation of DER in the Distribution Network (the DSO), that is, a Technical DSO and a Distribution Market Operator. The Technical DSO's role will be managing distribution system operation and will require increasingly sophisticated monitoring and network constraint communication. AEMO, consistent with its market functions, could operate a Distribution Market to ensure economic optimisation of distributed resources that aggregate to provide market and network services, co-optimising with the bulk energy system. This is a hybrid model that incorporates key elements of the Single Integrated Platform as well the Two-tiered Model.

AEMO believes this partnership model will be the most efficient structure for DER integration, and plans to test the detail of this model, including key design considerations, with stakeholders in upcoming Open Energy Networks workshops to be held during March 2019. Following these workshops and completion of cost benefit assessment, AEMO and the ENA will release a final report by mid-2019.

The introduction of a DSO and Distributed Market Operator in the SWIS would require that DER is visible and able to be coordinated with electricity supply from transmission-connected sources. This will enable a fully optimised two-way system and marketplace.

4.6 Integrated system planning in the WEM/SWIS

The current WEM/SWIS regulatory framework does not confer a function for long-term power system planning, or impose a requirement on any party to develop a plan for power system development. While complementary, two planning documents produced separately by AEMO and Western Power are produced for specific purposes and, arguably, either separately or taken together, fall short of integrated system planning.

In the NEM, AEMO undertakes the role of national transmission planner. In this role, AEMO is required to review and publish advice on the development of the transmission grid across the NEM, provide a national strategic perspective for transmission planning and coordination, and publish an annual 20-year outlook for NEM transmission planning, the National Transmission Network Development Plan (NTNDP).

In October 2016, the Council of Australian Governments (COAG) energy ministers agreed to establish the Independent Review into the Future Security of the National Electricity Market, chaired by Dr Alan Finkel AO, Australia's Chief Scientist. The "Finkel Review" provided a *Blueprint for the Future* Security of the NEM[43], with recommendations to deliver a smooth transition for the changing power system, and for energy consumers across the NEM.

The Australian Energy Regulator subsequently permitted AEMO to defer the 2017 NTNDP to enable its integration with the inaugural Integrated Strategic Plan (ISP), along with other material matters facing infrastructure planners in the NEM as identified through consultation. The inaugural ISP for the NEM was delivered by AEMO in July 2018.

As part of a new system planning function, AEMO might be authorised to develop and publish an ISP to provide an annual statement of transmission development and generation opportunities for the SWIS.

4.6.1 Current planning documents in the WEM/SWIS

There are two documents produced for the WEM, one by AEMO, and the other in relation to the SWIS by Western Power, which provide for planning over a 10-year horizon – the *WEM Electricity Statement of Opportunities* (ESOO) and the *Annual Planning Report* (APR).

- *WEM Electricity Statement of Opportunities*:
  - The WEM Rules require AEMO to develop and publish the WEM ESOO[44], which contains forecast demand scenarios and planned investment in generation and network investment over a (minimum) 10-year horizon.

[43] See *Independent Review into the Future Security of the National Electricity Market*, June 2017, available at https://www.energy.gov.au/government-priorities/energy-markets/independent-review-future-security-national-electricity-market.

[44] Clause 4.1.8 of the WEM Rules.

- Published mid-year, the WEM ESOO is one of the key aspects of the Reserve Capacity Mechanism. The WEM ESOO is limited in its scope, in that forecasts are used to determine how much generation capacity is required to meet the forecast demand for the next reserve capacity certification period.
- Western Power *Annual Planning Report*:
  - Western Power publishes an APR which focuses on identifying emerging network capacity and major assets issues, and potential solutions, on Western Power's transmission and distribution networks[45]. The APR offers Western Power's view of the nature and location of emerging capacity constraints on its transmission and distribution networks, and identifies potential network and non-network solutions to address the congestion areas and evolving consumer needs.
  - Published mid-year, the APR takes into consideration Western Power's responsibility for network reliability in terms of the services standards that it must meet. It also considers Western Power's funding constraints and an assessment of the efficacy of expenditure to recover a full commercial return on investment.

For the sustainable operation of any power system, long-term plans informed by likely changes in loads and generation facilities are essential. Without long-term planning, network equipment to regulate frequency and voltage may have insufficient capacity, capability, and redundancy to deliver securely and reliably the required power to the connected loads.

A SWIS ISP could include:

- Reporting on the consequences of a reduction in system inertia due to the retirement of synchronous generators and their replacement with non-synchronous generators.
- Reporting on AEMO's investigations into opportunities to use energy from renewable generation and rooftop PV DER at times of low demand.
- Proposing options to enable greater choice for electricity consumers and manage network congestion through the integration of renewable energy and innovative technologies.
- Proposing strategies for developing 'renewable zones' or identifying specialised network and non-network services (such as microgrids) for system security and supply reliability.

AEMO proposes to develop an integrated system plan for the SWIS and WEM as the system planner.

4.7 DER Roadmap

An effective DER Roadmap is critical and needs to be develop through the collaborative interaction of AEMO, Western Power, the PUO, Horizon Power, Synergy, and other market participants and interested stakeholders. The DER Roadmap needs to be underpinned by a DER strategy with the following overarching elements:

- Operational frameworks to support:
  - The coordination and optimisation of DER between system and network operations, with consideration given to potential new roles for aggregators, a Distribution System Operator (or equivalent), Distribution Market Operator, and other service providers; and
  - Multiple trading relationships to allow greater utilisation of DER.
- Sophisticated modelling undertaken by AEMO to identify all factors and issues contributing to system security threats (in accordance with recommendation 3 of this paper and Section 4.3).
- Initiatives to increase daytime demand (and reduce peak demand), such as removing barriers for and incentivising storage (large and coordinated small-scale) and small- and large-scale demand side management.

[45] There is no regulatory requirement on Western Power to produce and publish an Annual Planning Report.

- Funding of resourcing at the PUO to (via stakeholder engagement) develop policy settings, high-level design options, and the requisite regulatory changes needed to realise DER opportunities.
- Pilot projects to validate concepts and test DER capabilities (in regard to visibility, predictability, and controllability) and to inform necessary changes to regulatory instruments, technical and communications requirements and technical standards.

The specific actions required as part of a DER strategy should include:

- Mechanisms to provide visibility, predictability, and controllability of DER through the creation of a local DER Register and, relatedly, the imposition of improved technical standards.
- The conferral of a long-term planning function, including for the delivery of a strategic infrastructure development plan.
- An improved scope for the WEM Reform Program to incorporate actions for the integration of DER into the operation of the power system in the SWIS and into the market.

5. Recommendations

Table 5 Recommendations for the integration of DER and utility scale renewables

	Recommendations
1.	Update inverter standards to include advanced capabilities and implement within distribution connection requirements AEMO to work with Western Power to progress amendments to AS/NZS 4777.2 for the grid connection of DER via inverters, integrating recent improvements to IEEE 1547-2018 and other recently published international equivalent standards. This will include autonomous grid support including frequency and voltage disturbance ride-through and regulation from the inverters. AEMO is already engaging with: • The ENA and DNSPs nationally on local distribution and bulk system level needs and the adoption of advanced inverter capability within distribution connection requirements. • The CEC and manufacturers on transition to any new requirements and compliance. AEMO will work with Western Power on the development and implementation of new requirements in the inverter standard for the SWIS by end of 2019.
2.	Energy Storage in the SWIS AEMO to determine the requirement for energy storage installations for system security purposes in the SWIS and work with the Economic Regulation Authority, Western Power, government, and industry to: • Enable the registration, connection and operation of energy storage systems in the SWIS through regulatory reform and rule changes by end of 2019. • Propose a funding scheme or process to establish energy storage projects to commence installation during 2020.
3.	System security technologies AEMO to complete a detailed technical, economic and regulatory evaluation that includes: • Identifying the optimal locations and technical requirements for the deployment of synchronous condensers or other applicable technologies in the SWIS to manage system strength and inertia to required levels. • Costs of meeting the requirements. • Regulatory changes required to enable implementation at least cost.
4.	WEM Reform Program additional scope and focus The Government's WEM Reform Program must be completed on or ahead of the current schedule, with additional dedicated resources if required. Scheduled to go-live in October 2022 (with some changes implemented in 2020), the Government's WEM Reform Program will provide some of the fundamental changes that are necessary to facilitate the energy transition, such as co-optimised energy and essential grid support services dispatch and improved generator performance standard arrangements. Additional scoping of the objectives and timelines of the reform program is necessary to include mechanisms for DER integration in the detailed design in a timely manner.
5.	Integrated System Planning is required Confer a function for long-term integrated system planning on AEMO by the end of 2019. AEMO to deliver a SWIS strategic integrated development plan, based on sound engineering and economics, and with key input from Western Power, which can facilitate an orderly energy system transition under a range of scenarios – the Plan to be delivered by July 2020.
6.	DER Roadmap Develop a DER Roadmap that identifies the funding and resources requirements, and the technical, operational and regulatory changes, that are necessary to trial, implement and incentivise the use of DER by distribution utilities and AEMO to reduce costs and provide value to owners of these systems and the market.
7.	Distribution System Operator and Distribution Market Operator functions are required AEMO to work with Western Power and the PUO and develop recommendations for the development of distribution system operation and distribution market operator functionality to facilitate the optimised real time integration of distributed resources to support system security, reliability and economic efficiency.

A1. Power system requirements and Power System Limits

A1.1 Power system requirements

AEMO's Power System Requirements reference paper[46], released in March 2018, outlined the prerequisites (predictability, dispatchability) and technical attributes (resource adequacy, frequency control, voltage control, system restoration) that are required to keep the power system secure and reliable.

In summary these prerequisites and technical attributes are:

- Predictability: Ability to measure or derive accurate data on energy demand, power system flows, and generation output across numerous timeframes (real time, hours/days/weeks/years ahead) as key inputs into planning and operational decision-making; and to forecast upcoming power system conditions and have confidence in how the system will perform.
- Dispatchability: AEMO and participant capabilities to manage dispatch and configure power system services to maintain system security and reliability. The system balancing process hinges on the dispatchability of the overall portfolio of available energy resources and key characteristics of each technology. The concept of the dispatchability of an energy resource can be considered as the extent to which its output can be relied on to 'follow a target'. As well as understanding whether energy assets can adhere to a dispatch target, AEMO also needs to understand how controllable the assets it has at its disposal are, how much they can be relied upon, and how flexible they are.
- Resource adequacy: Provision of sufficient supply to match demand from customers (bulk energy and strategic reserves). Capability to respond to large continuing changes in energy requirements (operating reserves). Service to transport energy guaranteed to customers (transmission and distribution).
- Frequency control: Ability to set frequency (grid formation) and then maintain frequency within limits (inertial response, primary, secondary, and tertiary frequency control).
  - Inertial response – a rapid and automatic injection of energy to suppress rapid frequency deviations, slowing the rate of change of frequency.
  - Primary frequency control – active power controls act in a proportional manner to respond quickly to measured changes in local frequency and arrest deviations.
  - Secondary frequency control – automatic generation controls and manual dispatch commands act to restore frequency to 50 hertz (Hz) and relieve providers of primary frequency control.
  - Tertiary frequency control – active power controls, such as the start-up of new units or set point changes on already operating units, act to replace depleted secondary frequency control resources to ensure the system continues to remain within its normal operating band.

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

- Voltage control: Maintaining power system voltages within both operational and system design limits.
  - Fast response voltage control – provides large, rapid adjustments in reactive power to maintain stability in the event of system disturbances.
  - Slow response voltage control – managing small adjustments to reactive power during normal operation as demand and generation varies, in timescales within seconds or minutes.
  - System strength – complex interaction of electrical and mechanical elements which support system stability, including, but not limited to, fault levels and synchronising torque.
- System restoration: Ability to restore the system.
  - System restart services – procurement of these services.
  - Load restoration – energised part of the power system is used to start up additional generators, adequate voltage support is the most critical service.

A1.2 Power system security limits

The WEM Rules define Power System Security as "the ability of the SWIS to withstand sudden disturbances, including the failure of generation, transmission and distribution equipment and secondary equipment". In broad terms, "withstand" in the context of security means that the system remains operating within all relevant limits and standards. Some of the key limits and standards that apply are:

- Voltage Standards – the voltage must be kept within normal operating bands and must be recovered appropriately following a fault.
- Stability Limits – the limits in which the power system must be operated to ensure that, following a disturbance or event, the power system recovers to within normal limits within an appropriate timeframe and remains controllable within those limits, and there are no undamped oscillations. The power system must remain synchronised and is not in a position where it will collapse.
- Equipment Limits – these limits cover a range of different types of equipment and limit types. Some examples are line ratings, generator ratings, transformer ratings, and fault levels (that is, voltage withstand and power quality immunity limits).
- Inertia Limits – limits that may be required to ensure the frequency does not change at a rate that would either prevent automated protection systems from operating (UFLS relays) or cause generators to trip. Inertia also plays a role in ensuring power system frequency does not decay below key frequency limits following a credible contingency event.
- System Strength Limits[47] – limits that may be required to ensure that voltage step change limits are not breached, generators remain stable following a credible contingency event, and power system protection devices operate correctly. This is typically represented by a minimum fault current limit in a particular part of the power system.
- Frequency Operating Standards – specify the frequency levels for the operation of the power system (which is defined as the South West Interconnected Network and its connected generation and loads, operated as an integrated system). For the WEM, it is the standard set out in Table 2.1 under clause 2.2 of the Technical Rules.

The limits and standards do not set out the specific arrangements for how power system security is managed, such as the arrangements for generation and load shedding and the specification and procurement of frequency control ancillary services. However, the structure and settings of the limits and standards are an important factor for the determination of what essential services are required and what quantities are required (under the WEM Rules).

[47] While there is a difference between fault level and protection systems (minimum fault level limits) and system strength issues associated with generation voltage control, these two matters are related.

They also help to determine the process for managing dispatch, dispatch planning and outage planning to ensure reliability of supply while maintaining system security.

These limits and standards are also fundamental to the operation of the operating states framework under the WEM Rules. The operating states framework is pivotal to the actions AEMO can take as the operator of the power system in the SWIS and the market operator of the WEM in regard to its obligations to ensure system security and supply reliability.

The framework also sets out the requirements on various parties, such as Western Power as the Network Service Provider, generators, and other Market Participants, to cooperate with AEMO in fulfilling its obligations. For example, the *Normal Operating State* prevails when AEMO considers that the system is operating within the applicable Security and Equipment Limits[48] and the conditions of the system are secure in accordance with the requirements of the Technical Envelope[49].

A1.3 The need for a portfolio of technical solutions

Efficient policy frameworks will take a portfolio approach to sourcing system services, making optimal use of the capabilities of all assets in the power system, which, when used in combination, should be capable of providing the same or better system performance than in the past.

The following diagram from AEMO's *Power System Requirements* paper[50] outlines the present capability of various technologies to provide essential system services.

[48] A Security Limit means any technical limit on the operation of the SWIS as a whole, or on a region of the SWIS, necessary to maintain Power System Security, including both static and dynamic limits, and including limits to allow for and to manage contingencies. An Equipment Limit means any limit on the operation of a Facility's equipment.

[49] The Technical Envelope represents the limits within which the SWIS can be operated in each operating state.

[50] AEMO, *Power System Requirements*, March 2018. Available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf.

Service description				Supply side						Demand side		
				Centralised generation		Transfer within regions	Stabilising devices			Load	Decentralised resources	
System Attribute	Requirement	Service	Spatial level of need	Synchronous generator	Non-synchronous generator	Transmission and distribution networks	Grid reactor, grid capacitor, static VAR compensator	Static synchronous compensator	Synchronous condenser[1]	Large industrial, residential, commercial	Solar PV	Battery storage
Resource adequacy	***Provision of sufficient supply to match demand from customers***	**Bulk energy**	System wide	●	●	➔	○	○	○	●	●	●
		Strategic reserves	System wide	● [2a]	◐ [3a]	➔	○	○	○	●	◐ [3b]	◐ [3b]
	Capability to respond to large continuing changes in energy requirements	**Operating reserves**	System wide	● [2b]	◐ [3a]	➔	○	○	○	●	◐ [3b]	◐ [3b]
	Services to transport energy generated to customers	**Transmission & distribution services**	Local	● [4]	● [4]	●	●	●	●	● [4]	◐	◐
Frequency management	***Ability to set frequency***	**Grid formation**	Regional	●	◐ [5]	●	○	○	○	○	○	◐ [5]
	Maintain frequency within limits	**Inertial response**	Regional	●	◐ [6]	➔	○	◐ [7]	●	○ [8]	○	◐ [6]
		Primary frequency control	Regional	●	● [9]	➔	○	○	○	●	●	● [9]
		Secondary frequency control	Regional	●	● [9]	➔	○	○	○	●	●	● [9]
		Tertiary frequency control	Regional	●	● [9]	➔	○	○	○	●	●	● [9]
Voltage management	***Maintain voltages within limits***	**Fast response voltage control**	Local	●	●	○	●	●	●	●	◐	●
		Slow response voltage control	Local	●	●	○	●	●	●	●	◐	●
		System strength	Local	●	○	➔	○	○	●	○	○	○
System restoration	***Ability to restore the system***	**System restart services**	Local	●	◐ [10]	➔	○	○	○	○	○	◐ [10]
		Load restoration	Local	●	●	⇨	●	●	●	●	◐	◐

1 This includes generators with ability to operate in synchronous condenser mode.
2a While many synchronous generators can provide energy reserves, some less firm technologies (solar thermal or pumped hydro storage) will be limited by the amount of energy storage they include.
2b While many synchronous generators can provide flexibility services, coal generators are limited in their ability to provide such services.
3a Limited by duration for which service can be delivered.
3b Limited by duration for which service can be delivered; existing controllability is limited.
4 The provision of local voltage support from generators and loads can improve the network transport capability near their respective connection points.
5 Grid forming power electronic converters are available and have been proven on small power systems. Development of grid forming converters for large power systems is an emerging area of international research.
6 Some fast frequency response capabilities can provide emulated inertia response, but are not yet proven as a total replacement for synchronous inertia.
7 Static synchronous compensators with energy storage devices are being trialled as an emerging provider of inertial response.
8 Except for load relief.
9 Includes fast frequency response capabilities.
10 System restoration services from variable non-synchronous generators is an emerging area of international research. If they are grid scale, batteries are likely to provide some system restoration support.

Ability to provide service		
● Fully capable	◐ Partial or	○ Unable
➔ Enables delivery	⇨ Partial or limited delivery	

Note: Classifications are indicative of the general ability of each technology type. The extent to which technologies can provide each service must be assessed on the specifics of each individual system.

A2. Additional analysis of the incidence and implications of the ramping of coal units

Coal fleet generation data from SCADA readings for all of Synergy's coal Facilities in the SWIS was taken from AEMO's Market Data website[51] and analysed to compare current and historical patterns in Synergy coal plant movement. This analysis has focused on Synergy because it is the default provider of ancillary services.

Coal movement was calculated based on the difference between coal generation in one trading interval and demand in the subsequent trading interval.

Based on the analysis of publicly available SCADA data, Synergy coal fleet movements in calendar year 2018 are higher than in any other year.

Figure 14 compares total Synergy coal fleet generation[52] movement in 2018 against 2014, and shows the increased frequency of coal ramping over the four-year period from 2014. The percentage of periods with larger movements in Synergy coal fleet generation (more than 10 MW) has increased year-to-year since 2014, with a particularly rapid increase in larger movements from 2017 to 2018.

In 0, total Synergy coal fleet generation is disaggregated to display coal ramping movements on a Facility basis. Between 2014 and 2018, the number of intervals with zero coal movement has decreased for every Facility, indicating that each Synergy coal Facility is being ramped more often.

Further analysis of the generation profile for Synergy's coal units found that generation patterns have changed compared to previous years. Periods of high generation generally occur less often for each unit, and 2018 was the first year that Collie operated near its technical minimum generation level of 130 MW in a significant number of periods, indicating a movement away from previous operational practice.

A2.1 Conclusions

Greater demand variability in the SWIS has several key implications for system operation and scheduled generators. Scheduled generation not designed for frequent changes in output is likely to face challenges, and the increased frequency and size of coal fleet movement puts coal generators at risk of operating in a manner contrary to their original design.

Continued increases in coal fleet movements, particularly for the Synergy coal fleet, will potentially lead to additional maintenance requirements and a reduced economic return. Generation profiles of Synergy's coal units indicate that operational behaviours for Synergy's coal fleet were different in 2018.

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[51] Energy Generated (MWh) for each coal generator in http://data.wa.aemo.com.au/#facility-scada.

[52] Total Synergy coal fleet generation is the sum of all generation from Synergy's coal generators in a trading interval.

Figure 14 Total Synergy coal fleet movement in successive trading intervals

Probability distribution of total Synergy coal fleet movements, 2014 vs 2018 | **% of periods with movements in Synergy coal fleet generation more than 10 MW**

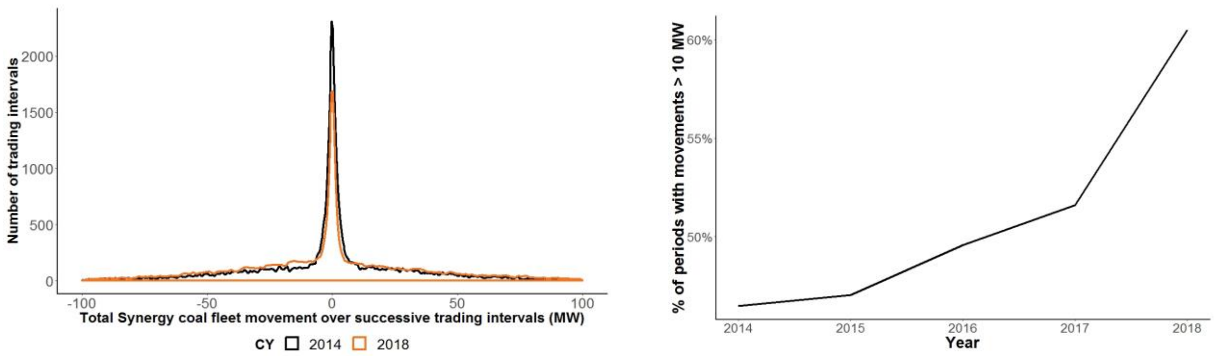
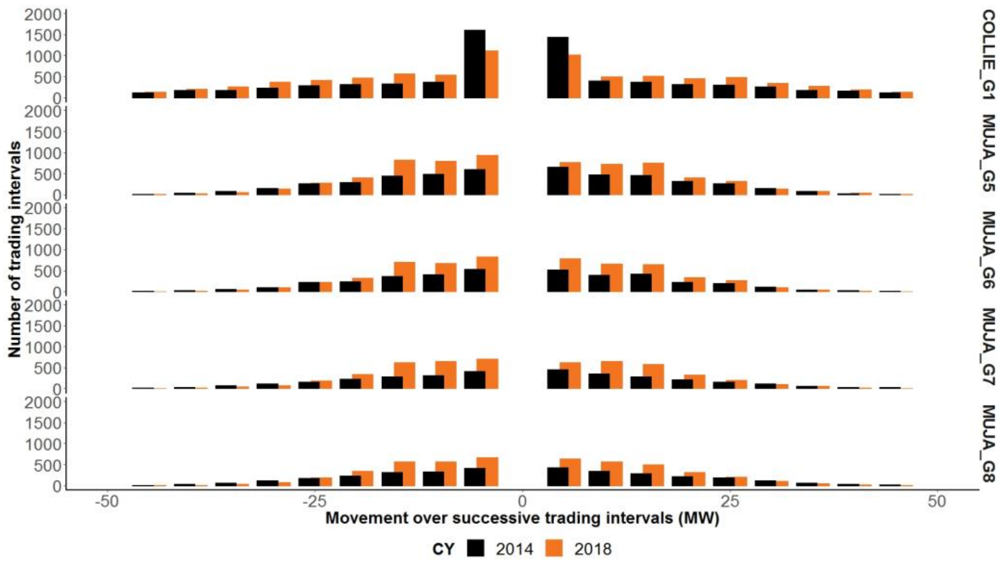


Figure 15 Synergy coal fleet movements in successive trading intervals, by Facility, 2014 vs 2018

Synergy coal fleet movements in successive trading intervals



% intervals with zero movement

2014	2018
58.1%	52.6%
72.2%	61.5%
77.3%	66.8%
80.5%	69.7%
80.1%	71.8%

Movements of zero have been removed for scaling purposes.

A3. Methodology to derive the system security threshold

Basis to derive the 700 MW system security threshold

AEMO's derivation of the system security threshold of 700 MW of market load was based on an assessment of the voltage control capability, system inertia, and dispatch limitations in the SWIS. The AEMO analysis was undertaken cognisant of the fact that the minimum synchronous generation required to be on the system is impacted by a number of factors, each of which may bind in different timeframes and under different operating conditions. The impact of some of these factors has been studied to date, but others have not yet been investigated, particularly at very low levels of synchronous generation.

Characteristics such as inertia and voltage control capability are largely dependent on the generators connected to the system. High penetration of DER results in low volumes of power being transported from utility-scale generators to loads, which results in a lightly loaded network and hence excess reactive power being generated by the network. This needs to be used by the load or absorbed by generators, reactors, static Var compensators (SVCs), and other reactive devices online.

Assumptions used in the analysis

The analysis undertaken by AEMO was based on a series of simplifying assumptions for the purposes of practicality, given the limited timeframe to undertake more detailed analysis which will be the subject of future work.

1. The locational impact of reactive power was not specifically considered. This broad assumption is only valid due to the location of synchronous generators at specific points on the network. Localised issues may need slightly different actions.
2. Generators were operated close to their minimum generation levels, or around mid-way for those providing ancillary services, which is likely given under low demand conditions prices would be expected to be low. This increases the quantity of reactive power which can be absorbed by the synchronous generators, as there are more generators online providing it. If fewer generators are operated at higher outputs, the minimum amount of synchronous generation required will be higher.
3. Reduction in network reactive power provision due to power flow was not considered in detail.
4. Dynamic reactive devices were held in reserve to enable response under contingencies, that is, their reactive absorption value was not considered in this analysis.
5. The Muja - Northern Terminal 330 kV line was assumed to be switched out of service to help absorb reactive power (approximately 87 megavolt amps (reactive) (MVAr) benefit). While other additional lines being switched out of service could further reduce reactive power levels, this is expected to increase system security risks relative to the benefit of the reduced reactive power levels because of the reduction in the redundancy in the network (that is, other contingency events may expose customers in that region to supply disruption or load shedding).

Limitations of the methodology

For the purpose of voltage control analysis, a reduction in network reactive power provision (reactive power losses) due to power flow was not considered accurately. At loadings such as a system loading of 1,962 MW, the resultant MVAr losses is about 387 MVArs. At a lower loading, such as a system loading of 1,251 MW, losses of about 225 MVAr occur. Significantly lower system loading will further decrease the level of MVAr losses, thus an approximation of ignoring this value (counteracted by all reactors being in service to manage voltages) is an acceptable approximation.

Limitations related to transient stability, adequate synchronising torque, system strength, adequacy of UFLS, detailed analysis of frequency control capability (and implications on ancillary services), and level of variability expected have not yet been studied on a system-wide scale.

Case study in determining a 700 MW Limit from a voltage control perspective

The following components were assumed to be available to reduce (absorb) the reactive power created by the network:

- Load power factor – actual scenarios show power factors at low loads around 0.99. Varying the power factor between 0.99 and 1 at a 1000 MW load case varies the reactive power requirements by about 150 MVAr. The assumptions for this analysis assumed that the power factor is 0.99.
- Reactors – up to 216 MVAr (108 MVAr of which are in the North Country).
- Generators – based on current information related to capability curves at minimum generation levels.

Case study

Example of scenario for ~860 MW system load (translating to approximately 700 MW Market Load)

Component	MVAr rating
Network charging	1,015
Line out of service	-87
Load reactive power requirement	122
Online generator absorption capability	560
All shunt reactors	216
Net excess reactive power on the system	30
System energy	Approximately 7,800 MWs

There are short-term operational mitigating actions which can be taken, but considering the uncertainty around exact system conditions and the increasing complexity and inflexibility which this introduces, these should not be considered long-term solutions without further analysis.

A number of similar scenarios, with varying generation patterns and system loading conditions, resulted in a similar outcome.

System strength

AEMO is yet to do any significant studies on system strength in the SWIS, however it is an emerging issue in weaker parts of the network, and is expected to become more prevalent as increasing non-synchronous penetration increases. More analysis is required to determine at what level of synchronous generation this could occur, and the impacts, although preliminary analysis suggests issues will occur at synchronous generation levels slightly below the 700 MW limit determined for voltage control.

Non-synchronous generation penetration

The current minimum net demand is around 1,350 MW. Assuming that 750 MW of DER was supplying load at that time, it translates to a gross minimum demand of 2,100 MW. Providing 860 MW of this by synchronous generation translates to about 60% non-synchronous penetration.

It should again be noted that without taking any action, the non-synchronous penetration could be higher. However, action will be required to manage this to a defined limit. EirGrid initially determined 50% was an appropriate limit, and after significant analysis and enhancements has increased the limit to 65%.

Conclusions

Although a number of limits are expected to influence the minimum amount of synchronous generation required to be online, the first limit that is expected to bind is related to voltage control. Actions may be taken to extend this particular limit, after which other limits would need to be mitigated. Further analysis is required to identify limits and operational practices necessary to manage higher non-synchronous generation penetration.

While limits will start to bind in earlier conditions, it will be possible to take actions that can mitigate these limits, although they will have a market impact. Eventually a hard limit will be reached, which can no longer be managed by manual intervention, indicating a risk to system security that cannot be managed with current technology.

The recommendation is to ensure that minimum amount (output) of synchronous generation to 700 MW is online until further analysis is done to undertake a comprehensive analysis of the system security requirements at low levels of operational demand.