Dispatchable energy generation and storage capability

Andrew Blakers

The Australian National University, Canberra, Australia

5th May 2021

The House of Representatives Standing Committee on the Environment and Energy inquiry into the current circumstances, and the future need and potential for dispatchable energy generation and storage capability in Australia.

Summary

1. Balancing high levels of variable PV and wind is straightforward using off-the-shelf techniques: stronger long distance transmission (to smooth out variable local weather), storage (pumped hydro and batteries) and demand management.
2. Solar and wind constitute 99% of new generation capacity in Australia.
3. Australia is the global pathfinder in deployment of variable solar and wind and the real-world cost of balancing.
4. **Australia has declining electricity emissions AND declining electricity prices.** This means that deep emissions reductions will have low or negative cost.
5. Investment in new balancing infrastructure is predominantly in pumped hydro (without new dams on rivers), batteries, demand management and transmission. This is both necessary and sufficient to balance 100% renewables at low cost.
6. The National Electricity Market and South Australia have reached combined solar and wind energy penetrations of 24% and 70% respectively and are tracking towards 40% and 100% respectively in 2024-25.
7. The current (2021) and market futures (2024) spot price for electricity in the NEM and South Australia is about AUD$40 per Megawatt-hour. This suggests that the balancing cost of high levels of solar and wind is low.
8. Detailed hourly modelling demonstrates that the cost of balancing 100% renewables is low: here and here.
9. Strongly connecting Perth and Far North Queensland to the southeast via High Voltage DC reduces electricity prices. Such a project would contribute to nation building.
10. Declining (legacy) coal and gas can help balance renewables – but is unnecessary.
11. Gas generates only 5% of electricity in the National Electricity Market and is declining
12. ***Stronger interstate transmission is the most important near-term requirement.***

Short CV: *Andrew Blakers is Professor of Engineering at the Australian National University. He founded the solar PV research group at ANU in 1991. In the 1980s and 1990s he was responsible for silicon solar cells with world record reported efficiencies of 18%, 19%, 20% and 22%. He was lead co-inventor of the PERC silicon solar cell, which has 90% of the global solar market and cumulative module sales of $90 billion. PERC cell deployment is mitigating 0.8% of global Greenhouse gas emissions through displacement of coal (and will go much higher). Prof Blakers engages in analysis of energy systems with 50-100% penetration by wind and photovoltaics for which he was co-winner of the 2018 Eureka Prize for Environmental Research. Prof Blakers' team developed a comprehensive global atlas of off-river pumped hydro energy storage sites.*

Terms of reference

https://www.aph.gov.au/Parliamentary_Business/Committees/House/Environment_and_Energy/DispatchableEnergy/Terms_of_Reference

- *a. current and future needs*
- *b. issues related to system integration, connection, and grid transmission requirements*
- *c. existing, new and emerging technologies*
- *d. comparative efficiency, cost, timeliness of development and delivery, and other features of various technologies*
- *e. applications to various scales and forms of end-use such as households, industry, and transport*
- *f. Australia's research and innovation development framework and policies*
- *g. opportunities for Australia to grow and export dispatchable zero-emission power; and*
- *h. other relevant matters, including reference to international examples.*

Policy recommendations

- consistent with 50% emissions reduction by 2030 (on 2005 levels) to match the USA target
- consistent with a stable electricity grid

1. Target 14 Gigawatts per year of new solar and wind to match the US emissions commitment
2. Strongly encourage electric vehicles; most new vehicle sales should be electric by 2027
3. Strongly encourage heat pumps and electric furnaces in place of gas for heating
4. Establish a National Transmission Network (NTN, by analogy with the NBN)
5. Strongly connect Perth and Far North Queensland to the southeast via High Voltage DC

Stronger transmission is urgently needed to bring new solar and wind power to the cities. An effective way to do this is to upgrade transmission lines from rural Renewable Energy Zones to the cities.

Solar and wind are absolutely dominant in capacity construction markets

In 2020, solar photovoltaics (PV) and wind power comprised about three quarters of net global capacity additions (Figure 1). New solar and wind capacity was 10 times larger than net new hydro and coal capacity and 100 times larger than net new nuclear, carbon capture & storage, bioenergy, geothermal, solar thermal and ocean energy generation capacity. Arguably, the fastest change in global energy systems in history is underway.

Extravagant deployment growth rates are required for other low-emission technologies to catch solar and wind. Other low emission generation technologies can supplement solar and wind, but solar and wind must do the heavy lifting.

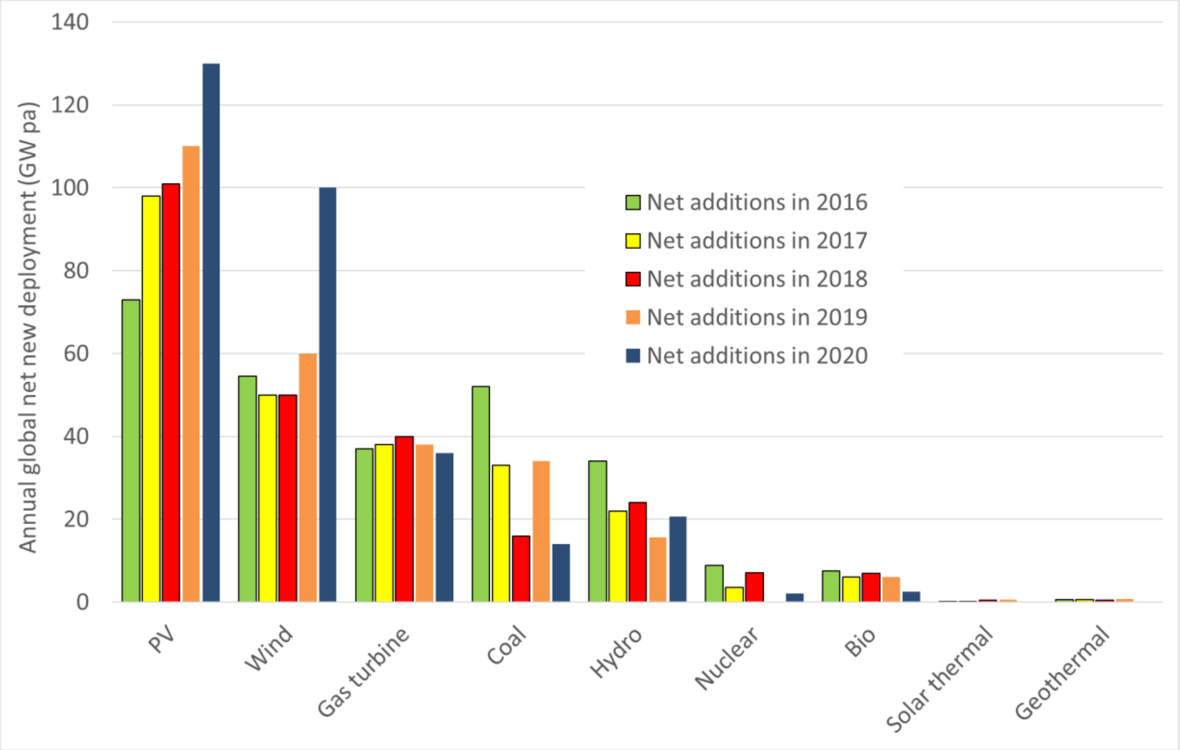

Figure 1: Solar and wind comprise three quarters of global net annual capacity additions. [Sources](#).

New solar and wind power capacity is being deployed in Australia three times faster per capita than in China and the USA, and ten times faster than the global average (Figure 2). Australia has the most existing solar capacity deployed per capita.

Australia is the global pathfinder in deployment of variable renewables and the real-world cost of balancing. Australia is an industrialised, middle-ranking, physically isolated country with little hydro, a functioning electricity market, and globally-leading per-capita solar and wind deployment.

About 18 Gigawatts (GW) of new solar and wind was deployed in Australia (population of 25 million) over the 3-year period 2018-2020, amounting to 250 Watts per person per year. In 2020, about 7 Gigawatts (GW) of new rooftop solar (3 GW) and new solar and wind farms (4 GW) were accredited with the Government's Clean Energy Regulator.

There is negligible investment in generation technologies other than solar and wind.

Continued rapid deployment of solar and wind is likely because of the compelling economic advantage of solar and wind due to low and falling prices.

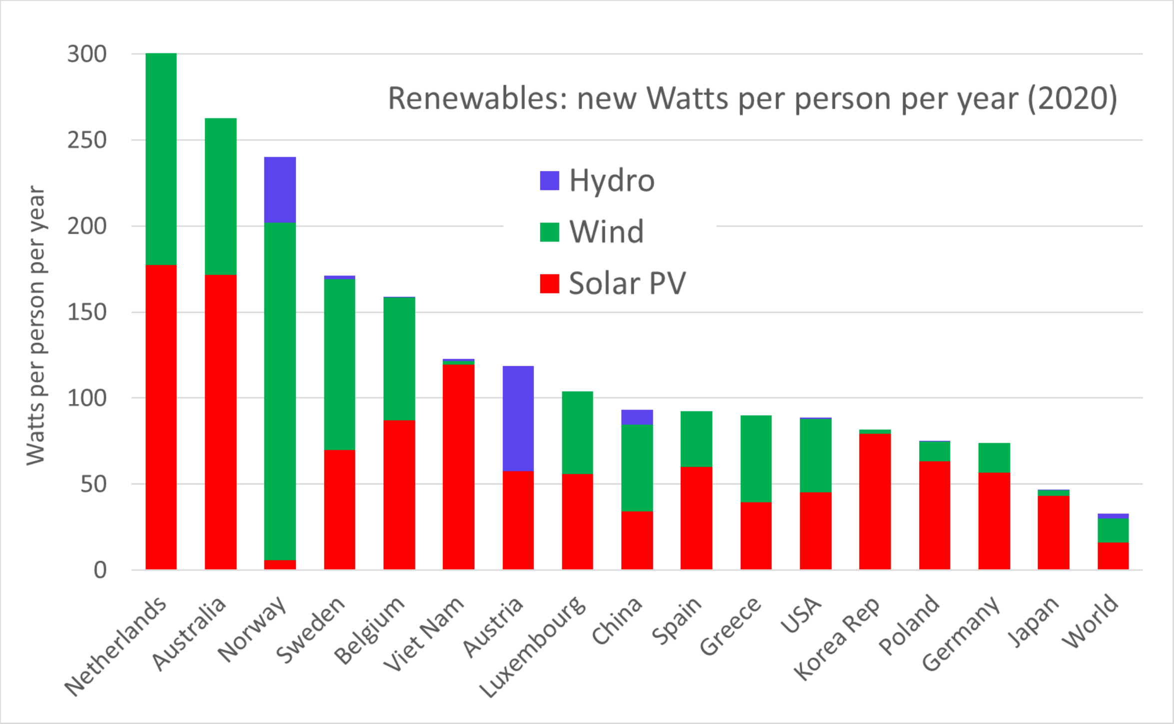

Figure 2: Per capita renewable capacity deployment rates (Watts per person per year)

Methods of balancing solar and wind

Supply of electricity must be balanced with demand for nearly every second of the year to meet reliability benchmarks. Methods of balancing variable solar and wind output at large scale comprise:

- Energy storage (mostly pumped hydro and batteries)
- Load-following fossil fuel power stations
- Hydroelectricity
- Strong interconnection between states
- Demand management
- Legacy coal & gas (while still available)

In practice, a combination of several methods is optimum.

The inclusion of both solar and wind is desirable because it adds to generation diversity. A combination is particularly valuable if the outputs of solar and wind generators are only weakly correlated or if the wind blows consistently at night or in winter.

Legacy fossil fuel power stations can contribute to balancing. However, the cost of holding a power station in readiness for occasional use is significant. Fossil gas fuelled power stations have fast response time (tens of minutes). Many coal power stations can follow the load in the range 50-100% of their nominal capacity, particularly if the load is predictable such as morning and evening demand peaks.

Hydroelectric power stations can generally respond quickly (minutes). They have varying amounts of energy stored as water in reservoirs. Regions with large amounts of hydro energy storage per capita can readily accommodate large fractions of solar and wind in the electricity grid.

Strong transmission interconnection within regions spanning tens of millions of hectares greatly reduces the required amount of energy storage because variations in solar, wind and demand can be moderated by averaging over large areas.

Demand management is already widely practiced. For example, time of use tariffs can ameliorate evening peak periods. On a different timescale, if an occasional wet windless week in winter causes supply stress in a solar/wind dominated electricity grid, then some factories can volunteer to be paid to shut down for those weeks. This could be more cost effective than holding large amounts of energy in storage for months or years.

Large-scale storage of excess solar and wind energy can be accomplished using many methods including pumped hydro, batteries (in electric vehicles, in buildings and at utility scale) and thermal stores in cities (e.g., molten salt stores in a factory, underground pebble beds, hot water in a tank, sensible heat in the building fabric, ice).

Off-river pumped hydro energy storage

Pumped hydro energy storage constitutes 95% of global storage power and 99% of global storage energy. It is by far the most mature and lowest cost storage technology for periods of more than a few hours. However, river-based pumped hydro is constrained by geographical availability, environmental and social factors.

An off-river pumped hydro system comprises a pair of reservoirs located away from any river and spaced several kilometres apart with an altitude difference (head) of 200-800 m and connected with pipes or tunnels. The reservoirs can be specially constructed or can utilise old mining sites or existing reservoirs. A pair of 100 Ha reservoirs with a head of 600 m, an average depth of 20 m, a usable fraction of water of 90% and a round trip efficiency of 80% can store 18 Gigalitres of water with energy potential of 24 GWh, which means that it could operate at a power of 1 GW for 24 hours. New dams on rivers and bespoke engineering in remote river valleys are avoided, and minimal provision needs to be made for flood control. Very little land and water is required: about 3 m^2 per person and 3 litres per person a per day respectively to support a 100% renewable electricity system.

The global pumped hydro storage atlas lists 616,000 sites (Figure 3) with an enormous 23 million Gigawatt-hours of combined storage. The capital cost of a Gigawatt-rated off-river pumped hydro storage system with 24 hours of storage in a good site is A$1.5-2.5 billion for a system that has a working lifetime of 50-100 years and low operating costs. This is far below the cost of an equivalent battery.

Pumped hydro energy storage and batteries complement each other.

Figure 3a: 616,000 potential off-river PHES sites with combined storage potential of 23 million Gigawatt-hours. Data61 hosting and Bing Map background.

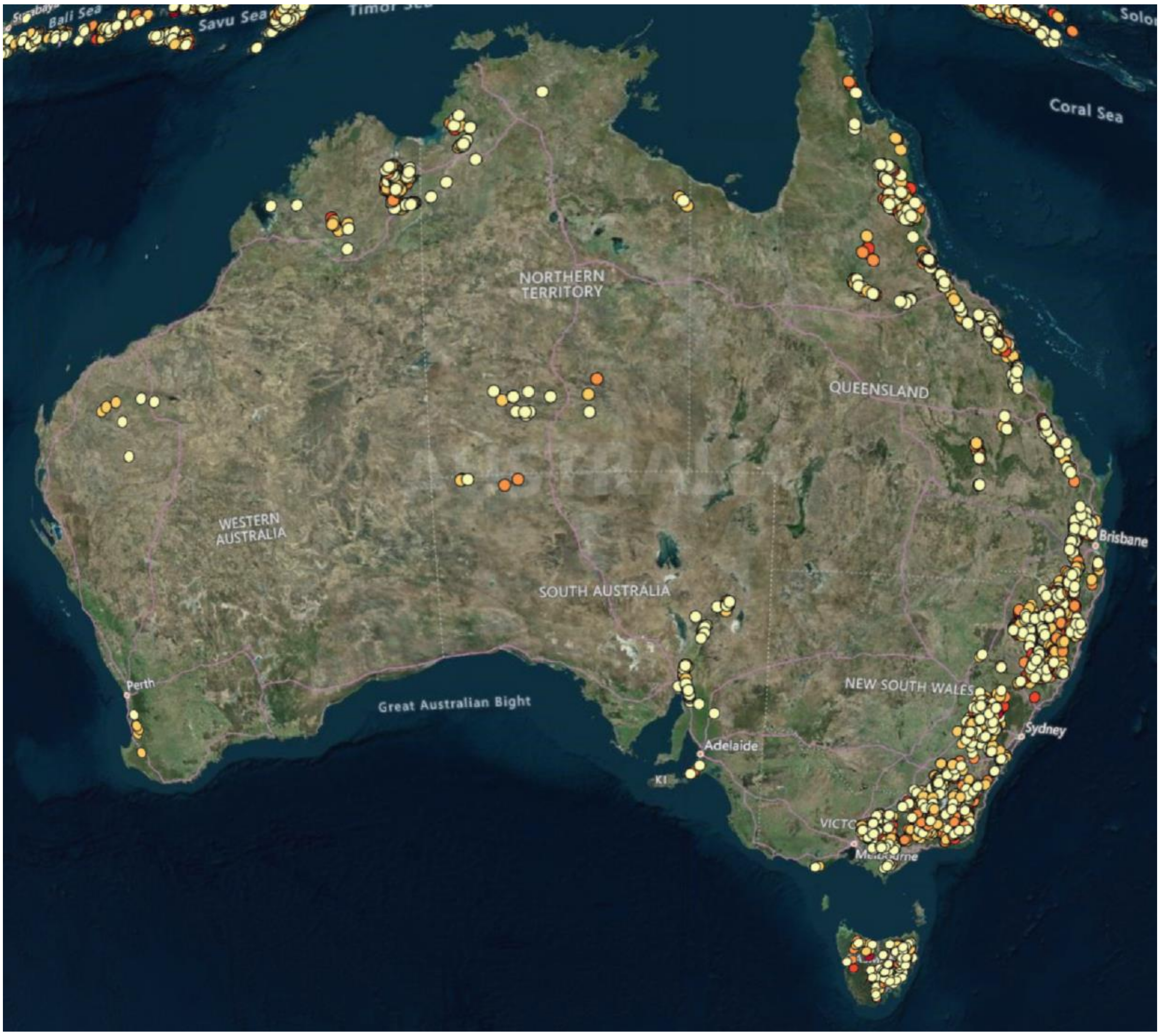

Figure 3b: 4,000 potential off-river PHES sites. Data61 hosting and Bing Map background.

The Australian electricity system

Australia is located in the latitude range 10-43 degrees south with relatively high levels of solar and wind deployment and a replicable balancing infrastructure response. Since Australia lies at moderate latitudes, only mountainous areas experience cold winters. The population-weighted solar seasonality (summer:winter) is 2:1. Substantial seasonal storage is not required in Australia, nor for most of the world's population (who live at low-moderate latitudes).

Australia is a large exporter of coal and liquified natural gas. Despite this, all eight State and Territory governments have committed themselves to reach zero emissions in 2050, and the Federal Government may make a similar undertaking. Because of the low cost of solar and wind generated electricity, several State Governments have ambitious goals to achieve 200-500 percent renewable energy through export of Australian renewable energy as energy-rich chemicals or by underwater high voltage transmission links.

Most of the Australian population lives along the eastern and south eastern coasts within 200 km of the sea. Most of the interior is arid and has low population density. Australia has a population of 25 million and an advanced economy with per capita electricity consumption of 10 MWh per year. Australia has good solar and wind resources in most regions.

The Australian electricity system comprises one large and isolated grid along the east and southeast coasts called the National Electricity Market (NEM) which services 80% of the national load, and several isolated smaller grids. The NEM has high reliability standards that are rarely breached.

Annual electricity consumption in the NEM is about 200 Terawatt-hours (TWh). Demand for electricity in 2020 was similar to previous years despite the impact of Covid-19. Table 1 shows the sources of electricity in the NEM states in 2020 together with the average wholesale spot price. Notably, Tasmania (99% hydro and wind electricity) and South Australia (59% solar and wind electricity) had average wholesale spot prices in 2020 that were below average.

Table 1: Technology share of demand and wholesale spot price in the NEM states in 2020

Year 2020	Tasmania	South Australia	Victoria	New South Wales	Queensland	NEM
Population (M)	0.5	1.7	6.4	7.5	5.1	20
Solar PV	2%	17%	8%	8%	13%	10%
Wind	14%	42%	14%	6%	2%	10%
Hydro	83%	-	5%	3%	1%	7%
Gas	1%	42%	3%	2%	11%	7%
Coal	-	-	74%	73%	80%	66%
Imports	12%	7%	3%	8%	-	-
Exports	12%	8%	7%	0%	7%	-
Renewables share	99%	59%	27%	18%	16%	26%
Price $/MWh	43	43	61	68	43	55

Deployment of solar and wind in the NEM is causing a rising share of renewable electricity (Figure 4). In figures 4 and 5, the shaded region is a linear projection of current trends, which means that generation in a future month is the same as in the corresponding preceding month but augmented by the change in generation in the preceding 12 months.

Currently, about 30% of NEM electricity comes from renewables (about 12% each of solar and wind and 6% from hydro). Black coal, brown coal (lignite) and fossil gas provides the balance. Renewable generation regularly exceeds 50% during the day. This will be quickly surpassed because deployment of solar and wind continues apace.

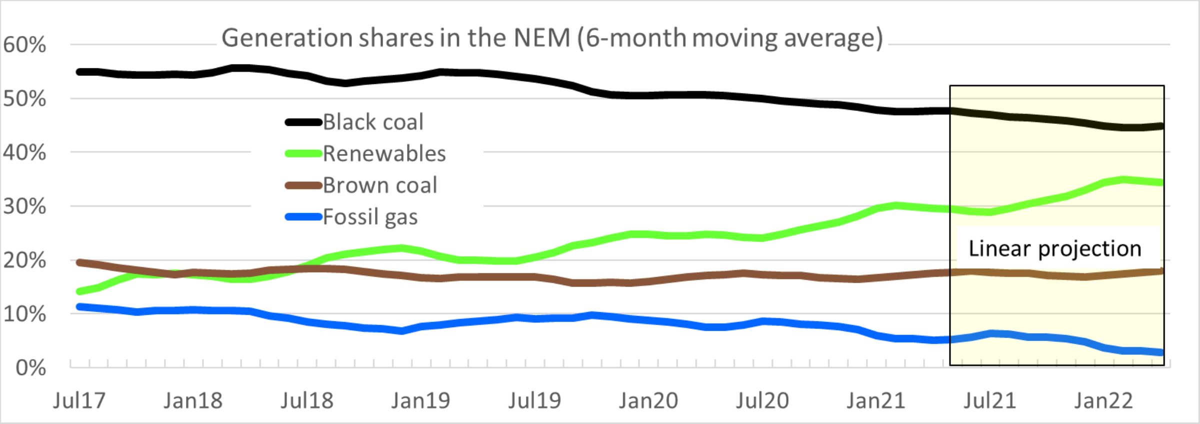

Figure 4: Generation shares in the NEM (6-month moving average). The shaded region is a linear projection of current trends.

The state of South Australia has a population of 1.7 million people. South Australia has reached 70% of its electricity from wind and solar (6-month moving average, Figure 5). The balance is generated from fossil gas with a small fraction (~1%) of net imports/exports. South Australia has no hydroelectric, coal, bio or nuclear generation. Recently, South Australia derived more than 100% of its electricity load from each of solar alone and wind alone for one hour. Combined, solar and wind regularly exceed 100% of the load for whole calendar days (midnight to midnight) with the excess being exported to other states. These landmarks will be quickly surpassed because deployment of solar and wind continues apace.

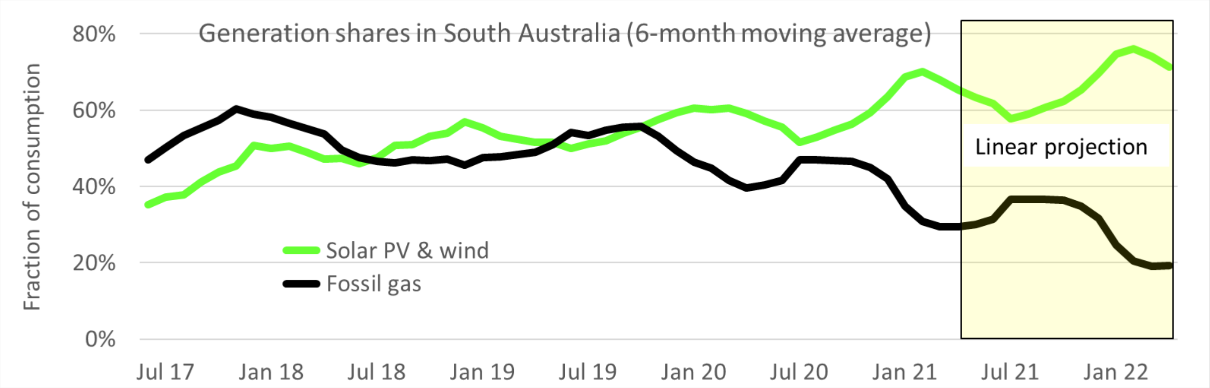

Figure 5: solar and wind energy generation fractions in South Australia (6-month moving average). The shaded region is a linear projection of current trends.

South Australia is part of the NEM but is relatively weakly connected to other states. Transmission capacity to and from other states amounts to about 0.9 GW from the combined Heywood and Murraylink interconnectors compared with average and peak demand of 1.6 GW and 3.2 GW respectively. In 2020, exports of electricity to neighbouring states were 8% and were nearly balanced by imports (7%). South Australia hosts about 0.3 GW of batteries with about one hour of storage, and this is expected to rapidly increase. Shortfalls in solar and wind generation are met using batteries, fossil gas generators and imported electricity.

Note the low and declining share of generation from fossil gas (around 5% in the NEM and falling).

Future deployment of solar and wind

The Clean Energy Regulator (CER) an Australian Commonwealth Government Agency charged with administering several clean energy, emissions reduction and greenhouse gas reporting programs. It tracks financial close announcements for utility scale wind and solar power stations and is privy to some confidential data information from companies considering construction of new solar and windfarms; and hence is well-placed to forecast future solar and wind farm deployment. The CER expects 6 GW or more per annum of new solar and wind to be added in each of 2021 and 2022. This adds to the 18 GW installed over 2018-2020. Multi-stage GW-rated solar and wind farms which benefit from economies of scale are now reaching financial close. Growing markets include mining precincts, industrial users “behind the meter” and rooftop solar. Many companies are investing in solar and wind generation for green credentials and for price certainty.

The declining cost of solar and wind encourages their increasing deployment. The increasing penetration of solar and wind decreases the capacity factor of some existing fossil fuel power stations, which may trigger their premature retirement, opening additional space for solar and wind.

A critical constraint is the need for additional transmission to bring the new utility-scale solar and wind power to the cities.

Most State Governments are supporting renewable energy investment through facilitation of infrastructure such as new transmission and purchase of renewable electricity to meet their own electricity needs. The State Governments recognise that large-scale deployments of solar, wind, storage and transmission occur in rural areas and supports local communities.

A continuation of trends in the NEM and in South Australia (strongly indicated by CER data) suggests that they are tracking towards 40% and 100% respectively of combined solar and wind generation in 2024.

Transmission

The NEM transmission system was constructed over many decades to service a predominantly coal-fired electricity system and is complemented by the lower voltage distribution system. The transmission system links major coal generators (located near coal fields) with the cities and with significant regional loads. Additionally, the five NEM states are interconnected, although relatively weakly compared with peak loads.

Major augmentation of the transmission system is required to cope with rising penetration of solar and wind because good sites for solar and wind farms are generally not co-located with coal power stations which current transmission primarily services. This includes stronger interstate interconnection for geographical smoothing of supply and demand, and interconnection of cities with Renewable Energy Zones (REZ). A REZ is a region with favourable characteristics such as good solar, wind and off-river pumped hydro resources, proximity to loads, and adequate access to existing or new transmission. Connection of a REZ to the transmission system is analogous to the connection of a new fossil fuel generator.

Large-scale storage is substantially equivalent to transmission augmentation by allowing higher utilisation of existing transmission (for example, transmission of stored solar energy to the cities at night-time).

In the past, most of the cost of the transmission system was borne by customers rather than generators and was not reflected in the electricity spot price. This may change in the future as electricity market rules evolve. In its 2020 Integrated System Plan, AEMO estimated the transmission cost for 28 actual and potential REZs in the NEM, and most were in the range $5-15/MWh.

Balancing infrastructure

Australia is tracking towards high levels of solar and wind, causing significant challenges for grid management. These include loss of mechanical inertia when coal power plants retire; low net demand in the middle of sunny days due to rooftop solar generation; difficulties meeting summer afternoon air conditioning peak loads after the sun sets; and the need to meet demand during wet windless weeks in winter. The speed of change is much higher than electricity systems generally experience. However, grid regulators and companies are finding solutions to these problems “on the fly”, technical and market rules and regulations are slowly being reformed, and investment in new balancing infrastructure is starting to occur.

New balancing infrastructure comprises Gigawatt-scale pumped hydro energy storage, batteries and new transmission as shown in Table 2. Additionally, black coal power stations and fossil gas generators contribute by load-following. Since solar and wind continue to increase and fossil fuel power stations continue to retire, more storage and transmission will be required in the future.

Demand management will also become more important. Other methods of storage such as thermal storage in factories and power-to-gas have not yet become significant.

In Australia there are 4000 higher quality potential off-river pumped hydro sites with combined energy storage of 180 TWh, which is about 300 times more than required to support 100% renewable electricity. Most of these sites are near populated regions. Australia has three operating pumped hydro facilities, two under construction and a dozen proposals under serious consideration. Some take advantage of existing reservoirs and mining pits, and others are entirely greenfield. None involve new dams or significant disturbance of rivers.

Table 2: New balancing infrastructure

	Technology	**Power (GW)**	**Energy (GWh)**	**Comments**
Tumut 3	Pumped hydro	0.6/1.8	60	Existing
Kangaroo Valley	Pumped hydro	0.2	<1	Existing
Wivenhoe	Pumped hydro	0.6	6	Existing
Snowy 2.0	Pumped hydro	2.0	350	Under construction
Kidston	Pumped hydro	0.3	2	Under construction
Battery of the Nation	Pumped hydro	0.6-2.5	6-25	Detailed planning
Oven Mountain	Pumped hydro	0.6	7	Detailed planning
Yetholme	Pumped hydro	0.3	3	Detailed planning
Baroota, Cultana, Dungowan, Fassifern, Highbury, Goat Hill, Kanmantoo, Middleback Ranges and others	Pumped hydro	0.1-0.4 each	1-2 each	Feasibility studies and detailed planning
Utility combined	Batteries	2.0	2	Existing, planned
Household combined	Batteries	-	1	Existing
EV combined	Batteries	-	1	Existing
Marinus Link	Transmission	1.5	-	Detailed planning
EnergyConnect	Transmission	0.8	-	Detailed planning
HumeLink, QNI, VNI, VNI-West, Central-West Orana REZ, Snowy 2.0 connection and others	Transmission		-	Feasibility studies and detailed planning

Utility batteries are becoming important for storage power (typically tens to hundreds of Megawatts with one hour of storage). Battery scale and cost are rapidly improving and are cost effective for storage from seconds to hours. Batteries are out-competing fossil gas generators for a range of ancillary services, as illustrated by declining gas usage in Figure 4. They provide faster, more reliable and more accurate response to disturbances of frequency and voltage in the grid than fossil gas generators. Batteries also allow solar and wind farms to better manage exports of energy to the grid when transmission capacity is constrained.

To provide a sense of scale, the modelled additional storage requirement to support 100% renewable electricity in the NEM is about 500 GWh of storage energy volume and 20 GW of storage power. This energy balance modelling had hourly resolution and was undertaken using historical data for wind, sun and demand for every hour of the years 2006–2010.

Figure 6 illustrates modelled levelized cost of balancing solar and wind in the National Electricity Market. The cost is divided approximately evenly between new storage, new transmission and curtailment. The cost is low for penetration of less than 75% but rises significantly as penetration approaches 100%. In the modelling, all new storage was assumed to be pumped hydro for which reasonably reliable costings are available. If batteries and other forms of storage decline below the cost of pumped hydro in the future, then the cost of balancing will be lower than modelled. Thus, Figure 6 represents an upper bound on balancing cost in the NEM.

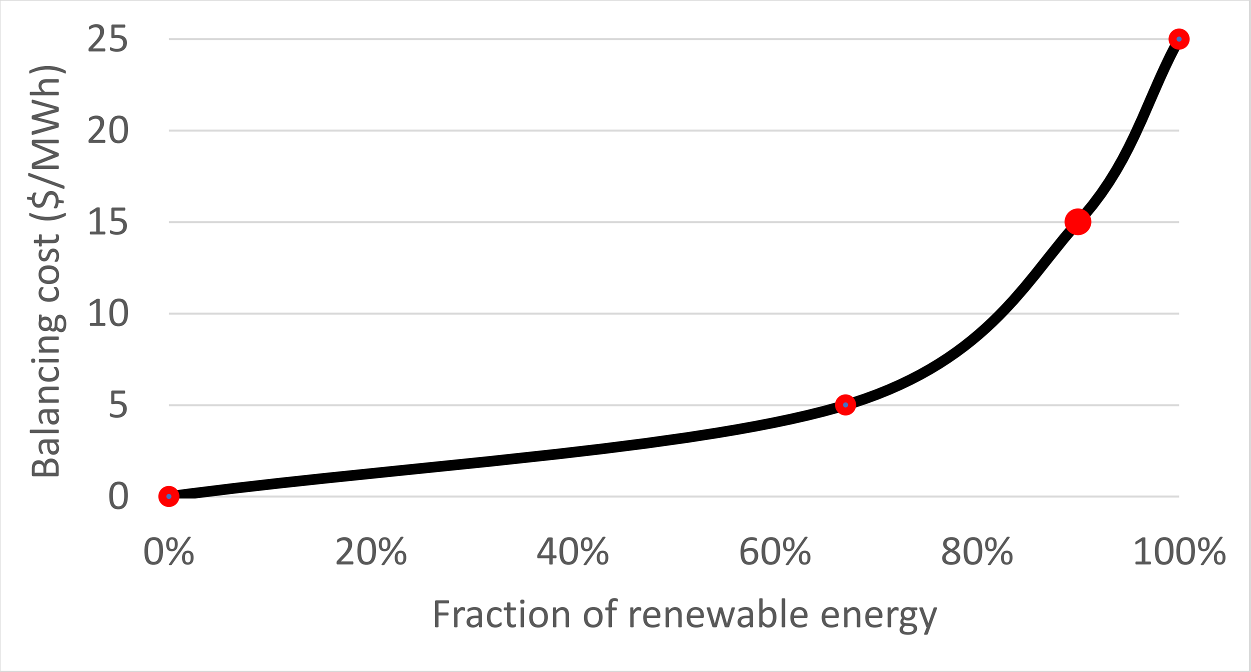

Figure 6: Levelised cost of balancing solar and wind ($/MWh) in the Australian National Electricity Market as a function of renewable energy penetration

Falling electricity prices

The cost of generating, storing and curtailing electricity production (including residual subsidies) in the NEM is internalised. There is negligible Government financial support for the electricity system and there is no connection to other electricity systems.

A great deal of experience is being gained in managing high levels of solar and wind. In South Australia, solar and wind generated more than 90% and 100% of the total load for 37 and 5 calendar days (24-hour periods) respectively in 2020. solar and wind produced more than 80% of the load for five discrete 7-day periods. This demonstrates an ability to manage high levels of solar and wind over lengthy periods.

Figure 7 illustrates wholesale spot prices in the NEM. They averaged $85/MWh over 2016-20 but averaged $41/MWh from the second quarter of 2020 coincident with large amounts of new solar and wind entering the market. The effect of COVID on demand was small since electricity consumption varied by less than 1% from preceding years.

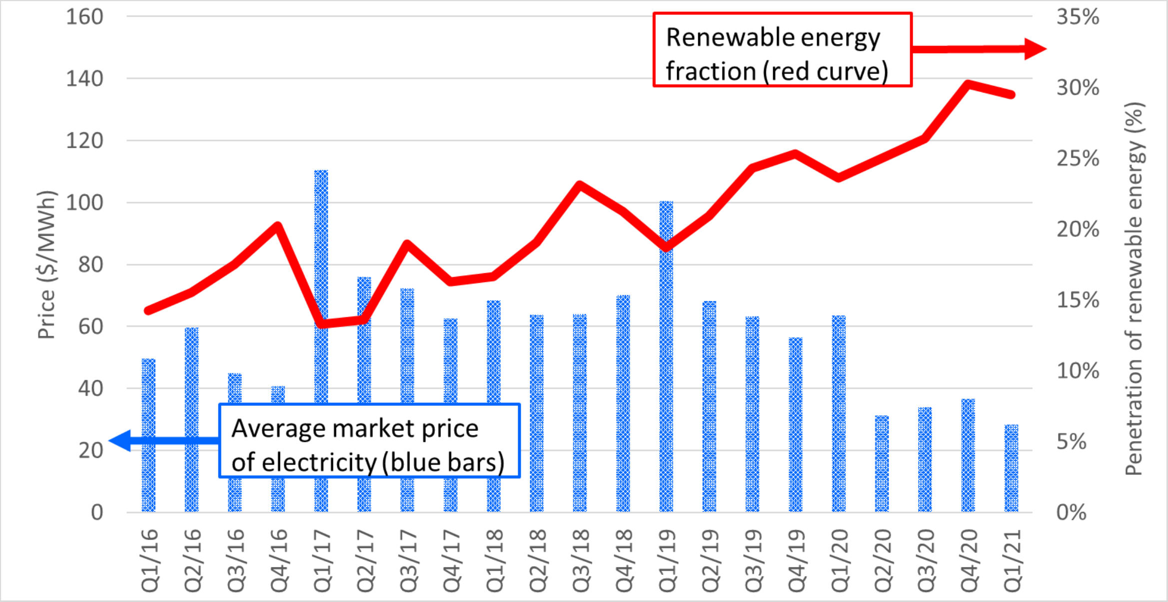

Figure 7: Average NEM quarterly wholesale spot price (blue bars, left land axis, $/MWh) and renewable energy fraction (red curve, right hand axis)

This low price means that the cost of balancing has not caused rising prices. The futures market for supply of electricity in the NEM suggests that prices will vary little in each NEM state over the period 2021 to 2024. During this period, the combined solar and wind energy fractions in the NEM and South Australia are tracking towards 40% and 100% respectively. Futures markets take into account that solar and wind prices continue to fall, that subsidies to solar and wind are falling to low levels, that coal fired power stations will continue to close and the expectation that solar and wind will continue to be deployed at similar rates to the present (6-7 GW per year). These prices are evidently sufficient inducement for companies to continue to invest in new solar and wind farms.

The cost of balancing solar and wind increases as their penetration increases. On the other hand, the cost of solar and wind generation continues to fall due to technology and manufacturing improvements. According to Figure 6, the cost of balancing in the NEM and South Australia at current renewable energy penetration is $2-5 per MWh, which is indistinguishable from noise in wholesale spot prices. The observation of low spot prices, both currently and on futures markets, supports the contention that balancing costs are small at least until penetration of solar and wind rises above 70%.

The real cost of a solar and wind generation system, including both generation and balancing, will become clearer as each year passes and the solar and wind fraction of electricity in the NEM and in South Australia continues to increase.

2030 emissions target

The USA has a target of halving emissions from 2005 levels by 2030. The equivalent Australian 2030 target is 306 Megatonnes (MT). This is 40% below current emissions (510 MT) and is well below the current “Paris target” (453) MT. Table 1 tabulates Australian emissions in 2020 and hypothetical emissions in 2030.

The easiest sector in which to make rapid reductions is electricity (through accelerated deployment of solar and wind). Australia is already tracking towards deep cuts in the electricity sector, and a 90% reduction by 2030 is entirely feasible at low cost.

The next easiest sector is land transport (via electric vehicles). The other sectors could not realistically move as fast as electricity and land transport. An emission cut in the transport sector of 30% is needed by 2030 (assuming that the remaining sectors can achieve small cuts of 10%). Most new vehicle sales would need to be electric by 2027.

Under the above scenario, electricity demand would increase by about 20% (mostly for the electric vehicles), all of which would come from new solar and wind deployment.

The current solar and wind deployment rate (7 GW per year) needs to double to 14 GW per year. This is straightforward provided that there is good planning for transmission and storage.

Table 1: Emissions (MT) by sector

SECTOR EMISSIONS (MT)	**2020**	**2030**	**Cut**	
Electricity	170	17	90%	Mostly coal power stations
Stationary energy	102	76	25%	Mostly low and high temperature heating
Transport	90	67	25%	About 90% is land transport
Fugitive emissions	51	51	0%	Mostly methane from coal & gas mining
Industrial processes & product use	30	30	0%	Mostly the chemical industry
Waste	13	10	25%	Mostly methane
Land sector	53	53	0%	Agriculture, land use change, etc.
TOTALS	**510**	**306**		

A simple interactive emissions spreadsheet showing table 1 is here:

Emissions.xlsx

Beyond 2030: zero fossil fuel energy, 70-80% emissions reductions

Market forces and emission reduction goals will lead to the emergence of new large-scale electrical loads. Electric vehicles are expected to become widespread, displacing oil and introducing large-scale storage in the vehicle batteries. Electric heat pumps are displacing gas for air and water heating. Electrical furnaces will compete with gas for high temperature industrial heating. The new storage associated with these new markets can substantially assist grid operation through time-of-use tariffs to favour daytime solar electricity charging of storages.

Renewable electrification of land transport and heating entails a doubling of electricity demand and would reduce Australian emissions by about 70% with insignificant impact on electricity prices. New solar and wind generation may be used substantially to meet new electrified transport and heating loads rather than displacing the remaining fossil fuel electricity generation. This means that Australia may not approach 100% renewable electricity for many years and the uptick in balancing cost illustrated in Figure 6 for 80-100% renewable electricity penetration could be correspondingly postponed. Also, the falling price of solar and wind will ameliorate both generation and balancing cost.

To accomplish this task by 2040, the deployment rate of solar and wind needs to double from 7 GW in 2020 to 14 GW per year.

Fugitive emissions from fossil fuel mining comprises a further 10% of emissions, which vanish as fossil fuel use and export vanishes.

The balance of emissions comprises waste (3%); chemical production, aviation & shipping (8%); and the land sector (10%). These sectors are harder to decarbonize. An early focus on electrification of land transport and heating buys time to scale up the technology needed to decarbonize these sectors.

Hydrogen has an important role in decarbonizing the chemical industry in the 2030s. However, electrification is by far the technology and market leader in decarbonizing electricity, transport and heating (80% of emissions).

A possible scenario for zero fossil fuel energy in 2040 is shown in figure 8.

Continued deployment of 7 GW per year reaches the current Paris target.

Doubled deployment rate (14 GW/year) produces much faster declines in emissions. This is not hard considering the ever-falling price of solar and wind, and the fact that their current deployment rate is already seven times faster than in 2015 (when it was 1 GW per year).

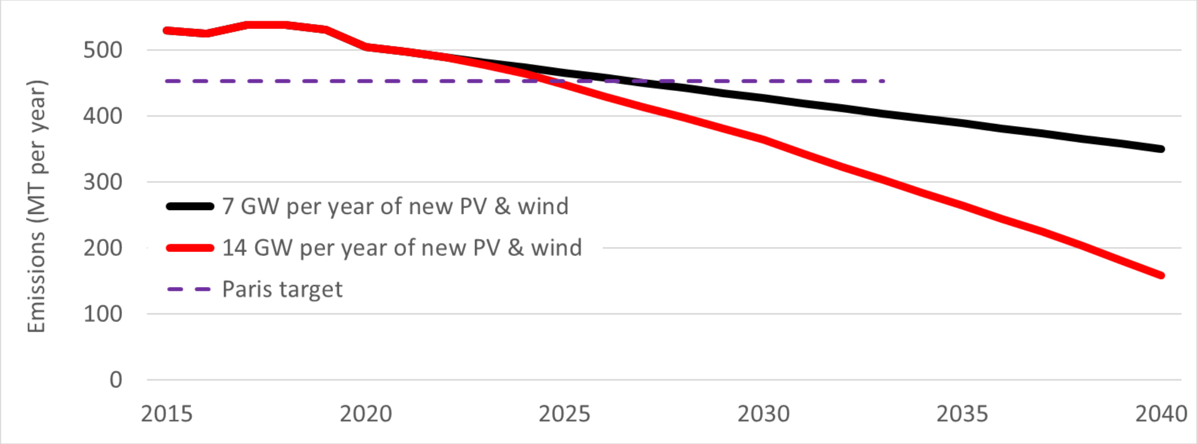

Figure 8: Scenario of rising electricity demand caused by renewable electrification of transport, heating and industry, which is met by solar and wind. This allows zero fossil fuel energy in 2040 and a 70-80% reduction in emissions.