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LETTER

Characterisation and mitigation of renewable droughts in the Australian National Electricity Market

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Abstract

In a decarbonising world, the electricity generation mix in Australia's National Electricity Market (NEM) is likely to be heavily dependent on wind and solar. Designing an electricity system dominated by variable renewable energy generation requires careful examination of periods of low renewable output to ensure storage or other back up generation is sufficient to avoid loss of load. This study uses 15 years of climate and electricity demand data to examine the frequency and nature of the occurrence of low renewable periods. It examines strategies for their mitigation so that unserved energy standards are not breached. We have found that the winter period, May to August, is the time where the NEM is at greatest risk of loss of load. This winter period is when the demand in southern Australian states is higher, solar generation is lower and a series of low wind periods can drain storage. It has been demonstrated that any proposed generation mix reliant on renewable energy generation should be stress tested across a low wind winter, like the complex winter of 2010, not just a single isolated low wind period. Storage was found to be ideal to provide energy for a few hours overnight, but firm dispatchable thermal generation is likely to be a lower cost option than long term storage for extended low wind periods. Diversifying generation with the addition of offshore wind may reduce the need for storage, although the need for floating wind turbines may make this alternative too expensive to add any value in the Australian context.

1. Introduction

The electricity mix that will serve us well in a decarbonised future continues to be a topic which is heavily debated and discussed [1–6]. As the generation mix becomes increasingly reliant on wind and solar power [7], the impact of low wind and solar generation periods becomes more relevant [8–11]. The importance of understanding how wind and solar variability impacts the whole system, its impact on the total system cost [12], and the degree to which storage can mitigate wind and solar variability [13–15] is important for system stakeholders [16].

In Australia, a fully renewable or even a renewables dominant system, must rely heavily on wind and solar energy [17], in this context, one important aspect is the electricity system reliability during low wind and solar generation periods [14, 18]. These are sometimes described as wind droughts, Dunkelflaute, dark doldrums or more simply—low wind and solar generation periods [19–21]. In these periods of low generation, energy storage and demand-side management are often proposed as the way to compensate for the lack of renewable generation.

These periods of low renewable power generation have previously been described in other jurisdictions, including the Germany [18], United Kingdom [22], Ireland [23], the United States [24] and Europe more broadly [21, 25, 26]. Australia, too, has weather patterns which provides the conditions for a wind drought in the National Energy Market (NEM). Most recently this was seen in both 2017 [27] and 2020 [28] where a much lower production level from wind farms across the NEM was observed.

Table 1. Technology cost assumptions (2021).

Plant Type	Capex ($/kW)	Fixed ($/kW/yr)	Variable ($/MWh)	Source / Comment
Wind (onshore)	1652	38	—	[37] High VRE Scenario, 2050
Solar	829	15	—	[37] High VRE Scenario, 2050
Legacy Hydro	—	59	—	[38] IRENA Hydropower report
Thermal	—	—	200	[39] Assumed Wood Pellets at US$200/t delivered
Plant Type	**Capex ($/kWh)**	**Fixed ($/kW/yr)**	**Variable ($/MWh)**	**Source/Comment**
Storage	20.3	97	—	[40] Snowy 2.0 Project

The NEM operates on one of the world's longest interconnected power systems, stretching from north at Port Douglas in Queensland to Port Lincoln in South Australia and across the Bass Strait to Tasmania—a distance of around 5,000 kilometres [29]. It incorporates around 40,000 km of transmission lines and cables [29]. The NEM supplies approximately 200 TWh of electricity to approximately nine million business and household customers, using some 59 GW of capacity (as at July 2021) [29–31]. Each of the states that make up the NEM have different types of resources and technologies available for generation, as well as different demand requirements.

This study seeks to bridge some of the knowledge gap on low wind and solar generation periods within the Australian NEM within the context of a fully renewable or even a renewables dominant generation system. We have analysed 15 weather years of potential renewable generation with long term storage to examine the Dunkelflaute or low wind and solar generation periods. We have also modelled the amount of storage or equivalent demand side management, required under fully or renewable dominated systems on a state-by-state basis and a whole of the NEM network basis.

2. Methods and data

2.1. Timeseries data

Where possible, timeseries data was based on actual generation and demand as recorded by NEM Review [32]. However, most renewable facilities have only been constructed over the last few years, so reanalysis data was used to derive the *probable* output of windfarms and solar parks in each state. The primary source of data for this reanalysis was the Renewables Ninja [33] dataset, which was set up by its creators specifically for this and other renewable modelling in Australia. Where these data were unavailable then US Department of Energy (DOE), National Centers for Environmental Prediction (NCEP) data[1] [34] was used, based on wind at 925mbar. Other pressure levels were tested but 925mbar was found to have the best correlation where actual generation data existed. The correlations were derived by comparing existing windfarm generation from the NEM Review data set [32] with the simulated output derived from a typical power curve and wind data from the NCEP data set [34] at each pressure level. The correlations were calculated for each reanalysis node (which are on a grid with 2.5 degree separation), within each model region, and the best nodes chosen to represent the Renewable Energy Zones [17] where wind farm data exists and further development is likely. This gave confidence in the reanalysis data for this specific application alongside others who have done much more detailed work to validate the reanalysis data generally [35, 36].

2.2. Cost

The costs assumed for this study are listed in table 1.

2.3. Methodology

The objective of this paper was to examine, at a high level, the issues associated with periods of low renewable output, as such, the calculations were kept relatively simple. For most scenarios only three types of plant were considered: wind, solar, and legacy hydro power. Some scenarios assumed a thermal plant met all periods of unserved energy. All calculations were done for each state assuming no interconnection, and for the NEM as a whole, where perfect (or 'copper plate' [41]) interconnection was assumed. This latter simplification is a limitation of the methodology employed and tends to favour variable renewable generation resources since localised peaks in wind and solar energy can be moved to all parts of the grid without penalty or restriction. The assumption that states are disconnected will tend to overestimate storage needs as they are unable to be shared. Together these assumptions bracket the reality of states that are weakly interconnected physically and exercise

[4] NCEP_Reanalysis 2 data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/kana/reanl2-1.htm (accessed Nov 2021).

significant autonomy. Wind was assumed to be all onshore (as is currently the case in Australia) except for an offshore sensitivity scenario.

Calculations were carried out sequentially on an hourly basis for the full 15 years from 2006 to 2020. Limiting the calculations to an hourly basis rather than the current 5 min settlement within the NEM will reduce the precision of the results, however the more coarse modelling has been shown to be suitably accurate for high level modelling [42, 43]. Historic load factor data was scaled according to the wind, solar and hydro capacities in each scenario to create a track of potential generation. For each hour, generation was used firstly to meet demand, and if there was surplus and sufficient headroom, any extra was put into storage at an assumed efficiency of 80% (a value used by Hydro Tasmania, as typical of pumped storage). Any remaining surplus was curtailed. If generation failed to meet demand, then energy was drawn down from storage. Once storage was empty then unserved energy was noted. If this exceeded the NEM's security standard the unserved energy was assumed to be met from thermal plant.

An Indicative System Cost (ISC) approach, rather than a full Total System Cost [12, 42, 44] approach was utilised for this study. The Total System Cost was considered to be too complex to demonstrate the possible shortfalls from a renewable drought, while acknowledging that a Total System Cost approach which incorporates renewables droughts will give the lowest system cost generation portfolio. The ISC was calculated by assuming that renewable and storage plant only had capital and fixed costs, and thermal plant only had a variable cost, these being the dominant costs for each type (refer to table 1). Furthermore, storage costs were assumed to be all associated with the storage volume and none with the output power, and all storage was assumed to be pumped hydro. These scenarios had no unserved energy, any energy not met from the algorithm above was assumed to come from biomass plant to retain carbon neutrality.

3. Results

This section begins with an overview of the base case scenario with equal contributions from onshore wind and solar in the generation mix, with sufficient capacity to meet 120% of demand over the year. It examines the last 15 years of weather data combined with the modelled renewable output (sub section 3.1). We then present an output where half of the contribution from wind is from offshore wind farms (sub section 3.2). Furthermore, we analyse the impact on system cost (ISC) of high renewables combined with storage outcomes with a technology neutral approach to generation (sub section 3.3).

3.1. Base case 50:50 wind and solar scenario

Figure 1 shows the modelled weekly average generation from a portfolio giving equal expected output from wind and solar, plus the legacy hydro power generation within the NEM, assuming a 20% generation over-build. Within this base case, the NEM is treated as a fully interconnected copper plate. This set of scenario assumptions leads to 57 GW wind and 84 GW PV in the NEM. The red bars indicate 1st of January (the summer period), the blue bars indicate the 1st of July (the winter period). The level of storage modelled in the base case is approximately 4 days (i.e. enough storage to cover 4 days of average demand) or 3.3 TWh, which is about 10 times the size of Snowy 2.0, a large pumped storage facility being developed.

On a year-on-year basis, figure 1(a) shows that the wind and solar generation charges large amounts of storage and are also routinely curtailed. This curtailment occurs significantly less frequently between June and August, as highlighted in the 15 year mean graph (on the right-hand side of the figure). Unserved energy is highlighted in black.

Figure 1(b) shows how the different technologies contribute to the weekly average generation mix. The legacy hydro power, while important for the provision of system strength and other grid services [17, 45–47], provides only a small contribution to the overall energy mix. Onshore wind has a relatively constant contribution over the year as shown by the 15 year mean, with little summer to winter impact. As expected [48, 49], the solar contribution dips significantly around the winter solstice.

The blackouts, or periods of unserved energy, if they occur, are during the low wind and solar generation periods, around the June, July and August timeframes figure 1(a). With 4 days' worth of storage, blackouts would have occurred within the copper plated NEM in 2006, 2008, 2009, 2010, 2017 and 2020, as shown by the storage being completely drained in those years (figure 1(c)). It should also be noted that to supply demand, the storage levels are being drawn down for periods much longer than the intense period of low wind and solar generation, both for more than a month before and after the lowest storage level point.

The highest deficit of wind and solar generation within the study period was in 2010. As shown in figure 2, in mid-May 2010, the storage levels are full. An initial wind lull in mid-May begins to draw down on the available long-term storage reserves, with the end of May still showing some storage reserves available. However, the relatively low wind generation in early June continues to require storage drawdown to meet demand, exhausting

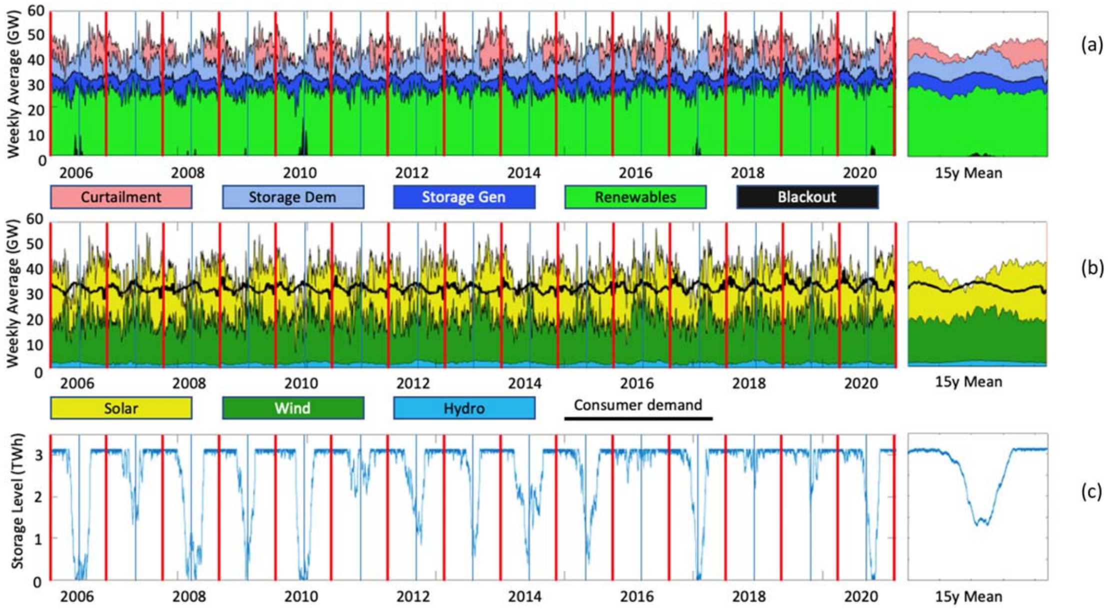

Figure 1. The base case of equal contributions from wind and solar added to legacy hydropower and modelling the NEM as a copper plate interconnected system.

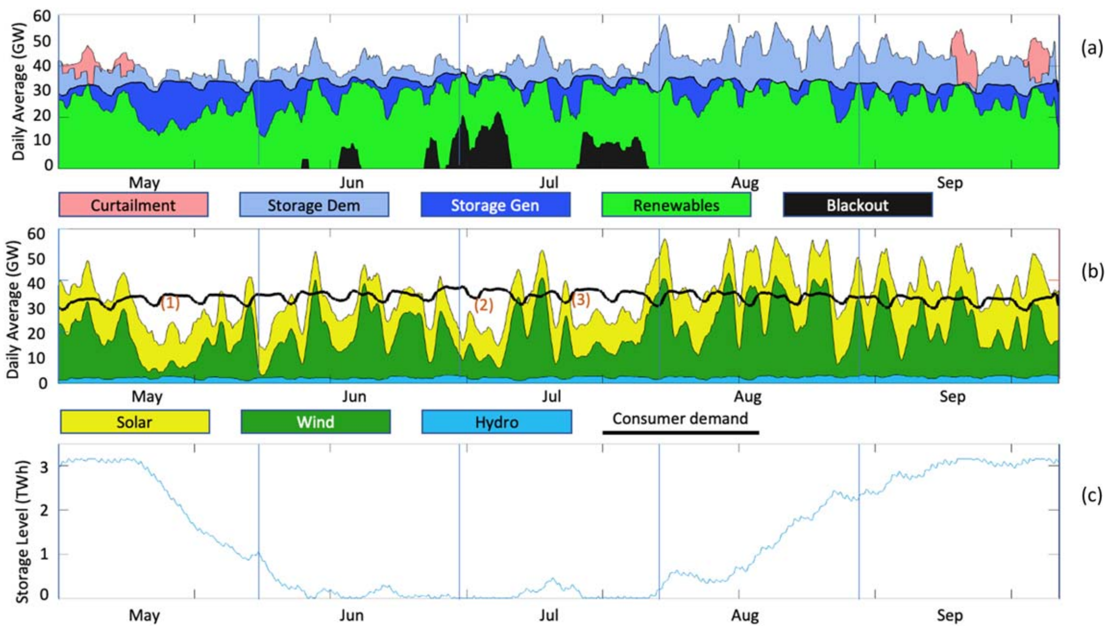

Figure 2. Highlighting the difficult low wind and solar generation period in 2010 within the NEM and its impact of energy storage levels using the base case scenario.

storage by early June. The second and third deep wind lulls in early and late July results in continued blackouts for most of June and July. It is not until early August where excess generation makes a marked impact on storage levels and not until mid-September does the storage level fully recover. Again, it must be noted, that this is best case for the NEM, with it being a fully interconnected copper plate. It will be seen below that isolated States require much larger volumes of storage to avoid blackouts, or they will suffer greater loss of load than seen here.

An examination of the impact of using a small amount of back-up thermal generation on the depth of storage required is shown graphically in figure 3 and tabulated in table 2. To maintain carbon neutrality this thermal portion could be sourced from carbon free sources, such as biofuels, or unabated fossil offset by a small baseload Bioenergy Carbon Capture and Storage (BECCS) plant. The relevant storage requirement level was set to meet the current 0.002% unserved energy limit and not the tighter interim reliability reserve of 0.0006% [50, 51].

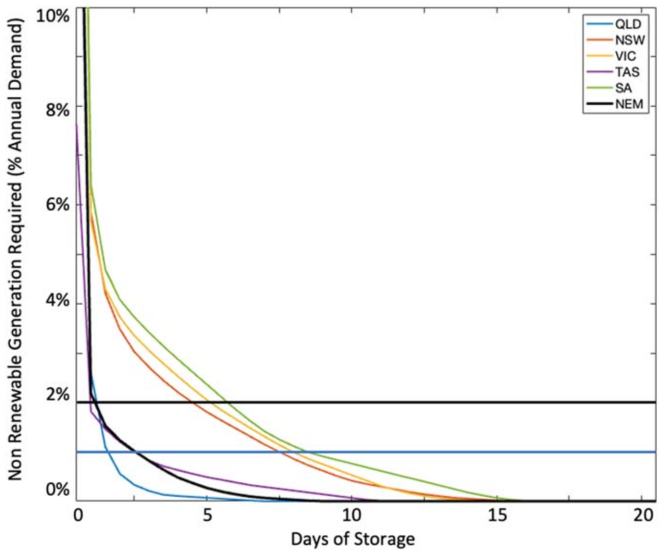

Figure 3. Impact of the depth of storage required on proportion of energy from firm generation to support a low renewable generation period.

Table 2. Storage requirement required to meet 0.002% unserved energy with 20% overbuild of wind and solar, showing States acting independently and a fully integrated NEM.

	100% VRE	99% VRE	98% VRE
Storage Required (days)			
QLD	6.5	1.5	1
NSW	15	7	4
VIC	14	7.5	5
TAS	11	2	0.5
SA	15.5	8	5.5
NEM (copper plate)	8.5	2.5	1
Storage Required (TWh)			
States act alone	9.5	4.2	2.6
NEM (copper plate)	6.7	2.0	0.8

It can be seen in figure 3, that decreasing the variable renewable energy (VRE) proportion of generation to 99% and 98%, the number of days of storage is dramatically reduced from 8.5 days in the 100% base case to 2.5 days at 99% and to 1 day at 98%. Table 2 shows the decrease in energy terms, reducing from 6.7 TWh at 100%, to 2.0 at 99% and 0.8 for the 98% VRE cases. These results are for a copper plate NEM, if states act alone then storage requirements are 2–3 TWh larger.

It can also be seen in both figure 3 and table 2 that the impact of introducing dispatchable thermal generation impacts the level of storage differently in the states within the NEM. Within the 100% renewable scenario, Queensland, has the lowest level of storage required at 6.5 days, nearly half of the next closest state Tasmania at 11 days. These differences are a result of differing peak demand periods, generation profiles and available resources.

3.2. Impact of offshore wind scenario

Figure 4 shows the modelled weekly average generation from the base case which included a 120% generation over build: the wind generation split 50:50 between on and offshore wind. Within this onshore and offshore wind case, the NEM is treated as a fully interconnected copper plate. The red bars indicate the 1st of January, and the blue bars indicate the 1st of July. As with the base case, the level of storage modelled in the base case is approximately 4 days (i.e., enough storage to cover 4 days of average demand) or 3.3 TWh.

The increase in geographic diversity and improved capacity factor of offshore wind compared with onshore wind has a significant impact on the modelled performance of the 100% renewable system. Only the 2010 period of low wind and solar generation results in period of significant blackouts, with only very minor blackouts

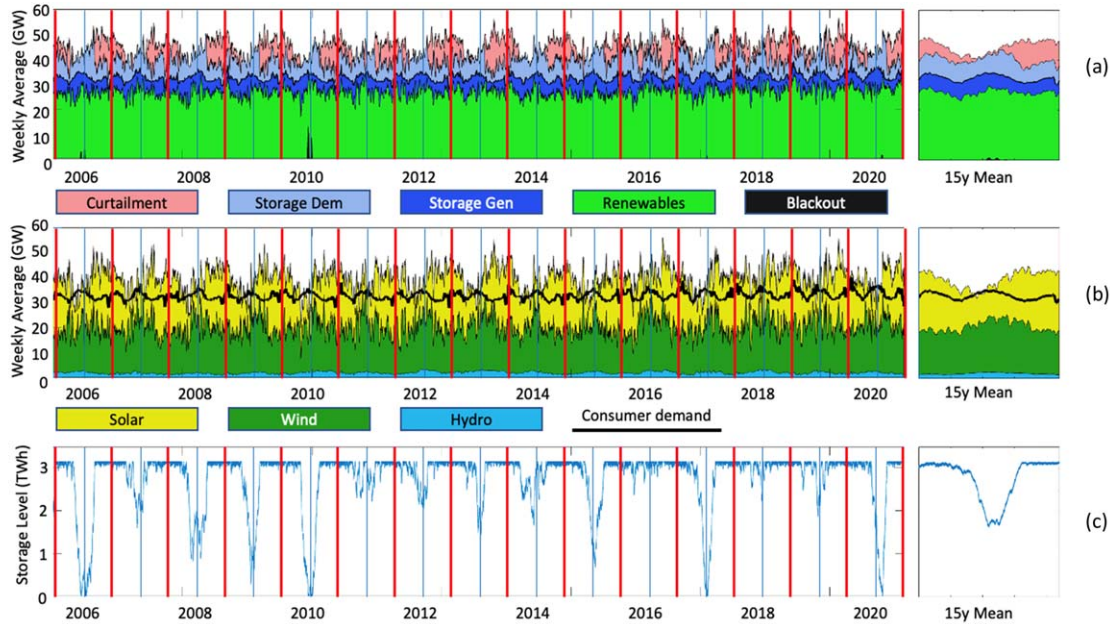

Figure 4. The impact of 25% offshore wind replacing onshore wind and 50% solar added to legacy hydropower, modelling the NEM as a copper plate interconnected system.

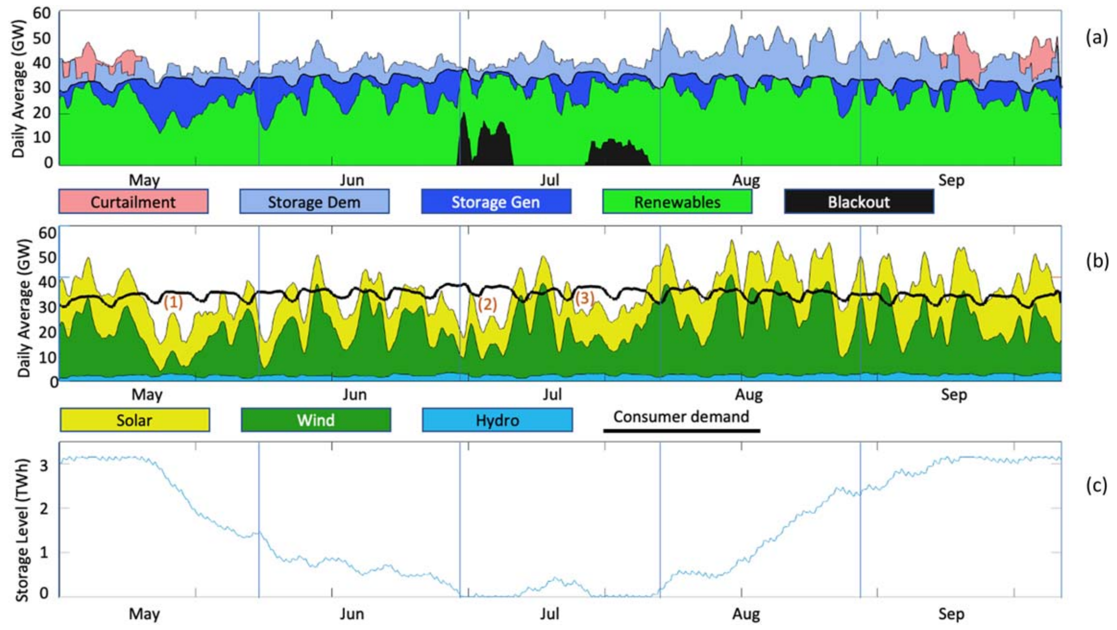

Figure 5. Highlighting the difficult low wind and solar generation period in 2010 within the NEM and its impact of energy storage levels using the offshore wind scenario.

modelled to occur in other years, in fact 2008 and 2009 no longer have any unserved energy. The overall improvement in performance is clearly seen in the 15 year mean graphic in figure 4.

As shown in figure 5, in mid-May 2010, the storage levels are full. As with the onshore scenario an initial wind lull in mid-May begins to draw down on the available long-term storage reserves, followed by further wind lulls. However, these are not so deep as the onshore scenario and blackout periods are less frequent and not so deep. While not acceptable in terms of grid performance, the addition of offshore wind into the energy generation mix improves the available generation substantially (compare with figure 2). Again, it must be noted, that this is best case for the NEM, with it being a fully interconnected copper plate. If strong interconnection is not built, or states choose to act autonomously, then periods of unserved energy will be greater.

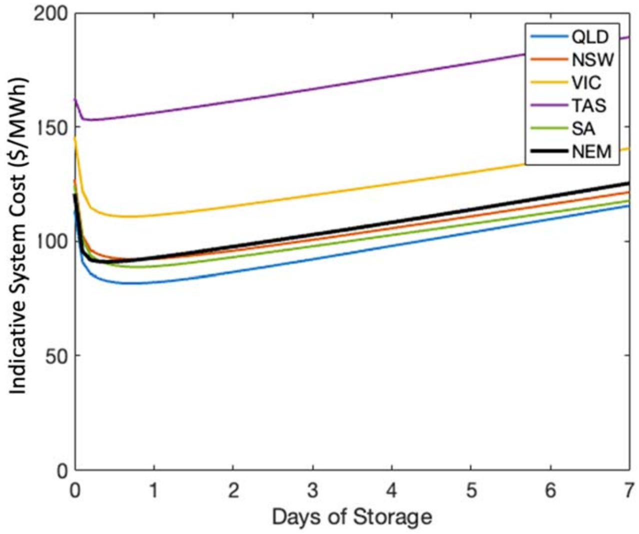

Figure 6. Indicative system costs for a copper plate NEM and individual states as a function of installed level of storage.

3.3. Optimising long term storage levels with biomass energy backup

The base case of 120% wind and solar energy generation, with the additional support of firm biomass generation, was examined to determine what the optimum length of long-term storage is required within the NEM. A shown in figure 6, a clear 'hockey stick' curve is apparent for the copper plated NEM and all the individual states. The optimum storage length is quite short, for the NEM its about 10 h of storage, the individual states vary from 5 h in Tasmania and 18 h in Queensland with its strong diurnal pattern of output. As found by others [52], the first few hours are the most valuable.

It could be that an overbuild of renewables is an alternative to building storage. To explore this, 11 different levels of storage were explored (from 0 to 2 days), each with 11 levels of renewable build (from 75% to 125%) for the copper plate NEM. Figure 7 shows how the indicative system cost varies, with a broad minimum cost area centred on 115% build and 10 h storage. In this scenario, 6% of the energy came from the firm capacity, with 94% from variable renewables.

4. Discussion

Designing an electricity system that is only secure against a single isolated Dunkelflaute event will likely prove insufficient to provide an adequate level system security over the longer term. A significant period of low wind and solar production may drain storage reserves, and if there is no prolonged period of high wind and solar output following that then these reserves cannot recover, and subsequent Dunkelflautes can lead to periods of unserved energy. This is particularly true for the southern states during winter when solar generation is guaranteed to be significantly lower than average and heating load higher (this would be exacerbated if heating in these states changes from gas to electric as some propose [53–55]).

The inclusion of offshore wind to replace half of the onshore wind reduced the severity of renewable energy droughts. This comes from the diversity added by the increased geographic spread, and the increased load factors from offshore wind farms. However, construction costs and maintenance costs are significantly higher, and offshore and onshore can still suffer correlated lulls in output. Therefore, their inclusion is not necessarily beneficial, but it is beyond this simple modelling to determine if offshore wind adds sufficient value to warrant the extra costs.

This analysis shows the lowest cost system must include an optimum proportion of thermal firm dispatchable energy as back-up. Although storage is often seen as part of the answer to renewables intermittency and seasonality, in reality, relying on storage alone will lead to a more expensive solution. Much of the storage is only used occasionally (once every few years) and yet large volumes are required to be held in readiness. The assessment of indicative system costs suggests that a lower cost solution for consumers is likely only to have short term storage of less than a day's duration. This is ideal for daily cycling, where solar generation can be smoothed, but the very significant cost of constructing large storage volumes makes it uncompetitive against low capex alternatives (such as biomass) even if they have a high fuel cost.

In this modelling, unlimited pump storage was available with a capex of $20/MWh, and no cost associated with power output. Actual costs are likely higher as short-term storage such as batteries would probably be

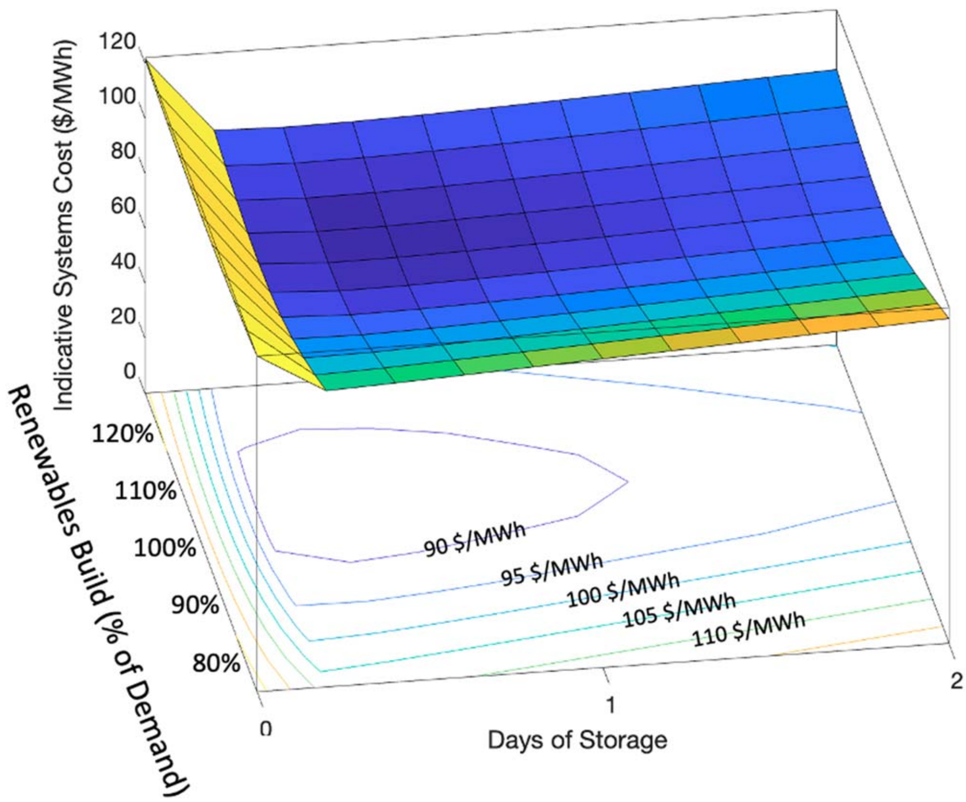

Figure 7. Indicative system cost as a function of both renewables build and storage.

needed alongside pumped storage to boost peak output. For example, the optimum storage for a perfectly interconnected NEM is just 10 h, or 330GWh, just slightly less than Snowy 2.0. However, the peak delivery of 18 GW is much higher than Snowy 2.0's capability of 2GW, so delivery of the optimum storage costs much more than just the capex of Snowy 2.0, even though in this simplistic model that is all that is accounted for. The extra costs (if modelled) would tip the balance more in favour of thermal back-up rather than storage.

The assessment has also demonstrated the value of interconnection. If states choose to act alone, then storage requirements are much larger, up to 3 times in one scenario, and more than 2 TWh in all scenarios modelled here. To put that into context, that is more than 6 times the volume of Snowy 2.0. However, the cost of achieving perfect interconnection has not been included and may well exceed the value gained.

This modelling is based on just 15 years of data based on the longest overlap of NEM data and reanalysis data, which isn't long enough to be certain the data encompasses a typical decade of weather. An alternative would be to characterise the stochastic inputs with distributions and undertake a probabilistic analysis. This would extend the number of scenarios that could be run almost indefinitely. However, this brings in another potential source of inaccuracy via the probabilistic modelling: getting the right distribution of output for each region, whilst having the correct spatial and temporal correlations is notoriously difficult [56]. Furthermore, climate change itself may change the frequency and duration of renewable droughts in unspecified ways. For these reasons it was decided not to add the extra complexity of probabilistic analysis.

Although this study is limited through several simplifying system model and cost assumptions, it still has value in demonstrating the value and limitations of storage. The assumptions of unlimited availability of relatively cheap pumped storage, and a net zero system will tend to maximise the proportion of VRE. However, even in this case, the optimum solution has a significant contribution of 6% energy delivered by thermal backup. A follow-up paper is in preparation that takes account of full cost of each technology and balances the supply of grid services against requirements [12].

5. Conclusions

Demonstrating that a system is secure (no involuntary disconnections) during single isolated Dunkelflaute does not ensure the security standard will be met. To be sure that a proposed system configuration is secure, it should be modelled over an extended winter period covering May to August and based upon historic weather (or a simulation) over several years.

Although long term storage can ensure system security over the winter months, it is short term storage that adds the most value to the system. The optimum amount of storage, with lowest cost, in scenarios modelled here is less than a day, and maybe only a few hours in states with less bountiful solar.

A series of wind droughts and seasonal reductions in solar output are dealt with by firm generation in a much more cost-effective manner, than using long term storage. For low utilisation events such as replacing renewables in a Dunkelflaute, low Capex, high Opex thermal plant leads to a lower cost to consumers than high capex storage which is only cycled once a year at most.

A diverse generation portfolio lessens the need for expensive long-term storage. Making use of offshore wind adds a certain amount of diversity, but it can still suffer low output periods when onshore wind is low. If Australia's coastal waters preclude the use of conventional offshore foundations necessitating the use of floating platforms, the extra cost and complexity may eliminate any advantage.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics

This work involved no human or animal subjects.

Data Access

The data that support this analysis are freely or commercially available from the following sources:

- NCEP_Reanalysis 2 data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/kana/reanl2-1.htm
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CRediT author statement

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