frontier economics

Potential for Gas-Powered Generation to support renewables

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1 Executive summary

The Australian electricity sector is in transition to a future with net zero emissions. APGA has engaged Frontier Economics to develop a robust and approachable evidence base on the role of gas-powered generation in that transition.

This study shows that gas powered generation can play a significant role in a net-zero future by unlocking extremely high levels of renewable generation at low cost, while ensuring a secure and reliable system. Our modelling shows total resource costs are reduced by as much as 36% when gas-powered generation is used to support a renewable electricity system.

Importantly, this study assumes that gas-powered generation will operate much as it operates today, while renewable technologies will continue to fall in cost. The gas industry is, however, seeing high levels of investment in innovation in zero carbon fuels—including hydrogen and biomethane—which have the potential to decarbonise Australia's domestic gas usage, and underpin a new large-scale export industry. This study has not sought to investigate the additional role that these zero carbon fuels may play in the future in Australia's electricity sector.

Our key findings are outlined in the following subsections.

Gas-powered generation can provide support when renewable generation is not available, at lower cost than alternatives

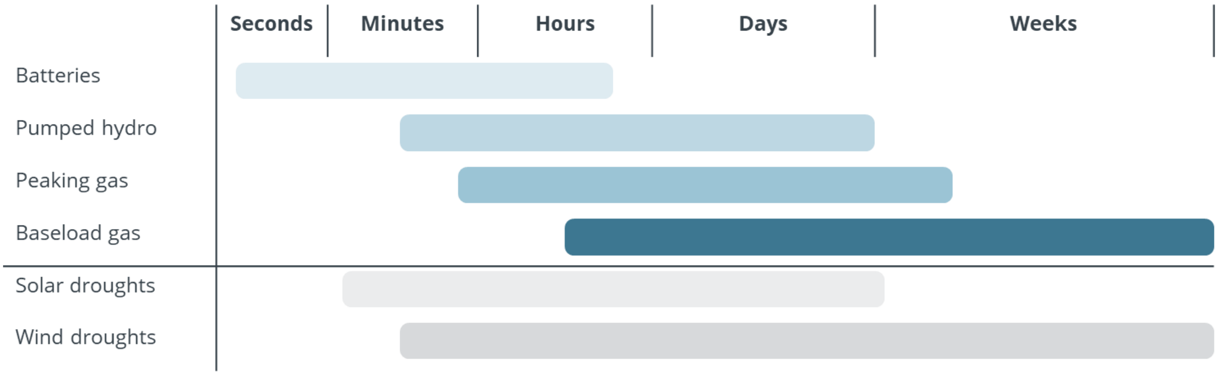
Gas-powered generation that is connected to the gas pipeline network can provide electricity from energy storages over periods of weeks and months, much longer time periods than batteries and pumped hydro can provide. This makes gas-powered generation particularly well-suited to managing energy requirements during sustained periods of low renewable generation, either due to seasonal weather patterns or prolonged renewable droughts.

Solar and wind are the most important sources of variable renewable energy (VRE) in Australia. The electricity available from these generation technologies varies in response to the intermittent availability of wind and solar energy. Solar generation, and wind generation, tends to occur at the same time within regions and even between regions in the National Electricity Market (NEM). This means that when solar or wind generation is not producing much energy in one region, it also tends not to be producing much energy in other regions.

To ensure a reliable supply of electricity, additional flexible sources (such as generation, storage or demand response) must be available to ensure supply meets demand even when variable renewable generation is low. Low levels of VRE generation can persist for a long period of time. Australian Energy Market Operator (AEMO) projections show renewable droughts can last from days to months. In high-VRE generation scenarios, additional generation or storage capacity is required to ensure the lights can be kept on during these renewable droughts.

The flexible nature of gas-powered generation means it is uniquely placed to provide support to renewable generation, protecting the security and reliability of the electricity system. **Figure 1** illustrates the capability of various effective storage options for dealing with renewable droughts.

Figure 1: Effective electricity storage comparison



Source: Frontier Economics

While gas-powered generation is uniquely placed to provide support to renewable generation, long-term investment modelling will often under-value this insurance role for gas-powered generation. Long-term investment models operate in a simplified representation of reality with perfect foresight over states of the world which are, in reality, difficult to predict. Gas-powered generation is well suited to support the system in all conditions and in the event of outcomes not predicted – such as an earlier than expected coal retirement, a long renewable drought or changing ramping requirements over time. While it is difficult to capture this 'insurance' benefit of gas in market modelling, it is important to keep this context in mind in thinking about the future role of gas.

Gas-powered generation provides security that supports high renewable generation

The security and reliability provided by the gas-powered generation system in South Australia has enabled the state to achieve the second highest level of VRE penetration in the world. Although the levels of gas consumed in the system reduced during this period, gas-powered generation continues to play a critical role in keeping the lights on in South Australia's high VRE system.

Electricity markets require more than just electrical energy to operate safely and stably. They require additional services broadly classified as security services. Different generation technologies have different capabilities to provide security services. The physical characteristics of gas-powered generation has inherent properties that support system security, and gas-powered generation can provide all generation-based security services currently required by electricity systems.

Gas-powered generation delivers important benefits in South Australia by providing reliability and system stability in a generation mix with a high proportion of variable renewable energy. South Australia saw a rapid uptake in VRE over the past decade and in the same period saw the retirement of its last coal-fired power station. This change has led to a number of challenges for the system operator, but gas-powered generation proved critical for maintaining system stability and reliability, particularly in times of high VRE output.

Gas-powered generation is a cost-effective way to manage renewable droughts

Providing reliable electricity supply in a 100% renewable electricity system is challenging and costly. Gas-powered generation that is connected to the gas pipeline network can allow very high renewable electricity systems (90%+) to function reliably at much lower cost.

To illustrate this, we developed a simplified model of the electricity system in South Australia to analyse the role of gas-powered generation to support an electricity system that is close to 100% renewable. Our modelling found that total system cost is highest with 100% renewable electricity generation and the lowest when the amount of gas generation in the system is not limited.

Figure 2 presents total system costs for two VRE output years modelled (2030 and 2035), indexed against the costs of the 100% renewable system costs in each year. We have chosen to model VRE output forecast by AEMO for 2030 and 2035 because 2030 includes a fairly typical renewable drought while 2035 includes a renewable drought that it among the most prolonged of the ~25 years for which AEMO provided forecasts of VRE output.

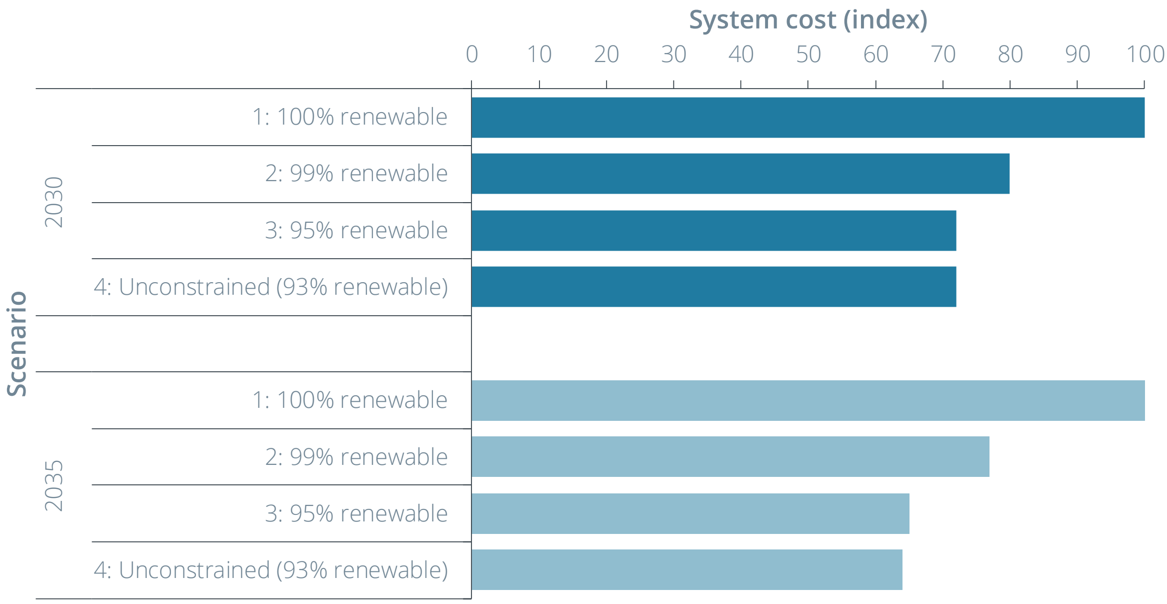
Figure 2 includes four scenarios: the 100% renewable system, a 99% renewable system, a 95% renewable system, and an optimised system (where the level of gas-powered generation is not stipulated) – with 93% renewables.

In 2030, which doesn't contain any particularly long periods of low wind output, the inclusion of a small proportion of peaking gas-powered generation reduced system costs by approximately 28%. In 2035, which features a prolonged wind drought, the inclusion of gas-powered generation reduced system costs by approximately 36%. This difference in system costs amounts to $320 million per annum in 2030 and $475 million per annum in 2035 in the model of the electricity system in South Australia. If these differences in system costs were scaled up to a NEM-sized system they would amount to $5 billion per annum and $7.5 billion per annum. Even if factors like diversity of renewable droughts between regions, or diversity in demand between regions, lessen the available savings in system costs as the NEM approaches 100% renewable (compared to South Australia), it is clear that there is the potential for substantial savings.

The costs differences identified in our model of the electricity system in South Australia primarily relate to the difference in the annualised cost of the mix of generation and storage to meet demand in our simplified model of the electricity system in South Australia. This reduction in total resource costs reflects our finding that some gas-powered generation capacity enables the system to avoid costly and wasteful overbuilding of renewable generation required to deliver system security to manage renewable drought.

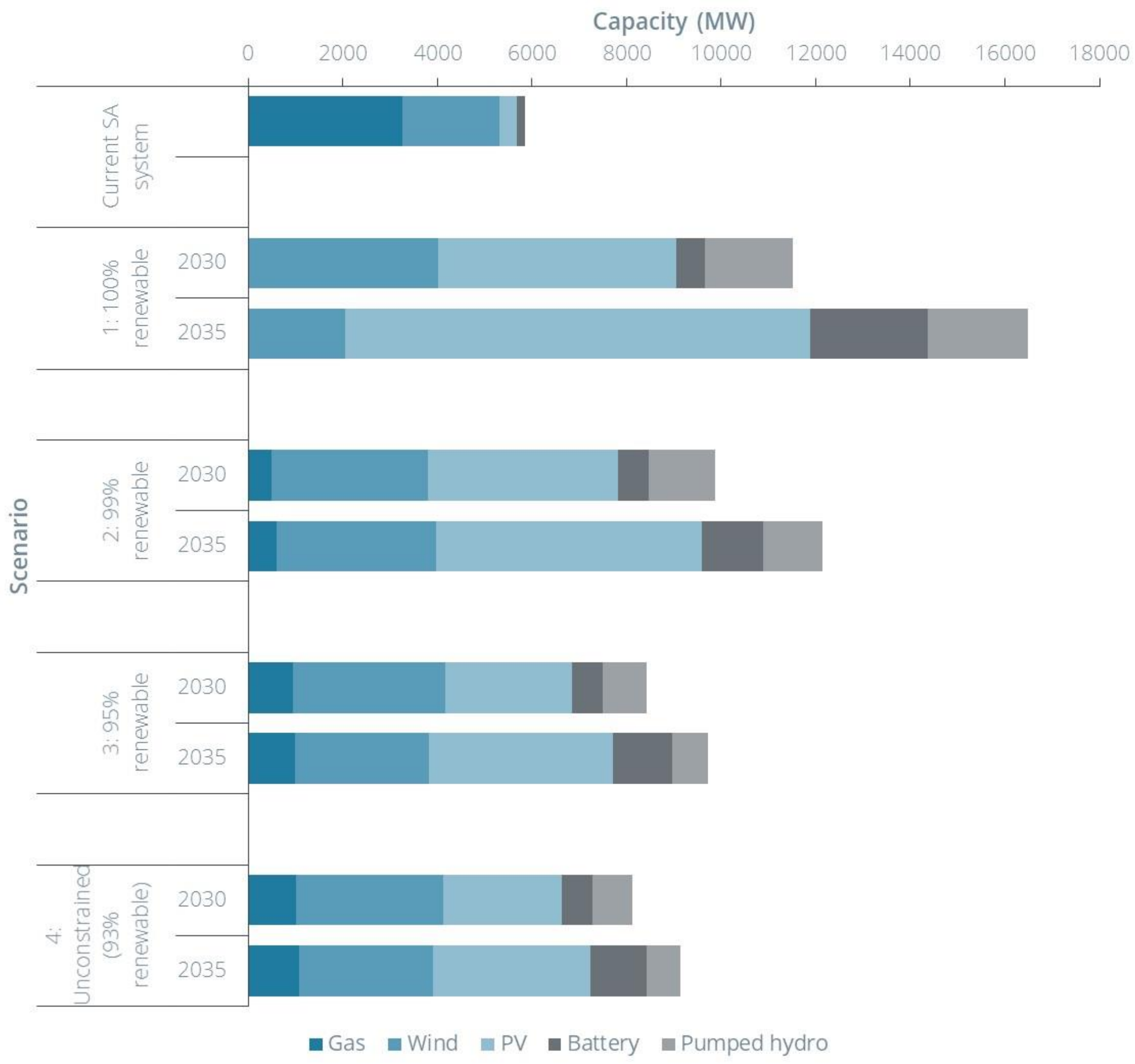
Figure 3 presents the corresponding gas, wind, solar PV, battery and pumped hydro capacity in each scenario, compared with the existing generation mix on South Australia. We note that our simplified model of the electricity system in South Australia ignores existing generation plant in South Australia, and considers generation capacity from the perspective of a future system that is optimised around delivering very high renewable generation.

Figure 2: Indexed system costs for 2030 and 2035



Source: Frontier Economics analysis

Figure 3: Required electricity generation and storage capacity by scenario



Source: Frontier Economics analysis

Gas powered generation provides a cost-effective means of navigating low wind generation without overbuilding all other components of the electricity system. Allowing for some gas-powered generation reduces costs and improves utilisation of assets materially. While a battery or pumped hydro storage may be depleted over the course of a day, gas-powered generation can continue to provide electricity over many days, weeks or months.

Gas-powered generators can continue to generate as long as they have access to gas. Gas storage in the NEM is plentiful and relatively low cost. This means that gas generators that are connected to gas pipeline network (and therefore are able to make use of the gas storage available through that network) can provide cost-effective 'insurance' against electricity shortages during renewable droughts.

While the simplified model of the electricity system that we developed to analyse the role of gas-powered generation to support an electricity system that is close to 100% renewable suggests that lowest cost would be achieved with gas-powered generation making up 7% of the generation mix, the optimal amount of gas-powered generation will obviously vary depending on the characteristics of electricity network. What our analysis reveals is that the insurance offered by gas-powered generation is primarily driven by the following:

- The intermittent nature of VRE, particularly variations that result in renewable droughts that extend over many days, weeks or months. As the amount of VRE in the system increases, the importance of managing this variation increases.
- The availability of other forms of generation or storage to manage renewable droughts that extend over many days, weeks or months. In the NEM, both coal-fired generation and gas-fired generation are able to provide insurance against renewable droughts because both coal-fired generation and gas-fired generation are able to operate at high capacity for long periods of time. However, as existing coal-fired generation retires over coming decades, the insurance role is likely to increasingly fall to gas-powered generation. As we have seen in South Australia, gas-powered generation becomes increasingly important as coal-fired generation retires.

The insurance provided by gas-powered generation does not imply significant carbon emissions

Much of the benefit of gas-powered generation is based on retaining sufficient capacity in the system to ramp up and provide electricity during periods of low renewable generation. This may require periods of high deliverability of gas, but doesn't necessitate high gas consumption, and is compatible with a future with net zero emissions.

Emissions are only produced when gas-powered generators are generating electricity. Gas-powered generators providing insurance for renewable generation in the future, and therefore running infrequently, are unlikely to produce emissions that would prevent the achievement of net zero emissions.

In the scenarios we modelled, we found that the capacity factors of gas-powered generation can remain low while providing a firming role. For example, in the scenarios that included gas-powered generation, the capacity factor was below 13% in each case. In practice, this means that the emissions from gas-powered generation supporting renewable generation in the future are likely to be relatively limited.

Electricity generated by gas-powered generation in the NEM, and the associated emissions, has fallen in recent years. Our modelling shows gas-powered generation operating to provide insurance is likely to generate infrequently in the future, limiting its carbon footprint.

Improvements in the efficiency of gas-powered generation have reduced operating costs and emissions. As the efficiency of gas-powered generation improves its emissions could fall further.

Potential developments in the NEM assist gas-powered generation in insuring against renewable droughts

The market mechanisms that facilitate electricity supply have not kept pace with the changing roles of different generation technologies. This undervalues the services provided by gas-powered generation and will provide inefficient investment signals in the future.

There are four important initiatives that may address the under-valuation of services provided by gas-powered generation in the future. These include:

- The Retailer Reliability Obligation was introduced to promote investment in dispatchable generation capacity, including gas-powered generation, at times of low reliability.
- The Energy Security Board is considering whether new resource adequacy mechanisms are required to ensure reliable capacity required to deliver energy security is available. This may make it easier for gas-powered generation to support variable renewable energy in the NEM in the future.
- The Energy Security Board is considering if ahead markets can better coordinate and dispatch generators providing security services across the NEM, including gas-powered generators, to protect the security of the energy system.
- Missing markets mean service providers are not directly rewarded for the security products or services they provide. The Energy Security Board is considering arrangements that could support the important role played by synchronous generation, including gas-powered generation, in supporting system security.

2 Introduction

2.1 Background and context

The Australian electricity sector is in transition

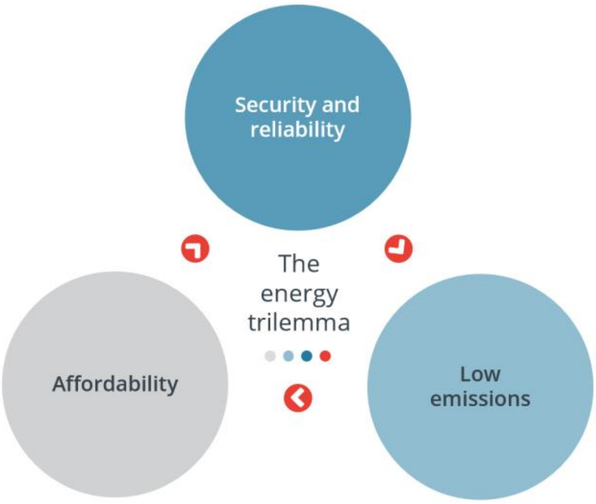
The Australian electricity sector is in transition as it moves towards a long-term goal of zero net emissions. Central to this transition is the adjustment in the mix of generation and supporting infrastructure required to ensure a secure, reliable and affordable source of electricity. Historically, electricity in the National Electricity Market has been provided by coal-powered, gas-powered and hydroelectric generation. The physical properties of variable renewable energy (VRE) sources, including wind and solar, can create challenges for ensuring energy security and reliability. Gas, pumped hydro, batteries, demand management and other ancillary technologies have an important role to play in managing these energy security challenges.

Gas powered generation can help navigate the energy trilemma

The energy trilemma poses the problem of managing three key aspects of our power system:

- The stable operation of the system, which broadly involves security and reliability. **Security** refers to the stability of the system with the ultimate goal of providing safe and uninterrupted electricity supply. Much attention is paid to the wholesale energy market and the price of wholesale electricity, but security services are equally important and are required for a functional electricity supply system. **Reliability** relates to energy being available where and when it is needed. Our electricity supply system needs to be large enough to meet demand. Where demand outstrips supply, load shedding may occur and other problems in the system may arise.
- **Affordability** relates to the cost of energy seen by consumers.
- **Low emissions** relates to the amount of greenhouse gases, measured in carbon dioxide equivalents (CO_2-e), emitted by the system.

Successfully transitioning to zero net emissions while delivering a secure and reliable source of electricity that is affordable to customers is complex. Gas-powered generation has an important role to play in enabling lower-emissions generation sources, underpinning security of electricity supply. It also has an important role to play in providing reliability and maintaining affordability during peak demand periods and during extended periods when renewable generation is low. Defining this role requires an understanding of the relationship between the economic and physical characteristics of gas-powered generation and renewable generation sources. This is necessary to ensure the transition to lower emissions can be navigated in a way that delivers its objectives without compromising energy security or affordability.



2.2 Scope and approach

Frontier Economics is developing the evidence base

In this context, APGA has appointed Frontier Economics to develop a robust and approachable evidence base on the role of gas-powered generation in Australia's future generation mix. This evidence base is intended to inform the development of future policy and technical advice in the electricity sector. In particular, our paper:

Security and reliability	Considers the security, reliability and affordability challenge facing renewables
Role	Identifies the potential role of gas-powered generation in the long-term transition to net zero emissions
Relationship	Explores the relationship between gas-powered generation and the NEM reforms

Paper methodology

In preparing this paper we undertook modelling and analysis, and a desktop review of academic and official literature. We drew on the significant expertise of our project team in electricity, carbon emissions, gas and energy systems:

Desktop review	Modelling	Case study
Review of academic and official literature	Modelling of the electricity system with a mix of generation and storage	Case study of the role of gas-powered generation in the South Australian region of the NEM

2.3 About this paper

This paper is structured as follows:

- Section 3 discusses the role of gas-powered generation in supporting variable renewable generation
- Section 4 demonstrates how cost-effective gas-powered generation is as a storage mechanism to support renewable generation
- Section 5 shows the contribution of gas-powered generation to a cost-effective renewable generation system
- Section 6 demonstrates that having gas-powered generation capacity does not necessarily result in high carbon emissions
- Section 7 considers the way future development of the NEM could support gas-powered generation.

Additional information about our modelling approach and outputs is presented in Appendix A.

3 Gas-powered generation provides support when renewable generation is not available

Gas-powered generation can provide electricity from energy storages over periods of weeks and months, much longer time periods than batteries and pumped hydro can provide. This makes gas-powered generation particularly well-suited to managing energy requirements during sustained periods of low renewable generation, either due to seasonal weather patterns or prolonged renewable droughts.

Key points:

- Solar and wind are the most important sources of variable renewable energy in Australia. The electricity available from these generation technologies varies to reflect the intermittent availability of wind and solar energy from the sun.
- Solar generation, and wind generation, tends to occur at the same time within regions and even between regions in the National Electricity Market (NEM). This means that when solar or wind generation is not producing much energy in one region, it also tends not to be producing much energy in other regions.
- To ensure a reliable supply of electricity, additional generation or storage must be available to meet demand even when variable renewable generation is low. Low renewable generation can persist for a long period of time.
- Australian Energy Market Operator (AEMO) forecasts show renewable droughts can last from days to months. In high-VRE scenarios, additional generation or storage capacity is required to ensure the lights can be kept on during these renewable droughts.
- The flexible nature of gas-powered generation means it is uniquely placed to provide support to renewable generation, protecting the security and reliability of the electricity system.
- Long-term investment modelling – of the type undertaken by AEMO for the ISP, for instance – will often under- value the insurance role that gas-powered generation is increasingly playing.

The most material sources of variable renewable generation in Australia are solar and wind generation. These renewable energy technologies rely on intermittent resources like the wind and solar energy. This means the electricity available from these generation sources is highly variable.

Solar generation is unavailable overnight and is much reduced on cloudy days and in winter, when the sun is lower and days are shorter. Wind generation is only available when there is wind, which varies across the day and from day to day. Other generation sources, including hydro and gas-powered generation, can provide electricity at times when solar and wind generation is low.

This section explores the role of gas-powered generation in providing electricity when variable renewable generation is low. It begins by considering the variable nature of renewable generation (Section 3.1) before discussing the implications for reliability (Section 3.2) and the potential role for gas-powered generation in supporting variable renewable generation (Section 3.3). It concludes by considering the challenge of properly reflecting this value of gas-powered generation when undertaking long-term investment modelling (Section 3.4)

3.1 Renewable generation is variable

The main forms of variable renewable electricity generation in Australia rely on intermittent resources such as the wind and the sun. This means there is no guarantee as to when and how much electricity will be produced by these generators.

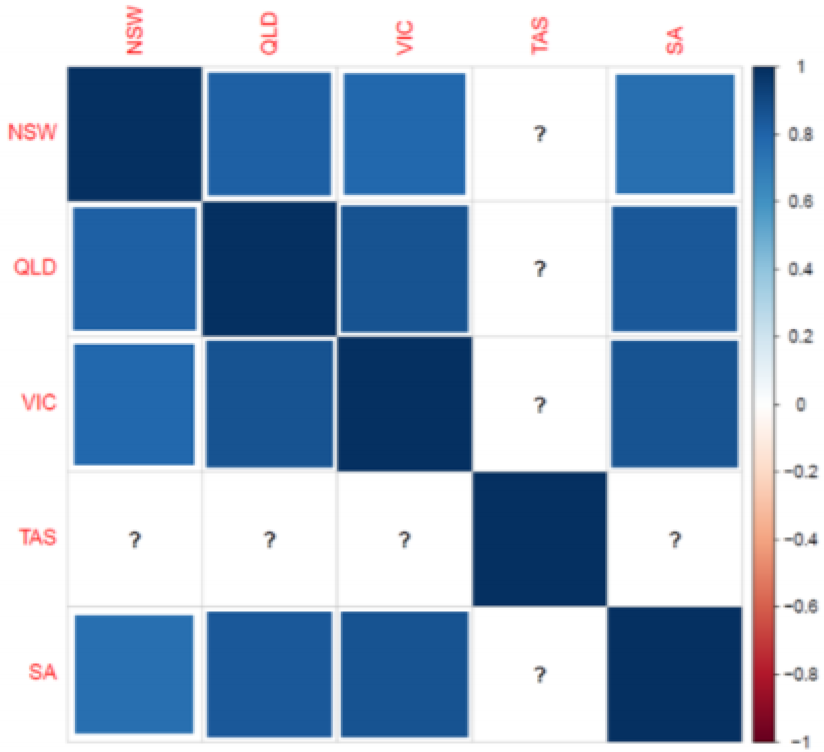
If intermittency between generators at different locations (e.g. northern NSW and southern NSW) or different regions (e.g. NSW and Victoria) was unrelated, it may be possible to achieve a reasonably reliable and relatively cheap generation fleet by overbuilding renewable resources at various locations – on average, these generators would produce enough electricity most of the time.

However, intermittent renewable generation is closely related, both within and between regions in the NEM. Intermittent renewable generators tend to produce electricity at similar times within and between regions, and tend to be unavailable to produce electricity at similar times.

Solar and wind generation tend to occur at similar times across regions in the NEM

Generation from solar PV occurs during daylight hours, which are largely the same across the NEM. This results in a close relationship between the times solar PV generators produce electricity across the NEM. **Figure 4** below presents the correlation between aggregate solar PV generation output between regions in the NEM. Solar PV generation in all regions is positively correlated.

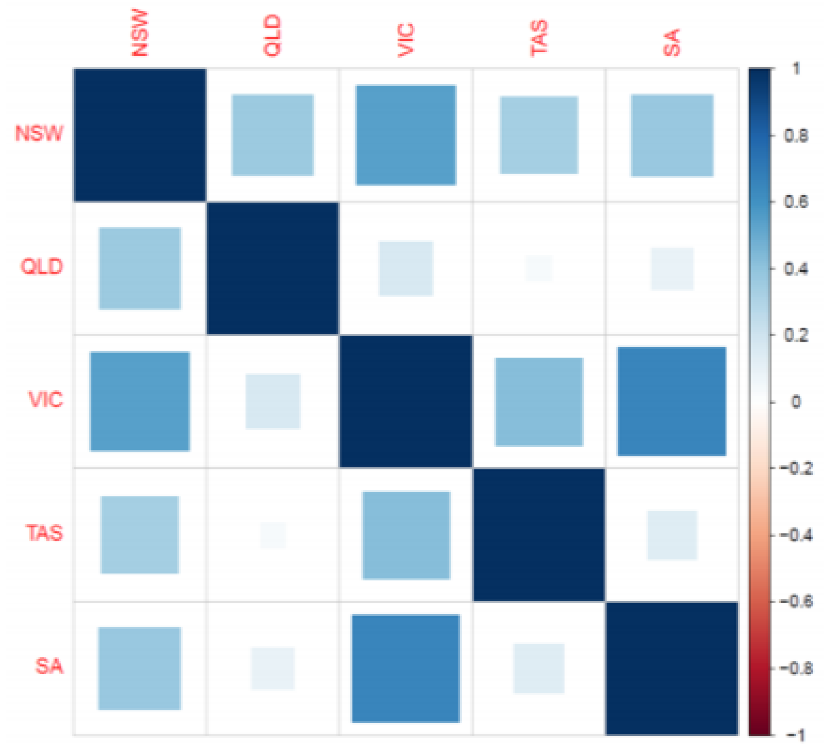
Figure 4: Correlations of solar generator output between regions in the NEM



Source: Frontier Economics bulletin – 'Sunny with a chance of wind', available https://www.frontier-economics.com.au/documents/2020/03/sunny-with-a-chance-of-wind-bulletin.pdf/

There is also a close relationship between the times wind generators produce electricity across the NEM. **Figure 5** below presents the correlation between aggregate wind generation output between regions in the NEM. Wind generation in all regions is positively correlated. In neighbouring regions (such as Victoria and South Australia or New South Wales), these correlations are particularly strong.

Figure 5: Correlations of wind generator output between regions in the NEM



Source: Frontier Economics bulletin – 'Sunny with a chance of wind', available https://www.frontier-economics.com.au/documents/2020/03/sunny-with-a-chance-of-wind-bulletin.pdf/

These positive correlations indicate that when renewable generators are producing a lot of energy in one region, they tend to also be doing so in other regions. Likewise, when renewable generators are not producing much energy in one region, they also tend not to be in other regions.

3.2 Variable renewable generation poses a challenge to energy reliability

The variable nature of renewable generation means that, in scenarios with high penetrations of VRE generation, additional generation capacity or storage resources are required to ensure electricity demand can be met at those times when variable renewable generation is unavailable. To ensure a reliable supply of electricity this additional generation or storage must be able to meet demand even when variable renewable generation is unavailable over a period of time – known as a renewable drought.

Support is required to protect against renewable droughts

Renewable droughts vary in time and severity. A severe renewable drought that results in a significant reduction in wind and solar generation could last for a day or a week. Alternatively, a renewable drought could result in a less material reduction in renewable generation but persist for a period of months.

Forecasts by the NEM's system operator – AEMO – demonstrate the expected nature of renewable droughts. **Table 1** presents an indication of the potential magnitude of wind droughts over different durations (from 1 day to 3 months) and in a selection of years forecast by AEMO forecasts in the 2020 Integrated System Plan (ISP). The magnitude of wind droughts is represented by the forecast average capacity factor across existing wind farms in South Australia, with the lowest capacity factor in any day, week, month, and three-month period presented.

Table 1: AEMO forecast wind droughts in South Australia (lowest capacity factor over period of time)

Year	Worst day	Worst week	Worst month	Worst 3 months	Annual average
2025	2%	7%	13%	26%	36%
2030	2%	16%	25%	31%	38%
2035	2%	7%	13%	25%	36%
2040	2%	17%	26%	32%	39%

Source: Frontier Economics analysis of AEMO ISP 2020 wind traces

In most years, the day of lowest forecast wind generation is similar, with output approximately 2% of capacity. However, over longer periods some years can have materially worse droughts than others. In the forecast 2035 traces, there is a three-month period where wind output is approximately 25% of capacity overall, and a month-long period where wind output is approximately 13% of capacity. This is considerably lower output than the worst month or three months in the forecast traces for 2030 or 2040. To ensure security of supply, the electricity system will need to manage periods of more severe solar droughts – such as those forecast for 2035 – not just periods of average solar droughts.

Table 2 presents the corresponding analysis for solar PV in South Australia. There are some differences in the patters of wind droughts and solar droughts evidence when comparing **Table 1** and **Table 2**: weekly and monthly solar droughts tend to be less severe than weekly or monthly wind droughts, but over 3 months solar droughts are as severe as wind droughts. The reason is the stronger seasonality to solar generation, with the lowest three months of generation consistently occurring for the 3 months of winter.

Table 2: AEMO forecast solar PV droughts in South Australia (lowest capacity factor over period of time)

Year	Worst day	Worst week	Worst month	Worst 3 months	Annual average
2025	4%	17%	20%	22%	29%
2030	3%	15%	18%	19%	29%
2035	4%	13%	20%	22%	29%
2040	3%	15%	17%	19%	29%

Source: Frontier Economics analysis of AEMO ISP 2020 solar PV traces

Climate change is likely to exacerbate unpredictable renewable droughts

Renewable droughts will become an increasing challenge into the future as weather patterns change, and become more extreme, as a result of climate change. We must be able to manage not just a typical renewable drought but also manage a bad renewable drought if we want to avoid supply interruptions. Just as we plan for one-in-ten-year peak demand events, as penetrations of VRE continue to increase, we should also plan for relatively extreme renewable drought events.

3.3 Gas generation can respond to unpredictable renewable droughts more flexibly than alternatives

There are a number of options for managing the variability in renewable generation to protect security and reliability in the event of a renewable drought – including batteries, pumped hydro and gas-powered generation. The physical characteristics of gas-powered generation mean it is well-suited to supporting renewable generation technology while ensuring a secure and reliable electricity system.

Gas-powered generation technology is adaptable

There are three common types of gas-powered generation technologies operational in the NEM that have different properties and favour different use-cases. These are steam turbines, gas turbines, and reciprocating engines (see Box 1). Gas turbines can be paired with steam turbines into an efficient configuration called a 'combined cycle' gas turbine (CCGT).

This range of options means gas-powered generation technology is relatively adaptable. It is able to fulfil a variety of base, mid-merit and peak load generation functions, together with providing system security support, as required.

Box 1: Gas generation comes in different forms

Gas turbines operate by combusting a mixture of compressed air and fuel gas. Hot combustion gas expands through the turbine, spinning blades which draw in more pressurised air and turning a shaft attached to a generator which produces electricity[1]. Gas turbines come in two main forms – aero-derivative turbines (based on aeroplane turbines, hence the name) and industrial turbines. Aero-derivative turbines are smaller and lighter and so faster to start up, although they are less efficient than their industrial counterparts. This makes aero-derivative turbines suitable for peaking applications. Industrial turbines are generally larger and more fuel-efficient but less flexible and hence more suited to baseload or mid-merit applications.

Gas turbines can be paired with steam turbines that used recovered heat from the operation of the gas turbines to produce steam and turn the turbine. This type of configuration is called a **'combined cycle' gas turbine (CCGT)** and is more efficient than gas turbines alone. This is because heat that was previously dissipated (i.e. lost energy) is used to produce additional electricity. CCGTs are relatively common in the NEM due to their high efficiencies, relatively low emissions, and relative flexibility compared with other baseload or mid-merit options.

Reciprocating engines use combustion of fuel gas with pistons to turn a shaft attached to a generator, in some ways similar to an internal combustion engine in a car. Reciprocating engines fuelled by gas are relatively fuel efficient and very flexible in their ability to start and stop quickly and to operate at low generation levels[2]. AGL has recently built a power station comprising reciprocating engine units in Barker Inlet in South Australia to replace an older gas steam turbine station retired around the same time.

Source: Frontier Economics

Gas-powered generation technology is firm

Gas-powered generation is a 'firm' or 'dispatchable' source of generation, meaning it is available to provide electricity when required. Pipeline connected gas-powered generation is able to continue to dispatch electricity indefinitely.

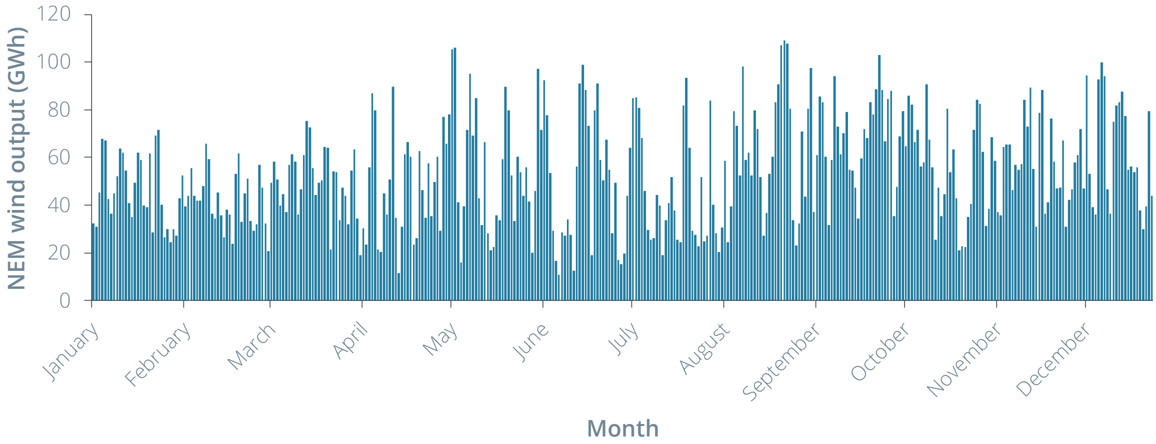
Electricity storage options, such as batteries and pumped hydro, are also generally considered firm or dispatchable. However, storage options are not firm indefinitely – they need to charge or pump prior to being able to dispatch, and can only dispatch while energy remains in storage.

Electricity storage options are good for increasing the degree of firmness of VRE, but are not a complete firming solution. This is because the nature of VRE is not regular – there are periods in which output is concentrated, and periods of 'resource drought' as illustrated in Section 3.2. This can be seen in annual daily output levels from wind in the NEM in 2020 in **Figure 6**.

1 https://www.energy.gov/fe/how-gas-turbine-power-plants-work

2 https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/Inputs-Assumptions-Methodologies/2019/Aurecon-2019-Cost-and-Technical-Parameters-Review-Draft-Report.PDF

Figure 6: Wind output in the NEM, 2020 (GWh)



Source: Data from opennem.org.au

To turn this wind output into a fully firm resource using only storage would require building storages to manage all VRE conditions. This becomes a particular issue when managing prolonged solar or wind droughts. Consider the task of managing prolonged solar or wind droughts using battery storage. Since batteries typically can store only a number of hours' worth or electricity, to use batteries to manage a solar drought of a week or longer would require a number of batteries to discharge in succession. The reason is that batteries are unlikely to be able to recharge until the solar drought ends. In contrast, because a pipeline connected gas-powered generator is able to continue to dispatch electricity indefinitely, a single gas-powered generator could be used to manage a solar drought of a week or longer.

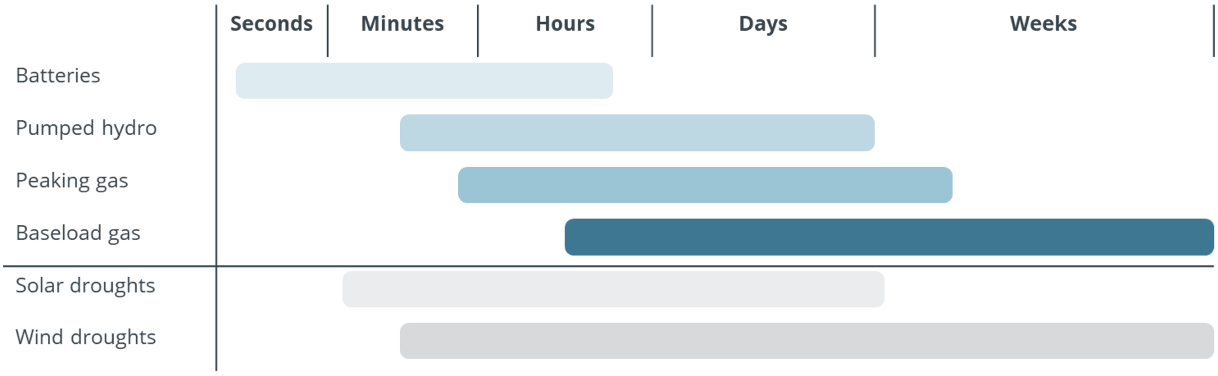
The issue with using storage to manage prolonged renewable drought is exacerbated by the need to cope with the worst sequence of low VRE output that is required by reliability standards. For instance, managing a one-in-ten year renewable drought would entail the need to manage a significant longer and more severe renewable drought than managing a one-in-two year renewable drought.

Gas-powered generation is uniquely positioned to help manage renewable droughts

As outlined in **Table 1** and **Table 2**, wind and solar PV resource droughts can take several different forms. There are periods in which output is significantly below average for a day or week, and there are periods in which output is somewhat below average, but for an extended period of months. In addition, there are shorter periods of time in which renewable generation may ramp up or down suddenly for a very brief period.

An energy system must be capable of maintaining secure and reliable operation over a wide range of time scales. There are a range of dispatchable technologies that provide system support over different time horizons (see **Figure 7**).

Figure 7: Effective electricity storage comparison



Source: Frontier Economics

Batteries are particularly well suited to managing fluctuations in the energy balance over short time periods. They can respond very quickly, and with very high levels of precision, as well as switching quickly from charging to discharging depending on system requirements. However, they have limited energy storage capacity (typically hours), and are not well suited to manage bulk energy requirements over any longer periods.

Pumped hydro storages are potentially capable of managing energy balances over longer periods. However, construction of pumped hydro facilities requires specific geological features and is therefore particularly location dependent. In the absence of very large water storages, pumped hydro is likely limited to a number of days of storage capacity. Depending on the water resources that pumped hydro makes use of, it may also be affected by seasonal weather patterns of droughts. AEMO's modelling for the ISP includes new pumped hydro options with storage capacity up to 2 days in most regions.

Gas-powered generation has considerable advantages over longer periods. Large volumes of gas may be stored in the gas network and in dedicated gas storages for very long periods in time, and the gas network supports continuous ongoing operation of gas generation over much longer periods. Gas powered-generation makes use of existing infrastructure to cost-effectively manage energy balances over long periods, which is a particularly useful complement to battery and pumped hydro storages. This is particularly well suited to managing prolonged periods of low wind generation, which may last for weeks or months.

3.4 It is important not to under-value the insurance benefit of gas-powered generation

As we have discussed, our view is that there is a role for gas-powered generation to provide support to the electricity system when renewable generation is not available. However, it is difficult to forecast the extent of gas-powered generation capacity that is required to fulfill this role.

The usual approach to forecasting new investment in electricity systems is to use a long-term market model of the electricity system to forecast efficient new investment by each available technology type. This is the kind of modelling methodology that is used by AEMO for the Integrated System Plan and is also the kind of modelling methodology that we use when undertaking our own modelling.

There are a number of reasons why the value of gas-powered generation in these models may not be fully captured. These include:

- Long-term investment models tend to operate by assuming the role of a 'central planner' making least-cost optimal decisions. While this is generally accepted to be the most reasonable basis available for projecting investment decisions, in reality investment decisions in the NEM will reflect commercial decisions of individual market participants. Given that individual market participants are likely to face the financial consequences of insufficient firming of VRE, these individual market participants may well place a higher value on the additional flexibility provided by gas-powered generation than does a central planning model.

- Long-term investment models tend to be based on deterministic input assumptions, and typically are not well suited to capturing the uncertainty that is a key feature of investment decisions in generation assets. For instance, long-term investment models will typically make use of deterministic VRE output traces that re known in advance (i.e. the model makes decisions based on perfect foresight of VRE outcomes). This enables long-term investment models to optimise exactly to the conditions provided, despite more extreme renewable droughts being a real possibility. While these models can incorporate a number of potential future states of the world, or scenarios can be run, the number of future states of the world that can be considered by models is necessarily limited. In the real world, individual market participants invest in a world of uncertainty. The need to manage this uncertainty increases the value in the additional flexibility that gas-powered generation offers.

- Long-term investment models need to simplify the complexity of actual electricity markets in order to be solvable. One area in which long-term investment models typically simplify the complexity of actual electricity markets is by modelling a representative sample of demand and VRE output, rather modelling sequential half-hour (or five minute) demand and VRE output. One consequence of this approach is averaging out some of the intermittency of VRE, meaning that long-term investment models are likely to understate the task of managing intermittency of VRE. In reality, individual market participants are likely to invest in gas-powered generation precisely to supply electricity at times of volatile prices caused by intermittency.

- Long-term investment models tend to model outcomes for typical conditions expected in the electricity market, or average conditions. This means that they are typically not well-suited to modelling investment decisions for generation or storage assets that earn a return during atypical conditions (such as periods of unexpectedly high demand, unexpectedly low VRE output or coincident outages); modelling these investment decisions typically takes additional modelling and analysis. Traditionally, this has meant that long-term investment models are not well-suited to modelling investment decisions for peaking plants, which have tended to earn a return during periods of peak demand or generation and network outages. Looking forward, long-term investment models that focus on outcomes for typical conditions are likely to understate the additional flexibility provided by gas-powered generation.

In short, long-term investment models operate in a simplified representation of reality with perfect foresight over states of the world which are, in reality, difficult to predict. Gas-powered generation is well suited to support the system in all conditions and in the event of outcomes not predicted – such as an earlier than expected coal retirement, a long renewable drought or changing ramping requirements over time. While it is difficult to capture this 'insurance' benefit of gas in market modelling, it is important to keep this context in mind in thinking about the future role of gas.

4 Gas-powered generation provides security that supports renewable generation

The security and reliability provided by the gas-powered generation system in South Australia has enabled the state to achieve the second highest level of VRE penetration in the world[3]. Gas-powered generation continues to play a critical role in keeping the lights on in South Australia's high VRE system.

Key points:

- Electricity markets require more than just electrical energy to operate safely and stably. They require additional services broadly classified as security services.
- Different generation technologies have different capabilities to provide security services. The physical characteristics of gas-powered generation has inherent characteristics that support system security.
- Gas-powered generation is a 'complete package' when it comes to providing security services and flexibility to support renewable generation. Gas-powered generation can provide all required generation-based security services.
- Gas-powered generation has provided important benefits in South Australia by providing reliability and system stability in a generation mix with a high proportion of variable renewable energy.

In electricity markets, the primary product that is bought and sold is electrical energy, measured in megawatt hours (MWh) at the wholesale level. All generators participating in a market produce electrical energy regardless of technology. However, electricity markets require more than just electrical energy to operate safely and stably. They require additional services broadly classified as security services. Different generation technologies have different capabilities to provide these services.

This section outlines what services are required and how they are provided (Section 4.1) before considering a case study of South Australia where gas has supported renewable generation for more than a decade (Section 4.2).

[3] On the impact of increasing penetration of variable renewables on electricity spot price extremes in Australia, Economic analysis and policy, 2020, available https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7326418/

4.1 Power systems require security services for stable operation

Large electricity systems require management to ensure security

Large electricity systems are complex systems that require active management by a system operator at all times. Broadly speaking, the system operator is responsible for:

- Ensuring there is enough energy available when required (resource adequacy and capability)
- Ensuring power system frequency remains within normal operating bands
- Ensuring voltage levels in the network remain within acceptable limits
- Ensuring the system can be restored in the event of a major failure (e.g. a blackout)

The market operator is able to manage these aspects of operating a power system by requesting changes in the way in which market participants behave.

The system operator accesses these security services from market participants

The system operator can manage these requirements through services provided by market participants. The system operator obtains these services in a number of ways:

- Some of these services are procured through markets. For example, frequency control services are procured by the system operator through a market called the Frequency Control Ancillary Services market, which operates in a similar fashion to the wholesale market for energy.
- Some of these services are procured through bilateral contracts. For example, the system operator may contract with a network business to provide voltage control services.
- Finally, some of these services are not able to be procured by the system operator. Where these services are required, the system operator may 'direct' market participants to operate in a certain manner to ensure these services are provided.

Different technologies provide different services

Services required for the stable operation of the NEM can be provided by generators, networks and large customers. While all generators produce electrical energy, their abilities to provide other system services depend on the technology they use to operate.

Gas-powered generation is a form of 'synchronous' generation that has inherent characteristics that provide voltage management services (e.g. system strength) and frequency management services (e.g. inertia). Gas powered generation also provides a fully firm source of generation (as discussed in Section 3) and can be used to restart a black system.

Inverter-based resources, such as wind and solar PV, don't inherently provide the same voltage, frequency, adequacy and system restart services that gas-powered generation does. The addition of storage to wind and solar PV increases the ability of inverter-based resources to provide some of these services, but this ability remains limited.

Other non-generation technologies can also provide specialised security services.

4.2 Gas generation has supported renewable energy in South Australia

Gas-powered generation has provided important benefits in South Australia by providing system stability in a generation mix with a high proportion of VRE.

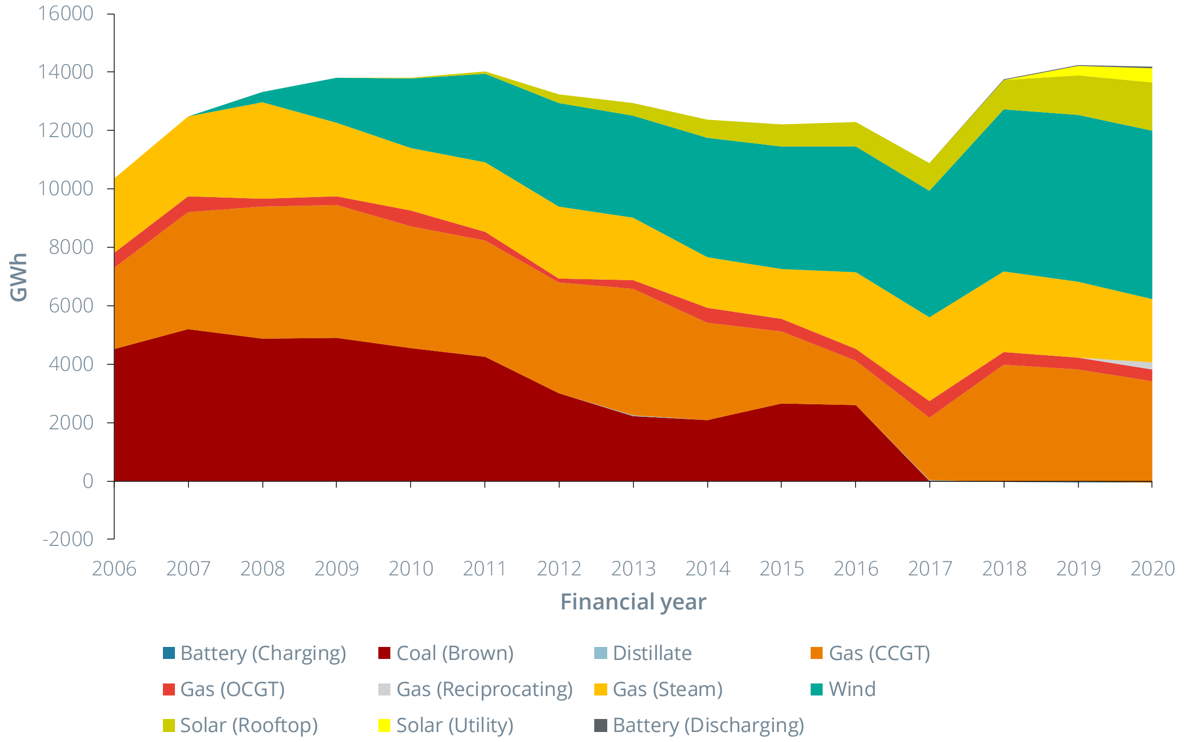
South Australia's electricity system has evolved rapidly

South Australia's electricity system has changed drastically over the preceding decade. In the space of ten years:

- The system has moved from virtually no rooftop solar PV to being the jurisdiction with the highest penetration rates of rooftop solar PV in the world (25 per cent, all dwellings[4]). Queensland is the second highest at 22 per cent (all dwellings).
- Due to an influx of wind and, more recently, solar investment, the system has seen a utility-scale renewable output share rise from 17% to 44% (17% to 55% if you include rooftop solar). This is seen in **Figure 8**, which shows South Australia's generation output from 2006 to 2020. South Australia has one of the highest penetrations of VRE in the world.
- The system had its last remaining coal-fired power station, Northern Power Station, retire in 2016. From 2016, South Australia's generation mix has consisted of wind, solar, gas and a small amount of storage.

4 http://premiumsolarsolutions.com.au/people-power-rooftop-solar-pv-reaches-3gw-in-australia/. Note that some penetration measures consider 'suitable' dwellings, which results in higher penetration rates. For example, the ABS considers a 'suitable' dwellings measure.

Figure 8: South Australia's electricity output mix, 2006-2020



Source: Data from opennem.org.au

The rapid evolution of South Australia's electricity system introduced challenges

The resulting state of the South Australian electricity system has led to new challenges around how a system such as South Australia's should be managed. New entry of renewable generation has provided low cost and clean energy when renewable resources are available. In small doses, the market has been able to accommodate this new energy, and consumers have benefited from lower market prices and cleaner energy. In larger doses, this generation has changed how the South Australian system operates and has required intervention into the market to keep the system operating smoothly.

South Australia's electricity market was a good candidate for new entrant wind early in the decade with a healthy amount of dispatchable generation capacity in the mix providing flexibility and stability services for the grid. Generally speaking, gas-powered generation is flexible in the way that it can adjust its output and start and stop operating. This flexibility enabled the South Australian generation system to work around the periods of high wind and solar output, and associated low prices, brought on by this new entrant generation. At this stage, gas was running frequently and there was no shortage of stability services in the grid.

As the amount of new entrant wind, rooftop solar and, more recently, utility-scale solar has increased in South Australia, market prices have fallen significantly when these resources are available. In effect, this renewable generation displaces gas-powered generation in South Australia, and so gas generators are running less frequently, and fewer security services were being provided.

While consumers may benefit from lower market prices and cleaner energy during windy and sunny periods, this new world presents other challenges to those responsible for keeping the lights on due to a lack of supply of security services. In response to a reduction in gas-powered generation and reduced availability of security services, the market operator has taken a number of measures to ensure that gas-powered generation continues to run in South Australia so that the system is otherwise always operating in a secure state.

Arrangements have been introduced to ensure gas-powered generation supports variable renewable energy

In South Australia the market operator has:

- Ensured that one of a number of combinations of gas units in South Australia is operating at all times.[5] Where market-based incentives are not sufficient for these combinations to be present, the market operator 'directs' a combination of units to run, who are compensated out of market.
- Limited the ability of the main interconnector between Victoria and South Australia to operate at times of low gas-powered generation in the region[6] in response to a ministerial direction. In case of interconnector fault, the islanded South Australian system needs gas-powered generation online to be able to deal with aftermath.

A number of other market arrangements support these changes. Under the market rules the Reliability and Emergency Reserve Trader (RERT) function enables AEMO to maintain power system reliability and system security using reserve contracts, where necessary. AEMO exercised RERT provisions following the 2016 blackout.[7] In addition, the retailer reliability obligation has been introduced to encourage investment in dispatchable generation when and where it is required.[8] The retailer reliability obligation has been triggered in South Australia.

System security issues in South Australia were brought to a head in September 2016 when South Australia experienced a 'system black' event where the whole state lost power for around eight hours.[9] System black events in first-world economies are rare and this put the spotlight on the state of security in South Australia. A considerable amount of effort has since been put in to studying power system requirements in a region like South Australia. The state government at the time also initiated the South Australian Energy Plan, a $550m plan to protect the state against future similar events.

Managing system security into the future is a key issue for South Australia

The next decade has many changes in store for South Australia's electricity system. A number of measures have been proposed, or committed, in order to bolster security in the region. These measures may change the way gas operates. In particular:

- ElectraNet, the South Australian transmission business, is building four synchronous condensers at various points of the network to alleviate some of the burden of system security services from South Australian gas-powered generators. These synchronous condensers are due to be completed this year and will provide some of the services in South Australia that could only be provided by gas-powered generators. These synchronous

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

[6] https://www.aemo.com.au/-/media/files/major-publications/ris/2020/ris-stage-1-appendix-b.pdf?la=en

[7] AEMO, South Australian Electricity Report, November 2017, Available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/SA_Advisory/2017/South-Australian-Electricity-Report-2017.pdf

[8] The retailer reliability obligation is discussed in more detail in Section 7.1.

[9] https://www.aer.gov.au/wholesale-markets/compliance-reporting/investigation-report-into-south-australias-2016-state-wide-blackout

condensers mean that gas-powered generators will be less likely to be directed to operate 'out of market' by the market operator.

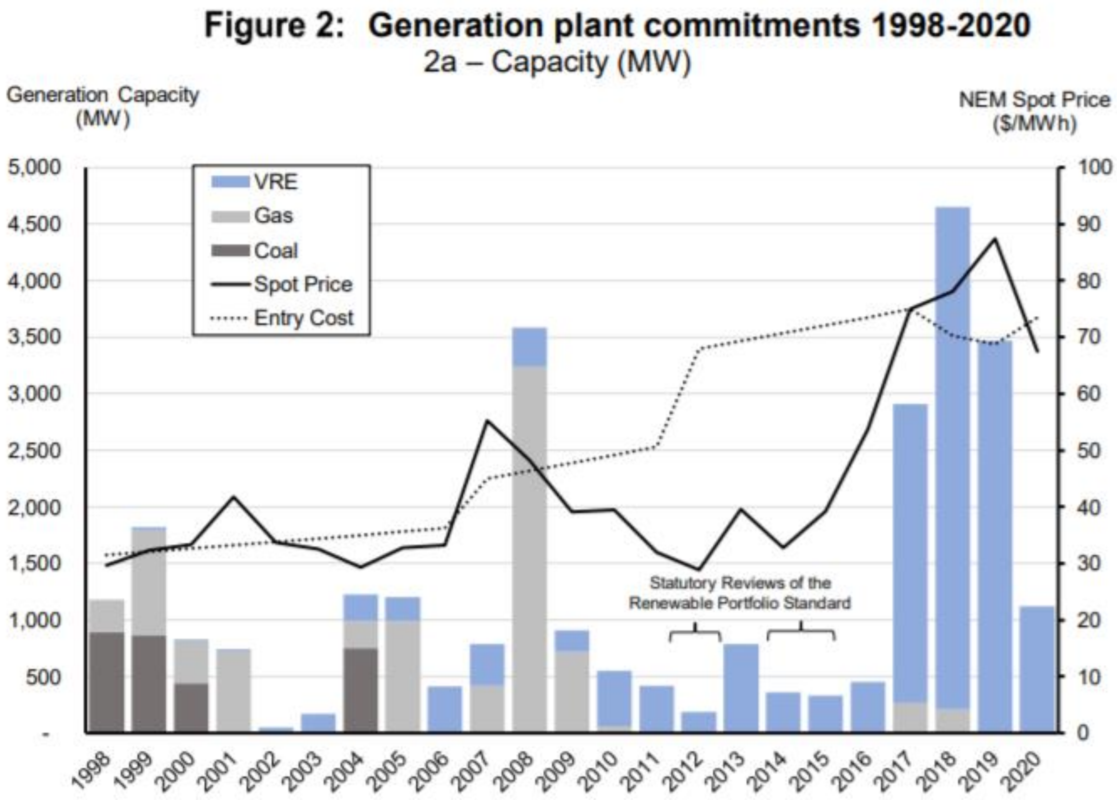
- Project EnergyConnect is a new interconnector between South Australia and New South Wales – due to be operational around 2024-25 – which should provide some redundancy to the existing interconnectors between South Australia and Victoria. This will enable the opening up of the Victoria-South Australia interconnector regardless of how gas-powered generation in South Australia is operating. It will also mean that South Australian gas-powered generation faces additional competition from generation sources in New South Wales, and that South Australian gas could also support renewables in New South Wales.
- It is likely that new markets or avenues to monetise the provision system security services will be made available to generators, including gas-powered generators. This will change gas-powered generator operating incentives and provide a better price signal for operating a secure and reliable electricity system.

Gas-powered generation is likely to remain an important part of the South Australian generation mix

While the outlook for gas-powered generation in South Australia is uncertain, if markets continue to function and be refined, gas-powered generation is likely to remain an important part of the South Australian generation mix, although it may operate less than it does today.

The actions of investors and the government signals that gas-powered generation still has a role to play in systems with high VRE penetrations. Over the past decade, South Australia has seen the only gas-powered generation investment in the NEM (and indeed the only thermal generation investment), as illustrated in **Figure 9**. The South Australian government invested in a 276MW peaking gas-powered power station in the wake of the 2016 blackout, and AGL invested in a fast-start 210MW reciprocating engine power station at Barker Inlet to replace an aging gas-powered power station due to be retired in the near future.

Figure 9: Generation investment in the NEM, 1998-2020



Source: Is the NEM broken? Policy discontinuity and the 2017-2020 investment megacycle, working paper, 2020, available https://www.researchgate.net/publication/341700642_Is_the_NEM_broken_Policy_discontinuity_and_the_2017-2020_investment_megacycle

5 Gas-powered generation can enable the reliability and viability of high VRE systems

Providing reliable electricity supply in a 100% renewable electricity system is challenging and costly. Gas-powered generation that is connected to the gas pipeline network can allow very high renewable electricity systems (90%+) to function reliably at lower cost.

Key points:

- We developed a simplified model of the electricity system to analyse the role of gas-powered generation to support an electricity system that is close to 100% renewable.
- Our modelling found that total system cost is highest with 100% renewable electricity generation and the lowest when the amount of gas-powered generation in the system is not limited.
- Gas-powered generation that is connected to the gas pipeline network provides a cost-effective means of navigating low wind generation without overbuilding all other components of the electricity system. Allowing for some gas-powered generation reduces costs and improves utilisation of assets materially.
- While a battery or pumped hydro storage may be depleted over the course of a day, gas-powered generation can continue to provide electricity over many days.
- Gas-powered generators can continue to generate as long as they have access to gas. Gas storage in the NEM is plentiful and relatively low cost. This means it can provide cost-effective 'insurance' against electricity shortages during renewable droughts.

The previous sections discussed how the flexible nature of gas-powered generation means it is well-placed to protect security and reliability in a renewable system. This section demonstrates that incorporating gas-powered generation into a renewable system also helps ensure electricity remains affordable for customers.

We present our modelling of the electricity system, which shows how gas powered-generation can reduce costs for consumers (Section 5.1), before considering the important role gas-powered generation can provide in the future given the unpredictable nature of renewable droughts (Section 5.2).

5.1 Gas-powered generation helps manage renewable droughts cost-effectively

A renewable electricity system needs the capacity and flexibility to manage the short, medium and long-term variability associated with renewable droughts. The most cost-effective way of managing this variability is to have a mix of different options, including batteries, pumped hydro and gas-powered generation. Gas-powered generation is particularly valuable in cost-effectively managing multi-day renewable droughts. Without gas-powered generation significant additional costly generation and storage capacity is required.

We modelled outcomes in a simplified electricity system

We developed a simplified model of the electricity system in South Australia to analyse the role of gas-powered generation to support an electricity system that is close to 100% renewable. The model optimises the build and operation of wind generation, solar PV generation, batteries (with 2 and 4 hours of storage), pumped hydro (with 6, 12, 24 or 48 hours of storage), and peaking gas-powered generation in some scenarios.

For this modelling, we make two important assumptions – we assume that South Australia is an island (i.e. not electrically connected to other regions) and that there are no security requirements of the system. We make these simplifying assumptions because our focus is on the management of renewable droughts; as noted in Section 3.1, renewable output between regions tends to be correlated, so interconnection increases complexity without mitigating the issue, and introducing security requirements would likely only increase the amount of gas-powered generation required in the modelled systems.

Our modelling shows gas-powered generation can improve utilisation and reduce cost in a renewable electricity system

The model is used to explore electricity generation and storage build requirements to navigate wind and solar droughts of varying magnitudes. It shows the role that gas-powered generation can play to support renewable electricity generation, improving utilisation and reducing cost. As outlined in **Table 1** and **Table 2**, the nature and magnitude of renewable generation droughts can vary significantly between years. We used the model to analyse outcomes in 2030 (which *does not* experience a substantial wind drought in the forecast AEMO ISP traces) and 2035 (which *does* experience a substantial wind drought that lasts for several months)[10].

The basic structure of the model is outlined in Box 2 below. A detailed overview of the model structure, inputs, and results is presented in Appendix A.

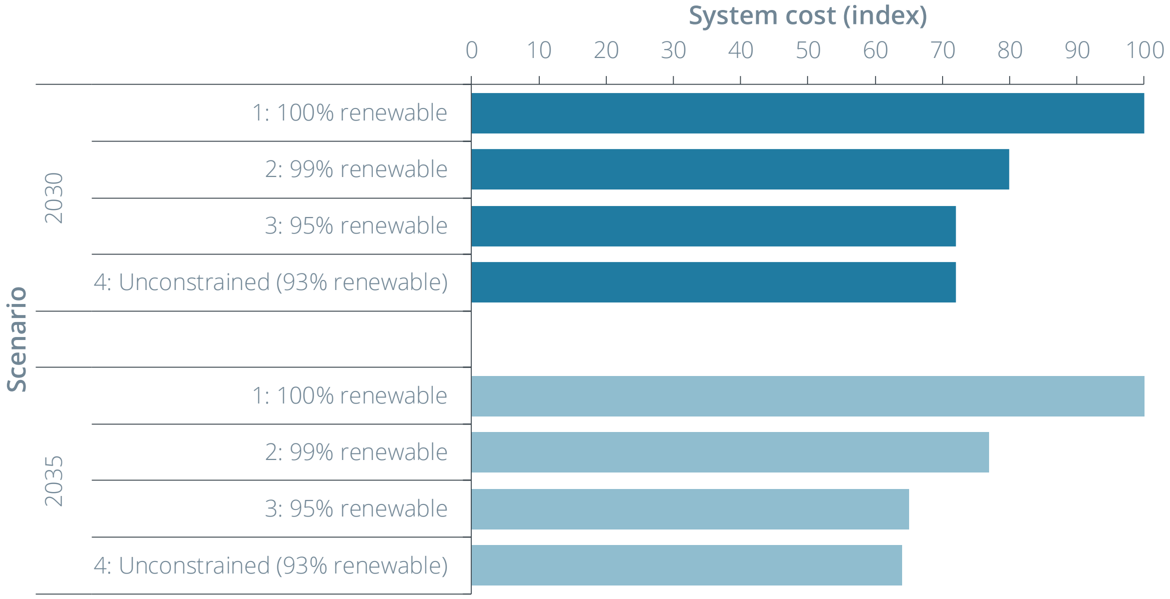
We compared the cost of a 100% renewable system (with no gas-powered generation) to that with a mix of renewables and gas-powered generation under a number of scenarios. We found that total system cost is highest with 100% renewable electricity generation and the lowest when the amount of gas-powered generation in the system is not limited. Our modelling showed a cost-effective mix of generating capacity is around 93% renewables and 7% gas-powered generation. This is conservative with regard to the amount of gas-powered generation – we have assumed away any security requirements, and the system is perfectly optimised around a single

10 While the renewable drought in AEMO's renewable traces for 2035 is among the most severe of the ~20 years of forecasts from AEMO, there are other years for which the renewable traces include comparably severe renewable droughts (such as 2025).

set of renewable generation conditions, rather than having to deal with real-world uncertainty as to renewable generation conditions.

Figure 10 presents total system costs for each scenario in 2030 and 2035, indexed against the costs of the 100% renewable system costs in each year. It includes four scenarios: the 100% renewable system, a 99% renewable system, a 95% renewable system, and an optimised system – with 93% renewables.

Figure 10: Indexed system costs for 2030 and 2035



Source: Frontier Economics analysis

In 2030, which doesn't contain any particularly bad wind droughts in the AEMO traces, the inclusion of a small proportion of peaking gas-powered generation reduced system costs by approximately 28%. In 2035, which features a prolonged wind drought, the inclusion of gas-powered generation reduced system costs by approximately 36%. This difference in system costs amounts to:

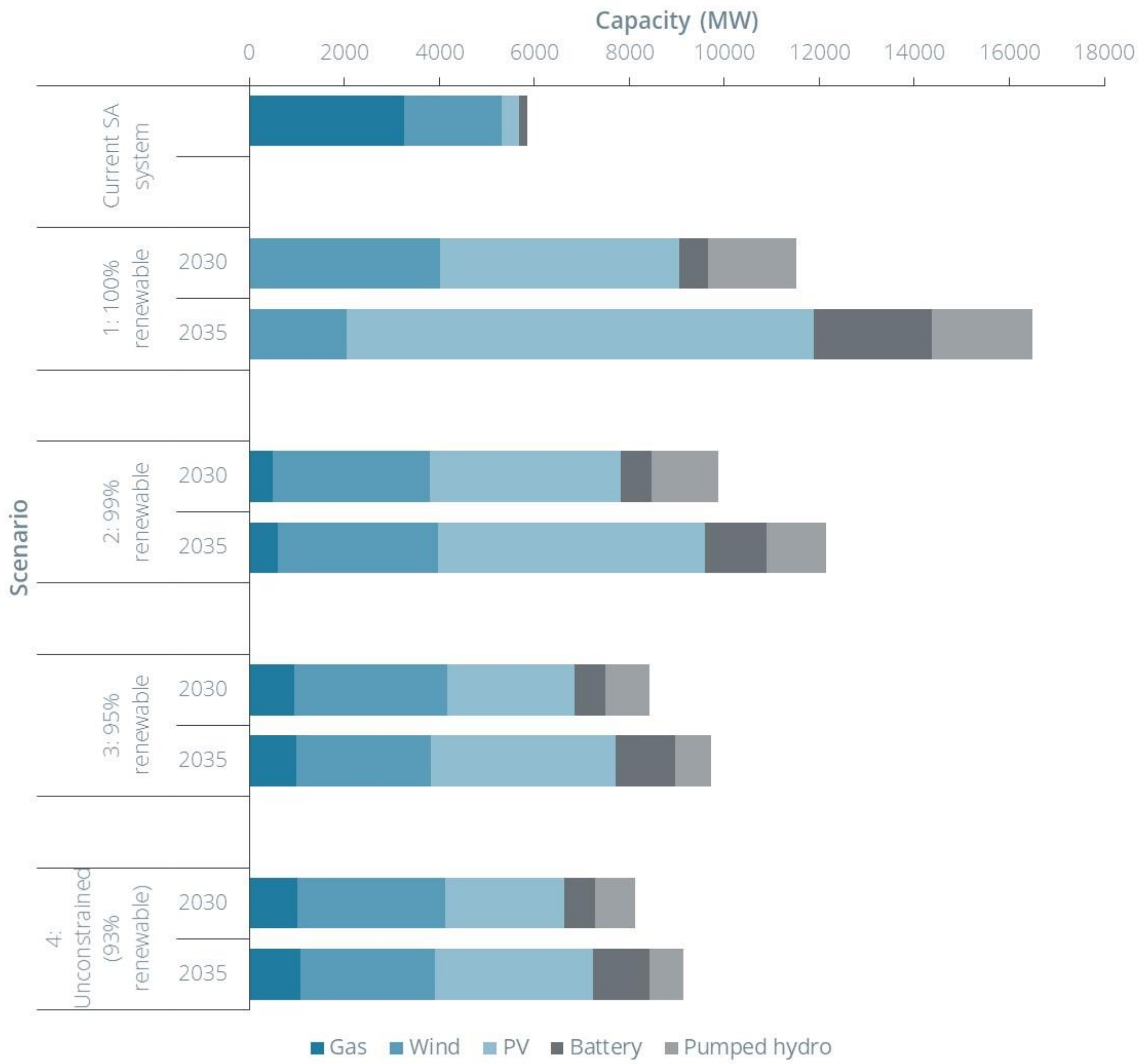
- a $320 million per annum saving in 2030 (relative to a cost of $1,130 million per annum in the 100% renewable case)
- a $475 million per annum saving in 2035 (relative to a cost of $1,330 million per annum in the 100% renewable case).[11]

These cost differences primarily relate to the difference in the annualised cost of the mix of generation and storage to meet demand in our simplified model of the electricity system in South

[11] To put these total annual costs in context, in 2030 the annual system cost in the 100% renewable case is approximately $105/MWh, falling to approximately $75/MWh in the unconstrained case with 93% renewables. In 2035 the annual system cost in the 100% renewable case is approximately $120/MWh, again falling to approximately $75/MWh in the unconstrained case with 93% renewables. Note that these are not forecasts of price outcomes, but forecasts of average system costs that would be required to recover the annualised cost of the mix of generation in the simplified model.

Australia. This reduction in total resource costs reflects our finding that some gas-powered generation capacity enables the system to avoid costly and wasteful overbuilding of renewable generation required to deliver system security to manage renewable drought. This is seen in **Figure 11**, which presents the necessary gas, wind, solar PV, battery and pumped hydro capacity in each scenario (and also shows the existing generation mix in South Australia). The results summarised in **Figure 11** show that in our simplified model of the electricity system in South Australia, around 1,000 MW of gas-powered generation capacity avoids the need for an additional 4,400 MW of wind, solar PV and pumped hydro capacity in 2030 (which doesn't have any particularly bad wind droughts). Around the same 1,000 MW of gas-powered generation capacity avoids the need for an additional 8,400 MW of wind, solar PV, battery and pumped hydro capacity in 2035 (which has a prolonged wind drought).

Figure 11: Required electricity generation and storage capacity by scenario



Source: Frontier Economics analysis

Note: there is no wind generation in the 100% renewable case in 2035 because the forecast wind profile for 2035 includes a substantial wind drought. In the absence of gas-powered generation, additional solar PV and storage is the most efficient way to *manage this drought. With this significant solar PV and storage capacity available to manage the wind drought, there is also sufficient capacity to meet demand the rest of the year without wind generation.*

The results of our simplified model of the electricity system in South Australia would differ when applied to other regions of the NEM. Differences in renewable resources, the availability of hydro generation, the extent of renewable droughts, patterns of demand and interconnection between the regions will all result in variations in the extent to which gas-powered generation will assist in managing renewable droughts. These factors can be accounted for in NEM-wide modelling, but care needs to be taken that this modelling captures the variability and uncertainty associated with renewable generation.

Nevertheless, it is clear that the opportunity for savings in system costs from gas-powered generation in a electricity system approaching 100% renewable are significant. Scaling up the results that we have identified in our simplified model of the electricity system in South Australia suggests that the available savings in a NEM-sized system would be:

- around $5 billion per annum in 2030 (relative to a cost of around $17.5 billion per annum in the 100% renewable case)
- around $7.5 billion per annum in 2035 (relative to a cost of around $21 billion per annum in the 100% renewable case).[12]

These costs savings are enabled by around 15,000 MW of gas-powered generation capacity. Even if factors like diversity of renewable droughts between regions, or diversity in demand between regions, lessen the available savings in system costs as the NEM approaches 100% renewable (compared to South Australia), it is clear that there is the potential for substantial savings.

12 Note that we have scaled the costs from the simplified model of the electricity system in South Australia to a NEM-sized system based on electricity demand, so that the average cost savings remain the same as in the simplified model of the electricity system in South Australia.

Box 2: Modelling analysis

- The model simulates calendar years 2030 and 2035 at the hourly level with full chronology. South Australia is modelled as an island system, with no interconnection to the rest of the NEM.
- Supply must match demand in each hour (or face a high penalty based on the Value of Customer Reliability). Supply includes existing wind and solar PV in South Australia, new build wind and PV, new build large-scale batteries (with 2 or 4 hour storage), new build large-scale pumped hydro (with 6, 12, 24, or 48 hour storage), and new build fast start gas-powered generation in some scenarios. Discharge from large-scale batteries and generation from pumped hydro is added to supply, while charging from large-scale batteries and pumping from pumped hydro is added to demand.
- Storage states for pumped hydro and charge levels for batteries are tracked through the year, and account for storage efficiency losses.
- The model has perfect foresight over demand and generation, including wind and PV output traces, so it can fully optimise. There is no uncertainty or margin for error built into the model. In practice, operating a system with a high proportion of renewable electricity generation would require some overbuild of storage capacity or generation capacity to account for unexpected high demand or low generation. The model does not include any other security or reliability based constraints.
- All demand traces, wind and solar PV generation traces, technology build and operating costs, generator efficiencies and storage efficiencies are taken from the AEMO ISP 2020 assumptions.
- The model co-optimises the build and operation of each type of generation and storage to minimise total system cost over the year. For the purpose of the optimisation, capital costs of new build generation and storage are annuitised over the economic life of the asset.
- The model does not include demand side response as an option. While demand side response clearly plays a role in the electricity system, it appears better suited to managing short periods of high demand rather than prolonged periods of renewable drought.

We modelled four scenarios, for each of 2030 and 2035:

1. 100% renewable; No gas-powered generation.
2. At least 99% renewable; no more than 1% of generation from gas-powered generation.
3. At least 95% renewable; no more than 5% of generation from gas-powered generation.
4. Unconstrained (model optimised to find least cost proportion of renewables and gas-powered generation). The optimal level was 93% renewable in 2030 and 2035.

Source: Frontier Economics

Gas-powered generation provides a cost-effective means of managing renewable drought

A particular challenge for a 100% renewable energy system to navigate is a prolonged period of low wind generation, for example lasting several months. Most wind generation in a region is strongly positively correlated, so building additional capacity of wind generation doesn't provide much assistance. It is necessary to build very large amounts of solar PV generation and storage capacity – much of which is excess to requirements the vast majority of the time. Building such capacity of solar PV and storage is costly and inefficient. It is possible that wind droughts far worse than those in the forecast AEMO traces could occur, meaning the system may need to be built to accommodate even worse periods.

Gas-powered generation that is connected to the gas pipeline network provides a cost-effective means of navigating such periods of low wind-generation without overbuilding all other components of the electricity system. Allowing for some gas-powered generation reduces costs materially.

The modelling is simplified, but provides an indication of likely direction

It is important to note that the model has several simplifying features, and in general the results should be interpreted as directional:

- It is an optimisation model with perfect foresight, allowing storages to be operated with no risk tolerance or waste.
- Each model run is based on a single year of demand and generation traces from AEMO.
- The model doesn't account for interconnection with other regions or detailed generator behaviour.
- We have assumed away security requirements of the system.

Nevertheless, what our analysis reveals is that the insurance offered by gas-powered generation is primarily driven by the following:

- The intermittent nature of VRE, particularly variations that result in renewable droughts that extend over many days, weeks or months. As the amount of VRE in the system increases, the importance of managing this variation increases.
- The availability of other forms of generation or storage to manage renewable droughts that extend over many days, weeks or months. In the NEM, both coal-fired generation and gas-fired generation are able to provide insurance against renewable droughts because both coal-fired generation and gas-fired generation are able to operate at high capacity for long periods of time. However, as existing coal-fired generation retires over coming decades, the insurance role is likely to increasingly fall to gas-powered generation. As we have seen in South Australia, gas-powered generation becomes increasingly important as coal-fired generation retires.

5.2 Gas-powered generation can provide insurance for unpredictable renewable droughts

Alternative to gas-powered generation in providing electricity during renewable droughts – batteries and pumped hydro – tend to be energy constrained. This is not to say that batteries and pumped hydro do not have an important role to play in electricity markets; indeed, our simplified model of the electricity system in South Australia indicates that both are important in managing the variability of renewable generation. However, the fact that they are energy constrained means:

- They are not well-suited to insuring against unexpected renewable droughts or longer than expected renewable droughts. For instance, battery operators are likely to charge and discharge their batteries based on expectations of future spot prices (which will reflect expectations of future weather conditions). Errors in forecasting future spot prices and weather conditions may mean that batteries are discharged at the commencement of a renewable drought.
- They may have to ration their response to renewable droughts to ensure they can respond for the duration of the renewable drought.

Gas-powered generation is more flexible than batteries and pumped hydro in the time that it operates. Gas-powered generators can continue to generate as long as they have access to gas. Gas used to generate electricity in the NEM can be stored in many locations and forms: off-shore fields, linepack, underground caverns and LNG. Gas storage in the regions of the NEM is plentiful and relatively low cost. This means in many cases, pipeline-connected gas-powered generation is effectively unlimited in the duration in which it can operate. Compared to the alternatives of batteries and pumped hydro, which must be charged or pumped in advance and can only store a limited amount of electricity, gas-powered generation is much more flexible in the duration of its operation. While a battery or pumped hydro storage may be depleted over the course of a day or days, gas-powered generation can continue to provide electricity over days, weeks or months.

The flexibility of gas-powered generation means it can provide cost-effective 'insurance' against electricity shortages during renewable droughts. Our modelling analysis shows using the bundle of gas storage and gas-powered generation to cover renewable droughts is significantly more cost-effective than the alternative of relying on renewable generation, batteries and pumped hydro. As discussed in Section 5.1 our modelling shows total resource costs are reduced by as much as 36% when gas-powered generation is used to support a renewable system.

6 The insurance provided by gas-powered generation does not imply significant carbon emissions

Much of the benefit of gas-powered generation is based on retaining sufficient capacity in the system to ramp up and provide electricity during renewable droughts. This may require periods of high deliverability of gas, but doesn't necessitate high gas consumption, and is compatible with a future with net zero emissions.

Key points:

- Emissions are only produced when gas-powered generators are generating electricity. Gas-powered generators providing insurance for renewable generation in the future, and therefore running infrequently, are unlikely to produce emissions that would prevent the achievement of net zero emissions.
- Electricity generated by gas-powered generation in the NEM, and the associated emissions, has fallen in recent years. Our modelling shows gas-powered generation operating to provide insurance is likely to generate infrequently in the future, limiting its carbon footprint.
- Improvements in the efficiency of gas-powered generation have reduced operating costs and emissions. As the efficiency of gas-powered generation improves its emissions could fall further.

The emissions associated with gas-powered generation may raise concerns about its role in a renewable energy system. This section considers the likely extent of emissions associated with gas-powered generation in the NEM (Section 6.1), and the improving relationship between the efficiency of gas-powered generation and emissions (Section 6.2).

6.1 Gas-powered generation providing insurance are likely to operate infrequently, generating few emissions

Renewable droughts occur infrequently. Gas-powered generation providing insurance to cover renewable droughts is therefore only likely to generate electricity for a small proportion of the time.

Emissions are only produced by gas-powered generators to the extent that they are used to generate electricity. This means gas-powered generation providing cost-effective support for renewable generation in the future, and therefore running infrequently, is unlikely to generate material emissions.

Gas-powered generators designed for 'firming' operate relatively infrequently in the NEM

In the financial year ending June 2020 the average capacity factor for gas-powered generation in Australia was around 20 per cent, which includes 'mid-merit' power stations with higher capacity factors and peaking power stations with very low capacity factors (e.g. around 1-2 per cent). Although gas-powered generation accounts for around 16 per cent of capacity in the NEM it generated only around 9 per cent of the electricity used in the NEM in the financial year ending June 2020.

This is evident in the changing operating patterns of Smithfield gas power station in western Sydney. The 109MW fast start OCGT power station was owned by Visy (paper/packaging manufacturer) and operated as a cogeneration facility – it provided electricity to the NEM and steam to Visy's factory. While operating as a cogeneration facility, its capacity factor was around 60 per cent. It was then purchased by renewable power producer Infigen Energy in May 2019 to support its portfolio of variable wind and solar generation assets. The power station provides "firming" capacity needed to enable Infigen to increase sales to commercial and industrial customers and grow its intermittent renewable generation capacity.[13] Infigen states its anticipated utilisation of Smithfield at 2-8% ensures a small carbon footprint while supporting growth in Infigen's intermittent renewable generation portfolio of 300-400MW.[14] Data to date suggests that Infigen is operating it at these low capacity factors as anticipated.

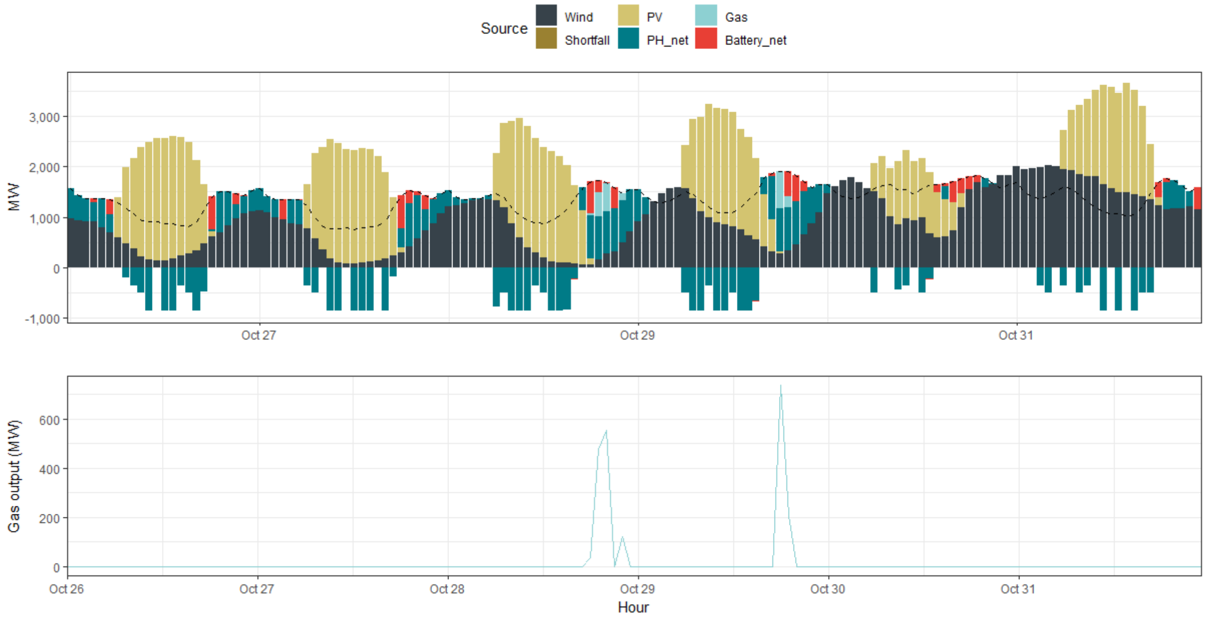
Gas-powered generators are likely to operate infrequently in the future

Our analysis of outcomes in the NEM shows the capacity factors of gas-powered generation could remain low in the future. **Figure 12** presents an outcome from our modelling described in Section 5. It shows gas-power generation providing a brief, but valuable, firming role during a few days in which wind generation drops to very low levels in the early evening, at the same time that solar PV generation drops off and demand reaches its peak. This is a brief lull in renewable output, during which the some operation of gas-powered generation alongside batteries and pumped hydro reduces system costs.

13 Infigen Energy, Infigen announces Smithfield OCGT firming acquisition and expected distribution for 2H/FY19, 23 May 2019, p1. Available at: https://www.infigenenergy.com/assets/Uploads/12-2019-Smithfield-OCGT-Acquisition-and-Capital-Management-Update.pdf

14 Infigen Energy, Infigen announces Smithfield OCGT firming acquisition and expected distribution for 2H/FY19, 23 May 2019, p1. Available at: https://www.infigenenergy.com/assets/Uploads/12-2019-Smithfield-OCGT-Acquisition-and-Capital-Management-Update.pdf

Figure 12: Example of gas firming



Source: Frontier Economics modelling

Our modelling found that the capacity factors of gas-powered generation can remain low while providing a firming role. For example, in the scenarios that included gas-powered generation, the capacity factor was below 13% in each case. In practice, this means that the emissions from gas-powered generation supporting renewable generation in the future are likely to be relatively limited. In the scenario with 93% renewable generation, annual emissions from gas-powered generation were approximately 812,000 tCO2e. For comparison, South Australia's electricity generation emissions for 2015 were estimated to be 5,100,00 tCOe2[15].

6.2 Gas-powered generation efficiency has improved over time

The efficiency of gas-powered generators ('thermal efficiency') relates to the amount of energy lost in the conversion of input fuels to electricity[16]. High efficiencies mean that there is little energy lost in the conversion process. High efficiencies are attractive for operators of gas-powered generators, because it means they require less fuel for a given amount of energy produced, require less transport capacity for fuel, and produce less emissions.

The efficiency of gas-powered generation has improved significantly over time due to technological improvements. The first industrial gas turbine, installed in Switzerland in 1939, had an efficiency of 17.4 per cent[17]. The first commercial CCGT plant was built in Europe in 1960 with an efficiency of 32.5 per cent. These efficiencies have been improved over time with technological

15 State and Territory Greenhouse Gas Inventories 2015, Department of Environment and Energy, available https://www.industry.gov.au/sites/default/files/2020-07/nga-state-and-territory-greenhouse-gas-inventories-2015.pdf

16 Efficiencies are sometimes expressed as 'heat rates', which relate the amount of input fuel (e.g. in GJ) required to produce a unit if electrical energy (e.g. MWh). In this instance, lower heat rates imply higher efficiencies.

17 https://www.powermag.com/a-brief-history-of-ge-gas-turbines-2/

developments including higher turbine inlet temperatures, improved cooling systems, and more heat-tolerant materials[18] among others. Modern CCGT power stations have efficiencies in the high 50 to low 60 per cent range.[19]

6.3 Gas generation efficiencies will continue to improve

Gas-powered generator manufacturers continue to develop generation technologies and further improvements in thermal efficiencies are likely.

These manufacturers are also thinking about how their products fit in to generation mixes with different compositions, including systems with high penetrations of VRE. For example, Wartsila emphasise the flexibility and low-load abilities of its modular reciprocating engine generators.[20] These generators would complement systems with high VRE penetrations in particular.

18 https://ijmme.springeropen.com/articles/10.1186/s40712-014-0002-y

19 https://www.edf.fr/en/edf/combined-cycle-gas-turbine-power-plants

20 https://www.wartsila.com/energy/learn-more/technical-comparisons/combustion-engine-vs-gas-turbine-advantages-of-modularity

7 Potential developments in the NEM assist gas-powered generation in insuring against renewable droughts

The market mechanisms that facilitate electricity supply have not kept pace with the changing roles of different generation technologies. This undervalues the services provided by gas-powered generation and will provide inefficient investment signals in the future.

Key points:

- The Retailer Reliability Obligation was introduced to promote investment in dispatchable generation capacity, including gas-powered generation, at times of low reliability.
- The Energy Security Board is considering whether a capacity market can ensure reliable capacity required to deliver energy security is available. This may make it easier for gas-powered generation to support variable renewable energy in the NEM in the future.
- The Energy Security Board is considering if ahead markets can better coordinate and dispatch generators providing security services across the NEM, including gas-powered generators, to protect the security of the energy system.
- Missing markets mean service providers are not directly rewarded for the security products or services they provide. The Energy Security Board is considering arrangements that could support the important role played by synchronous generation, including gas-powered generation, in supporting system security.

There are a number of workstreams underway considering changes to the future arrangements for the NEM. It is not yet clear how the NEM will evolve. However, much of the focus is currently on options to support more efficient provision of firming or reliability to support renewable generation. Options that have been introduced or have been discussed include:

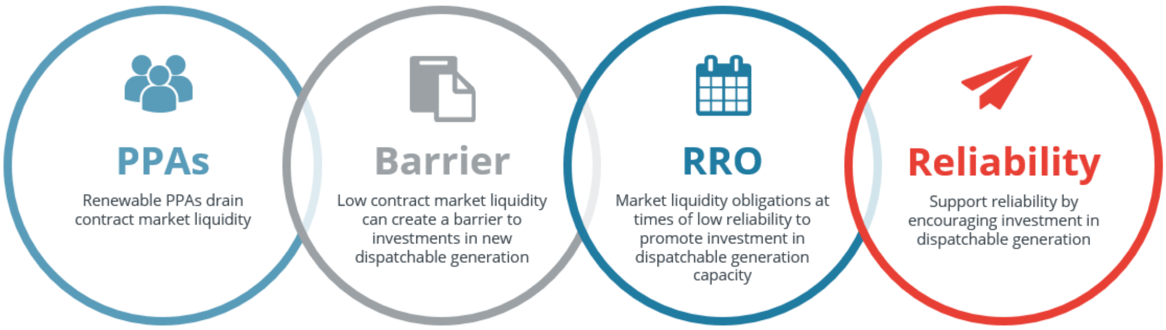
- Retailer reliability obligation (Section 7.1)
- Capacity markets (Section 7.2)
- Ahead markets (Section 7.3)
- Missing markets for inertia or other services (Section 7.4).

These options for the evolution of the NEM reflect the same concern for ensuring reliability as the generation mix shifts towards renewable generation. These evolutions of the NEM are likely to assist gas-powered generation fulfill the insurance role discussed in the previous sections.

We discuss each of these options in more detail below.

7.1 The Retailer Reliability Obligation is intended to support investment in dispatchable generation capacity

New investment in renewables in the NEM to meet state-based renewables targets tend to be financed by long term power purchase agreements (PPAs) or contracts for difference rather than hedge products in contract markets. This can drain liquidity in contract markets over time, creating a potential barrier to investment in new dispatchable generation capacity.[21] This concern has motivated the introduction of market liquidity obligations at times of low reliability to promote investment in dispatchable generation capacity, including gas-powered generation.



The Retailer Reliability Obligation (Box 3) is intended to support reliability by encouraging investment in dispatchable resources where and when it is required. This could provide a mechanism for supporting investment in gas-powered generation, recognising its important role in promoting a reliable and cost-effective supply of electricity to customers.

21 AER, State of the Energy Market 2020, p43.

Box 3: Retailer Reliability Obligation and market liquidity obligation

The Retailer Reliability Obligation (RRO) is intended to support reliability in the NEM, by encouraging investment in dispatchable and on demand resources where and when it is required. When the RRO is triggered retailers are required to demonstrate they have entered into sufficient firm contracts to meet their share of expected 1-in-2 year system peak demand. There are two ways the RRO can be triggered:

- AEMO is responsible for forecasting any reliability gaps in the NEM over the next five years. If a material gap is identified within three years and three months, it can apply to the AER to have the RRO triggered.
- The South Australian Energy Minister can elect to trigger the RRO in South Australia.

The market liquidity obligation (MLO) is intended to ensure there is sufficient liquidity to enable small retailers to meet their obligations when an RRO is triggered. The MLO applies if the RRO is triggered and requires generators to post bids and offers on an approved exchange for standardised products (base load futures, peak load futures and caps) that cover the period of the gap. The bids and offers must meet defined parameters in terms of parcel size, bid-offer spread and trading windows each day. Until June 2021 MLO obligations are imposed on large generators in each region based on scheduled generation capacity; after that time generation capacity will be linked to large trading groups in each region based on information provided by generators about their generation assets and trading rights.

The MLO parameters involve:

- Market makers participating in defined trading windows (11-11.30am and 3.30-4pm) each day
- Market makers offering a maximum spread on base and peak futures of the greater of 5% or $1.00 in Queensland, NSW and Victoria and the greater of 7% or $1.00 in South Australia
- Market makers offering a maximum spread on caps of the greater of 10% or $1.00 in all regions.

In January 2020 an RRO was triggered by the South Australian Minister for Energy and Mining for the first quarters of 2022 and 2023. South Australian generators Origin, AGL and Engie were required to start performing the MLO in February 2020.

Source: Australian Energy Markets Commission, Rule determination: National Electricity Amendment (Market making arrangements in the NEM) rule 2019, September 2019

7.2 Additional resource adequacy mechanisms are being considered to address the missing money problem

The Energy Security Board is investigating changes to the market and regulatory arrangements of the NEM to better integrate large-scale and small-scale renewables into the system. This body of work is known as the post-2025 market design program. One of the options being considered in this context is the introduction of additional measures to ensure resource adequacy.

In an energy only market such as the NEM, generators depend on extreme prices at times of scarcity in order to recover large fixed capital costs. This can be risky as it can mean several years of under-recovery of capital costs ("missing money" in the academic literature), with one extreme period of scarcity (extreme prices) required to cover all capital costs.

Capacity markets, also known as long-term ahead markets or forward capacity markets, are a feature of many electricity markets including the Wholesale Electricity Market (WEM) in Western Australia. Capacity markets can provide an additional source of revenue to assist generators to recover the costs of investments.

The ESB is considering whether an enhanced retailer reliability obligation can work alongside real-time price signals to ensure reliable capacity required to deliver energy security is available.[22] Changes to the NEM to enhance the retailer reliability obligation or introduce a capacity market may make it easier for gas-powered generation to support variable renewable energy in the NEM.

7.3 Ahead markets can provide increased certainty about the support from gas-powered generation

Short-term ahead markets, often referred to as day ahead markets, are also a feature of many established electricity markets. Ahead markets are often implemented in order to provide generators with increased certainty about power station operation in the short term. For instance, a day ahead market can provide a generator with day ahead certainty as to the operation of their power station the following day. This can serve a number of functions:

- it can assist generators arrange fuel supplies and staffing, and
- for generators that have start costs, shut-down costs, minimum run times or minimum shut down periods, day ahead markets can enable generators to explicitly reflect these operating costs or constraints in their offer to supply electricity to the market.

In contrast, markets that consist only of a real time spot market force participants to forecast future dispatch and to try and reflect these operating costs or constraints in the way they bid to supply electricity into the real time spot market.

As with forward capacity markets, there has been interest in short-term ahead markets as a result of the increase in VRE in the NEM. The intent is that short-term ahead markets provide dispatchable generators with improved opportunities to efficiently schedule their operation in a world of increasing variable and uncertain operation of renewable generation. For instance, for a gas generator with significant start costs, it may be necessary to have certainty about short-term operation in order to incur start costs in the face of uncertain wind and solar output.

The ESB considers that there is a need to better coordinate and dispatch generators providing essential services across the NEM, including synchronous thermal generators like gas-powered generation that require activation ahead of real-time.[23]

[22] Energy Security Board, Post 2025 Market Design Consultation Paper, September 2020, p40.

[23] Energy Security Board, Post 2025 Market Design Consultation Paper, September 2020, p73.

7.4 Missing markets are being investigated to provide financial reward for these services

In addition to the capacity and ahead markets being contemplated the post-2025 market design considers whether there are missing markets for essential system services. Missing markets mean service providers are not directly rewarded for the products or services they provide.

The NEM has historically been dominated by large thermal synchronous generation. Synchronous generation are large spinning machines that match the frequency of the grid and respond on command. When frequency deviates from a normal operating band, these large synchronous machines provide inertia through their rotational mass to resist and slow the deviation. They respond to signals sent by the market operator to restore frequency to an acceptable operating band. These same services are generally not provided by renewable generators and only partially supplied by inverter-based storage at this time. The physical properties of synchronous generation, which act to keep the electricity system operating securely have historically been in plentiful supply.

As thermal generation capacity retires, and the proportion of VRE increases, our ability to maintain operation of the system in a secure state diminishes. As renewable generation reaches significant proportions of total generation, for example in South Australia, these services need to be provided by other means, for example via synchronous condensers or from forcing gas-powered generators to operate even when there is sufficient renewable generation available.

Because there has historically been a reliable supply of these security related services (and in some states, there still is), the costs associated with maintaining the system in a secure operating state have not been reported and rewarded in the same way as other services in the NEM. The ESB has identified several essential system services that are not currently explicitly priced including fast frequency response, operating reserves, inertia and system strength.[24]

The post-2025 market design contemplates the form of procurement mechanisms and market arrangements required to keep the system in a secure and reliable operating state. Arrangements being explored include mechanisms to procure operating reserve through a spot market, arrangements to incentivise primary frequency response and support faster frequency response, a co-optimised inertia spot market or procuring and co-optimising faster frequency response.[25] These arrangements could support the important role played by synchronous generation, including gas-powered generation, in cost-effectively supporting renewable generation into the future.

24 Energy Security Board, Post 2025 Market Design Consultation Paper, September 2020, p33.

25 Energy Security Board, Post 2025 Market Design Consultation Paper, September 2020, p71.

A Modelling approach and outputs

Model structure and input assumptions

We developed a simplified model of the electricity system in South Australia to analyse the role of gas-powered generation in a 100% renewable (or close to) electricity system. It does not include the full functionality of a detailed dispatch simulation, such as the Frontier Economics *WHIRLYGIG* or *SYNC* models. For example, it does not reflect detailed operational constraints on thermal generation operation, interconnection across the NEM, or security based operational constraints. The model is a constrained linear optimisation model built using CPLEX. An overview of the model and key input assumptions is provided below.

Structure

- The model simulates calendar years 2030 and 2035 at the hourly level with full chronology. South Australia is modelled as an island system, with no interconnection to the rest of the NEM.
- Supply must match demand in each half hour period (or face a high penalty based on the Value of Customer Reliability). Supply includes existing wind and solar PV in South Australia, new build wind and PV, and new build fast start gas generation (in some scenarios). Discharge from large-scale battery and pumped hydro is added to supply and charging from the storages is added to demand.
- Storage state of charge levels are tracked through the year, and account for storage efficiency losses.
- The model has perfect foresight over demand and generation, including wind and PV output traces, so it can fully optimise. There is no uncertainty or margin for error built into the model. In practice, operating a system with a high proportion of renewable electricity generation would require some overbuild of storage capacity or energy to account for unexpected high demand or low generation. If a different output trace were applied with longer wind or solar "droughts" (with longer periods of low output) then more storage may be required, and conversely.

Demand

- Demand size and hourly shape is based on AEMO ISP 2020 operational trace for calendar years 2030 and 2035. This shape is net of rooftop PV generation and simple household storage operation. The impact of rooftop PV is to reduce midday/summer grid demand, though residential storage somewhat offsets this as it typically charges during the day.

Generation

- Generation is based on large-scale solar PV and wind generation, as well as fast-start gas generation in some scenarios.
- The model includes existing large-scale solar PV and wind in South Australia. The hourly output for these is based on AEMO ISP 2020 traces for the calendar years 2030 and 2035.
- The model co-optimises the development of new build solar PV and wind with storages (battery and pumped hydro) to minimise total system cost. For solar PV and wind, output is based on AEMO ISP 2020 traces for the calendar years 2030 and 2035. Output is based on a simple average of the solar PV and wind traces in each Renewable Energy Zone in South

Australia. The model may build wind and solar PV in whatever ratios are most efficient for the given scenario. We have made no adjustment for MLFs, for example for REZs away from demand centres.

- Costs are based on annuitised capital costs from the relevant year (2030 or 2050) taken from the AEMO ISP 2020 assumptions workbook, plus variable operating costs.
- Fast-start gas generation is included in some scenarios. Costs for gas are based on the annuitised capital cost for a new build Open Cycle Gas Turbine generator taken from the AEMO ISP 2020 assumptions workbook, as well as fuel costs, heat rate, and variable operating costs taken from the same source. Gas expansion and operation is co-optimised with renewable energy and storage build in the scenarios in which it is included.
- We have excluded concentrated solar thermal generation with salt storage from all scenarios. Cost estimates generally indicate that this is more expensive than alternative forms of renewable generation and storage.

Storage

- Storage options include batteries (2 and 4 hour) and pumped hydro (6, 12, 24 or 48 hour).
- The development of each storage option is co-optimised with new build generation of renewable energy to minimise system cost, so that the storage requirements are matched with the characteristics of the generation system.
- Costs and efficiency for batteries and pumped hydro are based on annuitised capital costs in the relevant year from the AEMO ISP 2020 workbook.
- Energy may be spilled if supply exceeds demand, including the charging and discharging of storages.
- The batteries and pumped hydro are required to end the year with at least the charge that they started the year with, so the system is in some kind of equilibrium.

Optimisation

- The model co-optimises the build of wind, solar PV, and gas generation (in some scenarios) with the build and operation of each type of energy storage (2 and 4 hour batteries and 6, 12, 24 and 48 hour pumped hydro storages) to minimise total system cost over the year.
- In each model run, there is necessarily some spare capacity in generation, storage, or both throughout the year. This results in spilled energy, and/or very low utilisation of storages in certain times of the year.
- The model co-optimises the build of generation and storage to trade-off between these based on the relative cost of building generation and storage.

Technology input assumptions

Table 3 and **Table 4** below provide a brief summary of the costs associated for each technology included in the modelling for 2030 and 2035 respectively. Note that this modelling exercise is not intended to estimate the cost of operating a 100% (or close to) renewable system, or market prices in such a system. The costs are used to direct the optimisation to a particular solution, based on efficient trade-offs between the relative costs of renewable generation, energy storage, and peaking gas dispatch.

Table 3: Summary technology input assumptions 2030

Technology	Annuitised capital cost – capacity ($/MW)	Variable costs ($/MWh)	Round trip efficiency (%)
Large wind	126.0	3.1	
Large solar PV	64.9	0	
Battery (2 hour)	78.9	0	81%
Battery (4 hour)	124.6	0	81%
Pumped hydro (6 hour)	164.9	0	80%
Pumped hydro (12 hour)	188.6	0	80%
Pumped hydro (24 hour)	242.4	0	80%
Pumped hydro (48 hour)	364.3	0	80%
Peaking gas	108.1	158.6	

Source: Frontier Economics based on AEMO ISP 2020 assumptions workbook and supporting documents

Table 4: Summary technology input assumptions 2035

Technology	Annuitised capital cost – capacity ($/MW)	Variable costs ($/MWh)	Round trip efficiency (%)
Large wind	119.3	3.1	
Large solar PV	57.8	0	
Battery (2 hour)	68.1	0	81%
Battery (4 hour)	107.5	0	81%
Pumped hydro (6 hour)	163.7	0	80%
Pumped hydro (12 hour)	187.3	0	80%
Pumped hydro (24 hour)	240.8	0	80%
Pumped hydro (48 hour)	361.8	0	80%
Peaking gas	107.3	161.3	

Source: Frontier Economics based on AEMO ISP 2020 assumptions workbook and supporting documents

Key results

We modelled the following core scenarios for 2030 and 2035:

5. 100% renewable; No gas.
6. At least 99% renewable; no more than 1% of generation from gas.
7. At least 95% renewable; no more than 5% of generation from gas.
8. Unconstrained (model optimised to find least cost proportion of renewables and gas).

Table 5 and **Table 6** provides a summary of key results for each scenario, for 2030 and 2035 respectively.

Table 5: Modelling results by scenario 2030

Scenario	Peak demand (MW)	Wind (MW)	PV (MW)	Gas (MW)	Battery (MW)	PH (MW)	Spill (% of demand)	System cost (indexed to 100)
1: 100% renewable	3,284	1,962	4,665	0	605	1,844	83%	100
2: 99% renewable	3,284	1,245	3,636	500	661	1,410	47%	80
3: 95% renewable	3,284	1,186	2,284	938	665	923	26%	72
4: Unconstrained (93% renewable)	3,284	1,056	2,130	1,020	642	852	22%	72

Source: Frontier Economics

We find that total system cost is the highest in Scenario 1, with 100% renewable electricity generation, and the lowest in Scenario 4, which doesn't constrain the amount of peaking gas generation in the system.

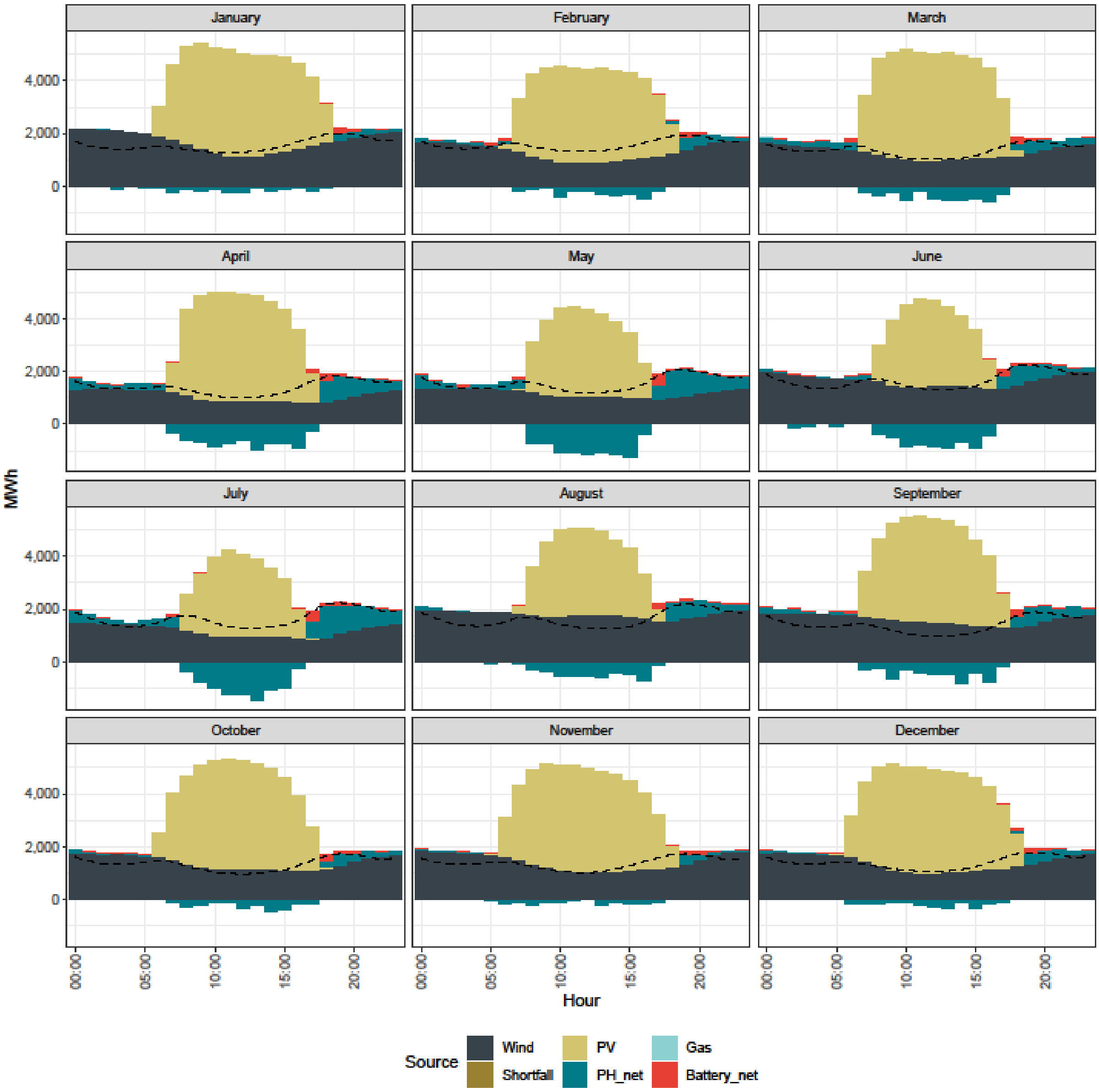
In the 100% renewable scenario, we find that the optimised outcome to match supply and demand for 2030 requires building 4,665MW of solar PV and 1,962MW of wind generation, supported by 2,449MW of storage. For the majority of the year, the generation from the solar PV is far in excess of demand. For almost every day of the, large quantities of energy are spilled, which cannot be stored in the batteries or pumped hydro. Over the course of the year, the total spilled energy is over 80% of system demand.

In a 100% renewable system, the requirement to build electricity generation and storage is defined by the period of the year with the lowest output from renewable generation. This period can differ from year to year. In some years, it may be a short period of one or two days in which generation from both solar PV and wind is much lower than average. In other years, it could be an extended 'drought' that is less dramatic, but lasts for a longer period of weeks or months. A fully renewable system which is built for these limits will have considerable spare capacity of energy, storage, or both during the remainder of the year.

AEMO forecasts wind and solar PV capital costs to fall steadily over the coming years, without a corresponding fall in storage capital costs. We typically find that it is relatively cheaper to overbuild on generation than storage, which results in the high levels of spilled energy.

Figure 13 presents the daily average generation from solar PV and wind in Scenario 1, as well as storage charging and discharging. Each panel represents average outcomes over a month, starting and ending at midnight on each side. The dotted line represents average demand.

Figure 13: Average daily generation and load: Scenario 1 (100% renewable) in 2030



Source: Frontier Economics modelling

As outlined above, the chart shows that average generation is typically well above demand, particularly during the period in which solar PV generates. Some of this is stored in batteries or pumped hydro, and discharged in the evening peak demand period after solar PV has stopped generating.

There are no particularly bad wind droughts in the AEMO traces during 2030. During the periods of low wind generation, solar can typically be relied upon to recharge storages, which cycle through charging and discharging periods as required.

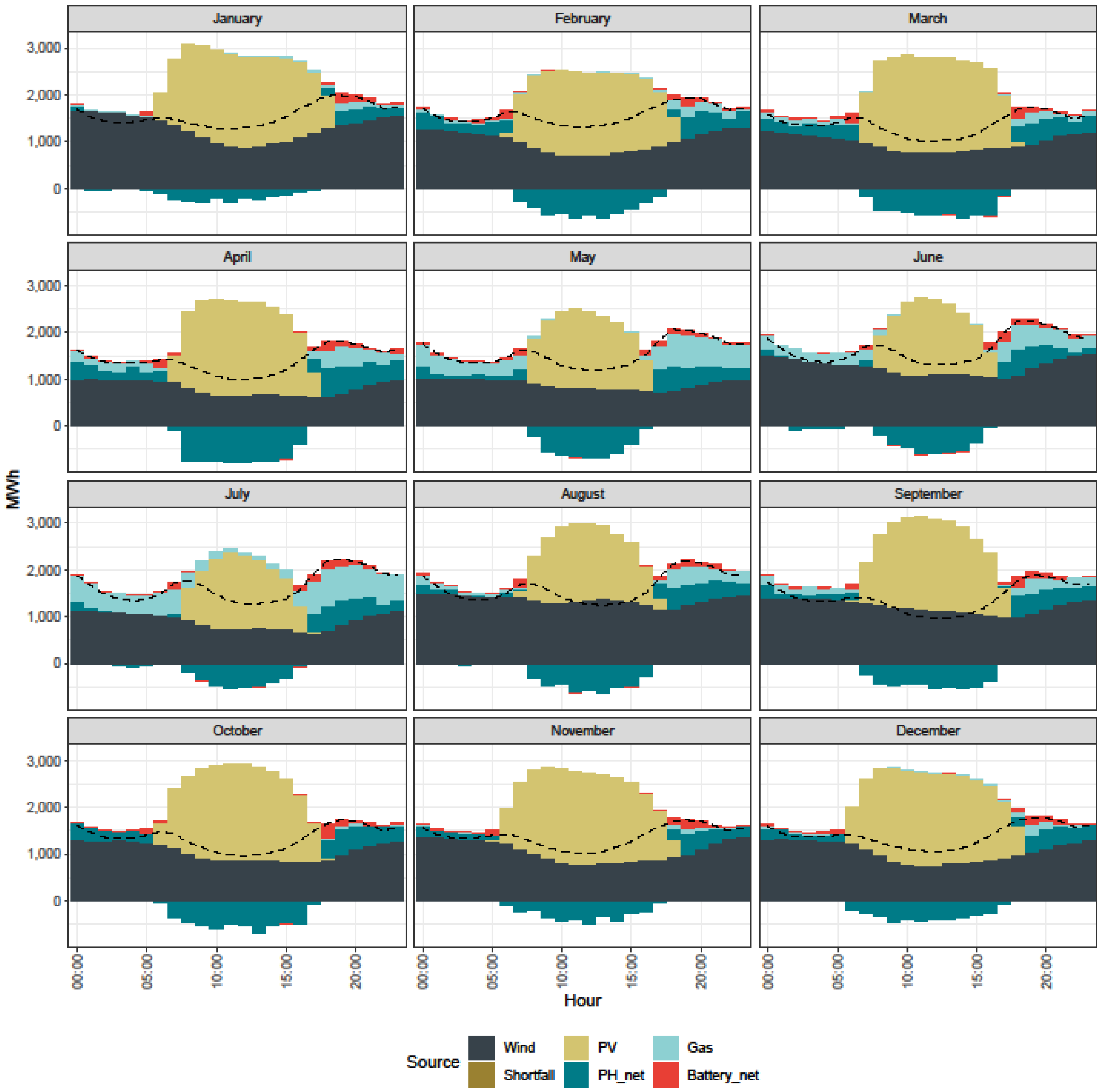
In the unconstrained scenario, the required renewable energy capacity is about half of the 100% renewable scenario and the required energy storage capacity is about 40% lower, particularly for the longer pumped hydro storages. However, there is an additional 1,020MW of peaking gas capacity.

The gas generation plays a limited role in the system. In most days, it is not required, and on others plays a targeted role in supporting the system through peak demand or days of low generation. Overall, gas makes up only 7% of the system generation, but improves system efficiency considerably.

It removes much of the requirement to overbuild on solar PV and reduces the spilled energy to approximately 22% of demand. This considerably reduces overall system cost. There are similar findings in Scenario 3, in which gas generation is limited to 5% of total generation output.

The daily average generation from solar PV, wind, and gas, and storage charge and discharge is presented in **Figure 14** below.

Figure 14: Average daily generation and load: Scenario 4 (unconstrained, 93% renewable) in 2030



Source: Frontier Economics modelling

The model results are somewhat specific to the year being modelling. The optimal mix of each type of generation and storage depends on the forecast AEMO traces of demand and renewable output for each year. We modelled the same outcomes for 2035 which includes a more prolonged period of low wind generation throughout May and June.

The results for 2030 are presented in **Table 6** below.

Table 6: Modelling results by scenario 2035

Scenario	Peak demand (MW)	Wind (MW)	PV (MW)	Gas (MW)	Battery (MW)	PH (MW)	Spill (% of demand)	System cost (indexed to 100)
1: 100% renewable	3,313	0	9,455	0	2,485	2,116	118%	100
2: 99% renewable	3,313	1,304	5,251	606	1,301	1,247	75%	77
3: 95% renewable	3,313	770	3,519	993	1,252	752	35%	65
4: Unconstrained (93% renewable)	3,313	786	2,933	1,077	1,188	719	27%	64

Source: Frontier Economics

Many of the findings for 2035 are the same as for 2030. Overall, the 100% renewable scenario requires considerable renewable generation and storage capacity. There is considerable spilled energy, in this case over 100% of spilled demand. If gas generation is allowed to play a supporting role in the system, the cost-effectiveness of generation and storage is much improved. However, some findings are particular to the generation and demand traces in 2035, and the differences to 2030.

As outlined above, the AEMO traces for 2035 are characterised by an extended period of low wind generation throughout May and June. In the 100% renewable scenario, the optimal system does not have any wind generation. To manage the May and June wind drought, it is necessary to build vast amounts of solar PV capacity and energy storage. Building additional wind would have little use in these months. The very high entry of solar PV and storage are sufficient to match supply and demand in the other months of the year as well, so no wind is built. However, almost all of this solar PV generation is surplus to requirement in other months, causing a very high proportion of spilled energy and high system cost.

If even a small amount of gas generation is allowed in these months (such as in Scenario 2), it cuts down considerably on the requirement to overbuild on solar PV and energy storage to make it through the most challenging months.

Qualifications

There are several features of this model that are important to keep in mind when considering the implications for the role of gas-powered generation in the transition to a renewable energy system. In general, the results of the modelling should be interpreted as indicative and directional due to the simplifications involved in the modelling.

Firstly, it is an optimisation model with perfect foresight. This means that the model can (and will) drive storages down to empty during resource droughts, knowing that output will pick up on a particular day and supply will continue to meet demand. There is no spare capacity built in, nor is there a risk tolerance built into the operation of gas generators or storages. In reality, foresight of renewable generation to this precision is impossible, and it would not be possible to operate storages in this manner.

Secondly, each model run is based on a single year of output and demand traces from AEMO. The storage requirements are built to manage the worst resource drought in the modelled year (with perfect foresight as to when it may end). In practice, storages must be built for a range of conditions, including a 'one in x years' expected resource drought. AEMO has data on historical output from a number of existing wind farms in South Australia, however it is limited by the age of each wind farm. There may be rare generation events based on unusual weather patterns which are yet to be observed in the data. The output for new wind and solar generation from Renewable Energy Zones is particularly uncertain as there is no historic data on generation for those areas, and it must be inferred based on historic weather patterns and observed relationships between weather and electricity generation. It remains unclear whether the AEMO traces capture a full range of outcomes that may be expected to occur over the long term. This may not be known until such outcomes occur.

Third, this model does not account for interconnection with other regions. Typically, this would be expected to reduce storage and generation requirements – as energy may be traded across regions. Depending on resource diversity, this may provide additional security as well as reducing spill energy. However, it is important to consider resource diversity during the periods of resource drought that most test the system. The correlation between renewable output across the NEM, particularly the timing of resource droughts in neighbouring states will be an important factor. Where the model builds excess solar PV, this is unlikely to have much value in an interconnected system due to the high correlation between solar PV generation in each region.

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