ATSE EXPLAINER

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Powering the net zero transition

Electricity security explained

Australian Academy of Technological Sciences & Engineering

The energy sector will play a crucial role in Australia achieving its national climate goals of reaching net zero emissions by 2050. Zero emissions electricity is a critical lynchpin for driving decarbonisation across a wide range of sectors, such as transport, buildings, and industry.

The imperative to reduce carbon emissions and the natural retirement of existing coal fired power stations at the end of their technical or economic life is fundamentally changing power systems in Australia, and around the world. Because of the central role of electricity, achieving net zero by 2050 will require electricity systems globally to be decarbonised by 2040.[1] Dramatic cost reductions have already accelerated widespread deployment of new renewable energy sources, including large-scale wind and solar farms and distributed rooftop solar photovoltaic (PV) systems.

In 2022, 35 per cent of Australia's electricity generation came from renewable energy, up 4 per cent from renewable energy generation levels in 2021.

As Australia moves towards a net zero energy system, electricity generated by solar and wind technology is set to become our dominant energy source. Solar and wind already comprise 99% of new electricity generation capacity in Australia, and the Federal Government currently targets renewable energy to account for approximately 82 per cent of Australia's total energy generation by 2030. However deployment rates of renewable energy, storage and supporting transmission expansion are currently not yet high enough to achieve this target.

For both households and businesses, access to a reliable and secure electricity supply is critically important. While we need to 'keep the lights on', the increasingly connected world we live in relies on our ability to access the internet for work and for services such as banking, telehealth, and communications. The growing adoption of electric vehicles (EVs) to meet low-emissions transport needs all depend on the maintaining a reliable electricity supply. The electrification of gas loads and increased demand for EV charging are emerging as leading issues for the local distribution grid.

Low-emissions energy generation technologies, including solar and wind, have profoundly different physical, technical, and economic features compared to conventional coal- and gas-fired power plants. The shift to these technologies poses some challenges to the security of existing, traditional power grids. These challenges can all be overcome through adequate planning and operation of the electricity system. Some of these challenges, and their potential solutions, are explored here.

ELECTRICITY RELIABILITY AND SECURITY

The reliability and security of the electricity system refers to our ability to keep the electricity system balanced at all different timescales and even when failures occur that are called ‘contingent events’ in the electricity industry.

RELIABILITY

Reliability means having sufficient generation capacity to always be able to service demand from households and industry. This includes having sufficient generation reserves even if a major generator or transmission line fails unexpectedly.

It also includes having sufficient generation reserves available to increase their output quickly (or absorb electricity quickly) if the output of a large wind or solar farm changes rapidly, for example when a major storm front is cutting across a plant.

SECURITY

Security refers to keeping other physical parameters of the electricity system, within clearly defined specifications.

KEY CHALLENGES IN A MODERN ELECTRICITY SYSTEM

Transitioning the electricity system to accommodate more renewable energy sources will require targeted investment in additional capabilities, but it is important to understand how our existing electricity system works.

There are two key concepts to consider, the first is that all sources of supply (generation) must be in instantaneous balance with use (demand), and the second is that all generators must have their outputs at the same point in the electrical cycle.

All modern electricity systems are alternating current (AC — the flow of electrical charge that changes direction periodically) and Australia's has a frequency of fifty cycles per second (or 50 Hz using technical language). That means electrical current changes direction fifty times each second so that each cycle is 20 milliseconds long: think of an everyday flashlight battery with current flowing from positive to negative, but then changing direction - about five-to-10 times in the blink of an eye. This change is ideally smooth and produces a perfect continuous wave; maintaining this waveform is important in ensuring that the electricity system functions normally. During periods when renewables already dominate supply in the power system, e.g. during so called 'minimum demand' periods when rooftop PV provides the majority of supply, the provision of the following system services becomes critically important:

Inertia

To maintain this waveform, the turbines of all conventional electricity generators — which use coal or gas as a fuel — are designed to spin at a constant speed and at the same point in the cycle. Hence, they are known as 'synchronous' generators. With many conventional generators connected to the system, it is important that they remain synchronised. If their output voltages and currents do not alternate at the same frequency, the system will collapse, resulting in a blackout. But in a system with conventional spinning turbines, there is rotational inertia (effectively stored energy within the rotation of the large turbine) that dampens any rapid changes. Just like a heavy car, once in motion, requires significant force to either accelerate or decelerate.

Frequency control

As more demand is exerted on the system (as usage increases), generators tend to slow down until power controls introduce more energy (for example, when the steam input into a turbine is increased). The rotational inertia — from heavy turbines in traditional coal, gas, and hydroelectric power plants — naturally resists frequency disturbances. The proliferation of rooftop solar installations has introduced a new challenge to maintaining grid stability. During the middle of the day, when solar generation peaks, negative demand can occur as the supply from rooftop solar panels exceeds local demand. This oversupply can strain the grid infrastructure, potentially overwhelming transmission lines and transformers. Significant deviations of the frequency of different generators across the system would lead to a collapse of the whole electricity system. Therefore, the electricity market operator (AEMO) aims to keep variations of frequency ideally below 0.03% and forces generators to start making interventions once the frequency moves outside of this band. This process is known as frequency control.

System strength

Non-synchronous generators such as solar PV work differently to conventional synchronous generators. Wind and solar PV technology is effectively looking for the signal from the synchronous generators and are trying to follow this signal. In a system with many conventional generators and only a few new renewable generators, often also referred to as system with strong system strength, this strategy works well. However, if there are many renewable generators and only a few conventional generators, the synchronous signal is weak, and they can become unstable. Conventional solar PV and wind generators struggle to operate in these weak systems.

Operating reserves

A further challenge for solar PV and wind farms is rapidly varying output due to changing weather conditions. Imagine a cloud covering a large solar farm (or a suburb that has many houses with solar panels installed). The output of this solar farm can reduce to close to zero within minutes or even seconds. It can return to full output just as quickly. As the percentage of renewables increases, so does the importance of a kind of shock absorber in the system - that is, an ability to release or absorb energy quickly to ensure there is exactly as much supply in the system as there is demand.

TECHNOLOGY SOLUTIONS

Fortunately, technological solutions can resolve all these electricity security challenges. The current imperative to decarbonise Australia's energy system demands a faster pace for development, planning and investment in the deployment of these solutions across the country. Technologies to solve these problems already exist:

Transmission

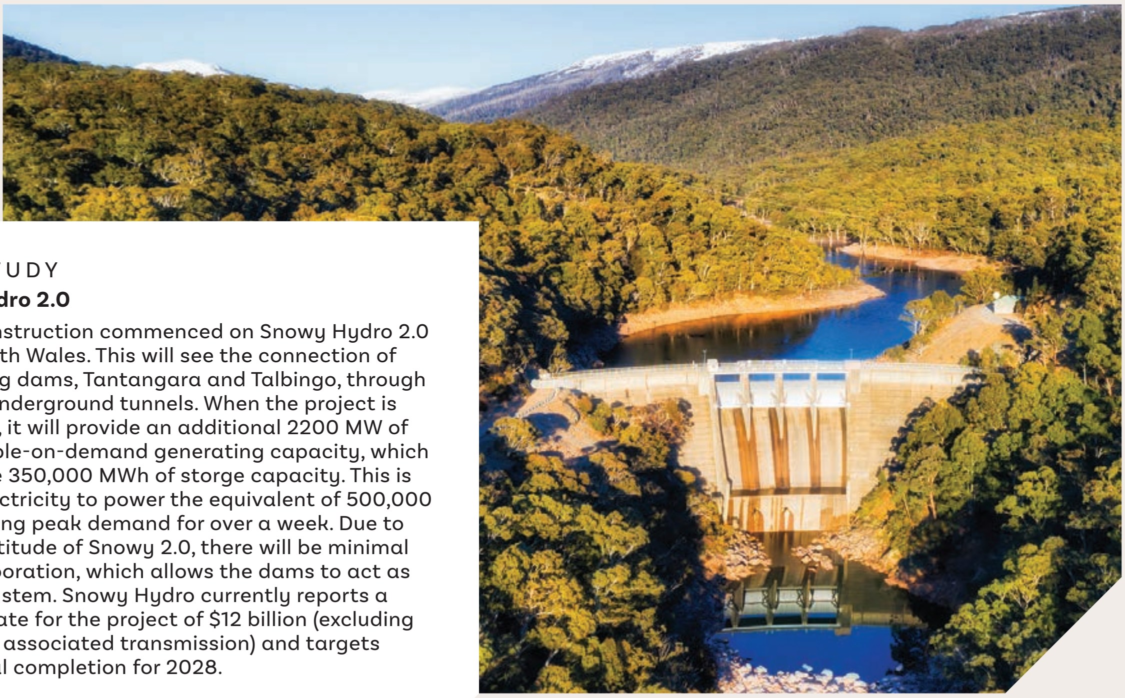
Building more transmission interconnections between networks will allow regions to share energy. AC interconnectors can provide a whole range of services between connected regions, such as inertia, frequency control, system strength and operating reserves. They also diversify sources of energy, reducing the impact of weather-driven variability. Australia's system operator has already identified priority inter-region transmission projects to strengthen the grid (in its comprehensive Integrated System Plan). However building new transmission takes time, and requires social licence from local communities.

Geographic spread of generation

Building solar and wind in a range of locations helps to provide a more constant supply of electricity, because when wind or solar generation is low in one location it can be high in another location. Similarly, having a mix of solar and wind helps to balance generation.

Pumped Hydro

Energy can also be stored by pumping water uphill when the sun is shining and the wind is blowing, and letting it run back down through a generator. This is known as pumped hydro. Pumped hydro is particularly effective when it comes to storing large amounts of electricity for long durations, which is crucial in the grid stability and resilience of renewable electricity systems. These large energy reserves can also be used to build system security, especially if they use synchronous turbines, i.e. pumped hydro can also provide inertia, frequency control, system strength and operating reserves. In contrast, short-term energy storage solutions, such as batteries, excel in providing rapid bursts of power and are well-suited for addressing immediate fluctuations in demand or supply. The distinction between energy storage and power delivery is essential for designing resilient energy systems that can balance the need for both short-term responsiveness and long-duration reliability.



CASE STUDY

Snowy Hydro 2.0

In 2019 construction commenced on Snowy Hydro 2.0 in New South Wales. This will see the connection of two existing dams, Tantangara and Talbingo, through 27kms of underground tunnels. When the project is completed, it will provide an additional 2200 MW of dispatchable-on-demand generating capacity, which will provide 350,000 MWh of storge capacity. This is enough electricity to power the equivalent of 500,000 homes during peak demand for over a week. Due to the high altitude of Snowy 2.0, there will be minimal water evaporation, which allows the dams to act as a closed system. Snowy Hydro currently reports a cost estimate for the project of $12 billion (excluding the cost of associated transmission) and targets commercial completion for 2028.

Snowy Hydro, NSW. Source: iStock

Batteries

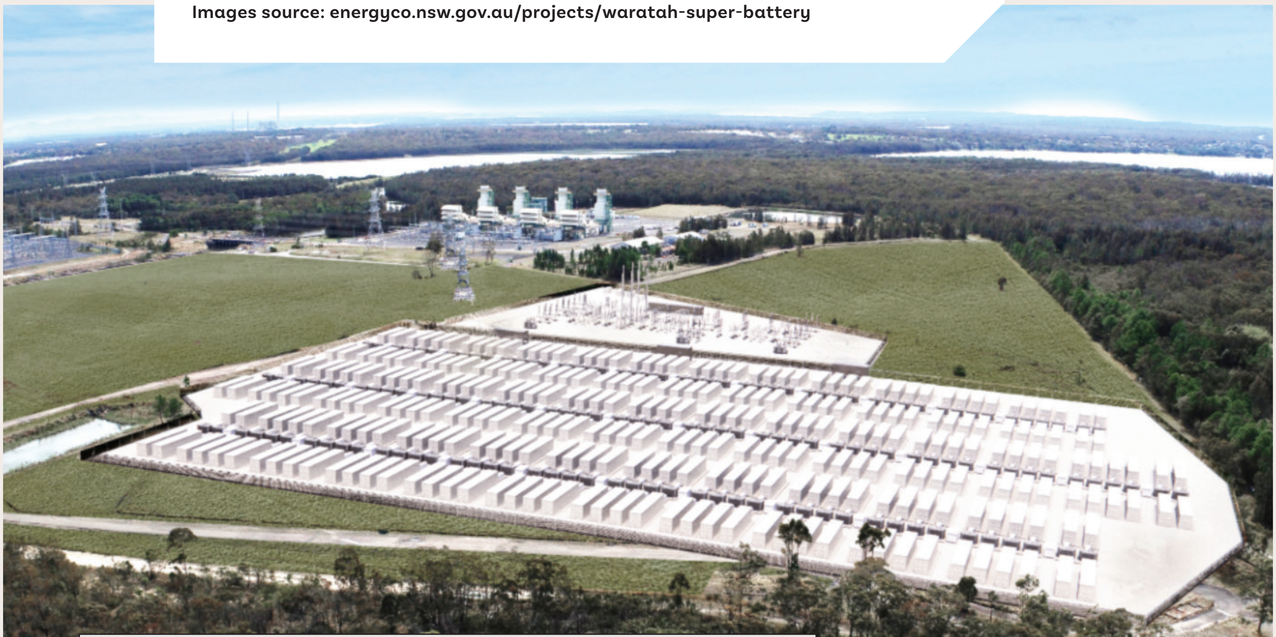
Batteries are extremely versatile technologies that are rapidly gaining popularity, both in Australia and across the world. They can store energy economically for a few hours and can provide very fast, even sub-second frequency response. They are ideal to provide frequency control and operating reserves. A recent trial at the Hornsdale Power Reserve also demonstrated that modern batteries can even provide 'synthetic' inertia. While battery storage systems are still relatively expensive, they are rapidly coming down in price.

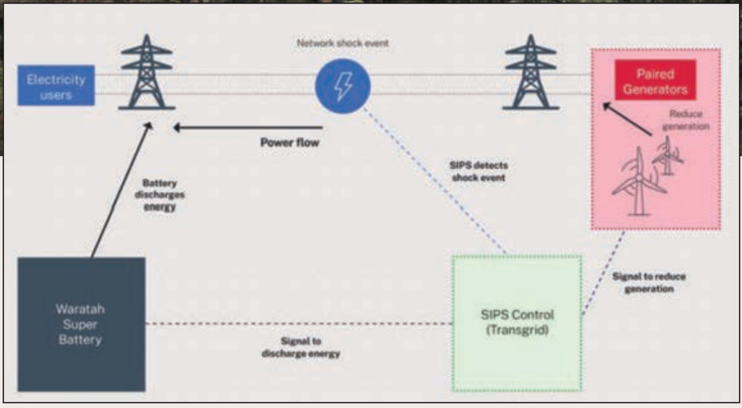
CASE STUDY

Waratah Super Battery

Due to the planned 2025 closure of the Eraring Coal Power Station at Lake Macquarie, there is a growing need for additional energy investment in New South Wales. To support this the NSW Government has announced the development of the Waratah Super Battery project. At 700 MW/1400 MWh the battery will be the largest in the Southern Hemisphere. It is designed to assist with the security and reliability of electricity supply to the Sydney, Newcastle, and Wollongong areas. The battery is being developed to run the existing transmission system at a higher capacity and thus increase the amount of power that can flow into NSW's most populous demand centre, especially during peak demand periods. In other words, the Waratah Super Battery will act as a form of shock absorber in the electricity system. The New South Wales government hopes to have the battery operational by 2024, well before the closure of Eraring.

Images source: energyco.nsw.gov.au/projects/waratah-super-battery





Synchronous condensers

Synchronous condensers are a mature technology and were used commonly in the early days of electricity grids. They are experiencing a renaissance and now play a role in supporting grid stability and security. While these machines do not produce active power, they provide inertia and system strength as well as several other system services.

Gas turbines

Gas turbines are another way of supporting more renewables to enter the system. Gas extraction and burning produces emissions, making it a controversial energy source. However, there are arguments supporting the use of small quantities of gas to firm supply. Depending on the actual turbine used, gas can support the integration of renewables by providing inertia, frequency control and system strength, as well as some level of operating reserve. However, as gas turbines can only produce energy, but not absorb energy, they are more limited in their application for renewable integration compared to batteries. However, gas turbines with an adequate supply of gas are also able to bridge extended 'dark and still' periods where the output of renewable generators might be reduced. Eventually it is possible that either 'green' hydrogen or 'green' methane could be used as a low emissions alternative to natural gas. There is currently work underway to determine if gas pipelines can be repurposed to carry hydrogen in the future.

EMERGING TECHNOLOGIES

Virtual Power Plants

Virtual Power Plants are the integration of large numbers of distributed solar rooftop PV systems, batteries and other appliances installed in households or commercial buildings through smart meters and digital control systems. They can help to better coordinate supply and demand in the system, particularly with growing and widespread adoption of solar PV and batteries, and electrification of heating and transport. For example, appliances like cooling systems do not need to run continuously. With a digital control system, a cooling system can be switched off rapidly if electricity demand spikes. Similarly, a battery connected to a PV system could be switched between charging from the PV panels to discharging to the grid. Such systems can provide greater flexibility on the demand side to quickly respond to system disturbances.

Hydrogen electrolysers

Hydrogen electrolysers use electricity to split water into hydrogen and oxygen. Like pumped hydro, hydrogen can be made using surplus electricity at times when output exceeds demand, stored, and then used to produce electricity later. Hydrogen electrolysers can also be operated flexibly to deliver relatively fast frequency responses and support secure operation under low-inertia conditions.[2]

Electric Vehicles

Another potential option in the medium to long term is using the batteries in Electric Vehicles to feed power to the grid (Vehicle to Grid, or V2G) or power to the home (Vehicle to Home, or V2H). This would be dependent on the uptake of EVs by consumers and the availability of systems to allow the use of EV batteries in this way.

'Grid forming' inverters and 'virtual' synchronous machines

'Grid forming' inverters and 'virtual' synchronous machines use advanced power electronics and control mechanisms to mimic the voltage forming capability of traditional synchronous generators. Combined with batteries, they could displace the use synchronous condensers, which are particularly useful in networks with low levels of system strength.

Small Modular Reactors

Traditional nuclear reactors are very expensive, take a long time (often decades) to construct. Nuclear power also suffers from low community acceptance and is currently illegal in Australia. Small Modular nuclear Reactors (SMR) seek cost and delivery time reductions through modularity which allows for a standardised design and further cost reductions through technology learning rates. Given the early development stage of most SMRs, it is difficult to accurately estimate future cost and capability of SMRs at this point in time.

ENERGY MARKETS AND POLICY CERTAINTY

The fundamental changes occurring in the physical characteristics of Australia's power grid call for new economic incentives which will reward investments that provide the system security services, which have previously been delivered by fossil fuel-fired electricity generation.[3] These economic incentives should be driven by policy certainty, which will underpin greater investment in clean energy infrastructure and grid security. These actions will reduce the risk of energy shortfalls and the associated brownouts or blackouts. Significant challenges lie ahead in developing markets for a new power system that is both secure and low emissions, but if markets and incentives are properly designed, great opportunities can be created.[4]

DEFINITIONS

Adequacy

Refers to the capability of the power system using existing and new resources to meet changes in aggregate power requirements in the present and over time.

Disturbance

Any deviation from the design parameters of an electricity system. For example, a lightning strike on a transmission line results in a surge of voltage and current travelling down the line and which unless arrested, can inflict major equipment damage. Likewise, the sudden loss of a generator can cause voltage and frequency deviations from design levels which must be accommodated by equipment designed to provide resilience in the system.

Frequency Control

Traditional generator turbines are designed to spin at constant speed to maintain output current frequency at (in Australia) 50Hz. Variations in demand tend to increase or decrease turbine speed, but generator controls adjust input power to maintain frequency and hence keep them synchronous with the whole system. With solar PV and batteries, the output is Direct Current (DC and so “asynchronous”) but must be “inverted” to be alternating current (AC) which remains synchronised with the power system. Power electronics technology is used to simulate the frequency control of turbine generators.

Frequency Disturbance

A deviation from the system design frequency of 50Hz caused by changes in the demand/supply balance or system faults. Deviations of 2% or more cause the system to collapse.

Kinetic Energy

Energy in moving objects. For example, a turbine can store kinetic energy which helps maintain the balance between supply and demand with only very minor deviations from design frequency of 50Hz.

Power Grid

The network of transmission and distribution lines and cables which transports energy from where it is produced to where it is consumed. Transmission refers to bulk transport at high voltage, whereas distribution refers to the much more widespread network which supplies power to end consumers.

Reliability

Sufficient generation capacity to always be able to service demand from households and industry. This includes having sufficient generation reserves even if a major generator or transmission line fails unexpectedly. It also includes having sufficient generation reserves available to increase their output quickly (or absorb electricity quickly) if the output of a large wind or solar farm changes rapidly, for example when a major storm front is cutting across a plant.

System Inertia

The energy stored in rotating machinery (such as in a flywheel) which enables the machine (usually a generator) to provide some leeway in allowing instantaneous balance between supply and demand to be maintained and for the machine to maintain synchronism with the system.

System Security

Refers to the capability of a power system using its existing resources to maintain reliable power supplies in the face of unexpected shocks and sudden disruptions in real time, such as the unanticipated loss of key generation or network components, loss of fuel, or rapid changes in demand

System Strength

The ability of a power system (or parts of it) to withstand shocks such as faults on transmission lines or generator failures which need to be cleared quickly to avoid damage to equipment.

Synchronous Inertia

The aggregate inertia of rotating machinery where all machines are at the same point in the cycle.

Synchronous Machines

Machines such as generators and synchronous condensers which can spin at constant speed and at the same point in the cycle of an AC system.

Variable Renewable Energy Systems

Generation sources such as wind and solar whose output depends on weather conditions and so is variable.

Voltage Control

Refers to operational measures to maintain voltage at various parts of the network to designed levels and within supply standards. For example, increased demand by consumers can lead to voltage drops unless generator settings are adjusted. Similarly, transformers (electrical equipment which changes voltage levels on different parts to the system), can be adjusted to maintain voltage levels.

Voltage Waveforms

Alternating electrical current changes direction 50 times each second (in 50Hz systems). This means that the plot of voltage and current over time is, in mathematical terms a sine function. To function normally, electrical equipment requires this plot (or ‘waveform’) to be as close as possible to the sine function, but some deviations can be tolerated.

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