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Renewable energy integration into the Australian National Electricity Market: Characterising the energy value of wind and solar generation

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ABSTRACT

This paper examines how key characteristics of the underlying wind and solar resources may impact on their energy value within the Australian National Electricity Market (NEM). Analysis has been performed for wind generation using half hour NEM data for South Australia over the 2008-9 financial year. The potential integration of large scale solar generation has been modelled using direct normal solar radiant energy measurements from the Bureau of Meteorology for six sites across the NEM.

For wind energy, the level and variability of actual wind farm outputs in South Australia is analysed. High levels of wind generation in that State have been found to have a strong secondary effect on spot prices. Wind generation's low operating costs will see it displacing higher operating cost fossil-fuel plant at times of high wind. At the same time, the increased variability of wind may impose additional challenges and costs on conventional plant which will also be reflected in wholesale spot market prices. It is shown that this is proving particularly important during high wind penetration periods, which are contributing to an increased frequency of low or even negative prices.

The solar resource in South Australia is shown to be highly variable; however, as seen with wind power, geographical dispersion of generators can significantly reduce power variability, even with as few as six sites. The correlation of the solar resource with spot prices also appears to be superior to wind generation. Modelling using the Adelaide solar resource showed that, for electricity sold into the spot market, two-axis tracking solar generators would achieve an average price that is over twice that received by wind generators over the year 2008-9 analysed. Of course, significant solar generation deployment might drive similar price impacts as seen with wind generation, thereby reducing this advantage. Considering the potential implications of both major wind and solar generation within South Australia, the solar and wind resources within the State appear, on average, to be non-correlated for the magnitude, and the change in magnitude, across half an hour.

The analysis shows that solar and wind resources within the NEM have key characteristics that can markedly impact on their energy value within the wholesale electricity market. High levels of renewable electricity are already affecting spot prices, highlighting the need for low bidding renewable generators to attain power purchase contracts and for developers to consider this effect when choosing a site location for renewable generators. Other generators within the NEM may also be significantly impacted by major renewable energy deployment. The long-term success of renewable generation will likely depend on maximising the energy value that it contributes to the electricity industry.

Keywords: Energy value, Integration, NEM, Solar, Variability, Wind

1.0 INTRODUCTION

Growing climate change concerns have heightened Australian interest in harnessing renewable energy resources including wind and solar. Deployment to date of these technologies in Australia is modest compared to numerous countries, however, a combination of supportive policy with the Mandatory Renewable Energy Target (MRET), an excellent wind resource and high site availability has seen South Australia achieve a world leading wind energy penetration. It is also now seeing greater wind deployment under the recently legislated expanded Renewable Energy Target (AEMO, 2010). The State also has an excellent solar resource and recent funding commitments from the Federal Government are expected to lead to the deployment of major solar (both PV and thermal) generation projects within high solar insolation regions.

South Australia is part of the Australian National Electricity Market (NEM) which covers all States and Territories other than Western Australia and the Northern Territory and establishes a common set of industry market arrangements. The result is that South Australia presents an opportunity to examine the implications of high wind penetrations across the NEM, and the potential implications of large-scale solar deployment.

This paper undertakes this task through examining how key characteristics of the underlying wind and solar resources may impact on their energy value within the NEM. Factors impacting the energy value of the resource include the variability and uncertainty of the resource, and its relationship with regional demand and wholesale energy prices. As renewable energy penetrations increase, the potential impacts of this variable and somewhat unpredictable generation on the operation of other generators and consequent market prices can be expected to increase. The low operating cost of wind farms means that wind generation can displace higher operating cost fossil-fuel plant and reduce prices. However, its variability and uncertainty will also put more demands on conventional plant operation that could conceivably increase prices. Significant solar generation may also add to this effect, creating issues for attaining the true energy value of the generation.

Other impacts of increasing renewable generation include growing security and reliability concerns within the NEM. The focus of our analysis is on the commercial aspects of half hour spot market operation on market participants. However, the design of the NEM closely links market prices to security concerns through a spot price that can range from -$1000/MWh to $12,500/MWh so such issues can be at least partially identified in our analysis.

2.0 DATA & METHODOLOGY

Analysis has been performed using half hour NEM data, obtained from the Australian Energy Market Operator (AEMO) website[1], for South Australian wind farm outputs, State electricity demand, interconnector flows and regional wholesale spot electricity prices. The data used is for the period 1st July 2008 to 1st July 2009 at which time the total rating of the nine wind farms was around 740 MW. Six of the wind farms were non-scheduled NEM participants whilst the remaining three where scheduled. Two of the wind farms had constraints placed upon them for the first 4 months of the period studied. Thus over this period the total rating of the wind farms increased around by 100 MW, with one wind farm still appearing to be operating at a maximum of around 54 MW instead of its installed capacity of 70 MW. Further information on the data

[1] AEMO website: www.aemo.com.au

acquisition is available in the appendix. The combined output of the nine wind farms of South Australia will be referred to from here on as SA Total Wind.

To analyse the potential integration of large scale solar generation within the NEM, operational information from several large-scale international solar plants has been used, along with estimates of solar plant outputs within the State, derived using half hourly direct normal solar radiant energy measurements for six sites across the NEM from the Bureau of Meteorology. These were obtained for the same period, 1st July 2008 to 1st July 2009. The locations of the six sites can be seen in Table 3 in the Appendix. The data has been collected using ground based pyrheliometers mounted on a solar tracker and is accurate to within about 2%. The measurement values were converted into half hour direct normal solar irradiance values. As only daylight hours are of interest in this analysis any time interval with radiation levels for at least five of the six sites equal to zero were deleted. For the majority of the analyses solar radiant energy measurements from the Adelaide Airport meteorological station (Adelaide being the capital of South Australia and its main load centre) have been used, to allow comparisons with the South Australian combined wind farm generation.

3.0 RENEWABLE RESOURCES AND DEMAND VARIABILITY

Figure 1 and Figure 2 demonstrate the type of output pattern that can be expected from wind generators and the solar resource.

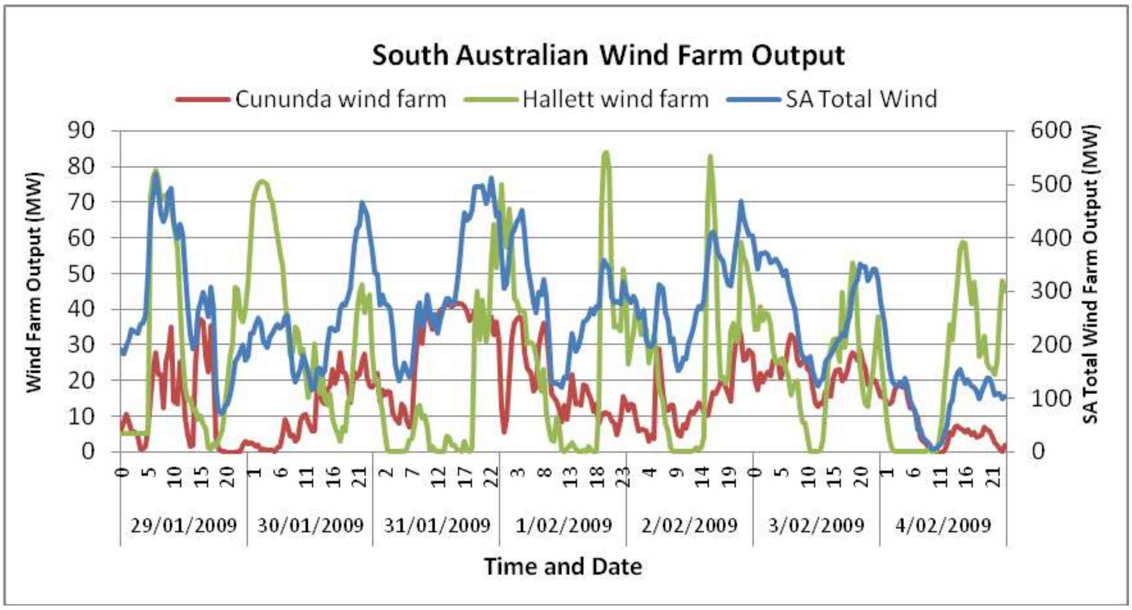

Figure 1: Wind farm outputs and the combined South Australian wind farm output for the 29th of January to the 4th of February 2009.

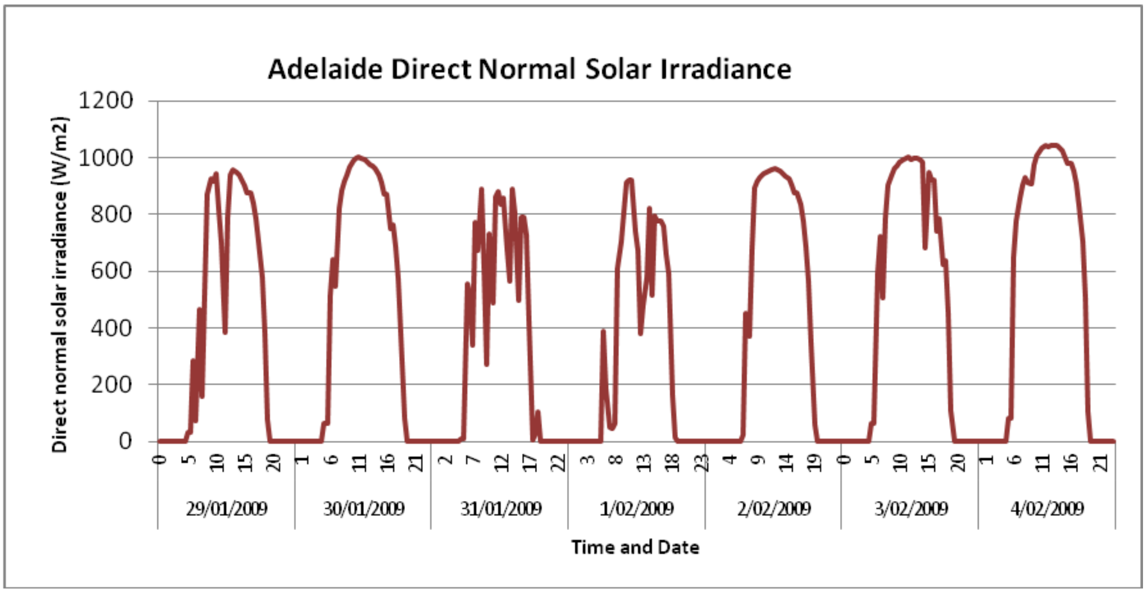

Figure 2: Adelaide direct normal solar irradiance for the 29th of January to the 4th of February 2009.

Figure 3 shows the average of South Australia's total wind farm generation and the average change in wind farm generation throughout the day for each season during the 2008-09 financial year. Two standard deviations for each average are presented for each half hour. It can be seen that the standard deviation is quite constant throughout each day and each season. It can also be seen that the two standard deviations for the change in wind power is much smaller than two standard deviations for the actual amount of wind power. Note however that this figure uses values from the combined output of the nine wind farms of South Australia, meaning that the reduction in the standard deviation from the effect of geographic dispersion is already included.

Figure 4 is similar except that it uses the direct normal solar irradiance measurements from Adelaide Airport. Note that the two standard deviations for the change across half an hour are of a similar magnitude to the two standard deviations of the solar irradiance level. However as this is a single measurement location the effect of geographic dispersion on reducing the standard deviation is not included. A characteristic of the solar resource is that the times of maximum variability obviously occur during daylight hours, which coincide with higher load levels. This has the benefit that a change in solar generator output will generally be occurring during reasonable levels of demand. During these times there will be higher levels of other generators online to adjust their outputs to ensure the supply demand balance is maintained. The disadvantage is that rapid reductions in solar power output could occur during very high demand periods, leading to price peaks.

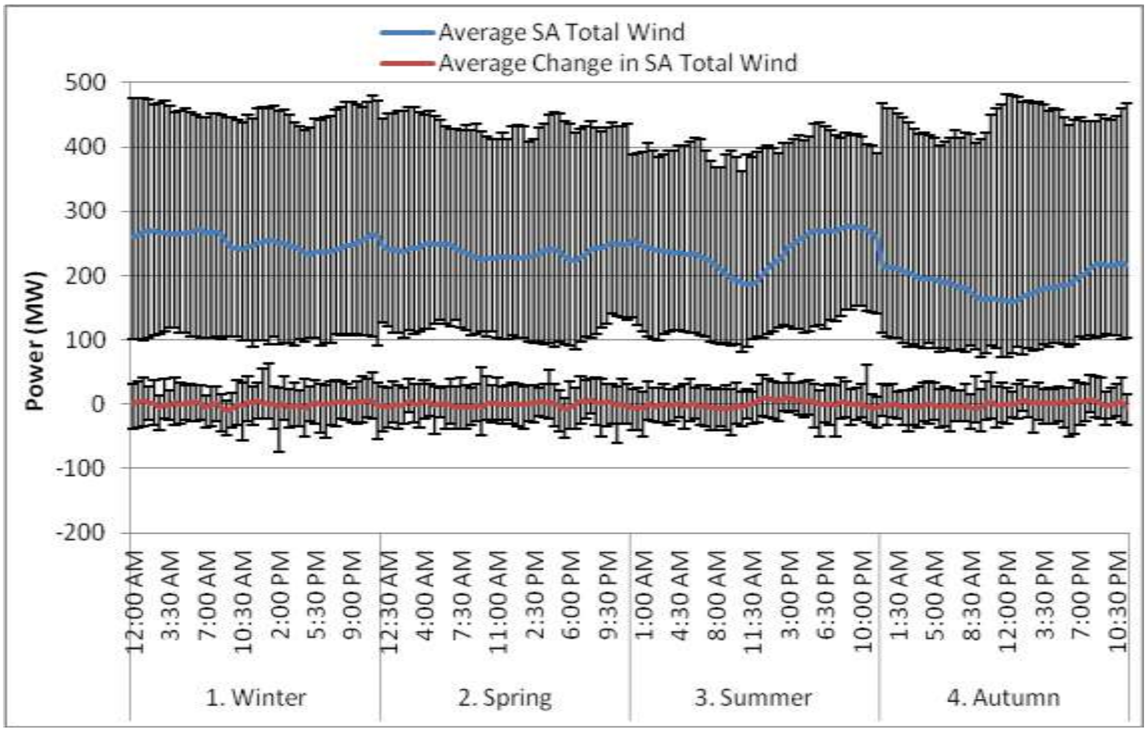

Figure 3: South Australia's average total wind farm output and average change in wind farm output for each season for the 2008-09 financial year. Two standard deviations are displayed for each average for each half hour.

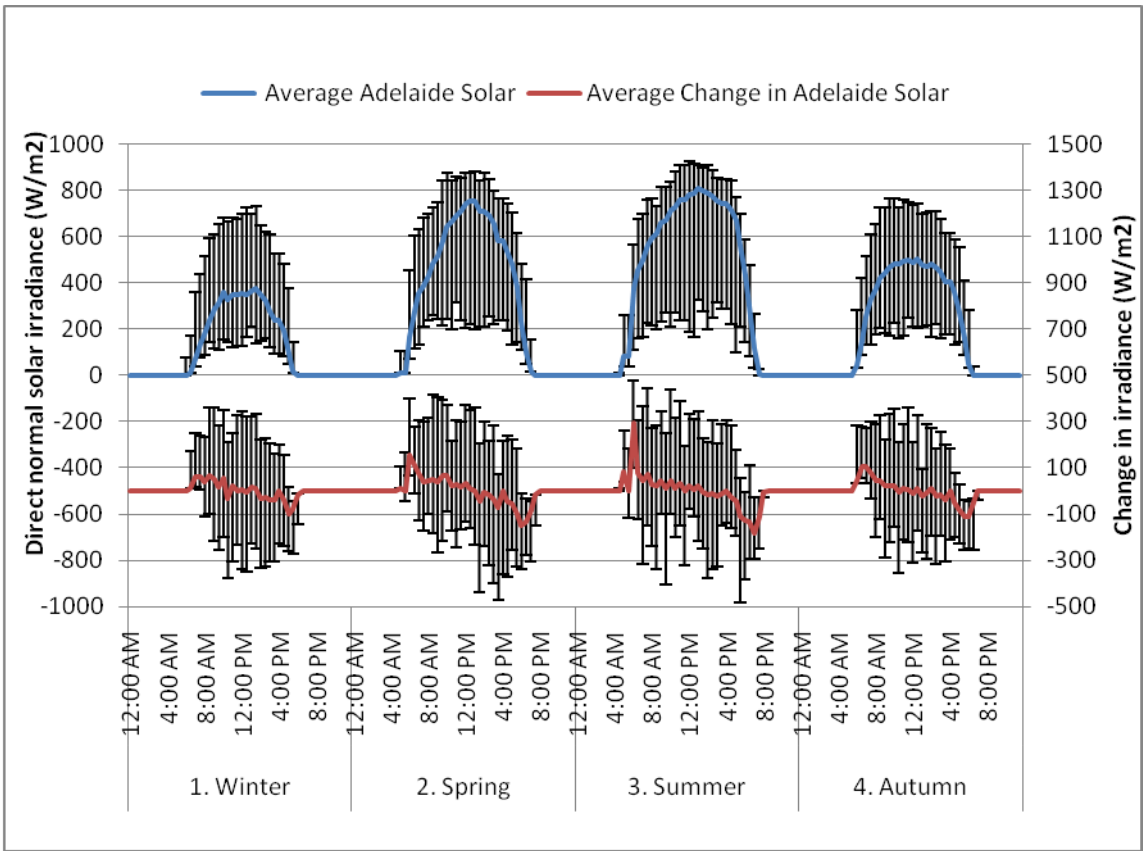

Figure 4: Adelaide's average direct normal solar irradiance for each season for the 2008-09 financial year. One standard deviation is displayed for the change in irradiance output across half an hour.

The daily solar resource profile obviously follows a diurnal pattern, which, on average peaks about noon. The resource also has a much stronger intensity during the summer and spring periods. Results to date show that SA Total Wind has no strong diurnal or seasonal pattern. Further detail on the resource profiles can be found in work by Boerema (2010) and Cutler (2009). Table 1 shows the maximum changes occurring over half an hour for the 2008-9 financial year. SA Total Wind has been normalised using 727 MW. Hallett S1 (a wind farm of South Australia) has been normalised using its rated capacity of 94.5 MW. Adelaide Solar is direct normal solar irradiance and has been normalised using 1000 W/m^2. For demand the maximum and minimum change and percentage change is shown. Figure 5 shows the probability of a level of change occurring over half an hour. The figure shows the comparatively high level of variability that is to be expected from the solar resource. Note however that the solar measurements are point source measurements, whilst the data for Hallett S1 incorporates an entire wind farm consisting of 45 turbines each rated at 2.1 MW (Baker, 2010). This creates difficulty in comparing variability between the resources. The diversity apparent between the two resources will also reduce the overall variability and will be covered further in the following sections.

Table 1: Maximum increases and decreases over half an hour for the 2008-09 financial year.

	SA Total Wind (MW)	Hallett S1 (MW)	Adelaide Solar (W/m2)	SA Demand (MW)
Maximum decrease	-186.8	-71.36	-902.7	-201.7
	-25.7%	-75.5%	-90.3%	-9.1%
Maximum increase	175.8	70.2	782.5	213.5
	24.2%	74.3%	78.3%	15.4%

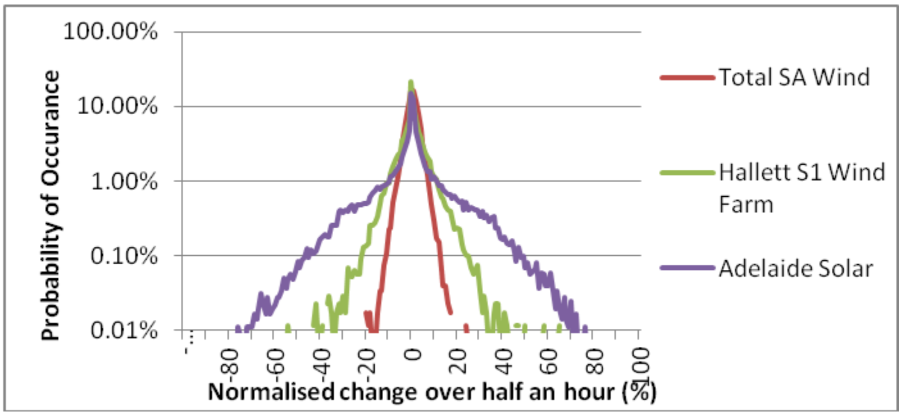

Figure 5: Probability of a change occurring over half an hour.

4.0 EFFECT OF GEOGRAPHICAL DISTRIBUTION

The average variability of power supplied by wind farms has been shown by Ernst et al. (1999) to reduce with geographical distribution of the wind farms. The average variability of the solar irradiance across the six sites was determined to establish if this reduction also occurs for the solar resource, compared to the variability of a single site.

Figure 6 is constructed using the largest changes observed for the entire data range at Adelaide and for the average of the six sites. The figure illustrates the large changes in irradiance levels that need to be expected for successful integration of solar technologies into the NEM. For generators whose outputs are sensitive to these changes, such as any of the solar technologies that do not include storage, the benefit of dispersing the technology across a greater number of sites can be appreciated and is considerable even for only six sites. For a particular time scale, if there are N completely uncorrelated but equivalent sites the average of the aggregated variability theoretically scales with $^1/\sqrt{N}$ relative to the variability of a single site (Mills, Ahlstrom et al., 2009).

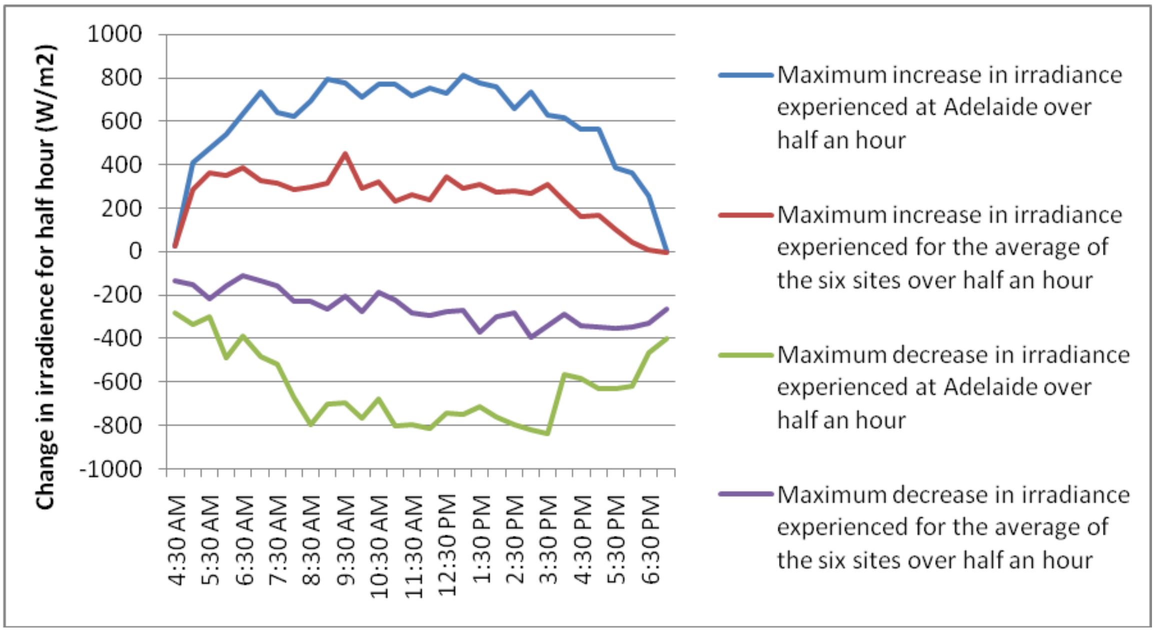

Figure 6: Maximum irradiance changes for time intervals for Adelaide and for the average of the six sites.

Figure 7 demonstrates the reduction in variability when considering the average of the six sites compared to one site. As can be seen, for the same probability of occurrence, the level of absolute change that can be expected is significantly reduced compared to a single site.

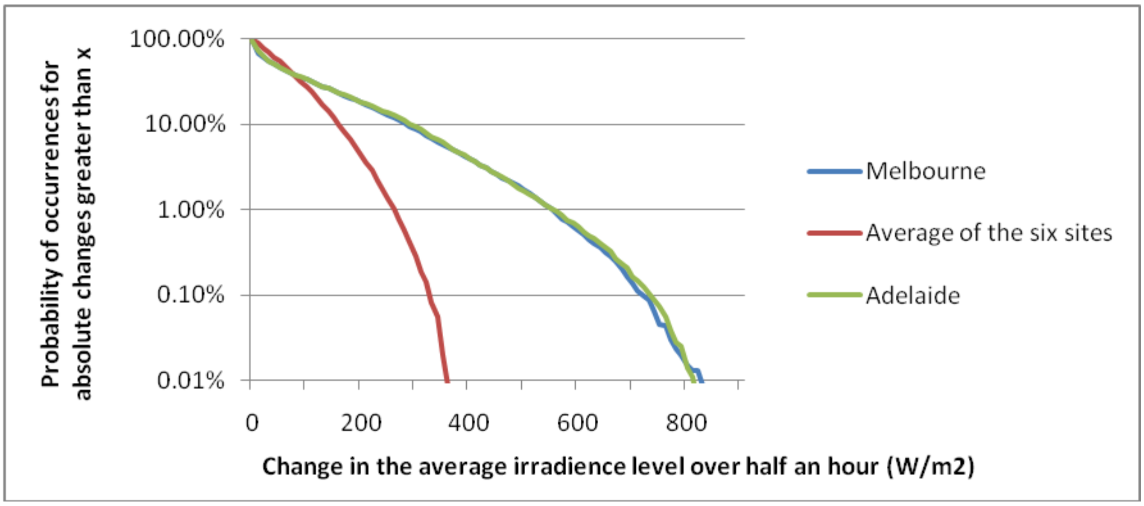

Figure 7: Probability of a change in irradiance levels occurring of magnitude greater than x.

5.0 CORRELATION OF THE WIND AND SOLAR RESOURCES WITH DEMAND

In South Australia daylight hours coincide with higher load levels as has been shown by Cutler (2009). This has the benefit that a change in solar generator output will generally be occurring during reasonable levels of demand (see Figure 8a). During these times there will be higher levels of other generators online to adjust their outputs to ensure the supply demand balance is maintained. The disadvantage is that rapid reductions in solar power output could occur during very high demand periods, leading to an increased number of price peaks. Alternatively the combined wind farm outputs of South Australia appear to have no clear correlation with demand, this has been further detailed by Cutler (2009).

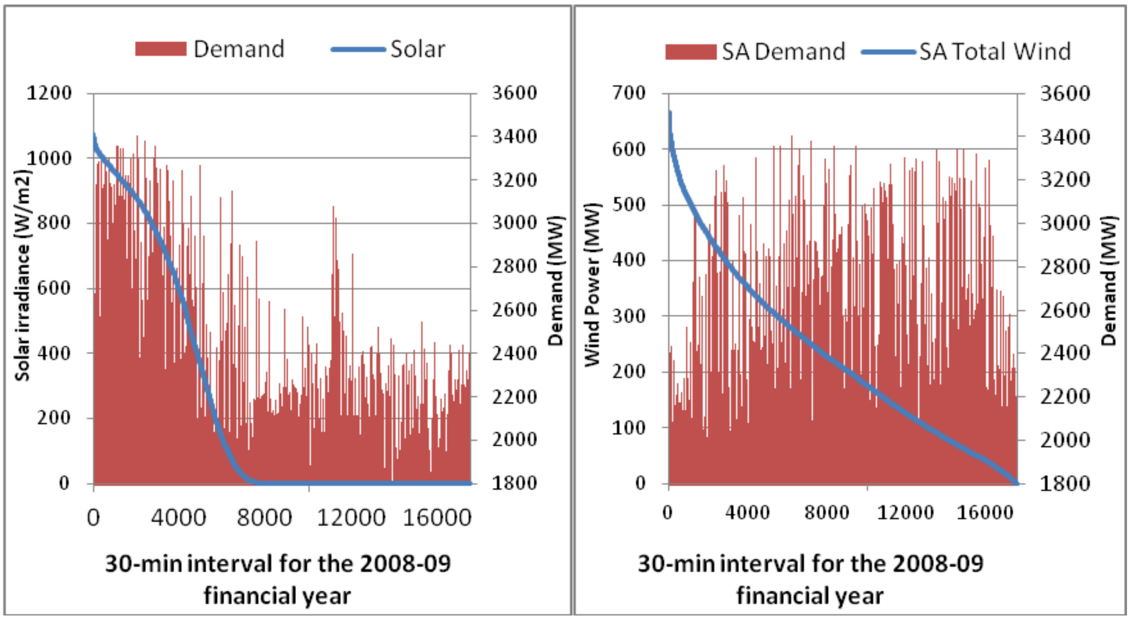

Figure 8: a) Adelaide solar and b) SA total wind. Duration curves for 2008-09 with corresponding SA demand.

6.0 CORRELATION OF THE WIND AND SOLAR RESOURCES WITH SPOT PRICES

Assuming a linear relationship between generator output and the solar resource, which is approximately true for two axis tracking PV, the average price for the financial year of 2008-09 that would have been achieved in South Australia was near to $102 per MWh. Comparatively, the combined output of the wind farms of South Australia achieved less than half of this value, around $47 per MWh, for the same period. This is due to the solar resource having a high correlation to the level of load (Figure 8) which in turn has a high correlation to the price as demonstrated by Cutler (2009). This results in many of the higher prices coinciding with times of high solar irradiance, as can be seen in Figure 9. In contrast it can be seen that there is a high count of negative price events at high levels of the combined SA wind farm output. As detailed by Cutler (2009) this appears to be due to wind having a secondary influence on the spot price.

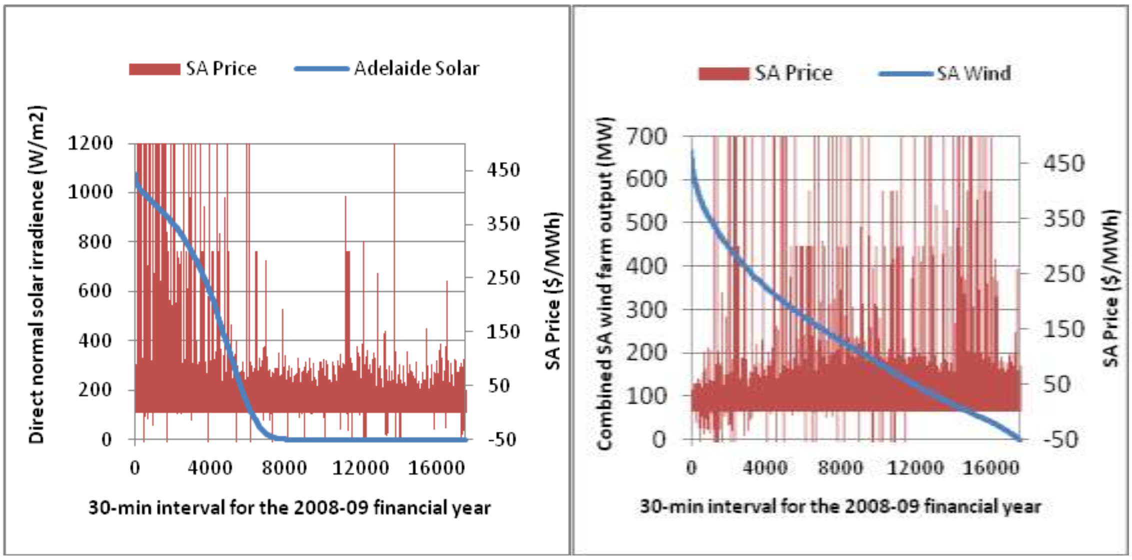

Figure 9: a) SA Solar and b) SA total wind. Duration curves for 2008-9 with the corresponding prices (price axis limited to between -50 and 500 $/MWh for visibility).

Of particular importance is the effect that wind appears to be having at high penetration levels. Wind on average is quite constant for all prices whilst the demand on average decreases with decreasing price. This means that during low demand periods, the penetration level of wind will on average be higher. The low operating cost of wind farms means that wind generation will displace the higher operating cost fossil fuel generation, in effect reducing market prices. Furthermore, generators with relatively inflexible plant will often bid some portion of their capacity at negative prices to try and guarantee their dispatch. These generators will often have derivative contract cover that shields their revenue stream from low prices. The result of this is that during high wind penetration periods, low or even negative prices are to be expected, as can be seen in Figure 10. The deployment of solar generators that also have low operating costs is likely to further exaggerate this phenomenon. This poses a significant issue for wind and solar investors, and highlights the necessity of low bidding generators to attain power purchase agreements.

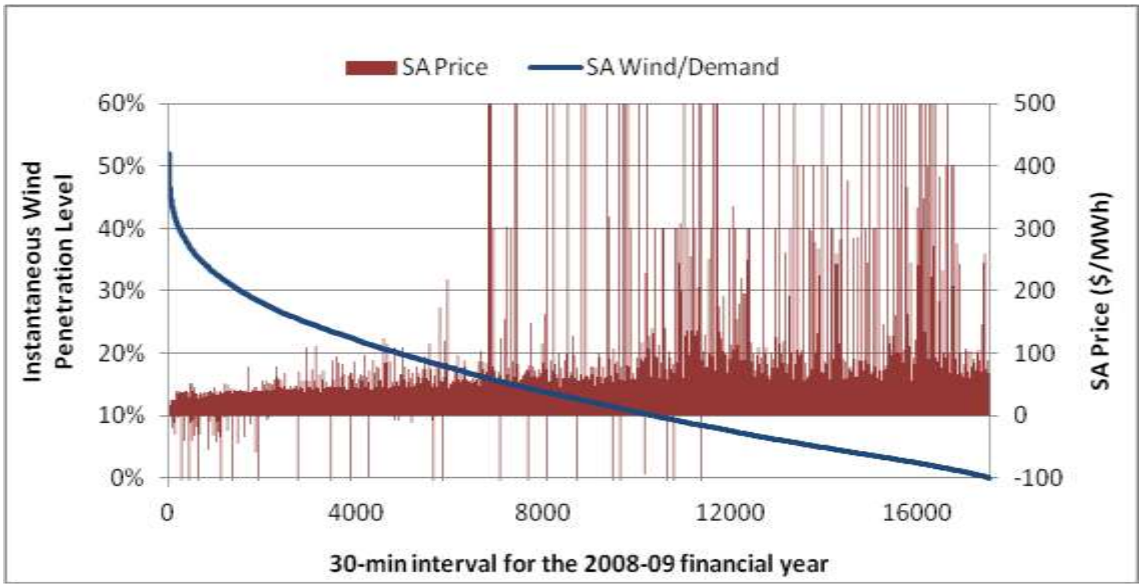

Figure 10: SA half hour wind penetration (total wind power/demand) duration curve with corresponding prices (price axis limited to between -100 and 500 $/MWh for clarity).

7.0 CORRELATION BETWEEN THE WIND AND SOLAR RESOURCES

As both wind and solar generators may coexist within the same region it is important to understand how the different resources interrelate. An increase in the net variability of supply and demand has the potential to increase price volatility and ancillary service needs.

The arrival of a weather system to a location can result in a simultaneous change in both the wind and solar resources. The change can be both negatively or positively correlated. A negative correlation would result in a smoothing of the overall energy supply from these resources, whilst a positive correlation would result in an increase in the ramp rate. The combined South Australian wind farm outputs and the direct normal solar irradiance data for Adelaide were used to determine whether synergies existed between the wind and solar resources.

Figure 11 shows the average over 24 hours of the SA Total Wind and the direct normal solar irradiance for Adelaide. It can be seen that for the majority of days the magnitudes of the two resources are largely uncorrelated. A similar lack of correlation was also found between the wind and solar resources for the amount of variability on a given day and between the level of solar variability and the amount of wind across the state (see (Boerema, 2010)).

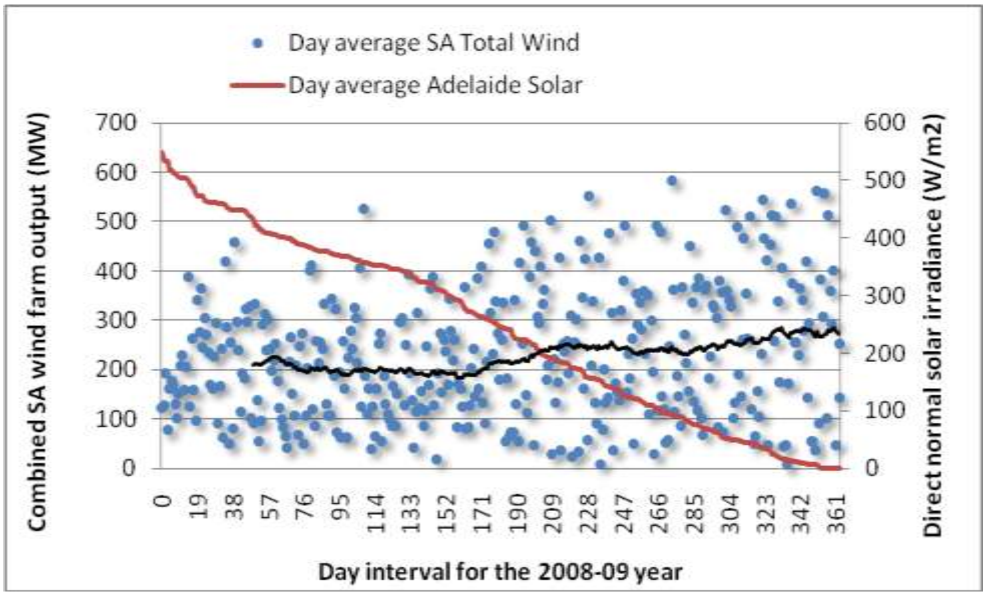

Figure 11: SA Total Wind and Adelaide solar irradiance averaged over 24 hours and sorted for solar. The moving average for the combined output of the SA wind farms is also shown (50 data points per window).

The lack of correlation for the majority of changes between the wind and solar resources will create a decrease in the level of variability for the combined power output, compared to the power being delivered from either just wind or solar. Note however that any increase in either wind farm capacity or solar technology with minimal or no storage, such as PV, will add to the absolute variability. Whilst the occasions of coinciding large ramp rates for the demand and the renewable technologies may be infrequent, they will invariably occur. This emphasizes the importance of improved forecasting to assist NEM participants in managing such variability and uncertainty as penetrations of wind and solar increase. The selection of solar technologies with storage over those without will facilitate integration and higher penetration levels. Currently however there are only limited economical signals to encourage such decision making. Greater levels of peaking plant capacity will be required to maintain the supply-demand balance with the same level of reliability during high ramp rate periods. Pre-emptive development of a forecasting system and the deployment of peaking generation would seem to be of growing importance for ensuring a robust and efficient transition into a high renewable penetration electricity market.

8.0 LOW BIDDING GENERATOR EFFECT ON SPOT PRICES.

During the period analysed the combined output of the South Australian wind farms achieved half hour penetration levels of greater than 50% and had an average penetration of 14.4%. At the time of writing, the variability in SA Total Wind had not yet surpassed that of the demand, however it is adding to the overall variability.

Figure 12 displays a wind variability duration curve with the days corresponding average spot price. This figure shows that days of high wind variability are not leading to days of higher average prices. It was also found that days of high wind variability are not leading to days of high price variability. This result is significant for showing the level of variability that can be managed. It is apparent that this variability is at least partly being managed through flows on the two transmission interconnectors to Victoria as discussed in the next section. This option will likely be reduced as South Australia's and Victoria's wind penetration increases, particularly if there is a correlation of the wind resource between the two regions. The use and benefit of interconnectors to manage wind power variability has been well documented for other high wind penetration countries (Garrad Hassan, 2005). Whilst the figure shows that wind variability does not yet appear to be affecting spot prices, we have not yet assessed potentially complicating factors such as Frequency Control Ancillary Services (FCAS) prices.

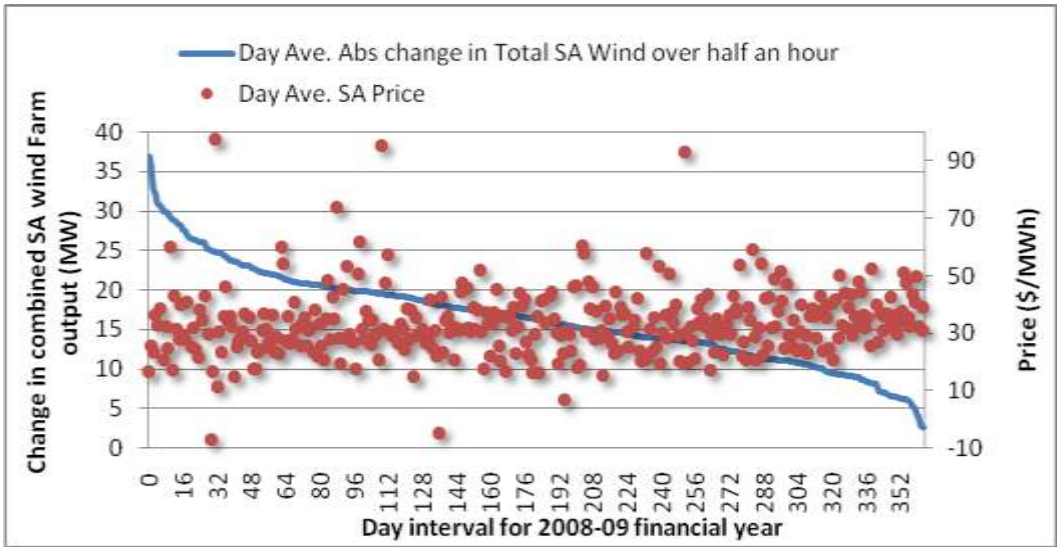

Figure 12: The average for each day of the change in Total SA wind power across half an hour and the corresponding spot price.

9.0 INTERCONNECTOR ABILITY FOR MANAGING VARIABLE GENERATION.

Victoria's demand is on average about 3.7 times greater than that of South Australia's, averaging 1561 MW and 5798 MW during 2007-08 for South Australia and Victoria respectively (AEMO, 2009). This means that Victoria would need an installed wind farm capacity of about 2700 MW to achieve a similar generation penetration level as South Australia during this period, significantly more than the States current 384 MW of wind capacity (ABARE, 2010). The high capacity of hydropower available within Victoria, which has very fast ramp rate abilities, would also assist the ease of utilisation of wind energy within Victoria, as would its interconnection to the state of New South Wales and Tasmania. Thus, South Australia's ability to manage wind generation variability through the use of its Victorian interconnectors is currently mainly limited by the capacity and security constraints of the interconnectors.

Figure 13 shows a SA Total wind penetration duration curve for 2008-9 with corresponding combined interconnector transmission (Vic to SA). Whilst interconnector flows are complex, it does appear that at least on average the Victorian region is contributing to managing high penetration levels of wind power within South Australia. On some occasions, at high wind penetration, the interconnector constraints are already being reached as can be observed in Figure 13 by the clear minimum export limit (from Victoria) of -420 MW. This is the minimum permitted export for the combined interconnector transmission (ElectraNet, 2010). Increasing the wind and solar generation within South Australia is likely to result in the interconnectors having a lower effectiveness in assisting to maintain the systems security and reliability.

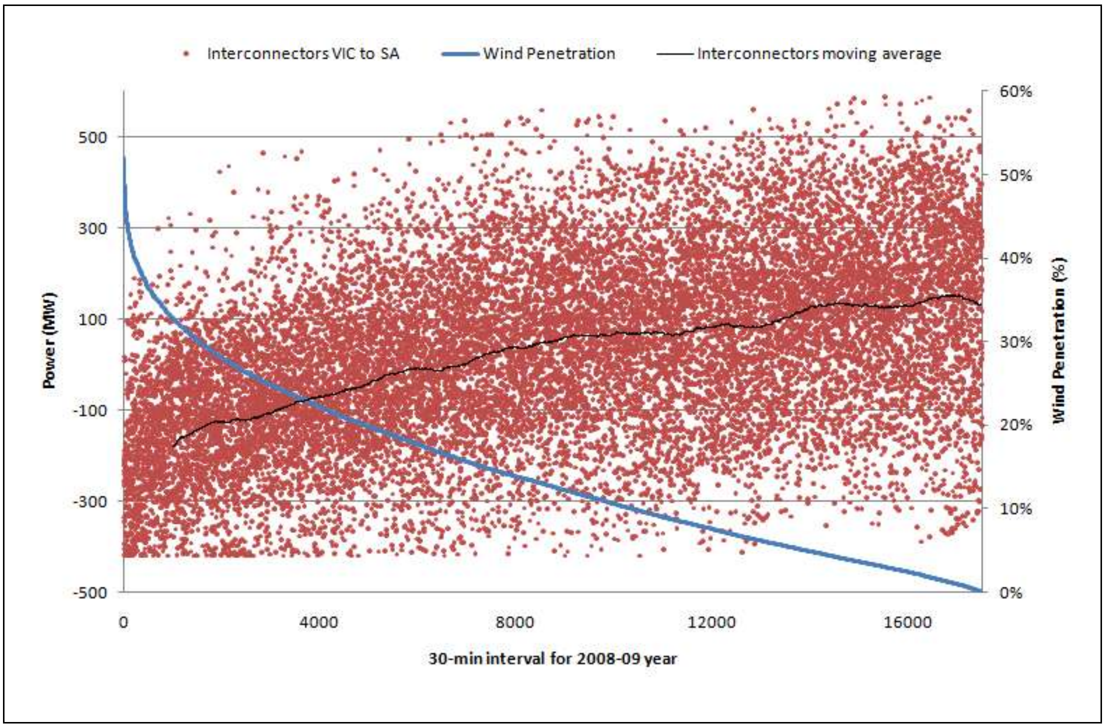

Figure 13: Penetration duration curve for 2008-09 with corresponding interconnector transmission (Vic to SA) and moving average (999 data points per window).

10.0 CONCLUSION

This paper has presented a characterization of the wind and solar resources within a key region of the NEM to determine how these resources may impact upon their energy value.

The method focused on using data available for South Australia where a high wind penetration is already present and where significant solar projects are planned. The results presented however can be used for understanding the possible issues as wind and solar penetrations increase across the rest of the NEM.

The solar resource is highly variable, however, it has been shown that geographical distribution of the solar generators, along with the non-correlation between the wind and solar resources will reduce the normalized variability. This will allow greater wind and solar penetration for the same level of variability. It was detailed that any increase in wind or solar capacity will lead to an increase in the overall variability of the system, highlighting the importance of improved wind and solar power forecasting, an area recommended for further study.

Another finding was that at current levels, wind variability does not appear to be leading to increased spot price volatility or higher spot prices, even though it is increasing the overall variability. This shows that the system is currently managing the added variability. It was detailed however, that the interconnectors are likely contributing to the management of wind variability and that as wind and solar penetrations increase their ability to continue to ensure system security and reliability will be diminished, unless interconnector capacity is increased.

Along with spot prices, FCAS prices and the level of use of FCAS are also important. Volume weighted FCAS prices are now being published on the AEMO website. This will allow for data analysis to be performed to determine the effect of wind penetration and wind variability on these prices and is a recommended research area.

The operation arrangements of electricity industries do not always accurately capture the energy value of different generation technologies. It has been shown that spot prices are likely to be low or even negative during high penetration periods of wind and low operational cost solar. This is an important finding for low-bidding generators and emphasizes the importance of power purchase contracts, such that income may be attained that better reflects the energy value of the energy supplied. Due to the variability inherent in the generation, traditional contracts are not as effective at minimising financial risk and thus alternative contracts are recommended as a topic for further study.

The solar resource more closely matches the demand and price profiles compared to wind generation. It was found that, as a result of this, solar generators would have, for the financial year 2008-9 in South Australia, potentially achieved an average price that is about twice that received by wind generators. Of course significant solar generation deployment may also drive similar price impacts as seen with the current wind generation reducing the price advantage of the solar resource.

Renewable generation in Australia will invariably displace some existing conventional fossil-fuel generation. However which generators are displaced depends on the various factors including the supply characteristics of the renewable generators, demand correlation, penetration, the bidding prices of both the renewable and conventional generators, and the possible ramp rates and start up times of the conventional generators. Interconnector and transmission capabilities along with generation in interconnected regions will also be important factors. Predicting which generators are likely to be displaced is important as it affects the economics of renewable generators, as we have seen, and the emissions reductions created. It will also be important for the economics of the conventional generators. Thus it is also recommended that further work is undertaken in this area.

APPENDIX

Table 2: National Electricity Market data information.

Data name	Description and comments	Location
SA Demand	From "Aggregated Price and Demand data in the Operational Market Data". Native demand for SA to be met by scheduled and non-scheduled generation is calculated by adding this demand figure to non-scheduled wind power generation.	http://www.aemo.com.au/data/aggPD_2006to2010.html (and requires 'non-scheduled wind power generation' – see below)
SA Price	NEM spot prices in South Australia from same data set as above.	Same as above
Non-scheduled wind power generation	The measured (metered) generation output from the 6 currently non-scheduled wind farms in SA. These are obtained with 5-min resolution but averaged in 30-min intervals. Total rating: 388.25 MW	http://www.aemo.com.au/data/csv.htm. See archived non-scheduled generation data.
Scheduled wind power generation	The dispatched scheduled generation from the 3 currently scheduled wind farms in SA. Total rating: 353.5 MW	http://www.aemo.com.au/data/csv.htm. See archived daily aggregated dispatch data.

Table 3: Solar resource measurement sites.

Name	State	Latitude	Longitude
ALICE SPRINGS AIRPORT	NT	-23.7951	133.889
ADELAIDE AIRPORT	SA	-34.9524	138.5204
ROCKHAMPTON AERO	QLD	-23.3753	150.4775
WAGGA WAGGA AMO	NSW	-35.1583	147.4573
MILDURA AIRPORT	VIC	-34.2358	142.0867
MELBOURNE AIRPORT	VIC	-37.6655	144.8321

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