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AUSTRALIAN ENERGY MARKET OPERATOR

Maintaining Power System Security with High Penetrations of Wind and Solar Generation

October 2019

International insights for Australia

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Important notice

PURPOSE

The purpose of this insights paper is to set the scene for AEMO's ongoing investigations into renewable integration in Australia and identify any additional priority focus areas, as described more fully overleaf in "Purpose of the Renewable Integration Study (RIS)". This insights paper is generally based on information available to AEMO as at 1 October 2019 unless otherwise indicated.

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ACKNOWLEDGEMENT

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Context and Purpose of this Insights Paper

The transformation of the power system is presenting new engineering challenges that must be addressed. Since Australia is leading in many regards in its increase in wind and solar, it is incumbent upon AEMO to understand the challenges and put solutions in place before they impair operations.

AEMO's Integrated System Plan (ISP)[1] articulates a whole-of-system development pathway for the National Electricity Market (NEM), to design and execute the transition in a way that maximises benefits at lowest cost and risk to consumers. AEMO develops a range of future scenarios in the ISP to evaluate the potential changes that can occur on the power system, and to identify no regrets investments that can be made to provide the best outcome for consumers.

In addition to the ISP, AEMO conducts further analysis where there is merit in a deeper level of inquiry, including analysis of those technologies that are at the forefront of the transformation. AEMO has published several relevant reports into the changing generation mix[2], including a recent study into storage as a significant component of the modern integrated power system[3] and an analysis of the implications of residential and commercial solar penetration in the Western Australian South West Integrated System (SWIS)[4].

As a supplement to developing the 2020 ISP, AEMO commenced the Renewable Integration Study (RIS)[5] to take a deeper review into the specific system implications and challenges associated with the integration of large amounts of variable inverter-based renewable generation and decentralised energy on the power system.

AEMO's Power System Requirements reference paper presented an overview of the specific requirements of the power system[6]. The RIS builds on that paper, to explore the specific opportunities and risks for maintaining the physical requirements of the power system while integrating variable inverter-based renewable resources at increasing levels of penetration. This in-depth review will inform future ISPs as well as providing foundational engineering advice to government and administrative policy-makers to support their consideration of future changes needed in electricity regulations and market designs.

The RIS is being undertaken in a series of steps:

1. A review of leading international experience in wind and solar photovoltaic (PV) integration (this report).
2. Detailed analysis of phenomena specifically related to wind and solar PV technologies[7], including:
   - Managing changes in wind and solar output.
   - Assessing the adequacy of frequency control in the power system.
   - Operating with increasing levels of distributed energy resources (DER).
3. Presenting a view of what operating the NEM could look like over the next decade. This will include the combined results of this international review, AEMO's detailed analysis in the RIS, and the results of ongoing industry investigation into the more localised limits to wind and solar PV penetration (for example, network congestion and localised system strength).

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

[2] Appendix A.3 provides a summary of relevant past AEMO publications into the changing generation mix.

[3] AEMO, ISP Insights – Building power system resilience with pumped hydro energy storage, July 2019, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/ISP/2019/ISP-Insights---Building-power-system-resilience-with-pumped-hydro-energy-storage.pdf.

[4] AEMO, Integrating Utility scale Renewables and Distributed Energy Resources in the SWIS, March 2019, at https://www.aemo.com.au/-/media/Files/Electricity/WEM/Security_and_Reliability/2019/Integrating-Utility-scale-Renewables-and-DER-in-the-SWIS.pdf.

[5] AEMO, Renewable Integration Study, July 2019, at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/Future-Energy-Systems/Renewable-Integration-Study.

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

[7] The study uses a projected generation mix and network configuration in 2025 as a focus for its detailed analysis. 2025 was chosen as the focus for the first stage of the RIS to enable more detailed focus and increase confidence and certainty in outcomes of power system models, because AEMO has a reasonable level of information about the generation projects that might be connected out to 2025.

4. Engaging with local and international organisations and independent experts to review and collaborate on AEMO's preliminary findings.
5. A final report in Q1 2020 into the technical challenges and any possible identified system limits associated with integrating increasing levels of variable inverter-based resources, and a roadmap of priorities to manage these challenges.

In this first step, AEMO is supplementing previous studies with a review on how Australia compares with other comparative international power systems. The objectives of this international review are:

- First, comparison of the technical challenges that Australia has experienced or identified with the experience of other jurisdictions to reveal any previously undetected challenges.
- Second, to update understanding of how these other jurisdictions are managing the technical requirements of their power systems during the transformation, and what practices appear effective from a technical perspective.
- Third, evaluating these various approaches to see if there are lessons that can be applied to achieve better outcomes in Australia's NEM and SWIS.

AEMO stresses that this international review is to help inform potential approaches to current and emerging technical challenges, not necessarily to prescribe specific approaches that have worked overseas. Although the physics underlying power system operation are universal, the need for a particular solution is impacted by different features of each system, including the level of interconnection with adjacent systems, geographic size, generation mix, and local climate conditions. Prevailing regulatory and market design considerations also influence how any necessary requirements can be most effectively implemented in a particular jurisdiction.

This international review has identified five key insights, which are summarised below and explored in more detail on the following pages:

1. Parts of Australia are already experiencing some of the highest levels of wind and solar generation in the world, including one of the highest levels of residential solar PV.
2. Successfully integrating high levels of DER requires an increasing level of visibility, predictability, and controllability of these small distributed devices. Australia can learn from several jurisdictions in its approaches to these challenges.
3. Managing variability and uncertainty is increasingly challenging at higher levels of wind and solar generation. Australia can learn from others in their approaches, including the assessment of system ramping requirements and fleet capability.
4. Australia should consider international approaches to frequency management in high renewable generation systems, including approaches to maintaining sufficient inertia and enablement of primary frequency response on all generators.
5. International power system operators have taken a staged approach to operating power systems with progressively less synchronous generation online. A similar approach could be considered in Australia.

Key international insights on renewable integration

Parts of Australia are already experiencing some of the highest levels of wind and solar generation in the world, including one of the highest levels of residential solar PV.

- Synchronously interconnected[8] power systems have operated for periods where wind and solar energy was larger than demand – including Denmark (157%) and South Australia (142%).
- Island power systems[9] have operated at high levels of wind and solar generation relative to demand – Ireland (85%), Tasmania (70%), and Great Britain (67%).
- Australia is achieving these very high levels while at the forefront of connecting wind and solar generation in areas with low system strength[10].
- Australia has one of the highest penetrations of residential solar in the world (20% of homes). The most comparable international system, in terms of both the penetration and impact of residential solar on system operation, is the island of Oahu in Hawaii.

Successfully integrating high levels of DER requires an increasing level of visibility and controllability of these small distributed devices. A minimum level of predictable performance during power system disturbances is also needed. Australia can learn from several jurisdictions in their approaches to these challenges, and how these approaches can benefit consumers.

- Lack of visibility of DER compromises the system operator's ability to understand their behaviour and appropriately manage the power system. The Electric Reliability Council of Texas (ERCOT) has taken steps to collect static information about DER installed on its networks and integrate this information in its power system models. New regulations have been introduced in the NEM mandating collection of static device information of all DER[11], and AEMO is in the process of developing updated load models[12]. Other jurisdictions have the advantage of a level of real-time operational visibility of significant portions of their DER fleet (for example, 70% of small-scale PV in Germany and Italy are commercial systems with telemetry). Currently AEMO and Australian distribution network service providers (DNSPs) have limited to no real-time visibility of PV systems less than 5 megawatts (MW).
- As passive DER increases, system operators' controllability of the power system reduces. EPRI found that control of DER is often the most cost-effective, and potentially the only, solution to ensure security[13]. Some form of feed-in management over a large fleet of residential solar PV systems has been implemented by system operators in Germany, Japan, and Hawaii, but so far these are only intended for isolated emergency situations. The NEM and SWIS do not currently have any means to actively control residential DER, even in emergency situations.
- Recognising the system impacts of increasing penetrations of residential PV, several jurisdictions have recently mandated improved inverter functionality for small-scale PV systems. In Europe, this has been through national level implementations of the European Network Code for Generators introduced in 2016, most notably Germany and Denmark. In the US, California and Hawaii updated their own local requirements in 2016, which in 2018 were integrated within the US national standard for DER connection.

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[8] Synchronously interconnected systems are connected to other power systems via alternating current interconnectors.

[9] Island power systems are either not interconnected or are interconnected using high voltage direct current.

[10] See Section 3.5 for a discussion of system strength.

[11] See https://www.aemc.gov.au/rule-changes/register-of-distributed-energy-resources.

[12] AEMO, Technical Integration of DER Report, pages 63 and 64, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/DER/2019/Technical-Integration/Technical-Integration-of-DER-Report.pdf.

[13] EPRI International Review on Opportunities to Activate DER, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols.

AEMO is leveraging learnings from international standards development, and in collaboration with DNSPs and local industry, is progressing the introduction of similar requirements in Australia.

Managing variability and uncertainty is increasingly challenging at higher levels of wind and solar generation. Australia can learn from others in their approaches, including the assessment of system ramping requirements and fleet capability.

- EUSysFlex – a large cooperative program of work in Europe – identified a likely reduction in system flexibility if variable generation displaces conventional generation in an uncoordinated way[14]. California has seen a steady drop in midday demand due to high levels of installed solar generation, creating a large ramp up to the evening peak[15].
- To ensure a sufficient amount of system flexibility is available to cover renewable variability, Ireland and California have implemented ramping constraints that interface with their scheduling process. The constraints account for uncertainty in demand, renewable generation (utility and distributed), and conventional generation.
- AEMO is undertaking detailed analysis as part of the RIS to understand how ramping challenges are likely to emerge in the NEM with increasing levels of variable wind and solar generation. Of particular focus will be quantifying how system variability changes as more variable generation is installed, and the level of inherent uncertainty in forecasting the output of these generators on any day.

Australia should consider international approaches to frequency management in high renewable generation systems, including approaches to maintaining sufficient inertia and enablement of primary frequency response on all generators.

- In Texas and Ireland, primary frequency response (PFR) is required from conventional and renewable generation in response to small and large disturbances. The SWIS shares this requirement, but the NEM does not – only a subset of available generation is required to respond to larger disturbances, when selected by the market. AEMO has recently recommended changes to the regulatory framework in the NEM to require PFR from all generators[16].
- Texas and Ireland have employed inertia requirements that are applicable at all times. Similarly, Great Britain and Ireland have employed rate of change of frequency (RoCoF) requirements that apply at all times. The NEM currently has select inertia and RoCoF requirements that are only active under certain circumstances.

International power system operators have taken a staged approach to operating power systems with progressively less synchronous generation online. A similar approach could be considered in Australia.

- Of the operators surveyed, EirGrid (Ireland and Northern Ireland) is taking a staged approach to relaxing power system operational limits related to minimum numbers of synchronous generators online.
- Consideration should be given to how new system conditions can be trialled safely in the NEM and SWIS. This could include taking a precautionary approach (such as mitigating risks and holding extra reserve) for a period (for example, one year) while the system is operated closer to its limits (for example, with fewer synchronous generators online) to build experience and confidence, before accepting those conditions as a new norm.

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[14] EUSysFlex Literature Review , accessed 11 September 2019, at http://eu-sysflex.com/wp-content/uploads/2018/12/D2.1_State-of-the-Art_Literature_Review_of_System_Scarcities_at_High_Levels_of_Renewable_Generation_V1.pdf.

[15] See https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf.

[16] At https://www.aemc.gov.au/rule-changes/mandatory-primary-frequency-response.

Contents

1. What does this insights paper explore?

Australia's large[17] power systems continue to undergo an unprecedented and rapid transition, changing the way in which they will be operated.

Supplying electricity via large interconnected power systems involves a continual balancing of variables over timescales from years ahead, down to days, hours, minutes, seconds, and sub-seconds. Public discussion regarding the increasing uptake of renewable energy resources as part of the electricity supply chain often touches on one or more of the following issues:

- **Sustainability** – seeking ways to reduce the greenhouse gas emissions associated with electricity supply.
- **Reliability of supply** – ensuring there is enough electricity available to meet demand at all times, particularly when power is being generated from sources that vary with the wind and the sun.
- **Affordability** – how increased reliance on renewable energy will affect electricity prices.

These questions typically focus on timeframes from years down to days.

Critically important, but less commonly covered in public discussion, is the need to always keep the system within safe operating limits (referred to as maintaining power system security). This relates to timeframes from days down to sub-seconds. The focus of this paper is these critical security challenges and how other jurisdictions are addressing them. If these security limits are exceeded, the power system is designed to systematically shut down parts of the system, to avoid permanent damage to equipment and prevent health and safety risks. System security events can lead to customer supply interruptions that last longer and affect more customers than supply shortfall events on hot summer days.

As an additional consideration, discussions of future energy policy are increasingly touching on the concept of resilience. A resilient power system is planned and operated to be robust in the face of disturbances, and to respond and recover from disturbances in a desired way[18].

An in-depth analysis of the implications of increasingly high levels of renewables onto Australia's power system helps prepare in advance for addressing the known and developing challenges the transformation presents. This international review provides an important baseline of analysis to help ascertain whether international experiences identify challenges and solutions that add to Australia's independent understanding of these challenges. AEMO's approach includes:

- The identification of power systems experiencing high levels of renewable penetration (Section 2.2).
- The analysis of different characteristics of these systems, to identify similarities and differences to the characteristics of Australia's large power systems (Section 2.3).
- The identification of large power systems with the highest levels of DER (Section 2.4).
- The key learnings from practical experience of large power systems regarding power system security with increasing levels of renewable energy (Section 3). This was based on discussions with the operators of five power systems deemed relevant to the Australian context, including:
  - Electric Reliability Council of Texas (ERCOT) (Texas, USA).

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[17] For the purposes of this report, 'large' power systems are defined as systems having a peak demand greater than 1 GW. Australia's two large power systems are the National Electricity Market (NEM) on the east coast, and the South-West Interconnected System (SWIS) on the west coast. The geographical extent of the NEM and SWIS are shown in Figure 3 in Section 2.3.

[18] AEMO explored the concept of power system resilience in its submission to the AEMC Discussion paper: *Mechanisms to enhance resilience in the power system*, page 7, at https://www.aemc.gov.au/sites/default/files/2019-09/AEMO%20-%20Submission%20to%20the%20Discussion%20Paper%20-%20EPR0057.pdf.

   - National Grid Electricity System Operator (National Grid) (Great Britain).
   - EirGrid (Ireland and Northern Ireland).
   - Hawaiian Electric Company (Hawaii, USA).
   - Energinet (Denmark).
- Leveraging the insights from AEMO's previously commissioned review of how comparable power systems around the world are integrating DER and resolving the associated system challenges (Section 3.6)[19].
- Identification of previous international reviews into the management of increasing levels of renewable generation, including a summary of key focus areas for maintaining power system security (Section 3.1).

Details on next steps and how to get involved with AEMO's ongoing RIS are provided in Section 4.

[19] EPRI International Review on Opportunities to Activate DER, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols.

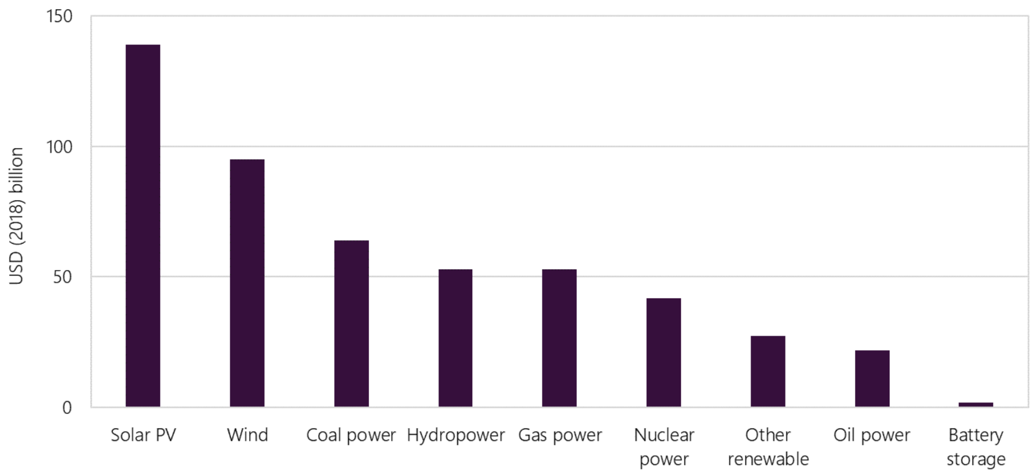
2. How does Australia compare?

2.1 Rise of wind and solar

Many countries with limited access to hydro, biofuel, or geothermal energy are looking towards more sustainable electricity supplies and have focused on wind and solar technologies.

Wind generation and solar PV technologies are evolving quickly, and a steady reduction in costs combined with a variety of government subsidies and incentives has led to increasing uptake over the last 20 years. Figure 1 shows that annual global investments in solar PV and wind exceeded investments in other generation technology in 2018.

Figure 1 Global investment in the power sector by generation technology, 2018



Sourced from International Energy Agency (2019) World Energy Investment 2019 review, at https://www.iea.org/wei2019/.

Wind and solar PV technologies have several characteristics that differ from those of historically dominant power generation technologies, including:

- **Variability** – having fuel sources that are based on weather, rather than sources that can be stockpiled for continuous use like coal, gas, or large hydroelectric schemes[20].
- **Inverter-based resources (IBR)** – devices that interface with the grid using a power electronic device (called an inverter) [21]. Solar PV systems, high voltage direct current (HVDC) converters, and most new wind turbines are all IBR. The inverters digitally synthesize an output to match the power system alternating current (AC) waveform. These devices operate in different ways to conventional generating systems in coal, gas, and hydro plants which interface to the grid with a rotating electro-mechanical generator.
- **Decentralised** – there is a growing uptake of small to medium generators spread out across the network (such as wind and solar farms in remote areas away from population centres) and highly decentralised micro generators like residential solar PV and batteries. This contrasts with traditionally having fewer large power stations, located as close as possible to major population centres.

[20] These resources are often referred to as variable renewable energy (VRE) resources.

[21] The terms 'non-synchronous' and 'asynchronous' have been historically used in Australia when referring to inverter-based resources. For the purposes of this paper, AEMO has used the term inverter-based resources (IBR).

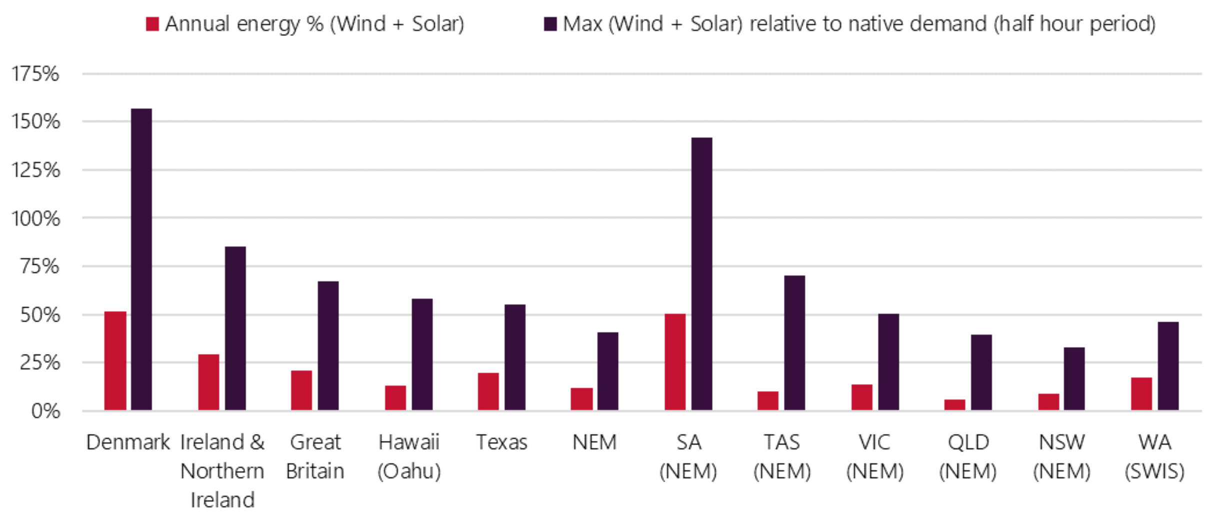
2.2 Pioneers in renewables

Australia is experiencing some of the highest instantaneous levels of wind and solar generation in the world. Synchronously interconnected[22] power systems have operated for periods where wind and solar energy was larger than demand – including Denmark (157%) and South Australia (142%). Island systems[23] have operated at high levels of wind and solar generation relative to demand – Ireland (85%), Tasmania (70%), and Great Britain (67%).

Electricity demand is continually varying – seasonally (depending on climate heating and cooling demand), daily (weekdays experience higher demand than weekends), and hourly (total demand is lowest in the middle of the night). Wind and solar generation also vary as the wind blows and the sun follows its daily cycle (or is interrupted by cloud cover). Periods of high renewable generation are not always coincident with high demand. As such, it is becoming more frequent for large power systems to operate during some periods where the majority of demand is being supplied by variable IBR.

Figure 2 compares Australian power systems to selected large international power systems with high penetrations of wind and solar generation[24] and a high degree of isolation[25].

Figure 2 Large international power systems operating with high instantaneous penetrations of wind and solar generation, and Australian comparisons [26]



The first column in Figure 2 shows the proportion of each region's annual energy served by wind and solar, and the second shows the period with the maximum proportion of wind and solar relative to system demand[27]. Parts of Australia are already operating at world-leading levels.

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[22] Synchronously interconnected systems are connected to other power systems via alternating current interconnectors.

[23] Island power systems are either not interconnected or are interconnected using high voltage direct current.

[24] https://www.iea.org/renewables2018/.

[25] As Denmark has the highest level of wind and solar in the world, it was included for comparative purposes despite being heavily interconnected with the European and Scandinavian power systems,

[26] Data sources for Figure 2: Denmark (https://docstore.entsoe.eu/Documents/Publications/Statistics/Factsheet/entsoe_sfs2018_web.pdf and http://osp.energinet.dk/_layouts/Markedsdata/framework/integrations/markedsdatatemplate.aspx?language=en), Ireland and Northern Ireland (http://www.eirgridgroup.com/site-files/library/EirGrid/System-and-Renewable-Data-Summary-Repor%20July%202019t.xlsx), Great Britain (https://www.gov.uk/government/statistics/uk-energy-in-brief-2019 and https://gridwatch.co.uk/), Hawaii (https://www.hawaiianelectric.com/about-us/power-facts), Texas (http://www.ercot.com/content/wcm/lists/172484/ERCOT_Quick_Facts_01.17.19.pdf), Australia (https://assets.cleanenergycouncil.org.au/documents/resources/reports/clean-energy-australia/clean-energy-australia-report-2019-fact-sheet.pdf, and internal database).

[27] Numbers greater than 100% are achieved if the variable inverter-based power is larger than demand and the excess power is exported.

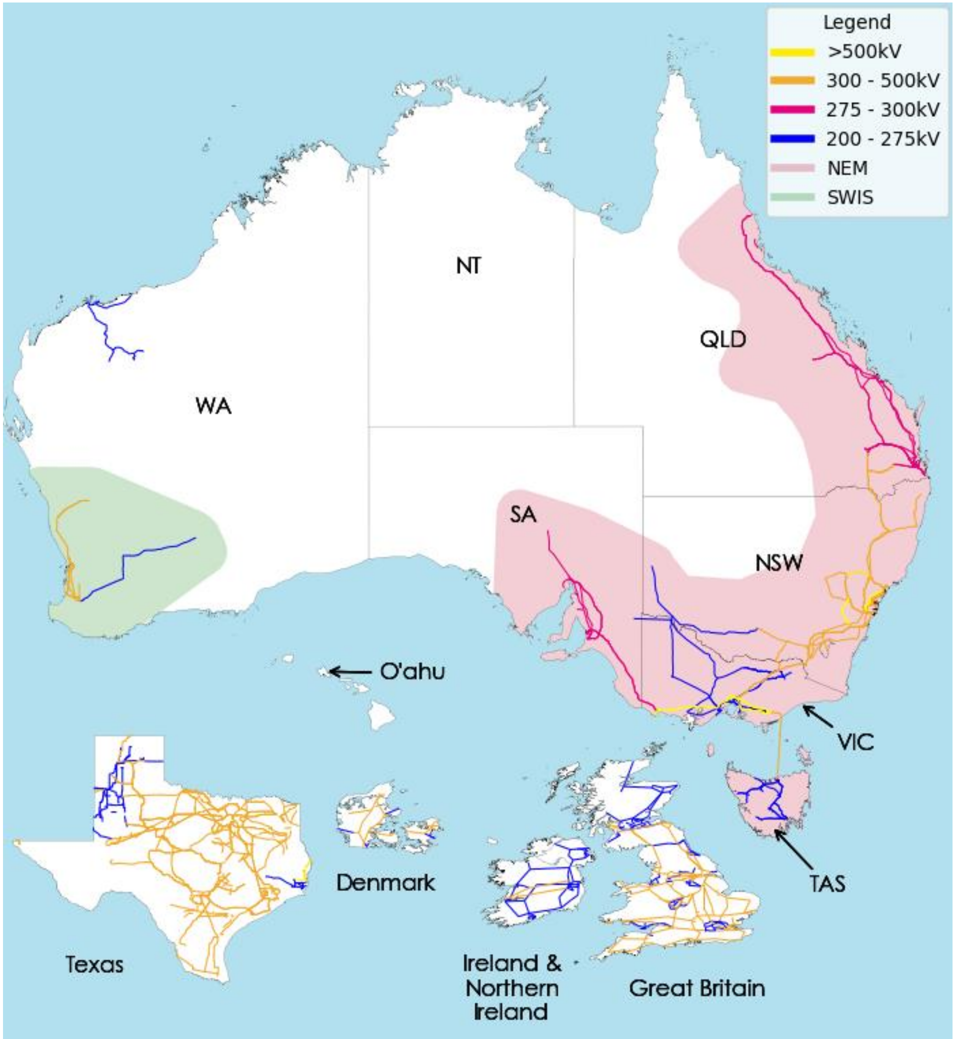
2.3 Comparing different systems

Every power system has physical characteristics that are unique, such as networks, generation mix, and load composition. There is no one system that can be looked to for direct comparative purposes. Instead, AEMO is identifying the comparable characteristics of each system, and combining the learnings to build a complete picture.

Each power system will have differing challenges as it transitions to a power system dominated by variable IBR. To understand the nature of the transition for each power system it is important to consider the following characteristics:

- **Resource location and network topology** – relates to the physical locations of generators and power lines and is a product of the geographic area being served, the location of major population centres, and the location of generators. Figure 3 below compares the bulk power system of the jurisdictions covered in this report. It demonstrates the vastly greater scale that the Australian system has compared to the different Irish, Danish, British, Hawaiian, and even Texan systems, which cover much smaller areas than the NEM in eastern Australia.

Figure 3 Comparison of network topologies



Source: Country outline/jurisdictions: https://gadm.org/data.html, Texas, Oahu Transmission: https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines/ European lines: Unofficial extract of ENTSO-E map by Gridkit, link: https://zenodo.org/record/55853#.XYsMRfkzaUk, Geosciences Australia - Electricity Transmission Lines database, Available here: https://data.gov.au/dataset/ds-ga-1185c97c-c042-be90-e053-12a3070a969b/details?q=

- **System complexity** – can be related to the number of connected participants and how difficult it is to predict the behaviour of the system. As an example, Hawaiian Electric owns and controls the network and the existing thermal generators, allowing more central management to accommodate variable IBR[28]. In comparison, large systems like Great Britain, Texas, and the NEM in Australia have hundreds of large generators competing in liberalised electricity markets. With such a large combination of possible outcomes in the energy market, constant analysis is required to ensure the system is secure. Figure 4 (column 4) compares the peak demand of high renewable systems identified.
- **System flexibility** – if the system is flexible, it will be able to accommodate more variable generation. The flexibility of a resource is the extent to which its output can be adjusted or committed in or out of service including speed of response to start up and shut down, rate of ramping, and whether it can operate in the full range of capability or has restrictions[29]. While new sources of flexibility, most notably the demand side, offer huge potential to increase system flexibility, historically the main source of flexibility has been from the generation fleet. The installed capacity by fuel type relative to peak system demand is shown in the first column of Figure 4. Tasmania's generation fleet is predominantly hydro, Hawaii's mostly oil, and South Australia, Ireland, and Western Australia are dominated by gas; these fuel sources are historically quite flexible. This contrasts with Queensland, New South Wales, and Victoria, whose existing generation fleet is predominantly coal-fired, which is historically less flexible. While fuel type can be taken as a proxy for flexibility, there can be a wide range of flexibility, depending on specific plant design.
- **Coincidence of resource and demand** – both are variable, based on season and throughout the day. Electricity travels at close to the speed of light and is consumed as it is generated; if the availability of energy is coincident with demand it can be accommodated more economically. The second column of Figure 4 shows the installed capacity of variable resources relative to system peak demand. The Australian mainland power system demand is higher in summer, which seasonally coincides with high solar output[30]. Conversely, Ireland has low demand at midday in summer when solar output is at peak, but wind is higher in winter when seasonal demand is high, but this may also be high during the night when demand is low.
- **Storage** – can be used to help balance the system, storing energy when there is a surplus and discharging when most needed. Installed storage capacity (gigawatts [GW]) relative to peak demand is shown in the third column in Figure 4. Storage has traditionally been installed using synchronous pumped hydro storage, and AEMO has published an ISP Insights paper on pumped storage developments in the NEM[31]. Battery storage technology is improving, and costs are reducing. An island like Hawaii (Oahu), which imports expensive oil to power the system and has a surplus of solar generation during the day, has an installed capacity of batteries equivalent to 14% of peak demand.
- **Interconnection** – can be used to help balance the system, exporting energy when there is a surplus and importing when needed. There are two types of interconnection between large power systems: AC interconnection allows the transfer of active power, synchronous inertia and system strength, while HVDC interconnection allows the transfer of active power. The third column in Figure 4 shows installed interconnection capacity relative to peak demand. Denmark is heavily interconnected with the central European and Scandinavian power systems with both AC and HVDC, which means it can rely on its neighbours for balancing and stabilising services. By contrast, Oahu in Hawaii, Western Australia's SWIS, and the NEM have no interconnection and must source all their requirements locally.

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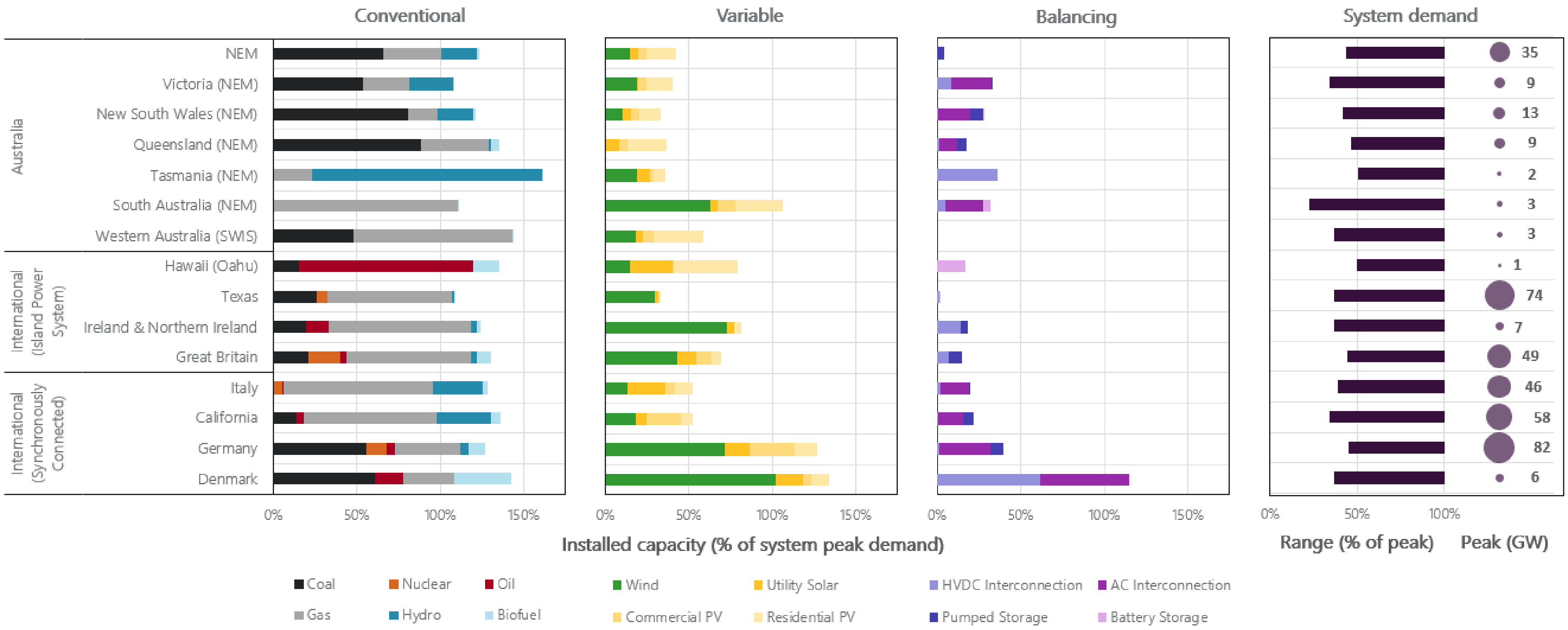
[28] From discussions with Hawaiian Electric.

[29] Resource flexibility is discussed in more detail in AEMO's Power System Requirements paper, p 6, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf.

[30] The daily peak demand is in the evening with peak generation during the day.

[31] At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/ISP/2019/ISP-Insights---Building-power-system-resilience-with-pumped-hydro-energy-storage.pdf.

Figure 4 Installed components of large international power systems relative peak demand



Data Sources: Australia (AEMO, Generation Information: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Generation-information, Australian PV Institute, PV Postcode Data: https://pv-map.apvi.org.au/postcode) Great Britain (Department for Business, Energy & Industrial Strategy, Digest of UK Energy Statistics: https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes; Department for Business, Energy & Industrial Strategy, Solar Photovoltaics Deployment: https://www.gov.uk/government/statistics/solar-photovoltaics-deployment) Oahu (Hawaiian Electric, Power Facts: https://www.hawaiianelectric.com/about-us/power-facts; Hawaii State Energy Office, Hawaii Renewable Energy Projects Directory: https://energy.ehawaii.gov/epd/public/energy-projects-list.html)Ireland (EirGrid, All-Island Generation Capacity Statement 2018-2027: http://www.eirgridgroup.com/site-files/library/EirGrid/Generation_Capacity_Statement_2018.pdf; Sustainable Energy Authority of Ireland, Ireland's Solar Value Chain Opportunity: https://www.seai.ie/publications/Solar-Chain-Opportunity-report.pdf) Denmark (Energi Data Service, Capacity Per Municipality Data: https://www.energidataservice.dk/en/dataset/capacitypermunicipality; IEA PV Power Systems Programme, National Survey Report of Photovoltaic Applications in Denmark 2017: http://iea-pvps.org/index.php?id=93&eID=dam_frontend_push&docID=4457) Germany, Italy (ENTSO-E, Net Generating Capacity: https://www.entsoe.eu/data/power-stats/net-gen-capacity/; ENTSO-E, Ten Year Network Development Plan 2018 Executive Report, Appendix: https://tyndp.entsoe.eu/Documents/TYNDP%20documents/TYNDP2018/consultation/Main%20Report/TYNDP18%20Exec%20Report%20appendix.pdf, Bloomberg New Energy Finance, New Energy Outlook 2019 data viewer: https://about.bnef.com/new-energy-outlook/)Texas (ERCOT, Capacity changes by fuel type: http://www.ercot.com/content/wcm/lists/162615/Capacity_Changes_by_Fuel_Type_Charts_November_2018.xlsx; ERCOT, Unregistered DG Installed Capacity Quarterly Report, http://www.ercot.com/services/rq/re/dgresource; U.S. Energy Information Administration, Electric Power Monthly with Data for July 2019: https://www.eia.gov/electricity/monthly/current_month/epm.pdf Table 6.2.B)California (California ISO, Key Statistics August 2019: California Energy Commission, Electric Generation Capacity & Energy: http://www.caiso.com/Documents/MonthlyStats-August2019.pdf https://ww2.energy.ca.gov/almanac/electricity_data/electric_generation_capacity.html; California Distributed Generation Statistics: https://www.californiadgstats.ca.gov/charts/nem; Self-Generation Incentive Program, State-wide Report: https://www.selfgenca.com/documents/reports/statewide_projects)

2.4 Leaders in distributed energy resources (DER)

A further dimension of the changing generation mix is the uptake of residential and commercial rooftop solar and batteries, increasing the decentralisation of energy supply. Australia has nearly 2 million rooftop solar installations covering 20% of all homes, up to a third in some regions, making it a world leader in household solar per capita.

DER are comprised of devices and capabilities co-located with customer loads (either in front of or behind the meter) or embedded within distribution networks. Compared to centralised sources, the disaggregated nature of DER poses some distinct integration challenges. Historically, distribution networks were not designed with the accommodation of local generation in mind.

Of the systems considered, the island of Oahu in Hawaii was the most comparable to Australia in terms of residential PV (where approximately 32% of households have PV systems installed)[32]. As illustrated in Figure 4, other jurisdictions with similar shares of distributed solar capacity to Australia typically have significantly smaller shares of residential PV. For example, around 30% of distributed solar in Germany and Italy are at the household level, with the bulk of installations being larger systems. In these jurisdictions, larger, commercial-scale systems have stronger performance requirements, a degree of system operator visibility, and (in some cases) controllability – which is not generally the case with smaller residential systems.

The extent to which distribution networks can accommodate DER is influenced by two main aspects:

- **Distribution network topology** – refers to the physical characteristics of the distribution system. Some high-DER subregions internationally – such as Vermont (US), Bavaria (Germany), and parts of Japan – are within highly meshed interconnected systems. In comparison, Australian distribution networks are characterised by longer distances serving lower average population densities (despite some high-density urban pockets). As a result, generalised DER hosting capacity rules of thumb[33] may not always be as appropriate in an Australian context. More sophisticated assessment techniques are being explored in Australia and internationally[34,35]. Efforts are underway in the NEM to collect and consolidate data across DNSPs for the development of adequate network models of low voltage distribution feeders[36] for hosting capacity assessment.
- **Distribution network monitoring and capability** – refers to the DNSPs' level of visibility of their low-voltage network assets and the extent to which they can actively manage these assets to accommodate changes in electricity flows due to increasing behind-the-meter generation from DER. Some distribution network operators internationally have a level of visibility via customer metering. In Australia, only Victoria has sufficient levels of advanced metering for DNSPs to take advantage of this. Jurisdictions in Australia experiencing higher levels of DER are installing advanced measurement facilities within their networks as an effort to improve network visibility. Australian and international jurisdictions are trialling a variety of active distribution network management initiatives[37].

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[32] Utility Dive, accessed 26 September 2019, at https://www.utilitydive.com/news/17-of-hawaiian-electric-customers-now-have-rooftop-solar/413014/.

[33] CIGRE Technical Brochure 586, WG C6-24, Capacity of Distribution Feeders for Hosting Distributed Energy Resources, 2014, at https://www.cigreaustralia.org.au/assets/ITL-SEPT-2014/3.1-Capacity-of-Distribution-Feeders-for-hosting-Distributed-Energy-Resources-DER-abstract.pdf.

[34] EPRI, Distributed PV Monitoring and Feeder Analysis, at https://dpv.epri.com/hosting_capacity_method.html.

[35] NREL, Advanced Hosting Capacity Analysis, at https://www.nrel.gov/solar/advanced-hosting-capacity-analysis.html.

[36] ARENA, Low-voltage Feeder Taxonomy Study, accessed 26 September 2019, at https://arena.gov.au/projects/national-low-voltage-feeder-taxonomy-study/.

[37] IEA PVPS, High Penetration of PV in Local Distribution Grids, at http://www.iea-pvps.org/index.php?id=373&eID=dam_frontend_push&docID=2210.

3. What can Australia learn from other systems?

While some characteristics of each power system differ, the underlying physics of large AC power systems are universal. For power system operators managing systems with high levels of wind and solar, there is a well understood group of technical challenges. Each system offers learning opportunities based on operators' progress to date managing changes in the context of their system.

When operating a secure and reliable power system, there are minimum technical requirements that must be maintained[38]. This chapter explores which technical requirements are most impacted by increasing levels of wind and solar generation, and the comparable experiences of power system operators internationally.

For the reasons stated in Section 2, each system faces a different combination of challenges depending on its characteristics. International power systems also differ in how advanced they are in addressing these challenges, creating opportunities for knowledge sharing and collaboration.

3.1 Priority focus areas

To focus our renewable integration efforts in the right places, AEMO sought out leading international efforts into the management of increasing levels of renewable generation, including:

- **EUSysFlex** – a 20 million euro, four-year, cooperative effort to test operation of the pan-European electricity system with more than 50% of renewable energy sources[39]. It involves a multinational consortium of system operators, aggregators, technology providers, research institutions, and consultants.
- **MIGRATE** – a multinational collaboration to address challenges of operating parts of the European electricity system during periods with very high levels of inverter-based wind and solar generation[40].
- **Electric Power Research Institute (EPRI)** review of international approaches to activating DER in the energy market[41].
- The distillation of **key learnings from practical experience** of power systems operating with increasing levels of renewable energy, particularly:
  - Electric Reliability Council of Texas (ERCOT) (Texas, USA).
  - National Grid Electricity System Operator (National Grid) (Great Britain).
  - EirGrid (Ireland and Northern Ireland).

[38] An overview of these physical prerequisites is provided in AEMO's Power System Requirements reference paper, published March 2018, at https://aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf.

[39] EUSysFlex, accessed 31 August 2019, at https://eu-sysflex.com/.

[40] MIGRATE, accessed 31 August 2019, at https://www.h2020-migrate.eu/.

[41] EPRI for AEMO (Jul-2019) Activation of DER in the Energy Market, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols.

The MIGRATE and EUSysFlex programs have published detailed reviews that summarise the main technical constraints or barriers for system operators to maintain power system security with high penetrations of IBR and renewable energy respectively[42,43].

EPRI recommended a set of best practice principles and resulting technical and market enablers for the efficient and secure integration of high penetrations of passive DER[44]. These priority focus areas fall into the categories shown in coloured columns of Table 1. The table then gives a high-level summary of the extent to which different power systems have defined specific limits that impact variable IBR for each technical requirement. Each system has defined its limits in different ways.

A breakdown of these different experiences is provided in the remaining sections of Chapter 3.

Table 1 Comparison of system limits by jurisdiction

			Defined system limits that impact renewables				
System Attribute	**Requirement**	**Focus Area**	**NEM**	**SWIS**	**Ireland / Northern Ireland**	**Great Britain**	**Texas**
Frequency Management	***Maintain frequency within limits***	***Primary Frequency Response Enabled***	See section 3.2				
		Synchronous Inertia	○	○	●	○	●
		RoCoF	○	○	●	●	○
Voltage Management	***Maintain voltages within limits***	***Voltage***	◐	◐	◐	◐	◐
	Maintain stability of system	***System Strength Bulk System***	●	○	○	○	○
	Maintain stability of individual generating system	***System Strength Generation Connection***	◐	○	○	○	◐
Other	***Maintain system in secure state***	***System Variability***	○	○	◐	◐	◐
		Minimum Synchronous Unit Combinations	●	○	●	○	○
		SNSP	○	○	●	○	○
		DER	○	○	○	○	○

● Limit specified which currently limits the penetration of wind and solar
◐ Limit specified which may indirectly limit penetration of wind and solar
○ No specified limit

[42] At https://www.h2020-migrate.eu/_Resources/Persistent/9bf78fc978e534f6393afb1f8510db86e56a1177/MIGRATE_D1.1_final_TenneT.pdf.

[43] EUSysFlex Literature Review , accessed 31 August 2019, at http://eu-sysflex.com/wp-content/uploads/2018/12/D2.1_State-of-the-Art_Literature_Review_of_System_Scarcities_at_High_Levels_of_Renewable_Generation_V1.pdf.

[44] EPRI International Review on Opportunities to Activate DER, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols.

3.2 Frequency management

Changes in the generation mix are fundamentally changing the way the system responds to imbalances in power.

All power systems must have the ability to set and maintain frequency within design limits. If frequency is not controlled, it can lead to a cascading failure, with generators disconnecting from the power system as the frequency decreases or increases. In 2016, AEMO commissioned a report, *International Review of Frequency Control Adaption*, much of which is still relevant today[45].

Frequency management is broken into two categories. The first relates to the system response after small continuous imbalances in power, and the second relates to managing large imbalances of power.

3.2.1 Small imbalances

The continuous matching of supply and demand is needed to keep the frequency as close to nominal as possible (50 Hz in Australia and Europe, and 60 Hz in North America).

- **Primary frequency response** (PFR) is when a generator measures the local frequency and adjusts its output in response.
  - **PFR capability** – it is mandatory in the jurisdictions assessed to have the capability to control the frequency for both conventional and renewable generators.
  - **PFR enablement for conventional generators** – this is mandatory in all the reviewed jurisdictions other than the NEM. In the NEM, there is no existing requirement for PFR to operate in a way that is sensitive to small frequency changes, however, there are some generators that currently do operate this way[46].
  - **PFR enablement for renewable generators** – in Texas and Ireland, it is also mandatory for renewable generators to have PFR enabled. In Ireland and Northern Ireland, the grid operator can change the settings of PFR on renewable plant in real time to make them more responsive to small frequency changes. This is currently being used to manage grid issues such as damping low frequency common mode oscillations[47]. This level of control in Ireland also allows the grid operator to control the frequency above or below the nominal to manage high and low frequency risk[48].
  - **Reserving headroom** – while PFR may be mandatory in some jurisdictions, reserving headroom and enablement of the service is remunerated through different mechanisms. AEMO has recently recommended changes to the regulatory framework in the NEM to require PFR from all generators[49].
- The NEM has a centrally dispatched frequency regulation service that operates through the **Automatic Generator Control** (AGC) system. The AGC system is responsible for five-minute dispatch of generator output as well as a faster service that adjusts generator output targets every four seconds. Texas employs a similar central system, but it is accompanied by requirements for generators to regulate through PFR. PFR and central regulation are not directly interchangeable, due to differences in the speed and qualities of the response from each. Central regulation provides a slower response suitable for assisting with correcting frequency over longer periods. It helps keep generators on their dispatch target and controls the average frequency, known as time error correction.

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[45] At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2016/FPSS---International-Review-of-Frequency-Control.pdf.

[46] At https://www.aemc.gov.au/rule-changes/mandatory-primary-frequency-response.

[47] At http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-Advisory-Council-23-May-2018.zip.

[48] Discussions with EirGrid.

[49] At https://www.aemc.gov.au/rule-changes/mandatory-primary-frequency-response.

3.2.2 Large imbalances

Large unexpected changes in power balance happen from time to time on the grid, caused by disconnection of sources or sinks of power. This can happen for several reasons, such as disconnection of customer plant. The system must have adequate reserves to quickly balance the energy change to keep the system stable.

- **Primary Frequency Response** – as with small imbalances, PFR is needed to arrest the frequency change following a large imbalance. The response is typically provided in the range of 0.1 to 15 seconds and is procured differently in each jurisdiction assessed. Definitions vary, but for the purposes of this report, Fast Frequency Response (FFR) is defined as a rapid injection of active power (in a time period of 1-2 seconds or less), to arrest the frequency decline following a contingency event. In Ireland, Great Britain, and Texas, operators have incentivised provision of an FFR-type service.

Table 2 Overview of primary frequency response requirements by jurisdiction

Jurisdiction	Conventional		Renewable	
	Capability requirement	Enablement requirement	Capability requirement	Enablement requirement
East Coast Australia (NEM)	Yes	Market Based	Yes	Market Based
Western Australia (SWIS)	Yes	Yes	Yes	For over frequency
Ireland/Northern Ireland	Yes	Yes	Yes	Yes
Great Britain	Yes	Mandatory when selected under contract	Yes	Mandatory when selected under contract
Texas	Yes	Yes	Yes	Yes

From Review of International Grid Codes, February 2018, at https://certs.lbl.gov/sites/default/files/international_grid_codes_lbnl-2001104.pdf. Definitive information for Denmark and Hawaii not available to AEMO at time of publication.

- **Largest risk covered** is the size of the unexpected imbalance for which the operator carries reserve. Typically, this is the largest source of power and the largest consumer. When a power producer is disconnected, additional power needs to be brought on, or sufficient load removed, to restore the power balance. When a load is disconnected, surplus generation must be removed. In the NEM, SWIS, Ireland, and Great Britain, the single largest loss is covered, which dynamically changes depending on the largest risk at the time. In the NEM, reserve coverage can be increased due to an increased risk, such as an environmental risk of lightning or bushfires near a double circuit interconnector. In Texas the amount of reserve carried is to cover the simultaneous loss of the two largest nuclear units. See Table 3 for a summary.
- **Synchronous inertial response** is the instantaneous transfer of energy from conventional rotating machines to the grid. This is provided by the physics of the conventional machine and does not require control system interaction. This transfer slows the Rate of Change of Frequency (RoCoF), giving control systems time to adjust their output. Ireland and Texas have defined a minimum inertia level. The NEM does not specify a minimum inertia level when the system is intact, but it does specify a minimum inertia level for each state if there is a predetermined risk of islanding. No inertia level is specified in the SWIS, although there is a requirement to avoid automated underfrequency load shedding for a single contingency. In Tasmania, several hydro units can stay connected, with no power output, providing inertia to the system[50].

[50] See https://www.aemo.com.au/Media-Centre/~/-/media/B47810C12E25473CB81968D5D4218F78.ashx.

- **RoCoF** limits have been set in two jurisdictions – Ireland and Great Britain. In Great Britain, this limit is determined by protection settings on the distribution system. If the RoCoF exceeds 0.125 Hz/s, then embedded generation on the distribution system will be disconnected, further worsening frequency stability[51]. Ireland has a similar problem, with distribution protection set to 0.5 Hz/s. In both jurisdictions there are programs of works to rectify this protection, with Great Britain moving to 0.5 Hz/s and Ireland moving to 1 Hz/s[52]. In Ireland, there was also a change to the generator connection rules for large generators, which has resulted in a multi-year program to study and test existing generators to show compliance with this new standard. While there currently is no system RoCoF limit in the NEM, generators must be compliant with National Electricity Rules (NER) which require 4 Hz/s for 250 milliseconds to meet the automatic access standard and 1 Hz/s for 1 second to meet the minimum access standard.

Table 3 Overview of power system requirements for frequency

	NEM	WA	IRL/NI	GB	Texas
Largest Risk Covered (No Units / GW)	1 / 0.75	1/0.34	1 / 0.5	1 / 1	2 / 2.75
RoCoF Limit (Hz/s)	No general requirement*	No general requirement	0.5	0.125	N/A
Minimum Synchronous Inertia Limit (GWs)	Regional limits under credible risk of islanding	N/A	23	N/A	100
Fast Frequency Response	No	No	Yes	Yes	Yes

* For South Australia, a 1 Hz/s requirement is maintained for a credible separation from the rest of the NEM, and a 3 Hz/s is maintained for a non-credible separation.
Data sources: NERC (https://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERS_Forward_Measures_124_Tech_Brief_03292018_Final.pdf), EirGrid (http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-Programme-Transition-Plan-Q4-2018-Q4-2020-Final.pdf), ERCOT (http://www.ercot.com/content/wcm/key_documents_lists/141324/Inertia_Basic_Concepts_Impacts_On_ERCOT_v0.pdf).

- **Emergency frequency control schemes** are control schemes that operators employ as a safety mechanism for unlikely events. If a power imbalance occurs that is larger than the primary reserves that are available, load or generation is automatically disconnected in a co-ordinated way to rebalance the system and avoid total system collapse. All countries surveyed utilised under frequency load shedding (UFLS), which disconnects uncontracted load sequentially in blocks to try to balance the system. This typically operates based on a frequency trigger and operates in the order of 1-10 seconds. One of the more recent examples of this scheme working was in Great Britain, where two units were lost and UFLS was used to balance the system[53]. These schemes are reliant on protection relays with time delays to operate, which does require a level of inertia to slow the RoCoF for them to work.
- **Voltage Dip-Induced Frequency Deviation** (VDIFD) is an issue with the recovery phase of active power of inverters after a disturbance. Figure 5 shows the difference between active power recovery of a synchronous unit and an inverter-based wind turbine for a voltage dip. The active power recovery of stable synchronous generators follows the recovering voltage and is therefore very quick. The active power recovery of wind turbine generators may be slower, to keep mechanical stress on the structure at acceptable levels. The impact of this issue is dependent on the type of wind turbine and is aggravated by decreasing system strength and a broader propagation of voltage dips (as covered in Section 3.5). Inverter-based generation without a mechanical prime mover, such as PV plant, can be controlled in such a way that recovery time is reduced[54]. National Grid found that all faults on the system will have a

[51] See https://www.nationalgrideso.com/document/146506/download.

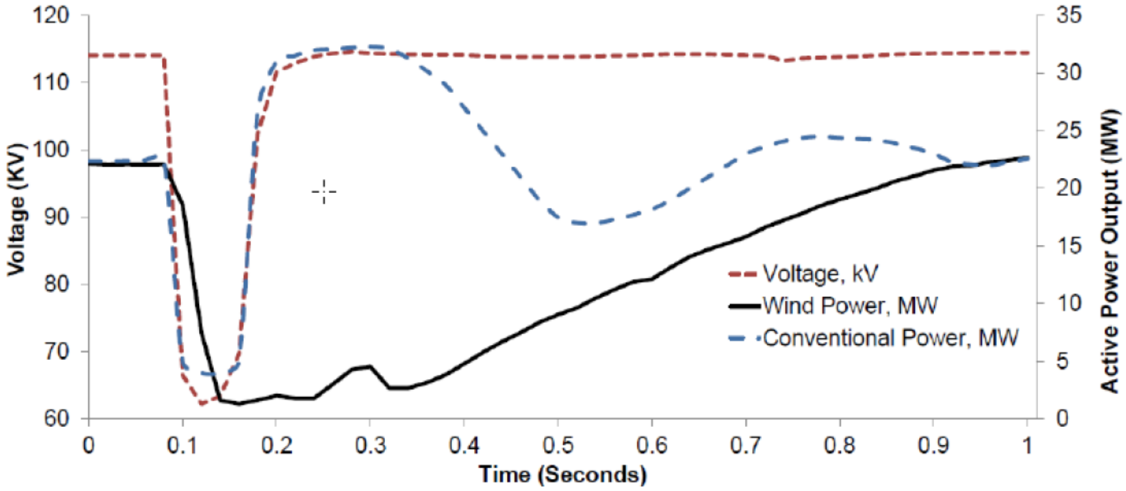
[52] See http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-Rate-of-Change-of-Frequency-(RoCoF)Workstream-Plan-2015.pdf.

[53] See https://www.ofgem.gov.uk/system/files/docs/2019/08/incident_report_lfdd_-_summary_-_final.pdf.

[54] EUSysFlex Literature Review , accessed on 31 August 2019, at http://eu-sysflex.com/wp-content/uploads/2018/12/D2.1_State-of-the-Art_Literature_Review_of_System_Scarcities_at_High_Levels_of_Renewable_Generation_V1.pdf.

combined frequency and voltage effect. In future, with the reduction in synchronous generation, combined events will be more significant and will need to be considered[55]. The NEM has taken a step towards managing this issue in its latest generator performance requirements for fast post-fault active power recovery[56]. This issue should be monitored to ensure it can be proactively managed in the NEM and SWIS.

Figure 5 Active power recovery characteristics of conventional and wind generators



Source: https://www.h2020-migrate.eu/.

3.3 Managing variability and uncertainty

The requirements of the system to manage variability are changing, due to higher levels of weather-driven generation. Uncertainty regarding wind and solar generation forecasts and the ability of aging conventional generation to quickly start and ramp must be managed.

Daily changes in demand and variable generation are forecast, and generation is scheduled to cover this level. The system must have enough flexibility to be able to maintain the supply demand balance over all periods[57]. The increase in variable weather driven generation, including DER, poses key challenges to balancing supply and demand in the power system:

- **Increased variability** in both generation and demand, driven by weather-dependent utility-scale wind and solar PV on the supply side and rooftop PV (DER) on the demand side[58].
- **Increased uncertainty** in forecasts for weather-driven renewable output (utility-scale and DER) and with aging conventional generation's ability to quickly start and ramp[59,60].
- **Reduction in system flexibility** during periods of high renewables driven by the displacement of online conventional generation, which has traditionally been used to manage ramps[61].

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[55] At https://www.nationalgrideso.com/sites/eso/files/documents/SOF%20Report%20-%20Frequency%20and%20Voltage%20assessment.pdf.

[56] National Electricity Rules, at https://www.aemc.gov.au/regulation/energy-rules/national-electricity-rules/current.

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

[58] At https://www.nrel.gov/docs/fy11osti/49218.pdf.

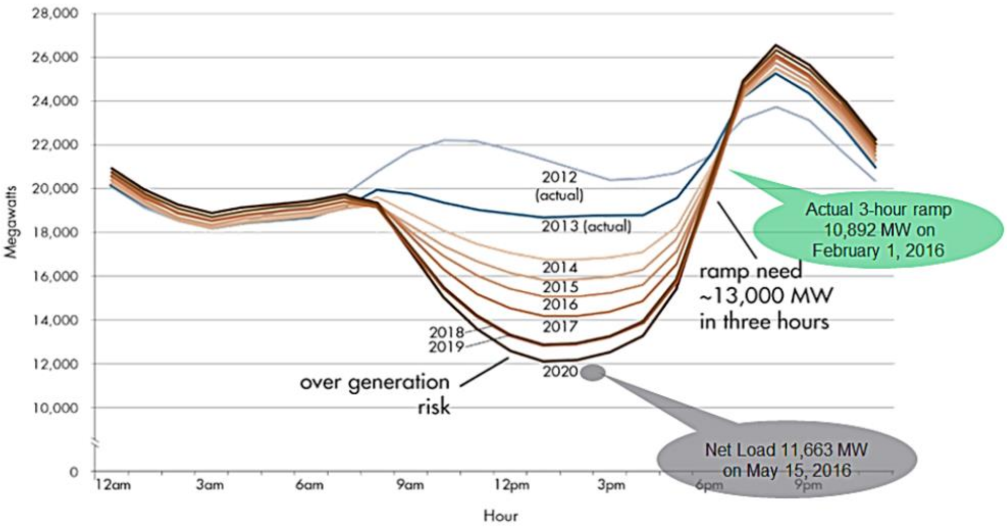
[59] At https://www.nrel.gov/docs/fy15osti/63037.pdf.

[60] At https://link.springer.com/content/pdf/10.1007%2Fs40565-019-0527-4.pdf.

[61] EUSysFlex Literature Review , accessed on 11 September 2019, at http://eu-sysflex.com/wp-content/uploads/2018/12/D2.1_State-of-the-Art_Literature_Review_of_System_Scarcities_at_High_Levels_of_Renewable_Generation_V1.pdf.

Figure 6 shows a typical spring day demand profile in California, where there has been a steady drop in the 'belly' of the 'duck curve' due to high levels of installed solar PV. This creates a large ramp that needs to be covered between the solar peak at midday and the evening peak. To utilise solar capacity during the day, conventional generation may be backed down so far that the fast ramp-up to meet peak evening demand may strain the operational capability of the system. Conversely, renewable generation may also be constrained during the day to the manage the ramp up to the evening peak[62,63].

Figure 6 CAISO duck curve chart



Source: CAISO, at https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf.

As the system transitions, dispatches that are optimised to cover traditional forms of variability (demand and primary reserve) may no longer be fit for purpose over all necessary timeframes to effectively manage the variability from renewables[64].

There are several international experiences that are relevant for managing variability introduced through increasing levels of wind and solar generation:

- **Managing uncertainty** – California has implemented several successive ramping tools, including the flexible ramping constraint between 2011 and 2016, which consider forecast ramps and an uncertainty margin[65,66]. Ireland in scheduling accounts for uncertainty for demand, and variable and conventional generation start up over longer timeframes [67]. In the NEM, AEMO assesses whether energy reserve levels in future time periods are likely to be sufficient to meet forecast demand. The reserve assessments include covering the uncertainty in forecast generation and demand.
- **Ramp rate limits** – Hawaii has implemented ramp rate limits for renewable generators[68]. In Denmark, for large wind and solar farms, a maximum ramp rate is imposed to reduce stress on the system[69].
- **Scheduling capability** – Great Britain, Ireland, Denmark, Texas, and California use day ahead generation commitment, which schedules the portfolio to be able to meet forecast ramps. This schedule takes

[62] EPRI for AEMO (Jul-2019) Activation of DER in the Energy Market, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols.

[63] At https://www.nrel.gov/docs/fy16osti/65023.pdf.

[64] At http://www.eirgridgroup.com/site-files/library/EirGrid/System-Services-Consultation-New-Products-and-Contractual-Arrangements-June_2012.pdf.

[65] At http://www.caiso.com/informed/Pages/StakeholderProcesses/CompletedClosedStakeholderInitiatives/FlexibleRampingProduct.aspx.

[66] At http://www.caiso.com/Documents/RevisedDraftFinalProposal-FlexibleRampingProduct-2015.pdf.

[67] EUSysFlex Literature Review, accessed 11 September 2019, at http://eu-sysflex.com/wp-content/uploads/2018/12/D2.1_State-of-the-Art_Literature_Review_of_System_Scarcities_at_High_Levels_of_Renewable_Generation_V1.pdf.

[68] At https://www.hnei.hawaii.edu/sites/www.hnei.hawaii.edu/files/Hawaii%20Solar%20Integration%20Study%20-%20Oahu.pdf.

[69] Energinet.dk. Technical Regulation 3.2.5 for Wind Power Plants Above 11 kW; Energinet.dk: Denmark, 2016; pp. 1-108, at https://en.energinet.dk/Electricity/Rules-and-Regulations/Regulations-for-grid-connection.

account of unit ramp rates to achieve dispatch targets. In the NEM, scheduled generators submit bid stacks 24 hours in advance and can be amended up until dispatch (5 minutes ahead). The capability of the generators to meet this dispatch is the responsibility of the participants. Where AEMO forecasts a lack of reserve in a future dispatch period, AEMO initially seeks a market response, or as a last resort can intervene in the market and direct a generator or load to take a particular action.

Much of the new generation currently being integrated into the NEM are solar and wind technologies. These technologies are associated with inherent variability, and their output cannot be forecast with perfect accuracy. At high penetrations, aggregate supply could be altered quickly, and sometimes unexpectedly, requiring adequate, flexible resources (generation and demand) that can provide effective balancing. AEMO has previously highlighted[70] the increased ramping requirement as a key challenge to reliability and security in the NEM. There is a need to estimate the NEM's operational capabilities and clarify potential areas for market change and operational enhancement to ensure the system can perform as required under all emerging conditions.

AEMO is undertaking detailed analysis as part of the RIS to understand how ramping challenges are likely to emerge in the NEM with increasing levels of variable wind and solar generation. Of particular focus will be quantifying how system variability changes as more variable generation is installed, and the level of inherent uncertainty in forecasting the output of variable generators on any day.

3.4 Voltage management

Voltage management is key to secure power system operation, and the changing generation mix is changing the needs of the power system.

Voltage is managed through balancing the production or absorption of reactive power[71]. An increase in reactive power increases voltage, and a decrease reduces voltage. If the voltage goes too high, components of the system may fail, causing cascading failure and damaging equipment – and if voltages go too low it may collapse. For these reasons, voltage must be kept within acceptable ranges.

With the increase in renewables, the needs of the power systems are changing. Some of the key changes are:

- **Location of renewables** can be far from population centres and connecting into network not designed for bulk power transfer. This increases the loading of transmission circuits, and the power is required to travel over greater distances. As loading increases, demand for reactive power increases[72].
- **Displacement of conventional generation** which historically were key sources of reactive power on the bulk transmission system. In Ireland it was found that without key reactive power sources at the right locations, the voltage stability of the All Island Power System deteriorates with increasing wind power[73].
- **Reducing minimum demand** on the bulk power system is causing high voltages issues in Great Britain. Figure 7 shows the change in demand for reactive power over the period 2005 to 2016. This has led National Grid to constrain on conventional plant to provide voltage support[74]. The additional power delivered due to the constraints often means reducing the output of renewables. In Australia, operational demand is also decreasing, due to increasing residential PV uptake and improved energy efficiency[75].

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

[71] A more detailed introduction to voltage management is provided in Section 3.3. of AEMO's Power System Requirements paper, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf

[72] At http://eu-sysflex.com/wp-content/uploads/2018/12/D2.1_State-of-the-Art_Literature_Review_of_System_Scarcities_at_High_Levels_of_Renewable_Generation_V1.pdf.

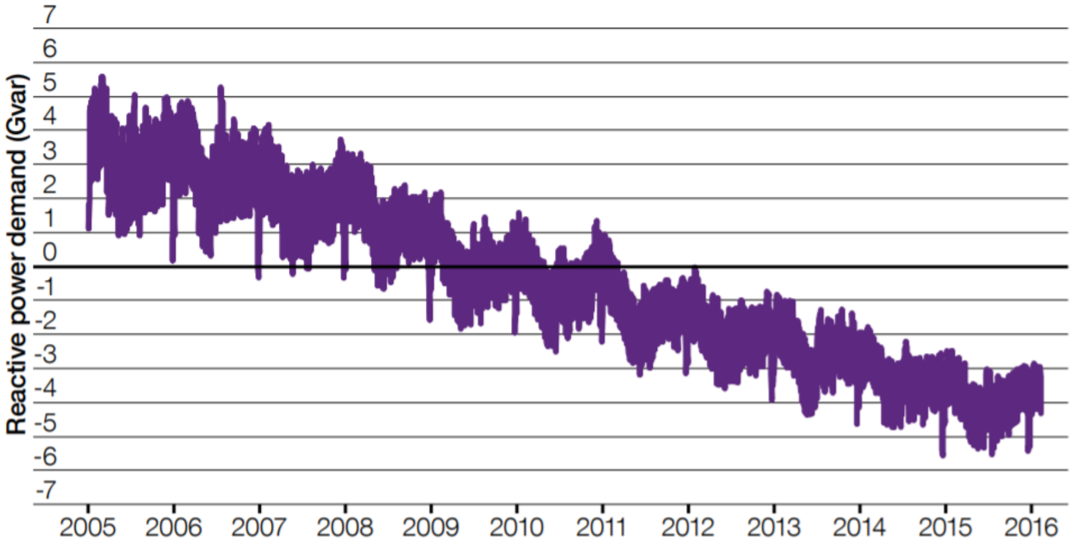
[73] At http://www.eirgridgroup.com/site-files/library/EirGrid/Facilitation-of-Renewables-Report.pdf.

[74] At https://www.nationalgrideso.com/document/146506/download.

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

- **Dynamic reactive power** – in Great Britain, a greater proportion of the reactive power must be dynamic, to follow the daily reactive load profile and ensure voltage containment and recovery after a disturbance. Denmark has increased the need for dynamic reactive power to support older wind turbines[76].

Figure 7 Great Britain daily lowest reactive power demand from 2005–2016



Source: System Operability Framework 2016, at https://www.nationalgrideso.com/document/63481/download.

Of the jurisdictions reviewed, many have had to adjust their approaches to voltage management for new dispatch patterns as renewable penetrations increase. While changes have been required, voltage management challenges do not appear to have presented major long-term barriers to renewable penetration levels.

Early challenges with voltage management have already been observed in the NEM[77] and identified as an emerging limit in the SWIS[78]. The suitability of frameworks for voltage management in the NEM and SWIS should be reviewed to ensure they are sufficient to manage the changing needs of the system[79].

3.5 System strength

Australia is at the forefront of challenges in connecting wind and solar generation in areas with low system strength, and therefore has had to implement world-leading regulations in response.

System strength is the ability of the power system to maintain the voltage waveform at any given location, with and without a disturbance. This includes resisting changes in the magnitude, phase angle, and waveshape of the voltage.

System strength can be related to the available fault current at a specified location in the power system, with higher fault current indicating higher system strength with greater ability to maintain the voltage waveform. System strength is not a universally defined power system term. Definitions vary across international

[76] See https://www.ieee-pes.org/presentations/gm2015/PESGM2015P-003046.pdf.

[77] At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/Victorian_Transmission/2018/Victorian-reactive-power-support-RIT-T-PSCR.pdf.

[78] See https://www.aemo.com.au/Electricity/Wholesale-Electricity-Market-WEM/Security-and-reliability/Integrating-utility-scale-renewables

[79] As part of its ongoing collaborations with the ESB, AEMO commissioned FTI-CL Energy to prepare two reports on international transmission planning frameworks, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Planning-and-network-regulation.

jurisdictions and continue to evolve as the international power system community's collective understanding of power system phenomena continues to evolve.

Some of Australia's best renewable energy resources are in lightly interconnected parts of the network with low system strength[80]. An area of the grid is generally considered to have low system strength if the short circuit ratio (SCR) drops below three[81]. As noted in Section 3.2, the international power systems considered in this review are typically more heavily meshed, giving them a higher underlying system strength.

Even with a heavily interconnected system, periods with less synchronous generation online will reduce system strength, and there are a number of international experiences to consider:

- **Managing generating system instability** – with increasing amounts of IBR (wind, solar, and HVDC) and decreasing system strength, National Grid in Great Britain is aware of the increasing risk of controller instability[82]. Denmark relies on synchronous condensers to improve system strength and increase operational reliability of the HVDC interconnectors[83].
  - In 2016, ERCOT carried out detailed analysis in the Panhandle Region of Texas that identified low system strength limitations to the integration of over 5 GW of wind generation capacity[84].
  - In 2017, the Australian Energy Market Commission (AEMC) established some of the first regulations to ensure new generator connections in areas with low system strength do not adversely impact stable operation of the NEM[85]. In parallel, AEMO has been pioneering new analytical techniques to simulate the complex interactions between IBR in these areas[86]. Similar regulations have been recently announced by the North American Electric Reliability Corporation (NERC)[87].
- **Voltage dip propagation** – National Grid is increasingly aware of the changing relationship between voltage and frequency events[88]. EirGrid has identified this as an issue which can lead to a large power imbalance due to IBR reduced power output during and after voltage dips. Figure 8 shows the propagation of voltage dips across the Irish system. AEMO identified voltage dip propagation as an emerging issue in 2016[89].

[80] 2018 Integrated System Plan, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/ISP/2018/Integrated-System-Plan-2018_final.pdf.

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

[82] SOF, https://www.nationalgrideso.com/document/102876/download.

[83] See https://en.energinet.dk/-/media/FDC2E007EC274EE88C74090DEB349D35.pdf.

[84] See http://www.ercot.com/content/wcm/lists/144927/Panhandle_and_South_Texas_Stability_and_System_Strength_Assessment_March....pdf.

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

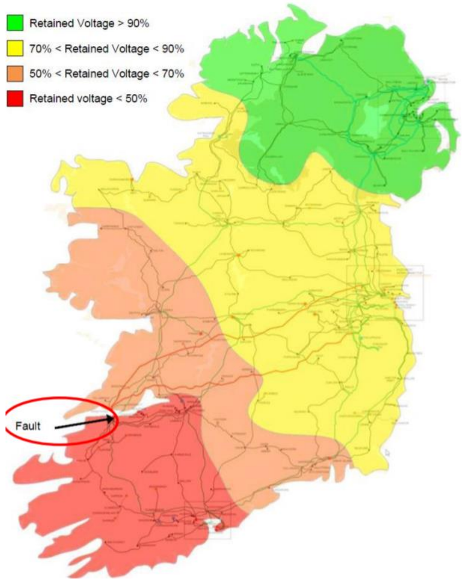
[86] AEMO, System Strength Impact Assessment Guidelines, at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/System-Strength-Impact-Assessment-Guidelines.

[87] See https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Reliability_Guideline_IBR_Interconnection_Requirements_Improvements.pdf#search=IBR%20interconnection.

[88] See https://www.nationalgrideso.com/sites/eso/files/documents/SOF%20Report%20-%20Frequency%20and%20Voltage%20assessment.pdf.

[89] AEMO, 2016 National Transmission Network Development Plan, page 79, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/NTNDP/2016/Report/2016-NATIONAL-TRANSMISSION-NETWORK-DEVELOPMENT-PLAN.pdf.

Figure 8 Voltage dip propagation for a fault in south west of Ireland



Source: http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-Industry-Forum-Presentation-June-2015.pdf.

- Low system strength can also affect the operation of protection devices, and it can increase the potential for voltage step changes that breach system standards following routine network switching.

To support the system during periods of low synchronous generation, new regulatory obligations were established in the NEM to ensure minimum fault levels are defined by AEMO and maintained by transmission network service providers (TNSPs)[90]. AEMO is not aware of any other jurisdiction having yet specified such a limit, although the minimum inertia requirements of Texas and Great Britain outlined in Section 3.2.2, and the minimum synchronous generation requirements of Ireland (Section 3.7), would likely be supporting a minimum fault level in those systems as a by-product of keeping synchronous generators online for other purposes.

This constraint now frequently binds in South Australia and is beginning to bind in Victoria[91]. At its worst, in Q2 2018, synchronous machines were being directed to stay online over 40% of the time in South Australia. This has since reduced to 12% following the completion of a major outage of synchronous plant[92]. Synchronous condensers are being procured for South Australia to reduce the number of directions to conventional thermal power stations[93]. This will in turn reveal an inertia shortfall – to mitigate this, additional flywheels will be integrated to the synchronous condensers, thus in combination meeting both the inertia and system strength issues. Synchronous condensers were procured for similar reasons in Denmark (discussed further in Section 3.7.1).

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

[91] At https://www.aemo.com.au/-/media/Files/Media_Centre/2019/QED-Q2-2019.pdf.

[92] AEMO Quarterly Energy Dynamics Q2 2019, at https://www.aemo.com.au/-/media/Files/Media_Centre/2019/QED-Q2-2019.pdf.

[93] At https://www.electranet.com.au/what-we-do/projects/power-system-strength/.

3.6 DER integration

DER integration poses distinct challenges to power system operation relating to its lack of visibility, controllability, and level of performance. Strategically managing these challenges will support both the power system and consumers.

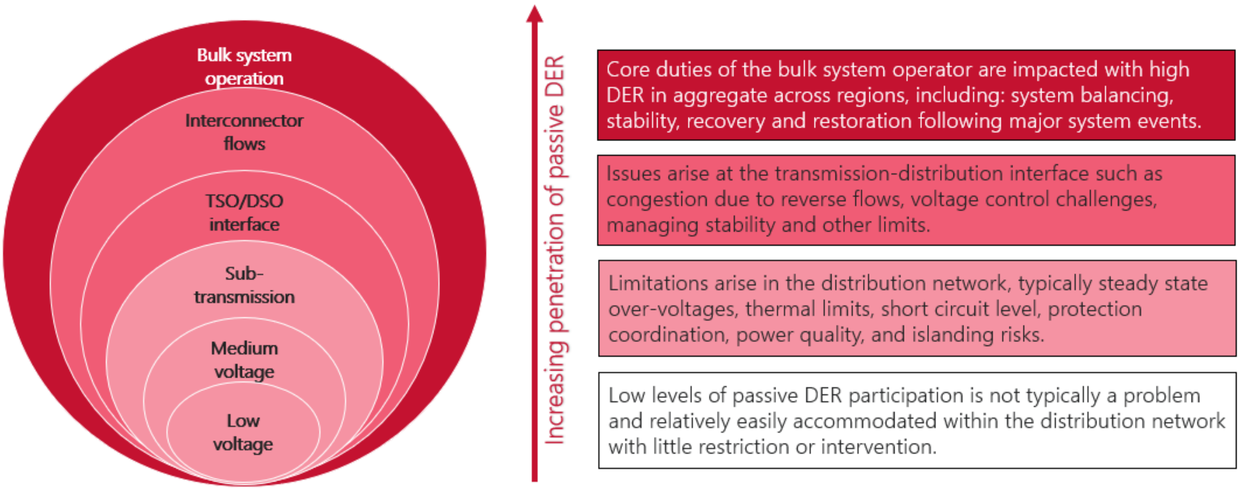
AEMO's DER Program has been established to optimise the integration of DER into the power system in a way that creates value for consumers. This can be achieved by developing new DER markets, services, and technical capabilities that provide the grid with adequate system security responses from DER; capabilities that can also be used by consumers to harness the full potential of their systems and create savings. Due to the increasing prominence and system implications of passive DER[94], AEMO engaged the Electric Power Research Institute (EPRI) to undertake two separate reviews of DER integration experience internationally. The reviews considered international case studies, observing:

- Technical DER integration challenges and how they are being addressed[95].
- DER integration initiatives in comparable energy markets[96].

Leveraging learnings from these case studies, with a focus on their relevance to Australian energy systems, EPRI recommended a set of best practice principles and resulting technical and market enablers for the efficient and secure integration of high penetrations of passive DER.

EPRI's work highlighted a typical trajectory of system challenges of increasing DER, as summarised in Figure 9. Issues first arise within the distribution network, then gradually aggregate up higher voltage levels as local clusters grow. As this growth continues, the lack of visibility and inability to actively manage these devices eventually becomes a bulk system level concern.

Figure 9 Trajectory of system challenges with increasing penetrations of passive DER



3.6.1 DER challenges

Managing power system security as penetrations of passive DER increase will become increasingly critical as it begins to dominate certain operational periods. This relates to the aggregate behaviour of the overall fleet, which in turn depends on specific attributes of the DER device and coordination:

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[94] Passive DER refers to resources such as solar, batteries, hot water services and other electrical equipment that operate under local controls only, with no ability for remote control by a third party (such as an aggregator or NSP).

[95] EPRI International Review on PV Feed-in Management, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols.

[96] EPRI International Review on Opportunities to Activate DER, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols.

- **Performance** – EPRI identified improvements to technical capability that better align DER performance with both local distribution and bulk system operational needs. This spans both autonomous responses that support the system during normal variability and withstand and ride-through capability improving system resilience during larger disturbances.
  - Germany in 2012[97] and Hawaii in 2015[98] both experienced concerns with the simultaneous disconnection of large amounts of small-scale PV in response to an over-frequency event. In both instances, this was resolved via the updating of inverter frequency ride through settings en masse – a costly program of physical retrofitting in Germany, and the remote reprogramming of a large proportion of legacy PV systems in Hawaii[99]. The NEM and SWIS have experienced several instances where deep voltage dips have resulted in the tripping of significant portions of the residential rooftop PV generation fleet[100].[103]
  - Recognising the system impacts of increasing penetrations of residential PV, several jurisdictions have recently mandated improved inverter functionality for small-scale PV systems. In Europe this been through national level implementations of the European Network Code for Generators introduced in 2016[101], most notably Germany and Denmark. In the US, California and Hawaii updated their own local requirements in 2016, which were then subsequently integrated within the US national standard for DER connection in 2018[102], following an almost four-year extensive cross-industry collaboration. AEMO is leveraging learnings from these processes, and in collaboration with DNSPs and local industry, is progressing the introduction of similar requirements in Australia[103].
- **Visibility and predictability** – an inability to see or adequately predict both local and aggregated DER behaviour compromises the system operator's ability to securely manage the power system. This impacts the accuracy of load inputs to the dispatch process and bulk system balancing, resulting in more conservative operating practices and an increasing need for reserves as penetrations increase.
  - Solar eclipses in Europe (March 2015[104]) and North America (August 2017[105]) involved extensive efforts by grid operators to predict the extent of the generation loss and the capability of the system to handle it. Australia is expecting its next solar eclipse on 22 July 2028.
  - In 2017, ERCOT in Texas developed a framework to collect static data on current and future commercial scale DER (at least 1 MW) and better integrate this fleet within power system load models[106]. The NEM is also in the process of introducing a register of static data for all DER less than 30 MW in size[107].
  - Several jurisdictions, including Italy and Germany, require some level of real-time visibility for larger, commercial-scale DER installations. In Australia, there is currently a lack of consistency on the telemetry requirements for the small-scale fleet and its integration with AEMO systems.

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[97] J. von Appen, M. Braun, T. Stetz, K. Diwold, and D. Geibel, Time in the Sun: the Challenge of High PV Penetration in the German Electric Grid", IEEE Power and Energy Magazine, March/April 2013, at http://magazine.ieee-pes.org/files/2013/02/11mpe02-vonappen-2234407-x.pdf.

[98] Getting it all in the mix – integrating DER, Setting the solar standard, Collaborations between Hawaiian Electric and the National Renewable Energy Laboratory. IEEE Power and Energy Magazine (Nov-Dec 2018), at https://ieeexplore.ieee.org/document/8495081.

[99] This was implemented through the inverter manufacturer, Enphase Energy's remote reprogramming service. A large enough proportion of inverters in Hawaii were Enphase systems.

[100] AEMO. Technical Integration of DER, published April 2019, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/DER/2019/Technical-Integration/Technical-Integration-of-DER-Report.pdf.

[101] EU Commission Regulation (April 2016), further information ENTSOE. Requirements for Generators, at https://www.entsoe.eu/network_codes/rfg/.

[102] IEEE Standards Association. IEEE1547-2018 – IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, at https://standards.ieee.org/standard/1547-2018.html.

[103] AEMO. Technical Integration of DER, published April 2019, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/DER/2019/Technical-Integration/Technical-Integration-of-DER-Report.pdf. On this basis, AEMO officially opened AS/NZS 4777.2 for review.

[104] ENTSOE, Solar Eclipse: The successful stress test of Europe's power grid 2015, at https://docstore.entsoe.eu/Documents/Publications/ENTSO-E%20general%20publications/entsoe_spe_pp_solar_eclipse_2015_web.pdf.

[105] NREL, Evaluating the Impact of the 2017 Solar Eclipse on U.S. Western Interconnection Operations, at https://www.nrel.gov/docs/fy18osti/71147.pdf.

[106] ERCOT, Distributed Energy Resources (DER) Reliability impacts and recommended changes. 22 March 2017, at http://www.ercot.com/content/wcm/lists/121384/DERs_Reliability_Impacts_FINAL_032217.pdf.

[107] See https://www.aemc.gov.au/rule-changes/register-of-distributed-energy-resources.

- To manage changes in load over time, the Western Interconnection in the USA (led by the Western Electricity Coordinating Council [WECC]) developed a dynamic "composite load model" in 2015. This is applied by system operators to model the individual features of their own power systems by specifying the proportions of DER and each load type (as a function of location and time period), and by specifying the parameters of each component of the model to represent the trip settings, deadband, response time, and other individual behaviours of those loads in that power system. AEMO has developed a work program looking to update 20-year-old load models[108], to better account for the changed characteristics of electrical load in Australia and how it responds during power system disturbances, particularly with increased penetrations of DER.

- **Controllability** – increasing shares of passive DER gradually erode the network and system operators' ability to securely manage the power system. EPRI found that 'activating' the DER fleet through some form of control provides the most cost-effective, and potentially the only, means to address the reduced capabilities.
  - Internationally, active management of DER is largely limited to emergency actions, such as periods of severe over-generation. Some jurisdictions have implemented more coarse methods, such as disconnect switches in dedicated small-scale PV revenue meters as seen in Hawaii[109] and ripple control in Germany[110]. Japan has trialled multiple demonstrations using DER management systems sending commands to devices and home energy management systems over the internet[109]. Australia does not currently have a mandated mechanism to actively control DER, even in emergency situations. The current standard for small-scale PV inverters does include remote shutdown capability, however this has not been utilised widely in practice.
  - More continuous active management of DER is an emerging area internationally. Hawaii and California recently mandated interoperable communication requirements for DER inverters, as well as defined roles and responsibilities for the aggregation of these devices[111]. Active co-optimisation of DER within distribution network operation is largely restricted to smaller-scale, microgrid contexts, with some trial initiatives in large-scale power systems[111]. In Western Australia, Horizon Power, operating 32 separate microgrids, is trialling DER management system (DERM) technologies to actively manage DER within its franchise area[112]. AEMO's DER program and various aggregation trials[113] in Australia are currently considering how to best activate the DER fleet – including how communication will take place, cybersecurity, and scalable information architectures for participation and data visibility.

3.6.2 Maximising DER value and creating savings for consumers

Given its world-leading penetrations relative to its minimum demand, Australia must become a world leader in activation of DER within its energy systems. Active DER management will enable more DER to be utilised, while minimising the level of network investment required to manage the technical impacts of DER. Active management of DER will provide AEMO and NSPs with the operational tools required to manage the power system, while maximising the benefits from DER to all consumers.

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[108] AEMO, Technical Integration of DER Report, pages 63 and 64, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/DER/2019/Technical-Integration/Technical-Integration-of-DER-Report.pdf.

[109] EPRI International Review on PV Feed-in Management, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols.

[110] Mandatory DER curtailment through ripple control for all PV systems larger than 30 kW. This capability is also required for smaller systems, as an alternative to a 70% of rated capacity default export limit of 70%.

[111] California Public Utilities Commission. Rule 21 Interconnection, at https://www.cpuc.ca.gov/Rule21/.

[112] Horizon Power Carnarvon Distributed Energy Resources (DER) trial, at https://horizonpower.com.au/carnarvonder/.

[113] AEMO, Pilots and Trials, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Pilots-and-Trials.

3.7 Other system limits

To manage the complex multidimensional nature of system security, operators in some jurisdictions are determining additional operational limits.

3.7.1 Combinations of synchronous generator requirements

As discussed in previous sections, synchronous units provide an array of services that help manage power system security (for example, controllable active and reactive power, synchronous inertia, and system strength). With increasing penetrations of IBR, many of these services are not being replaced, despite the displacement of synchronous generators. To manage the complex multidimensional nature of system security, operators in some jurisdictions are determining secure combinations of synchronous units in advance of operation, and enforcing during dispatch, such as dispatching out of merit order.

Due to high generation from wind, Ireland has a minimum combination of synchronous units to manage the system for dynamic stability. This is currently set at eight large units, with five in Ireland and three in Northern Ireland[114]. EirGrid's 2018 annual dispatch down report indicates the minimum synchronous unit limit was responsible for 3% curtailment of available wind energy[115].

Similarly, Energinet in Denmark historically required six must run units for several technical reasons (fault level, dynamic and continuous voltage regulation, and fault-ride-through capability of older wind plant). This requirement had cost implications for the energy market, and in 2014 Denmark installed synchronous condensers to provide these services[116], significantly reducing the number and duration of must run requests for conventional thermal power stations.

As noted in Section 3.5, there are requirements in the NEM to define and maintain minimum fault levels at designated points around the transmission network. This indirectly leads to a minimum number of synchronous machines being required in each region[117].

3.7.2 System non-synchronous penetration

As part of its 2010 All-Island study[118] into the stable operating limits for IBR, EirGrid found that after assessing power system security outcomes for a variety of different generation and load combinations that the secure limits for their system could in part be defined by a proxy operational metric, System Non-Synchronous Penetration (SNSP). SNSP is the ratio of generation from wind and HVDC imports to demand and HVDC exports.

As shown in Figure 10, EirGrid's 2010 studies found that:

- At the time, it was possible to securely operate up to 50% SNSP (green).
- If mitigating actions were taken to resolve several technical challenges, it should be possible to operate the system up to 75% SNSP (orange).
- Secure operation beyond a 75% SNSP level was not deemed possible, given known technology capabilities at the time[119]. With the evolution of technology and understanding, in its discussions with AEMO for this paper EirGrid noted that higher levels are now believed to be possible and being targeted over the next decade.

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[114] At http://www.eirgridgroup.com/site-files/library/EirGrid/Operational-Constraints-Update-Mar_2019.pdf.

[115] At http://www.eirgridgroup.com/site-files/library/EirGrid/Annual-Renewable-Constraint-and-Curtailment-Report-2018-V1.0.pdf.

[116] At https://www.ieee-pes.org/presentations/gm2015/PESGM2015P-003046.pdf.

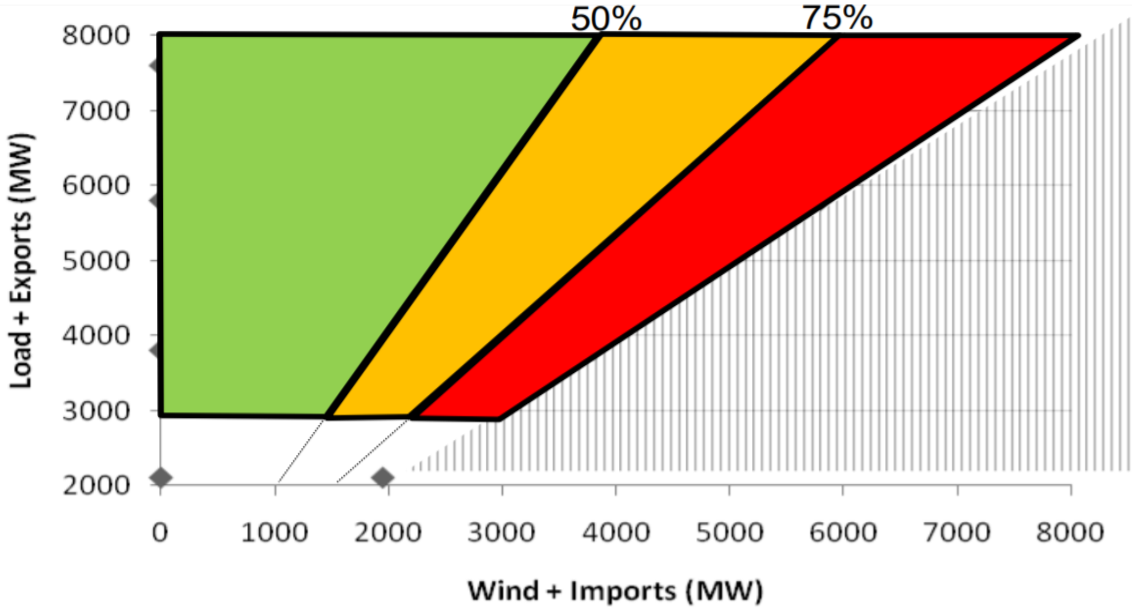
[117] At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Congestion-Information/2018/Transfer-Limit-Advice---South-Australian-System-Strength.pdf.

[118] See http://www.eirgridgroup.com/site-files/library/EirGrid/Facilitation-of-Renewables-Report.pdf.

[119] At http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-Programme-Overview-2014.pdf.

The first limit was set at 50% SNSP in 2010 and has progressively been relaxed to the current limit of 65%, and is to be increased to 75% by end of 2020. EirGrid's 2018 annual renewable constraint and curtailment report shows the SNSP limit was responsible for less than 1% curtailment of available wind energy[120].

Figure 10 Operating zones in the Ireland and Northern Ireland Power system



Source: EirGrid: Facilitation of Renewables 2010.

None of the other system operators that AEMO has engaged with during this review have attempted to apply a limit like SNSP in their systems, with any penetration limits on IBR arising as a secondary outcome of other system constraints binding (for example, minimum inertia levels necessitating minimum numbers of synchronous generators online, causing IBR to be dispatched down).

3.8 Staged transition

The power system must continually evolve to meet consumer needs. Change can introduce new risks to power system security, and the velocity of this change means there is less time to understand and mitigate new risks.

New plant that is added to the system can introduce new risks to the security of the system. Risks associated with new technologies such as inverter-based resources can be more complex and harder to simulate, and these risks are often not as well understood.

Looking internationally, there are several examples where unanticipated risks have emerged as the generation mix has evolved:

- **Distribution protection** – in Great Britain and Ireland, generation was installed with protection which created a risk of a co-ordinated loss of generation that could collapse the system (see Section 3.2.2).
- **DER protection settings** – Germany retrofitting hundreds of thousands of inverters connecting small-scale PV systems to the electricity grid (see Section 3.6).
- **Performance of DER** – residential PV disconnecting in response to system disturbances (see Section 3.6).

[120] At http://www.eirgridgroup.com/site-files/library/EirGrid/Annual-Renewable-Constraint-and-Curtailment-Report-2018-V1.0.pdf.

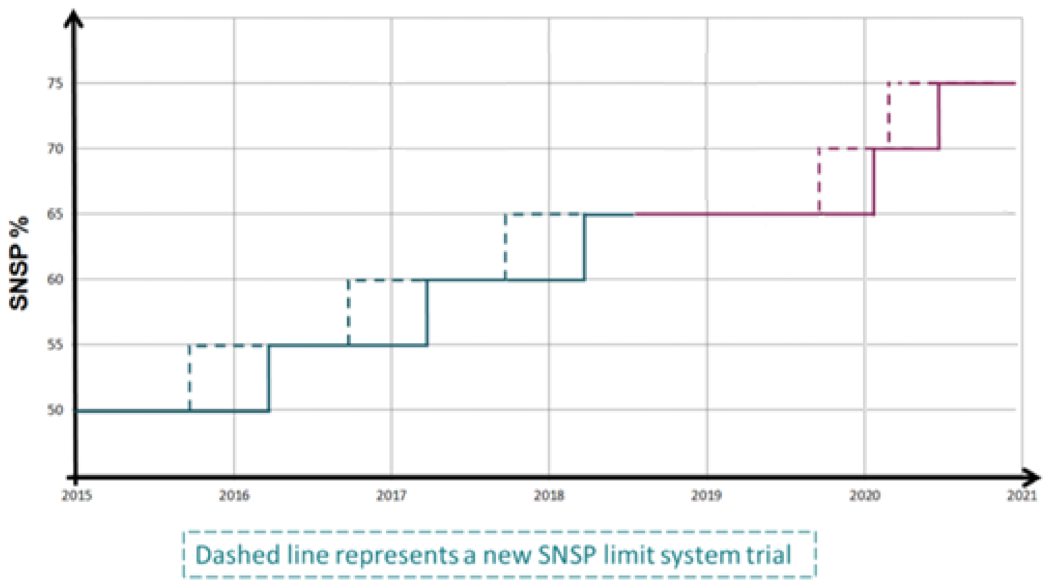
- **Generator protection settings** – in South Australia, a number of wind farms disconnected on experiencing a number of successive voltage dips, immediately prior to system collapse[121].

Operating the system in new ways can also increase risk. EirGrid is taking a staged approach to relaxing power system operational limits (minimum inertia, RoCoF, minimum units, and SNSP). Figure 11 shows the transition of the SNSP limit as discussed in Section 3.7.2. From discussions with EirGrid, the process it follows to relax operational limits is:

- Carry out detailed analysis with a report recommending moving to a provisional operating strategy.
- Operation Policy Review Committee (OPRC) approves the move with required operational defensive measures. (These can include need for new control centre tools, policies, and mitigating key risks, but not always.)
- Online analysis determines stable operation. If there are issues operators revert to latest official policy.
- After 100 hours of running (approximately three months to obtain), ex post sensitivity studies are completed to analyse system resilience.
- The OPRC then decides on the success of the trial.

Australia can learn from the staged transition Ireland has taken to relax power system limits, particularly in areas where Australia is leading the world, such as low system strength. This could include taking a precautionary approach (such as holding extra reserves as insurance) for a period (for example, one year) while the system is operated closer to its limits (for example, with fewer synchronous generators online) to build experience and confidence, before accepting those conditions as a new norm.

Figure 11 EirGrid timeline to achieve new SNSP limits



Source: http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-Programme-Transition-Plan-Q4-2018-Q4-2020-Final.pdf.

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

4. Next steps

4.1 Actions AEMO is taking

This paper represents the first deliverable from AEMO's RIS[122] and sets the scene for subsequent stages of work.

Table 4 summarises key areas where Australia could learn from international experience, and the actions currently planned to progress these areas.

Table 4 AEMO actions arising from this review

#	Key learnings	Report section	Actions
1	The NEM should consider requirements for primary frequency response on all generators.	3.2	• AEMO has lodged two Rule changes with the AEMC: – Removal of disincentives to primary frequency response[123]. – Mandatory Primary Frequency Response in the NEM[124].
2	Consideration should be given to an inertia requirement for the NEM and SWIS that applies at all times.	3.2	• AEMO is currently assessing the potential need for such a requirement in the NEM as part of its Renewable Integration Study[125]. Findings will be leveraged to assess their applicability for the SWIS.
3	Any issues associated with fast post fault active power recovery should be monitored into the future to ensure it can be proactively managed.	3.2	• Following an AEMO Rule change proposal, the AEMC has established Rules for new generator connections regarding post fault active power recovery times[126,127]. • Further consideration of risks associated with active power recovery times are being considered as part of AEMO's Renewable Integration Study and DER Program[128].
4	Managing variability and uncertainty is increasingly challenging at higher levels of wind and solar generation. Australia can learn from others in their approaches, including the assessment of system ramping requirements and fleet capability.	3.3	• AEMO is currently assessing the risks associated with unforecast ramps in a higher renewable NEM as part of its Renewable Integration Study. Findings will be leveraged to assess their applicability for the SWIS.
5	The suitability of frameworks for voltage management in the NEM and SWIS should be reviewed to ensure they are sufficient to manage the changing needs of the system.	3.4	• As part of its ongoing collaborations with the Energy Security Board (ESB), AEMO commissioned FTI-CL Energy to prepare two reports on international transmission planning frameworks[129].

[122] AEMO, Renewable Integration Study, July 2019, at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/Future-Energy-Systems/Renewable-Integration-Study.

[123] See https://www.aemc.gov.au/rule-changes/removal-disincentives-primary-frequency-response.

[124] See https://www.aemc.gov.au/rule-changes/mandatory-primary-frequency-response.

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

[126] AEMC, Rule Determination: National Electricity Amendment (Generator Technical Performance Standards) Rule 2018, P 217, at https://www.aemc.gov.au/sites/default/files/2018-09/Final%20Determination_0.pdf.

[127] See https://www.aemc.gov.au/sites/default/files/2018-09/Final%20rule%20%28in%20mark-up%29.pdf.

[128] AEMO DER Program webpage, at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program.

[129] AEMO, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Planning-and-network-regulation.

#	Key learnings	Report section	Actions
6	Parts of Australia are already experiencing some of the highest levels of wind and solar generation in the world, Australia is achieving these very high levels while at the forefront of connecting new generation in areas with low system strength.	3.5	• AEMO will continue to explore opportunities to improve the management of system strength in the NEM. • AEMO will continue to share its learnings internationally regarding system operation with low system strength.
7	Australia should review its DER performance standards to align with leading international standards (such as Germany and the USA).	3.6	• AEMO's DER Program includes a workstream aimed at improving the performance and capability of DER for system security needs[130]. • In April 2019, AEMO published a report on the preliminary findings on the behaviour of DER during disturbances, this led to recommendations for changes to the Australian Standards for Grid Connected Inverters (AS/NZS4777.2)[131]. • A review of the AS/NZS4777.2 Standard has since begun, to align it with international best practice and capabilities of large-scale generators in the NEM and SWIS.
8	Australia should consider integrating representative DER information into power system load models.	3.6	• AEMO has an ongoing program of work to uplift its DER and load models for the NEM as part of the DER Program.[132].
9	Due to a unique combination of factors, more active management will be essential to effectively integrate high levels of DER in Australia.	3.6	• AEMO is currently assessing the potential system limits to passive DER as part of the Renewable Integration Study and DER Program. This includes the potential need for remotely communicating with DER devices (for querying or updating settings, and real-time coordination) as well as technical enablers to achieve this. • AEMO is continually informing this workstream through international experience[133]. This includes engaging EPRI to undertake international review on approaches PV Feed-in Management[134] plus collaborating with networks with high penetrations of DER, such as Germany, California, and Hawaii. • Practical experience on the development of regulatory and market frameworks and operational processes for DER activation is being gained through various VPP trials and demonstrations undertaken in the NEM[135].
10	International power system operators have taken a staged approach to operating the power system with progressively less synchronous generation online. A similar approach could be considered in Australia.	3.8	• Potential approaches for the NEM are being considered as part of AEMO's Renewable Integration Study.

[130] See https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols.

[131] AEMO, Technical Integration of DER, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/DER/2019/Technical-Integration/Technical-Integration-of-DER-Report.pdf.

[132] AEMO, Technical Integration of DER, Chapter 4, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/DER/2019/Technical-Integration/Technical-Integration-of-DER-Report.pdf.

[133] AEMO, Coordination of Distributed Energy Resources; International System Architecture Insights for Future Market Design, at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Markets-Framework.

[134] EPRI International Review on PV Feed-in Management, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols.

[135] AEMO, Pilots and Trials, at https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Pilots-and-Trials.

4.2 What AEMO intends to do from here

The insights from this paper and the ongoing RIS work are being incorporated into AEMO's work on the 2020 ISP[136], AEMO's contributions to the Energy Security Board (ESB) Post 2025 Market Design program for the NEM[137], and the Western Australian Government's Energy Transformation Strategy[138].

Leveraging the insights from this paper, AEMO's focus for the RIS will now be on:

- Quantifying the technical limits of the NEM for a projected generation mix and network configuration in 2025.
- Identifying any ultimate theoretical limits on renewable penetration levels in the NEM.
- Identifying potential technology options to help enable system operation up to these ultimate limits.

AEMO's report on these investigations is scheduled for Q1 2020. At the conclusion of these studies, AEMO will outline a roadmap of priority activities for AEMO, regulatory bodies, and policy-makers to help maintain power system security as the generation mix changes in the NEM. The roadmap is anticipated to cover:

- Priority focus areas for AEMO's analysis of future power system scenarios for the NEM.
- Priority focus areas for regulatory changes to allow the ongoing maintenance of power system security in the NEM.
- Identifying potential improvements to AEMO's processes and procedures that will help accommodate the changing needs of the power system.

AEMO will continue to think globally and leverage the latest international experiences in renewable integration.

4.3 How to get involved

AEMO will engage with stakeholders on the RIS in parallel with its ISP consultation processes. Detailed engagement will occur once the study results become available.

Information on the RIS, supplementary resources, and links to other related projects are available on the AEMO website[139].

For further enquiries, please contact AEMO's Future Energy Systems team at FutureEnergy@aemo.com.au.

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

[137] See http://coagenergycouncil.gov.au/publications/post-2025-market-design-national-electricity-market-nem.

[138] See https://www.wa.gov.au/organisation/energy-policy-wa/energy-transformation-strategy.

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

A1. Abbreviations

Abbreviation	Description
AC	Alternating current
AEMO	Australian Energy Market Operator
AEMC	Australian Energy Market Commission
AGC	Automatic Generator Control
CAISO	California Independent System Operator
DC	Direct current
DER	Distributed energy resources (see Glossary for further details)
DERM	DER management system
DMS	Distribution management systems
DNSP	Distribution network service provider
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
ENA	Energy Networks Australia
ESB	Energy Security Board
EUSysFlex	A cooperative program of work to test operation of the pan-European electricity system with more than 50% of renewable energy sources (see https://eu-sysflex.com/ for more)
FCAS	Frequency control ancillary services
FFR	Fast frequency response
GW	Gigawatt – one billion (10^9) watts
HV	High voltage
HVDC	High voltage direct current
IBR	Inverter-based resources
ISP	Integrated System Plan
kW	Kilowatt – one thousand watts
MV	Medium voltage
MW	Megawatt – one million watts
NEM	National Electricity Market
NERC	North American Electric Reliability Corporation
NSP	Network service provider
NSW	New South Wales

Abbreviation	Description
OPRC	Operation Policy Review Committee
PFR	Primary frequency response
PV	Photovoltaics
QLD	Queensland
RIS	Renewable Integration Study
RoCoF	Rate of change of frequency
SCADA	Supervisory control and data acquisition
SCR	Short circuit ratio
SNSP	System non-synchronous penetration
Solar PV	See PV
SWIS	South West Interconnected System
TAS	Tasmania
TNSP	Transmission network service provider
UFLS	Under frequency load shedding
VDIFD	Voltage dip-induced frequency deviation
VIC	Victoria
VPP	Virtual power plant
VRE	Variable renewable energy
WA	Western Australia
WECC	Western Electricity Coordinating Council

A2. Glossary

Term	Definition
Distributed energy resources (DER)	Resources embedded within the distribution network and behind the meter which can be used individually or in aggregate to help balance supply and demand or provide system services. Examples include residential or commercial installations of solar PV, wind turbines, energy storage, demand management systems, electric vehicles (EVs), combustion generators, variable speed motor drives, and cogeneration units. The capabilities of DER depend on the specific technology. AEMO currently has limited visibility of DER.
Inverter-based resources (IBR)	Inverter-based resources are devices that interface with the grid using a power electronic device (called an inverter). Solar PV systems, HVDC converters, and most new wind turbines are all IBR. The inverters digitally synthesize an output to match the power system AC waveform. These devices operate in different ways to conventional generating systems in coal, gas, and hydro plants which interface to the grid with a rotating electro-mechanical generator.
Island power system	For the purposes of this report, Island power systems are either not interconnected to other power systems or are interconnected using high voltage direct current.
Large power system	For the purposes of this report, large power systems are defined as systems having a peak demand greater than 1 GW. Australia's two large power systems are the National Electricity Market (NEM) on the east coast, and the South-West Interconnected System (SWIS) on the west coast. The geographical extent of the NEM and SWIS are shown in Figure 3 in Section 2.3.
Non-synchronous generator	See *inverter-based resources*
Passive DER	Refers to resources such as solar, batteries, hot water services and other electrical equipment that operate under local controls only, with no ability for remote control by a third party (such as an aggregator or NSP).
Power system security	Power system security arises when the power system is operating within defined technical limits and is likely 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 or major powerline).
Power system stability	Ability of the power system to return to stable operating conditions following a physical disturbance.
Small power systems	For the purpose of this report, small power systems are defined as systems that have a peak demand less than 1 GW.
Synchronously interconnected	Synchronously interconnected systems are connected to other power systems via alternating current (AC) interconnectors.

A3. Reference resources

AEMO has published several relevant reports into the changing generation mix, a shortlist of which are provided in Table 5.

Table 5 Relevant AEMO publications

Publication	Notes and location	Publication date
Renewable Integration Study (RIS) information sheet	At https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/Future-Energy-Systems/Renewable-Integration-Study	June 2019
Integrated System Plan	With supporting material, at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Integrated-System-Plan.	July 2018
WA Renewable Integration Report	At https://www.aemo.com.au/Electricity/Wholesale-Electricity-Market-WEM/Security-and-reliability/Integrating-utility-scale-renewables.	March 2019
Distributed Energy Resources (DER) Program	Full program details available at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program	April 2019
Power System Requirements paper	At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf.	May 2018
International Review of Frequency Control Adaptation	At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2016/FPSS---International-Review-of-Frequency-Control.pdf	October 2016
Technical Integration of DER	At https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Improving-DER-Capability.	April 2019
International Review of Opportunities to Activate DER	At https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols	October 2019
International Review of PV Feed-in Management	At https://aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program/Standards-and-Protocols	October 2019
System Strength Impact Assessment Guidelines	At http://aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/ System-Security-Market-Frameworks-Review/2018/System_Strength_Impact_Assessment_Guidelines_PUBLISHED.pdf	July 2018
System Strength Requirements Methodology and Fault Level Shortfalls	At http://aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/ System-Security-Market-Frameworks-Review/2018/System_Strength_Requirements_Methodology_PUBLISHED.pdf	July 2018
Inertia Requirements Methodology and Shortfalls	At http://aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/System-Security-Market-Frameworks-Review/2018/Inertia_Requirements_Methodology_PUBLISHED.pdf	June 2018
ISP Insights - Building power system resilience with pumped hydro energy storage,	At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/ISP/2019/ISP-Insights---Building-power-system-resilience-with-pumped-hydro-energy-storage.pdf	July 2019
Rule Change Proposal - Generator Technical Requirements	At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/ Reports/2017/AEMO-GTR-RCP-110817.pdf. Details of the AEMC's final Rule determination, plus consultation papers and AEMO submissions available at https://www.aemc.gov.au/rule-changes/generator-technical-performance-standards.	August 2017

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