2014 ASIA-PACIFIC
SOLAR RESEARCH CONFERENCE

Peer Reviewed
2014 Solar Research Conference

paper ID # + First author name

Electric Energy Storage in the Australian National Electricity Market – Evaluation of Commercial Opportunities with Utility Scale PV

Jiefei Wang[1], Anna Bruce[1], Iain MacGill[2]

[1.] School of Photovoltaic and Renewable Energy Engineering, UNSW, Sydney Australia
[2.] School of Electrical Engineering and Telecommunications, UNSW, Sydney, Australia
E-mail: jiefei.wang@unsw.edu.au

Abstract

Recent increases in highly variable and somewhat unpredictable renewable energy generation in the Australian National Electricity Market (NEM) and rapidly decreasing costs of a range of electrical energy storage (EES) technologies present new economic opportunities for the integration of EES, including as a means of improving the profitability of utility scale PV. In this paper, applications and economic opportunities of EES devices, alone, and in combination with utility scale PV in the NEM, are examined. The analysis focuses on using EES for energy arbitrage purposes in the NEM's energy-only spot markets. The results demonstrate that presently there are economic opportunities for certain types of battery technologies, as well as highlight the NEM's current asymmetric market arrangements.

1. Introduction

Currently, there is renewed interest in the applications and benefits electrical energy storage can provide for renewable energy technologies, as a result of both increasing renewable energy generation in electricity networks and rapidly decreasing EES costs.

In 2013, the global cumulative installed capacity of solar PV grew by 37% while global wind capacity (onshore and offshore) grew by 12.5%, and growth in renewable energy capacity is expected to continue to grow strongly (IEA, 2014). A growing share of renewable energy generation is now challenging conventional business models and broader electricity industry arrangements. Some stakeholders argue that the intermittency of renewables is placing greater strain on electricity systems that were designed for stable and predictable fossil fuel generation technologies. In practice, of course, the electricity industry is already required to handle load variability and uncertainty. However, there is no doubt that higher renewable penetrations are adding to the challenges of electricity industry operation.

EES promises to help address growing challenges in terms of temporal supply-demand balance, while also offering opportunities to improve power quality, provide frequency ancillary services for the grid, and defer upgrades to transmission and distribution networks (Sandia National Laboratories, 2010). However, using storage for these application and benefits has often been economically unviable in the past due to its high capital cost, and a range of existing lower cost alternatives such as fast-start gas generation. However, the confluence of growing renewable penetrations and falling EES costs is changing the perception around the economic viability of storage in the electricity market (James & Hayward, 2012).

Although Australia's National Electricity Market (NEM) has so far managed to accommodate the integration of renewable energy technologies without the need for large amounts of storage (there is some pumped hydro storage), higher renewables penetrations and rapidly decreasing prices for storage could make EES a cost effective option to provide the aforementioned benefits to the electricity network and help facilitate the integration of renewable energy technologies. This paper explores the potential value of EES for energy arbitrage in the Australian NEM in the context of growing utility-scale PV deployment. Section 2 outlines potential applications for, and economic benefits to EES in a deregulated electricity market. Section 3 briefly outlines the methodology used to analyse commercial opportunities in Section 4. Section 5 will discuss the implications of the results for market structure and co-location of EES and PV.

2. Applications and Benefits of Storage in a Deregulated Electricity Market

The term EES encompasses a wide array of technologies that are capable of converting electrical energy into a form that can be stored, and then at a later time, converted back to electrical energy. They range from super capacitors that operate in the milliseconds to pumped hydro that operate for tens of hours a day. Batteries are the focus of this paper because of their operational flexibility. They sit between these extremes, offering a discharge time ranging from seconds to hours and a wide range of power ratings, thus satisfying a host of potential applications.

Overviews of potential applications of EES have been undertaken by a number of US research institutions. For example, Sandia National Laboratories (2010) explored 17 applications in a deregulated electricity market, which were categorised in 5 groups: electric supply (eg energy arbitrage[1]), ancillary services, grid system (eg network upgrade deferral), end user (eg time of use management), and renewable integration (eg energy arbitrage). The majority of the other reports (such as Denholm et al, 2010) categorise EES applications into similar groups.

Australia's National Electricity Market (NEM) is structured such that the most direct application of EES from which monetary benefit can be derived is through energy arbitrage or ancillary services. In particular, there is currently no assured monetary incentive to use EES to defer network upgrade and deferral, even though it might provide highly valuable network-wide benefits. For ancillary services, there are a number of markets for providing Frequency Control Ancillary Services. However, in the NEM the monetary value of FCAS is currently low, due to competition from a large number of generators who can offer such services, and limited demand due to a stable system (Marchment Hill Consulting, 2012). Energy arbitrage – specifically the charging of storage at times of low wholesale prices for 'sale' at times of high prices – does offer some potential revenue in the NEM. US literature on energy arbitrage argues that there is potential for such applications in a deregulated electricity market (Walawalker et al, 2007; Sioshansi et al, 2009). In the Australian context, Figueiredo et al (2006) have used analysis of a hydro power plant, to show that Queensland and South Australia have amongst the highest energy arbitrage revenue potentials in the world, although other work (Marchment Hill Consulting, 2012) suggests that arbitrage in Australia may only be commercially attractive after 2020 as storage costs are expected to decline and fuel prices to increase over the period. The purpose of this paper is to assess the energy arbitrage potential of EES in the NEM alone, and when directly complementing utility-scale PV plant.

[1] Also known as energy time-shift, which is the term used by Sandia National Laboratories

3. Methodology

Two broad scenarios are developed and analysed:

Scenario 1: EES operating independently for energy arbitrage purposes within the NEM, both with and without perfect foresight of spot market prices.

Scenario 2: EES operating in conjunction with utility-scale PV for energy arbitrage purposes with perfect foresight. In this case, the EES is charged directly from the PV plant. This scenario explore potential synergies in joint operation of PV and storage.

Analysis of perfect foresight scenarios used actual half hour spot market clearing prices for the calendar year 2010-13 from AEMO's Aggregate Price and Demand Data Files. The imperfect foresight scenario analysis used 2010 and 2013 AEMO 30 minute predispatch files. These are forecast prices, based on AEMO's estimate of short-term supply and demand.

Weather data were sourced from ROAM Consulting's contribution to the AEMO's 100% Renewable Project (AEMO, 2013). Satellite-derived solar irradiance data from the Australian Bureau of Metrology for 2010 were used to match the scope of this paper. The chosen locations include: Cobar (NSW), Longreach (QLD), Woomera (SA), and Mildura (VIC). PV output were simulated using NREL's System Advisory Model (SAM) in conjunction with the aforementioned weather data for each location.

EES costs were obtained from Ferreira et al's (2013) review of a spectrum of technologies that covers lead-acid (Pb-a), nickel cadmium (Ni-Cd), lithium ion (Li-ion), sodium sulphur (NaS), sodium nickel-chloride (zebra), veradium redox (VRB), and zinc bromide (ZnBr). All of these technologies are commercially available, however, the level of maturity and deployment to date varies. The best-case performance scenario (highest cycle life with lowest cost) for each technology was assumed given the likelihood of future performance improvements.

The algorithm approach is based loosely on the linear programming approach used by Figueiredo et al (2006) and Sioshansi et al (2009), where the system of storage, PV plant, electricity network prices and revenue stream are described with a series of linear equations.

4. Results and Analysis

4.1. EES only – energy arbitrage

Energy arbitrage revenues for a 1MW ESS with capacity between 1-8MWh are summarised in Figure 1, using NEM price data for years 2010-2013 with perfect foresight. The model assumes 90% single trip efficiency (10% loss for charging the EES and then 10% loss for discharging). The results are highly location and time dependent. For instance, NSW, on average the worst performer, offered a very poor return in 2013 and 2012, but more than double the revenue in 2011 and 2010. Although SA was consistently the high performer among the NEM regions, revenue from 8 hours of capacity can vary from $40,000/MW in 2012 to $150,000/MW in 2010.

This result largely agrees with a study on revenue from pumped hydro in the NEM (Hearps et al, 2014). Direct comparison is difficult as the analysis in Hearps et al. (2014) was conducted over a different timeframe (financial year 2013, July-July). In addition, round trip efficiency was assumed to be 75% and only SA was covered. Nevertheless, results for SA 2010-2013 exhibited similar trends and value.

Overall, the results show that SA is the NEM region with the highest opportunity for energy arbitrage applications with EES.

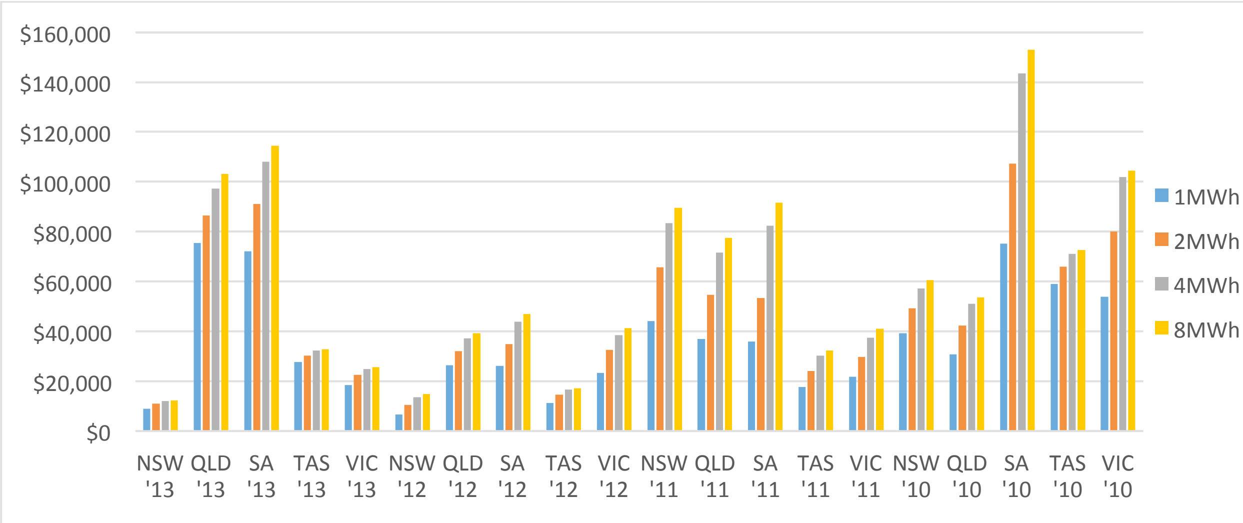

Figure 1. Scenario 1 - EES only energy arbitrage revenue, 2010-2013 with perfect foresight

4.1.1. Dependence on High Price Events

The daily revenues from EES across the states for 2013 were analysed (Figure 2). This was done by ordering daily revenues in increasing order, and then calculating the cumulative percentage of total revenue and time. Perfectly distributed revenue is demonstrated with the straight blue line in Figure 2, where 1% of the time in the year would generate 1% of total revenue. It can be seen that for all regions, the majority of revenue for each year occurs in a short amount of time. The extreme case can be seen in NSW, where 50% of the revenue is earned through 1 day. The results highlight the dependence of arbitrage value on the occurrence of high price events in the NEM, as the economic opportunities are highly skewed towards a small percentage time of the year.

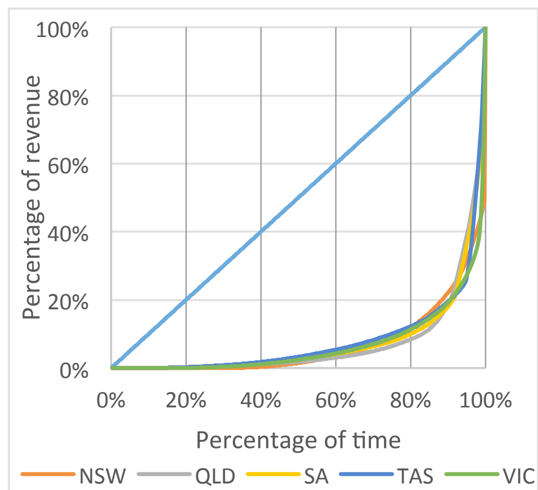

Figure 2. Revenue distribution, 2013

Analyses of the spot price across NEM regions show that SA's spot market has a high frequency of extreme price events (>$400/MWh) as well as a high average value of such extreme price events. These two factors, combined, explain well the trends in energy arbitrage revenue results from this analysis across the different NEM regions and years (Figure 1). One of the factors driving this variability in the SA spot market price is a high penetration of renewable generation (Forest and MacGill, 2013). As such, the value of EES can be expected to increase in future with the share of renewable generation.

4.1.2. Impact of Capacity

Increasing EES capacity leads to a decrease in total revenue per MWh capacity ($/MWh). The reduction in the marginal value of capacity is due to the typically short duration of high price events, and agrees with previous US studies (Sioshansi et al, 2009). This has strong implications for EES, as low cost scalability of energy capacity may not be a financial advantage.

4.1.3. *Impact of Efficiency*

Efficiency can have a material impact on energy arbitrage opportunities, with annual revenue losses of between 16%-50% when single trip efficiency decreased from 100% to 90%. Analysis showed that revenue for years and states with low value arbitrage opportunities were most affected by low efficiency. On days with minimal price spreads, a lower efficiency EES could not economically operate at all, as low value arbitrage opportunities are offset by efficiency losses. The research found that for years with frequent high price events, lower EES efficiency resulted in relatively smaller, but definitely not negligible revenue losses. This result is in contrast to Hearps et al (2014), which stated that round trip efficiency should virtually have no effect on revenue, since the majority of revenue is earned during price spikes, when efficiency losses are much smaller than the charging-discharging price differential.

4.1.4. *Impact of Capital Cost on Payback Period*

Capital cost and cycle life figures from Ferreira et al (2013) are used to calculate the payback period for different EES technologies of different energy storage capacities in the NEM. Payback is first calculated as total revenue generated over the EES' cycle life divided by its initial capital cost – any EES with a ratio greater than 100% has the ability to pay back the capital cost within its cycle life (Table 1). The revenues and cycles of SA were used, as SA already has a relatively high renewables penetration, which is expected to extend to other states in time. 2010 data are presented here to correspond to the EES with PV results in subsequent sections (2010 weather data was used for PV output simulations). Discounting was not considered.

Table 1. Scenario 1 – Lifetime ESS payback as percentage of initial capital, and years

Payback	Pb-a	Ni-Cd	Li-ion	NaS	Zebra	VRB	ZnBr
1MWh/1MWh	27%	22%	63%	44%	136% (3.3 yrs)	197% (10 yrs)	27%
2MWh	35%	24%	85%	64%	174% (3.3 yrs)	294% (8.4 yrs)	41%
4MWh	38%	23%	96%	79%	189% (3.8 yrs)	375% (8.4 yrs)	53%
8MWh	36%	21%	95%	84%	181% (6.2 yrs)	413% (11.8 yrs)	60%

The results in Table 1 have several implications in terms of scaling cost and cycle life. For example, although a lead-acid EES has a relatively low capital cost, its poor life cycle means that it will not be suitable for the purposes of energy arbitrage involving frequent cycling. In this analysis, Zebra batteries have the fastest payback period, which is in agreement with a recent study on the economic viability of arbitrage potentials in the US electricity market (Bradbury et al. 2014), which showed that Zebra batteries has the highest internal rate of return of battery technologies studied. VRB batteries' superior life cycle allows it to be economically viable, albeit with longer pay back time.

For Zebra and VRB, a 2MWh/1MW ratio has the lowest payback period. This is due to a combination of low scaling cost of the batteries and reduced cycles compared to 1MWh/1MW. Although, as concluded in section 4.1.2, 1MWh/1MW offers better revenue per MWh of capacity, higher capacity could lead to faster paybacks and higher returns on investment.

4.1.5. Impact of imperfect foresight

The percentage of perfect foresight revenue captured by a non-dynamic EES control algorithm, based on 24 hr ahead NEM pre-dispatch price forecasts, and a dynamic algorithm, based on 30 minute pre-dispatch price forecasts, are compared for all states in 2010 and 2013. The results for 2010 indicated that the EES with a dynamic control algorithm captured 60-85% of the perfect foresight results for different states, increasing with capacity, demonstrating the value of capacity in uncertain environments. However, using the same method in 2013, the algorithm only captured 20-50% of the perfect foresight revenue, increasing with capacity. In most cases the dynamic method of using the most recent predispatch data only marginally outperformed the non-dynamic method. Preliminary analyses showed that AEMO's 30 minute predispatch price may not be consistently accurate across years and regions. In practice, it is unlikely that generators would use 30 minute forecast data to capitalize on high price events, but would rely on information with higher resolution, such as 5 minute forecast data or real time price, which would allow them to react to pricing signals within the NEM's 30 minute settlement and 5 minute dispatch periods.

Sioshansi et al (2009) found that backcasting (making current decisions based on past price data) captured 85% or more of the potential arbitrage value in the US Pennsylvania-New Jersey-Maryland (PJM) electricity market for storage with 12 hour capacity across 2002 to 2007. Although 12 hour capacity EES was not tested in this study, the results in this section show that although this is possible for some years in the NEM, such high percentage may not occur consistently.

The NEM pumped hydro study by Hearps et al (2014) also employed a "rolling window" non-perfect foresight strategy using predispatch data. Their results are limited to SA 09/2012 to 09/2013, and show similar performance compared to the SA 2013 4MWh results here, but better performance for 8MWh. The cause for the difference is unclear, as the authors did not describe how the rolling window approach was implemented. Moreover, due to the limited data, the study did not assess the variability of predispatch data performance across regions or years.

4.2. EES + PV – energy arbitrage

For large scale PV participating in an electricity spot market, there is an incentive to use EES to store generation during periods of low prices and increase total output during periods of high prices. Figure 3 shows the additional revenue from using 1MW EES for energy arbitrage in conjunction with a 10MWdc PV plant, compared to the revenue from operating the PV plant alone. For a 1MWh system, the EES on average increased overall revenue by around 4%, with little variation across the states. For 8MWh systems, there are much bigger variations, almost a 10% increase in revenue collected in SA, but only a 6% increase in NSW and QLD.

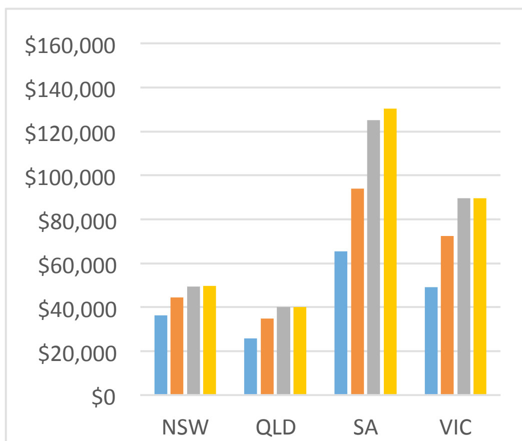

Figure 3. Scenario 2 - EES + PV energy arbitrage revenues, 2010

Due to the charging limitations placed on this mode of operation – no import from grid and operation during daylight hours when PV is generating – it is logical that the revenues are lower than in the EES only scenario. A 1MWh/1MW, 90% efficient EES system operated in this way in combination with PV is able to capture on average 89% of the potential energy arbitrage revenue compared to a perfect foresight EES-only system.

4.2.1. *Impact of Capacity*

The percentage arbitrage revenue collected by an EES-PV system as described above decreases as the capacity increases. An 8MWh/1MW system can capture only 82% of the total possible revenue from a perfect foresight EES-only system of the same size. Considering the operational limitations, the reduction is modest, particularly for smaller capacity systems. The plateau of improvement over PV only revenue seen in Figure 3 can be attributed to the limited hours of operation (when the PV system is generating). There is a relatively short time frame in which the EES can charge to full capacity. Consequently, on a day with few price fluctuations (arbitrage opportunities), the 8MWh may never reach full SOC. Even on days with significant price spikes, the 8MWh system might still not reach full capacity due to PV generation times and EES power rating constraints. This underutilisation explains the decreasing revenue per MWh capacity, which is in agreement with previous results.

4.2.2. *Impact of Capital Cost on Payback Period*

Compared to Scenario 1 (EES-only), some of the uneconomical technologies are now viable in combination with PV, though over a relatively long period. For technologies such as ZnBr, payback is now possible, but only for EES capacity greater than 8 hours (8MWh/1MW). On the other hand, the payback period for Zebra and VRB has increased marginally. This highlights the complex relationship between system capacity, cycle life, scaling cost and number of cycles experienced by the EES.

Despite the decrease in revenue and the underutilisation of larger systems, reducing the number of cycles used can offset these effects and make more technologies economically viable. This result highlights the importance of cycles on the financial returns of EES participating in energy arbitrage. A truly optimal algorithm designed to capitalise on arbitrage opportunities should not only maximise revenue, but also reduce the number of cycles used such that it accounts for the cost (fixed and variable) associated with using one cycle of the EES.

Table 2. Scenario 2 – Lifetime ESS payback as percentage of initial capital, and years

Payback	Pb-a	Ni-Cd	Li-ion	NaS	Zebra	VRB	ZnBr
1MWh	37%	30%	87%	60%	187% (3.8 yrs)	270% (11.4 yrs)	37%
2MWh	50%	35%	121% (25.6)	91%	250% (3.7 yrs)	421% (9.6 yrs)	58%
4MWh	63%	39%	160% (28.8)	131% (17.6)	314% (4.4 yrs)	624% (9.6 yrs)	89%
8MWh	73%	42%	192% (46)	170% (26.1)	364% (7.3 yrs)	833% (13.8 yrs)	121%

5. Co-location of EES and PV

The combination of Scenario 1 and Scenario 2 results suggest that using EES in combination with PV to participate in energy arbitrage will result in lower revenue than for the same EES system without PV due to the operating constraints placed on the EES. This means that a higher financial return can be obtained by operating EES and PV as two independent systems. Consequently, if PV and EES can and might more profitably be operated as separate systems, then it raises the question of why the two must physically be in the same location. As long as they are in the same price region, they only need to be co-optimised. The likely major economic benefit of co-location is in the sharing of a site, network connection and, potentially, some power equipment.

Such theory only holds true when charging and discharging the EES occur at the market clearing price. In reality, regulatory arrangements could heavily influence system setup and operational decisions. Current NEM regulations do not adequately define EES well enough to determine with certainty potential network tariffs that could be imposed on energy imports. This is because EES can behave as both a generator and a load. For example, large generators on the transmission network do not have to pay the network component for energy imports that are part of their auxiliary load. Loads, of course, are required to pay network tariffs on all consumption. Additional analyses were done based on the assumption that the same 10MW PV plant could be located on the distribution network, and be charged a high network tariff for all energy imports including its auxiliary load. These tariffs can be as high as 22c/kWh, which is in line with prices imposed on small businesses for most distribution network operators. If this is the case, then energy arbitrage applications will no longer be economically viable with EES only, as it will eliminate all opportunities below spot market price of $220/MWh. But, if the EES and PV were co-located, then the EES could be charged directly with PV generation, perform energy arbitrage, while avoiding any network tariffs. Under this arrangement, other applications of the EES would also be possible, such as minimising the PV plant's auxiliary load to avoid energy imports and its associated tariffs. However, our modelling suggests that the economic opportunities only ranges from around $3,000-$4,000 per year for an EES sized to the auxiliary load (around 50kW) under present tariff and market arrangements.

6. Conclusion

Opportunities for EES in energy arbitrage applications alone, and with large scale PV were analysed using historical NEM outcomes. The results indicated that for energy arbitrage applications, some EES technologies would seem to already be economically viable in the NEM. The economic return will depend on, of course, on future market outcomes but also how well the EES is operated under uncertainty, whether high price events can be adequately captured, as well as the ability to size it optimally. The comparison of EES only and EES with PV results raised the question of co-location. Although there may be significant cost savings from shared infrastructure for the two facilities, in a market where import price equals export price, there is little need for co-location. However if regulatory arrangements treat EES charging as a load, which is eligible to pay network use of system charges, performing energy arbitrage with EES-only may not be profitable, and the co-location of EES and PV generation may provide additional benefits. This reflects the present asymmetry in NEM arrangements for loads versus generation. Of course, other potential value propositions may exist such as the use of local storage to permit a smaller network capacity requirement for the PV plant. These opportunities are beyond the scope of this paper but certainly represent avenues for further research.

References

AEMO, 2013, '100 per cent renewables study – modelling outcomes', *AEMO*

Bradbury, K., Pratson., L, and Patino-Echeverri., D, 2014, 'Economic viability of energy storage systems based on price arbitrage potential in real-time US electricity markets', *Applied Energy*, 114, p512-519.

Denholm, P., Ela, E., Kirby, B. and Milligan, M, 2010, 'The role of energy storage with renewable electricity generation', *National Renewable Energy Laboratory*

Eyer, J. and Corey, G, 2010, 'Energy storage for the electricity grid: benefits and market potential assessment guide', *Sandia National Laboratories*.

Ferreira H., Garde, R., Fulli G., Kling W. and Lopes, J, 2013, 'Characterisation of electrical energy storage technologies', *Energy*, 53, p288-298.

Figueiredo, F., Flynn, P., and Cabral, E, 2006, 'The economics of energy storage in 14 deregulated power markets', *Energy Studies Review*, 14, p131-152.

Forrest, S., MacGill, I, 2013, 'Assessing the impact of wind generation on wholesale prices and generator dispatch in the Australian National Electricity Market', *Energy Policy*, 59, p120-132.

Hearps, P., Dargaville, R., McConnell D., Sandiford M., Forcey T. and Seligman T, 2014, 'Opportunities for pumped hydro energy storage in Australia', *Melbourne Energy Institute*.

IEA, 2014, 'Tracking Clean Energy Progress 2014', *International Energy Agency*.

James, G., and Hayward, J, 2012, 'AEMO 100% renewable energy study', *CSIRO*

Marchment Hill Consulting, 2012, 'Energy storage in Australia - commercial opportunities, barriers and policy options'. *Clean Energy Council*.

Sioshansi, R., Denholm, P., Jenkin, T., Weiss, J, 2009, 'Estimating the value of electricity storage in PJM: arbitrage and some welfare effects', *Energy Economics*, 31, p269-277.

Walawalkar, R., Apt., J and Mancini., R, 2007, 'Economics of electric energy storage for energy arbitrage and regulation in New York', *Energy Policy*. 35, p2558-2568.