Wind speed and electricity demand correlation analysis in the Australian National Electricity Market: Determining wind turbine generators' ability to meet electricity demand without energy storage

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The University of Queensland

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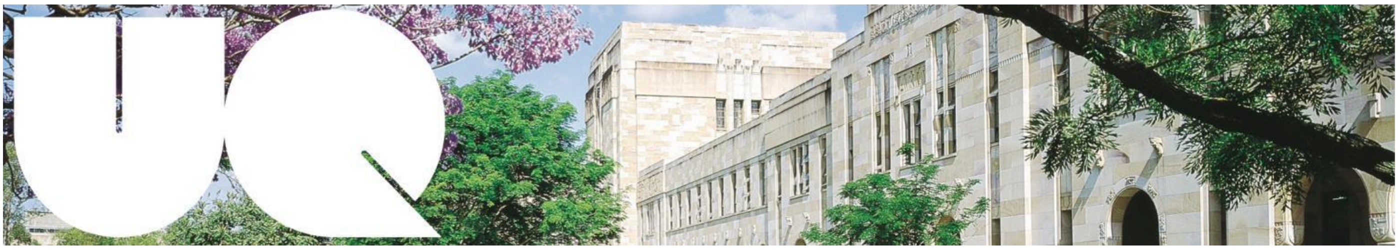

Wind speed and electricity demand correlation analysis to determine the ability of wind turbine generators to meet electricity demand in the Australian National Electricity Market

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ARC Linkage Project (LP110200957, 2011-2014) - An investigation of the impacts of increased power supply to the national grid by wind generators on the Australian electricity industry

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Preface

This report analyses wind speed and electricity demand correlation to determine the ability of wind turbine generators to meet electricity demand in the Australian National Electricity Market without the aid of energy storage. The report is part of research project titled: *An investigation of the impacts of increased power supply to the national grid by wind generators on the Australian electricity industry: ARC Linkage Project (LP110200957, 2011-2014).*

The aim of the project is to discover the most economical and effective way to accommodate large increases in wind power into the national grid and to understand the effects on the national electricity market. This is crucial to ensure stability of electricity supply and affordable prices in the transition towards a low carbon economy.

Significant increases in Australian power generation using wind are planned for the coming years. This project answers urgent questions concerning the capability of the existing power grid to cope with a volatile source of supply, required grid modifications, impacts on the national electricity market (NEM), the optimal placement of wind farms and the Large-scale Renewable Energy Target (LRET). This is, necessarily, an interdisciplinary project involving economists, electrical engineers and climate scientists with very strong support from the wind generators. A coherent government policy to phase in renewable energy in a cost effective manner will not be possible without high quality research of this kind.

The project's electricity market modelling tool is the *Australian National Electricity Market (ANEM) model version 1.10 (Wild et al. 2015). Wild et al. (2015)* provides extensive details of the version of the ANEM model used in this project and the wind speed and electricity demand calculations used in this report. Table 1 provides a list of the project's interim and final reports.

Table 1: The project's publications

Journal articles:

Bell, WP, Wild, P, Foster, J, and Hewson, M (2015), Wind speed and electricity demand correlation analysis in the Australian National Electricity Market: Determining wind turbine generators' ability to meet electricity demand without energy storage, *Economic Analysis & Policy*, Vol. In press.

Wild, P, Bell, WP and Foster, J. (2015) Impact of Carbon Prices on Wholesale Electricity Prices and Carbon Pass-Through Rates in the Australian National Electricity Market. *The Energy Journal*, *36* 3: doi:10.5547/01956574.36.3.5

Final reports:

Bell, WP, Wild, P, Foster, J, and Hewson, M (2015), *Australian National Electricity Market Model version 1.10*, EEMG Working Paper 2-2015, The University of Queensland, Brisbane, Australia.

Bell, WP, Wild, P, Foster, J, and Hewson, M (2015), *The effect of increasing the number of wind turbine generators on transmission line congestion in the Australian National Electricity Market from 2014 to 2025*, EEMG Working Paper 3-2015, The University of Queensland,

Brisbane, Australia.

Bell, WP, Wild, P, Foster, J, and Hewson, M (2015), *The effect of increasing the number of wind turbine generators on wholesale spot prices in the Australian National Electricity Market from 2014 to 2025*, EEMG Working Paper 4-2015, The University of Queensland, Brisbane, Australia.

Bell, WP, Wild, P, Foster, J, and Hewson, M (2015), *The effect of increasing the number of wind turbine generators on carbon dioxide emissions in the Australian National Electricity Market from 2014 to 2025*, EEMG Working Paper 5-2015, The University of Queensland, Brisbane, Australia.

Bell, WP, Wild, P, Foster, J, and Hewson, M (2015), *The effect of increasing the number of wind turbine generators on generator energy in the Australian National Electricity Market from 2014 to 2025*, EEMG Working Paper 6-2015, The University of Queensland, Brisbane, Australia.

Bell, WP, Wild, P, Foster, J, and Hewson, M (2015), *NEMLink: Augmenting the Australian National Electricity Market transmission grid to facilitate higher wind turbine generation and its effect on transmission congestion*, EEMG Working Paper 9-2015, The University of Queensland, Brisbane, Australia.

Bell, WP, Wild, P, Foster, J, and Hewson, M (2015), *NEMLink: Augmenting the Australian National Electricity Market transmission grid to facilitate higher wind turbine generation and its effect on wholesale spot prices*, EEMG Working Paper 10-2015, The University of Queensland, Brisbane, Australia.

Interim reports:

Wild, P, Bell, WP, and Foster, J (2014), *Impact of Transmission Network Augmentation Options on Operational Wind Generation in the Australian National Electricity Market over 2007-2012*, EEMG Working Paper 11-2014, The University of Queensland, Brisbane, Australia.

Wild, P, Bell, WP, and Foster, J (2014), *Impact of increased penetration of wind generation in the Australian National Electricity Market,* EEMG Working Paper 10-2014, The University of Queensland, Brisbane, Australia.

Wild, P, Bell, WP, and Foster, J (2014), *Impact of Operational Wind Generation in the Australian National Electricity Market over 2007-2012*. EEMG Working Paper 1-2014, The University of Queensland, Brisbane, Australia.

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Abstract

This paper analyses wind speed and electricity demand correlation to determine the ability of wind turbine generators to meet electricity demand in the Australian National Electricity Market (NEM) without the aid of energy storage. The paper is part of a project whose aim is to discover the most economical and effective way to accommodate large increases in wind power into the national grid and to understand the effects on the NEM. This is crucial to ensure stability of electricity supply and affordable prices in the transition towards a low carbon economy. Significant increases in Australian power generation using wind are planned for the coming years. This project answers urgent questions concerning the capability of the existing power grid to cope with a volatile source of supply, required grid modifications, impacts on the NEM, the optimal placement of wind farms and the Large-scale Renewable Energy Target (LRET).

We calculate correlations between wind speed and electricity demand data for the years 2010 to 2012 using Weather Research & Forecasting Model wind speed data and AEMO electricity demand data. We calculate State level correlations to identify potential bottlenecks in the interconnectors that link each State's transmission network. The transmission lines within each State tend to be less of a constraint.

We find a small temporal increase in correlation between electricity demand and wind speed. This we attribute to an unwitting renewable energy portfolio effect with the increase in Solar PV and Solar Water Heating. Strengthening this portfolio effect is the decline in manufacturing that makes domestic demand relatively larger. Comparing our study with an earlier correlation analysis by Bannister and Wallace (2011) tends to confirm our initial findings.

We find the most advantage from the lack of correlation between wind speed between the NEM's peripheral States including Queensland, South Australia and Tasmania. Additionally, the correlation between electricity demand and wind speed is strongest between these States. Similarly, we find the most advantage from the lack of correlation between electricity demands in each of these States. The self-interest groups within Victoria and NSW and the transmission companies being geographic contained within each State hinders the development of optimal interconnector capacity to maximise the benefit of wind power in the peripheral States and the NEM generally.

Keywords:

Wind speed
Electricity demand
Correlation
Australian National Electricity Market
Wind turbine generators
Renewable energy
Renewable energy portfolio
Solar PV

1. Introduction

This paper's primary aim is to analyses wind speed and electricity demand correlation to determine the ability of wind turbine generators to meet electricity demand in the Australian National Electricity Market (NEM) without the aid of energy storage. This research topic is important in two respects. The first is in evaluating the potential economic and network benefits that wind generation might possess in contributing capacity to meet peak load demand. The second relates to issues of network adequacy and geographic dispersion of wind resources to help achieve system balancing in the presence of intermittent wind power.

Of particular interest, is South Australia that has the highest penetration of wind generation in the NEM. In South Australia, the wind often blows during period of low electricity demand, producing a negative correlation coefficient between demand and wind speeds. Two factors exacerbate this situation in South Australia. (1) South Australia's baseload coal and gas thermal generation plant's inability to shut down and start-up quickly enough to balance wind power's intermittency or to reduce production below their minimum operating level. This leads to situations where wind power plus the minimum operating levels of baseload thermal generation exceeds demand in South Australia. (2) The relatively low thermal capacities of the two interstate interconnectors, Heywood and Murraylink, restrict South Australia's ability to export surplus power to Victoria. Both factors combine to produce negative prices in South Australia and the potential spilling of carbon-emission free wind power.

Given these considerations, a more general assessment of demand and wind speed correlations between and within the different States of the NEM would help determine whether similar situation occurs more generally in other states. Assessment of correlation between wind speeds in different regions of the NEM is the first step in identifying the potential to exploit geographical dispersion of wind power in system balancing. Balancing without energy storage requires shifting excessive wind power from one region where the wind is blowing to another region without wind. This latter consideration when combined with assessment of state and regional demand correlations informs debate about transmission adequacy to facilitate system balancing and to meet peak load demand. This paper forms part of the Australia Research Council Industry Linkage project titled *'An investigation of the impacts of increased power supply to the national grid by wind generators on the Australian electricity industry'.*

The correlation analysis in this paper uses half hourly wind speed and electricity demand profiles for the years 2010 to 2012 for windfarms and electricity demand centres across the NEM. In an earlier and similar study, Bannister and Wallace (2011) investigate the correlation between wind speed and demand in the National Electricity Market at the State level but their study excludes Queensland's wind speed. In contrast, we include the wind speed for Queensland and investigate regional wind speed correlations at the regional level.

Table 2: Correlation of wind speed and demand

		Demand					Wind speed			
		NSW	**QLD**	**SA**	**TAS**	**VIC**	**NSW**	**SA**	**TAS**	**VIC**
Demand	**NSW**	1								
	QLD	0.83	1							
	SA	0.81	0.67	1						
	TAS	0.72	0.54	0.58	1					
	VIC	0.89	0.75	0.85	0.78	1				
Wind Speed	**NSW**	0.08	0.11	0.05	0.1	0.07	1			
	SA	-0.16	-0.08	-0.07	-0.15	-0.16	0.34	1		
	TAS	-0.06	0.04	-0.06	-0.04	-0.04	0.31	0.24	1	
	VIC	-0.08	-0.05	-0.06	0	-0.05	0.44	0.64	0.47	1

(Source: Bannister & Wallace 2011, p. 15)

Section 2 discusses the methodology for the correlation analysis and the derivation of the wind speed and electricity demand profiles that are also detailed in *Wild et al. (2015).* Section 3 presents the results of the correlation analysis. Section 4 discusses and compare our results with Bannister and Wallace (2011). Section 5 concludes the paper.

2. Methodology: a correlation analysis between wind speed and electricity demand

The correlation coefficient analysis in this paper uses half-hourly electricity demand profiles and wind speeds from three calendar years 2010, 2011 and 2012 to produce both annual and a three-year correlation coefficient matrix between windfarms grouped by regional nodes and their nearest regional demand centres.

Section 1 discusses the derivation of the demand profiles and Section 2 discusses the derivation of the wind speed profiles. These discussions are a condensed extracts from Wild et al. (2015).

2.1. Demand profile derivation

This section discusses the derivation of half-hourly electricity "total demand" for the 50 regional nodes shown in Wild et al. (2015 figs. 2-6). We derived this load data for Queensland and New South Wales using regional load traces supplied by Powerlink and Transgrid. This data was then re-based to the state load totals published by AEMO (2014) for the 'QLD1' and 'NSW1' markets. For the other three States, the regional shares were determined from terminal station load forecasts associated with summer peak demand (and winter peak demand, if available) contained in the annual planning reports published by the transmission companies Transend (Tasmania), Vencorp (Victoria) and ElectraNet (South Australia). These regional load shares were then interpolated to a monthly based time series using a cubic spline technique and these time series of monthly shares were then multiplied by the 'TAS1', 'VIC1' and 'SA1' State load time series published by AEMO (2014) in order to derive the regional load profiles for Tasmania, Victoria and South Australia.

The "total demand" equates to the sum of the output of scheduled and semi-scheduled generation, large non-scheduled generation, transmission losses and large independent loads directly connected to the transmission grid. The "total demand" excludes contributions from small scale solar PV and WTG.

2.2. Wind speed derivation

The Weather Research & Forecasting Model (WRF 2015) provides the wind speed data for the project for the years 2010 to 2012. WRF is a *"numerical weather prediction and atmospheric simulation system for both research and operational applications"* (Skamarock et al. 2008, p. 1) that can generate 5-minute interval wind velocity at 90 meters above ground level for regions surrounding windfarms.

We use WRF version 3.5. This version corrects a known topographic effect on wind bias that exists in earlier versions (Jiménez & Dudhia 2013). We setup WRF in accordance using a physics scheme configuration found suitable for Australia (Evans, Ekström & Ji 2012) with the main selections being:

- Microphysics – WSM (WRF single moment) 3-class;
- Longwave radiation – RRTM (Rapid Radiative Transfer Model) scheme;
- Shortwave scheme – Dudhia scheme;
- Surface layer option – Monin-Obukhov scheme;
- Land surface option – Unified Noah land-surface model;
- Boundary layer option – YSU (Yonsei University) scheme;

- Cumulus option (outer domain only) – Kain-Fritsch scheme; and
- Vertical velocity damping switched on.

The WRF three dimensional spatial scheme used a standard three nested domain design which made optimal use of six-hourly Global Forecasting System reanalysed meteorological data archive, yet provided 1 km fine spatial resolution for the inner most domain. The model atmospheric depth was divided into 30 terrain following, sigma coordinate levels. Each WRF run was constrained to a calendar month with a 2-day prior spin-up time to equalise model dynamics and a model run time-step of 45 seconds. Taken together, these model configuration specifications were an optimal trade-off of WRF spatial and temporal accuracy against computing processing resources available to the project. The 5-minute interval, 90 m height wind speed data was extracted from selected wind farm positions within each of the 20 different model geographic scenes.

In this project, we use the latitude and longitude coordinates of representative clusters of Wind Turbine Generators (WTGs) based on existing or planned wind farms. We group existing and planned windfarms into five levels of wind penetration scenarios.

a. No wind generation
b. Operational and under construction
c. Advanced planning *(+all the windfarms above)*
d. Less advanced planning *(+all the windfarms above)*
e. Least advanced planning *(+all the windfarms above)*

Details of the windfarms within the five groups are in the project report *'ANEM model version 1.10'* (Wild et al. 2015, tbls. 4 & 5). However in this paper, we analysis only the wind speed of operational and under construction windfarms, that is Scenario B, and their nearest demand centres.

3. Results

This section presents the results of correlation coefficient analysis for 23 regional supply nodes housing windfarms and 50 regional demand nodes comprising the National Electricity Market. Wild et al. (2015 figs. 2-6) show these regional demand and supply nodes. The time interval is half-hourly, unless otherwise discussed.

Section 1 presents the State level correlation coefficients between wind speed and electricity demand. Sections 2 present regional level correlation coefficients between the wind speeds of the 23 regional nodes with windfarms. Section 3 presents regional level correlation coefficients between electricity demands for those 23 regional nodes with windfarms.

3.1 Correlation between wind speed and demand by State

Section 1 presents the correlation over the combined years 2010 to 2012 to identify any geospatial trends. Section 2 presents the correlation for each individual year 2010, 2011 and 2012 to identify any temporal trends.

3.1.1 Correlation over combined years 2010 to 2012 to identify geospatial trends

Table 3 shows the half-hourly correlation coefficients between the wind speed and electricity demands for the years 2010 to 2012. The State half-hourly demand is the sum of the half-hourly regional demand within each State. The State half-hourly wind speed is the half-hourly average wind speed of those regional supply nodes with windfarms within each State. These regional supply node wind speeds are the half-hourly average of the wind speed of the wind farms in each supply node.

Table 3: Correlation of half-hourly wind speed and demand for the years 2010-12 by States in the NEM

		Demand					Wind speed				
		QLD	NSW	VIC	SA	TAS	QLD	NSW	VIC	SA	TAS
Demand	QLD	1.00									
	NSW	0.79	1.00								
	VIC	0.74	0.87	1.00							
	SA	0.63	0.76	0.84	1.00						
	TAS	0.49	0.73	0.72	0.54	1.00					
Wind Speed	QLD	0.21	0.27	0.28	0.25	0.21	1.00				
	NSW	0.19	0.17	0.14	0.02	0.12	0.12	1.00			
	VIC	0.04	0.07	0.05	-0.06	0.02	-0.00	0.44	1.00		
	SA	0.21	0.16	0.13	0.02	0.08	0.12	0.41	0.53	1.00	
	TAS	-0.04	-0.01	-0.03	-0.13	-0.08	-0.11	0.32	0.68	0.24	1.00

Section 4.1 discusses **Table 3** within a wider context but we make a few immediate observations based on the three quadrants:

- pure demand side correlations (demand-demand)
- pure supply side correlations ("wind speed"-"wind speed") and
- supply and demand correlations ("wind speed"-demand)

On the pure demand side, we discuss the correlation of demand between the States. The lack of correlation of demand between States is important to determine potential investment deferment in generation and planning interconnector capacity to utilise the lack of correlation. The demand between Queensland and Tasmania is least correlated and demand between Tasmania and South Australia is the next least correlated. In contrast, the demand between New South Wales and Victoria is the most correlated. These results are hardly surprising given the States relative physical locations. However, for the NEM's peripheral States: Queensland, South Australia and Tasmania to exploit the lack of demand correlation requires suitable transmission capacity via both New South Wales and Victoria but from a self-interest perspective there is little incentive for New South Wales and Victoria to invest in increased interconnector capacity between themselves.

On the pure supply side, we discuss the correlation of wind speed between the States. The lack of positive correlation is important to balance wind power fluctuations between the States to maintain a more consistent supply. Again, for the NEM to avail itself of this benefit requires sufficient interconnector capacity. The wind speed between Queensland and Tasmania is the least correlated. In fact, there is a negative correlation between the two States' wind speeds. This makes Queensland a suitable destination to balance fluctuations in Tasmania's surplus wind power. Furthermore, the magnitude of wind speed correlation between Queensland and the other States is weakest. Tasmania and South Australia are the States whose wind speed is least correlated with other States after Queensland. In contrast, the wind speed between Victoria and Tasmania and between Victoria and South Australia are the most correlated. This makes Victoria less suitable a destination for surplus wind power from Tasmania and South Australia to balance wind power fluctuations. However, there is a requirement for sufficient transmission capacity through both Victoria and New South Wales to enable wind power balancing in the NEM's peripheral States.

On the interaction of the supply and demand sides, we discuss the correlation between wind speed and demand of each State. This determines the ability of wind power to match changes in demand for instance to meet peak loads. The NEM requires sufficient interconnector capacity to avail itself of interstate demand-wind speed correlations. Queensland's winds speed is the most correlated with changes in demand in the NEM's States. A positive correlation between demand and wind speed means that wind generation is capable of contributing energy to meet increases in demand and providing network benefits. Notable positive correlations exist between Queensland, New South Wales and South Australia and to a lesser extent between Queensland, New South Wales and Victoria. In contrast, Tasmania's wind speed is least correlated with changes in demand in the NEM's States, including its own demand. This situation also arises in the case of Victoria and South Australia. This suggests that Tasmanian wind power requires supplementing with energy storage to meet peak demand. Augmenting Tasmania's hydroelectricity generation fleet with pump-storage could help meet this requirement.

3.1.2 Correlations over each year 2010, 2011 and 2012 to identify temporal trends

Table 4 and **Table 5** help identify yearly changes in the correlation of half-hourly wind speed and demand for years 2010 to 2012. **Table 4** shows the correlation of half-hourly wind speed and demand by State for the years 2010, 2011 and 2012 in Panels (a), (b) and (c), respectively. **Table 5** shows the difference between **Table 4** and **Table 3** that is the difference between each year's correlation and the correlation over the combined years 2010-12.

The wind speed-electricity demand quadrant in **Table 5** shows an increase correlation between 2010 and the years 2011 and 2012. This implies an improvement in wind power addressing peak demand but it is premature with a time series of three data points claim a trend. A longer time series is required. However, an explanatory mechanism does exist.

Table 4: Correlation of half-hourly wind speed and demand by State and by year

(a) Correlation of half-hourly wind speed and demand by State in 2010

2010		Demand					Wind Speed				
		QLD	NSW	VIC	SA	TAS	QLD	NSW	VIC	SA	TAS
Demand	QLD	1.00									
	NSW	0.82	1.00								
	VIC	0.73	0.88	1.00							
	SA	0.64	0.79	0.87	1.00						
	TAS	0.48	0.73	0.73	0.59	1.00					
Wind speed	QLD	0.18	0.23	0.26	0.25	0.20	1.00				
	NSW	0.20	0.15	0.14	0.00	0.06	0.12	1.00			
	VIC	0.02	0.02	0.01	-0.09	-0.01	-0.04	0.49	1.00		
	SA	0.17	0.14	0.10	0.02	0.06	0.08	0.48	0.56	1.00	
	TAS	-0.06	-0.06	-0.05	-0.16	-0.09	-0.13	0.36	0.69	0.31	1.00

(b) Correlation of half-hourly wind speed and demand by State in 2011

2011		Demand					Wind Speed				
		QLD	NSW	VIC	SA	TAS	QLD	NSW	VIC	SA	TAS
Demand	QLD	1.00									
	NSW	0.80	1.00								
	VIC	0.75	0.88	1.00							
	SA	0.66	0.76	0.82	1.00						
	TAS	0.45	0.70	0.72	0.50	1.00					
Wind speed	QLD	0.20	0.26	0.25	0.21	0.22	1.00				
	NSW	0.21	0.22	0.18	0.07	0.19	0.13	1.00			
	VIC	0.06	0.13	0.10	-0.03	0.09	0.07	0.36	1.00		
	SA	0.24	0.19	0.14	-0.00	0.08	0.20	0.39	0.49	1.00	
	TAS	0.02	0.07	0.03	-0.05	-0.02	-0.10	0.24	0.67	0.19	1.00

(c) Correlation of half-hourly wind speed and demand by State in 2012

2012		Demand					Wind Speed				
		QLD	NSW	VIC	SA	TAS	QLD	NSW	VIC	SA	TAS
Demand	QLD	1.00									
	NSW	0.77	1.00								
	VIC	0.72	0.88	1.00							
	SA	0.57	0.72	0.83	1.00						
	TAS	0.54	0.74	0.71	0.51	1.00					
Wind speed	QLD	0.23	0.31	0.32	0.29	0.22	1.00				
	NSW	0.18	0.15	0.12	0.00	0.13	0.13	1.00			
	VIC	0.05	0.07	0.05	-0.06	0.00	-0.02	0.46	1.00		
	SA	0.22	0.19	0.18	0.08	0.12	0.09	0.37	0.54	1.00	
	TAS	-0.06	-0.04	-0.07	-0.16	-0.13	-0.10	0.36	0.69	0.22	1.00

Bell, Wild and Foster (2013) discuss the explanatory mechanism as the transformative effect of unscheduled solar PV on the NEM total demand. The solar PV in effect shaves demand from the middle of the day to meet many of the demand peaks previously occurring during the sunniest parts of the day. The residual peaks in demand occur later in the afternoon and early evening. This in effect shifts the peak demand to later in the afternoon and early evening. This is a period when higher wind speed are often more prevalent. Exacerbating the effect of this change in demand profile is the decline of Manufacturing in Australia that relatively increases the importance of household demand as a proportion of total demand. Households own most of the unscheduled solar PV and the number of households owing solar PV continues to increase.

Table 5: The difference between the wind speed and demand correlation by year and by years 2010-12

(a) The difference between the wind speed and demand correlation over 2010 and 2010-12

2010		Demand					Wind Speed				
		QLD	NSW	VIC	SA	TAS	QLD	NSW	VIC	SA	TAS
Demand	QLD										
	NSW	0.03									
	VIC	-0.00	0.01								
	SA	0.01	0.03	0.03							
	TAS	-0.01	-0.00	0.01	0.05						
Wind speed	QLD	-0.02	-0.04	-0.01	-0.00	-0.02					
	NSW	0.01	-0.02	-0.01	-0.02	-0.06	-0.01				
	VIC	-0.02	-0.05	-0.04	-0.02	-0.03	-0.04	0.05			
	SA	-0.04	-0.02	-0.04	-0.01	-0.02	-0.04	0.07	0.03		
	TAS	-0.02	-0.05	-0.02	-0.04	-0.01	-0.02	0.04	0.01	0.07	

(b) The difference between the wind speed and demand correlation over 2011 and 2010-12

2011		Demand					Wind Speed				
		QLD	NSW	VIC	SA	TAS	QLD	NSW	VIC	SA	TAS
Demand	QLD										
	NSW	0.01									
	VIC	0.02	0.00								
	SA	0.03	0.01	-0.02							
	TAS	-0.03	-0.02	0.00	-0.04						
Wind speed	QLD	-0.01	-0.00	-0.03	-0.04	0.00					
	NSW	0.01	0.05	0.04	0.05	0.07	0.01				
	VIC	0.02	0.07	0.05	0.03	0.07	0.07	-0.07			
	SA	0.04	0.03	0.01	-0.03	0.00	0.08	-0.03	-0.04		
	TAS	0.05	0.08	0.06	0.07	0.06	0.01	-0.08	-0.01	-0.05	

(c) The difference between the wind speed and demand correlation over 2012 and 2010-12

2012		Demand					Wind Speed				
		QLD	NSW	VIC	SA	TAS	QLD	NSW	VIC	SA	TAS
Demand	QLD										
	NSW	-0.02									
	VIC	-0.02	0.00								
	SA	-0.06	-0.04	-0.01							
	TAS	0.05	0.01	-0.01	-0.03						
Wind speed	QLD	0.03	0.05	0.04	0.04	0.01					
	NSW	-0.01	-0.02	-0.02	-0.02	0.01	0.00				
	VIC	0.01	0.00	0.00	0.00	-0.02	-0.02	0.02			
	SA	0.02	0.03	0.05	0.05	0.04	-0.03	-0.05	0.01		
	TAS	-0.03	-0.03	-0.04	-0.04	-0.06	0.01	0.04	0.01	-0.02	

3.3 Wind speed correlations with higher geographic and time resolution

The previous section presented the results at the State level and at half-hourly resolution. The maximum temporal resolution of the demand data being half-hourly determined the hour-hourly study. However, our wind speed modelling provides 5 minutes resolution.

Section 1 compares wind speed correlations using the half-hourly and five-minute data. Section 2 compares wind speed correlations at the regional level with the State level.

3.3.1 Comparing wind speed correlations using five-minute and half-hourly data

Panels (a) and (b) in **Table 6** shows the wind speed correlations by State based on half-hourly and five-minute data, respectively. Panel (c) shows the difference between half-hourly and five-minute wind speed correlations. Panel (c) shows that the half-hourly data tends to overstate the wind speed correlation between States but the difference is so small that the half-hourly data in the previous section proves sufficiently accurate to discuss wind speed correlations.

Accounting for the slightly higher correlations in the half-hourly data, the averaging of the five-minute wind speeds to form the half-hourly wind speeds smooths out volatility in the five-minute wind speed data.

Table 6: The difference between half-hourly and five-minute wind speed correlations by State and by years 2010-12

(a) Hour-hourly wind speed correlations

	QLD	NSW	VIC	SA	TAS
QLD	1.0000				
NSW	0.1243	1.0000			
VIC	-0.0009	0.4359	1.0000		
SA	0.1205	0.4138	0.5347	1.0000	
TAS	-0.1068	0.3185	0.6817	0.2390	1.0000

(b) Five-minute wind speed correlations

	QLD	NSW	VIC	SA	TAS
QLD	1.0000				
NSW	0.1241	1.0000			
VIC	-0.0008	0.4352	1.0000		
SA	0.1203	0.4133	0.5338	1.0000	
TAS	-0.1063	0.3177	0.6797	0.2384	1.0000

(c) Hour-hourly less Five-minute wind correlations

	QLD	NSW	VIC	SA	TAS
QLD					
NSW	0.0002				
VIC	-0.0001	0.0007			
SA	0.0002	0.0005	0.0010		
TAS	-0.0005	0.0008	0.0020	0.0007	

3.2.2 Regional wind speed correlations using five-minute data

Table 7 shows the coefficient of correlation between wind speeds on nodes in the NEM that have windfarms. The alternative grey shading indicates the States: Queensland, New South Wales, Victoria, South Australia and Tasmania. The less correlated the wind speed between nodes indicates the ability of wind to maintain a more consistent supply across the NEM but also indicates the requirement for transmission infrastructure to transfer the wind power between nodes in the NEM. The correlation calculations use five-minute interval wind speed averaged across wind farms on a node for the years 2010 to 2012. The shading from dark red to dark green indicates the correlation coefficient values from 1.0 to -0.1. The correlation coefficients 1.0, 0 and -0.1 represent perfectly correlation, perfectly uncorrelated and slightly negative correlation.

The wind speeds in Queensland is negatively or uncorrelated with the rest of the NEM excepting nearby Armidale. Armidale also shows little correlation with the rest of the NEM excepting the Mount Piper and Wellington nodes.

As expected the wind speed within each State is correlated. The following list provides the States in descending order of intra State wind speed correlation: Tasmania, Victoria, South Australia, New South Wales and Queensland.

Table 7: Wind speed regression coefficients for the years 2010 to 2012 based on five-minute data average across wind farms on a node in the NEM

	Node No.	1	7	13	20	21	23	24	25	26	30	32	33	34	35	37	39	40	41	42	44	45	46	50
Node No.	Node Name	Far North QLD	Tarong QLD	Armidale NSW	Mt Piper NSW	Wellington	Marulan NSW	Yass NSW	Canberra ACT	Tumut NSW	Morwell VIC	Melbourne VIC	Sth. West VIC	Regional VIC	South West SA	Adelaide	Mid-North SA	Upp.-North SA	Eyre Peninsula	George Town	Burnie TAS	Farrell TAS	Hadspen TAS	Tarraleah TAS
1	Far North QLD	1.0																						
7	Tarong QLD	0.1	1.0																					
13	Armidale NSW	-0.1	0.6	1.0																				
20	Mt Piper NSW	-0.1	0.3	0.5	1.0																			
21	Wellington NSW	-0.1	0.3	0.5	1.0	1.0																		
23	Marulan NSW	-0.1	0.1	0.3	0.8	0.7	1.0																	
24	Yass NSW	-0.1	0.2	0.4	0.7	0.7	0.7	1.0																
25	Canberra ACT	-0.1	0.0	0.2	0.7	0.7	0.9	0.7	1.0															
26	Tumut NSW	0.0	0.1	0.2	0.3	0.3	0.2	0.3	0.1	1.0														
30	Morwell VIC	-0.0	0.0	0.1	0.3	0.3	0.5	0.3	0.5	0.1	1.0													
32	Melbourne VIC	-0.1	-0.0	0.1	0.3	0.3	0.5	0.3	0.5	0.2	0.8	1.0												
33	South West VIC	0.0	0.0	0.1	0.3	0.2	0.3	0.2	0.4	0.2	0.6	0.7	1.0											
34	Regional VIC	-0.0	0.1	0.1	0.3	0.3	0.4	0.3	0.4	0.3	0.6	0.7	0.8	1.0										
35	South West SA	-0.0	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.2	0.5	0.6	0.9	0.7	1.0									
37	Adelaide SA	-0.0	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.4	0.3	0.4	0.6	0.6	0.7	1.0								
39	Mid North SA	0.0	0.2	0.2	0.2	0.3	0.1	0.2	0.1	0.7	0.1	0.1	0.2	0.3	0.3	0.5	1.0							
40	Upper North SA	0.0	0.2	0.3	0.4	0.4	0.2	0.3	0.2	0.7	0.2	0.2	0.3	0.4	0.4	0.6	1.0	1.0						
41	Eyre Pen SA	0.0	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.3	0.2	0.3	0.5	0.5	0.6	0.8	0.5	0.6	1.0					
42	George Town TAS	-0.1	-0.1	0.0	0.3	0.2	0.4	0.3	0.4	0.1	0.7	0.6	0.6	0.5	0.4	0.2	0.1	0.1	0.1	1.0				
44	Burnie TAS	-0.1	-0.0	0.0	0.3	0.2	0.4	0.3	0.4	0.1	0.7	0.6	0.6	0.6	0.5	0.2	0.1	0.1	0.2	0.9	1.0			
45	Farrell TAS	-0.1	-0.0	0.1	0.3	0.2	0.4	0.3	0.4	0.1	0.7	0.6	0.6	0.6	0.5	0.2	0.1	0.1	0.2	0.9	1.0	1.0		
46	Hadspen TAS	-0.1	-0.1	-0.0	0.2	0.2	0.3	0.2	0.4	0.0	0.6	0.5	0.4	0.4	0.3	0.1	0.0	0.0	0.1	0.9	0.6	0.6	1.0	
50	Tarraleah TAS	-0.1	-0.1	0.0	0.3	0.2	0.4	0.3	0.4	0.1	0.7	0.6	0.6	0.5	0.4	0.2	0.1	0.1	0.1	1.0	0.9	0.9	0.9	1.0

4. Discussion

We have conducted a correlation analysis of the wind speed and electricity demand in the NEM for the years 2010 to 2012 to determine the ability of wind power to meet electricity demand without energy storage or as part of a renewable energy portfolio. This is a useful preliminary exercise before determining energy storage requirements and other renewable energy sources as part of renewal energy portfolio to best argument wind power. Our Australian National Electricity Market (ANEM) Model report (Wild et al. 2015) discusses the electricity demand and wind speed profiles and data on planned and existing windfarms in detail.

Section 3.1 discusses immediate observations from the half-hourly correlation coefficients between the wind speed and electricity demands for the years 2010 to 2012 in **Table 3**. In contrast, this section discusses **Table 3** within a wider context.

In **Table 8**, we make a comparison between this paper's wind speed and electricity demand correlation by State and an earlier similar study by Bannister and Wallace (2011). For the convenience of the reader, Panel (a) is replicated from **Table 2** that is the study from Bannister and Wallace (2011) and Panel (b) is replicated from **Table 3** that is this paper's correlation analysis. Panel (c) shows the difference between Panel (a) and Panel (b).

Relative to our study, the study by Bannister and Wallace (2011) produces higher correlation between the States' wind speeds and between the States' electricity demands but produces lower correlation between demand and wind speed. We discuss the consequence of these differences based on the following three quadrants:

- pure demand side correlations (demand-demand)
- pure supply side correlations ("wind speed"-"wind speed") and
- supply and demand correlations ("wind speed"-demand)

On the pure demand side, we discuss the correlation of demand between the States. The lack of correlation of demand between States is important to determine potential investment deferment in generation and planning interconnector capacity to utilise the lack of correlation. Relative to this study, Bannister and Wallace (2011) have higher correlation between the State's demands. This leads them to conclude a lesser role for increasing interconnection capacity.

On the pure supply side, we discuss the correlation of wind speed between the States. The lack of positive correlation is important to balance wind power fluctuations between the States to maintain a more consistent supply. Again, for the NEM to avail itself of this benefit requires sufficient interconnector capacity. Relative to this study, Bannister and Wallace (2011) have a higher wind speed correlation. This also leads them to conclude a lesser role for increasing interconnection capacity.

On the interaction of the supply and demand sides, we discuss the correlation between wind speed and demand of each State. This determines the ability of wind power to match changes in demand for instance to meet peak loads. The NEM requires sufficient interconnector capacity to avail itself of interstate demand-wind speed correlations. Relative to this study, Bannister and Wallace (2011) have lower correlation between wind speed and demand. Again, this leads them to conclude a lesser role for increasing interconnection capacity.

Table 8: The difference in correlation coefficients between Bannister and Wallace (2011) and this study

(a) Correlation of wind speed and demand by State (excluding Queensland's wind speed)

		Demand					Wind Speed				
		QLD	NSW	VIC	SA	TAS	QLD	NSW	VIC	SA	TAS
Demand	QLD	1.00									
	NSW	0.83	1.00								
	VIC	0.75	0.89	1.00							
	SA	0.67	0.81	0.85	1.00						
	TAS	0.54	0.72	0.78	0.58	1.00					
Wind speed	QLD										
	NSW	0.11	0.08	0.07	0.05	0.10		1.00			
	VIC	-0.05	-0.08	-0.05	-0.06	0.00		0.44	1.00		
	SA	-0.08	-0.16	-0.16	-0.07	-0.15		0.34	0.64	1.00	
	TAS	0.04	-0.06	-0.04	-0.06	-0.04		0.31	0.47	0.24	1.00

(Source: Bannister & Wallace 2011, p. 15)

(b) Correlation of half-hourly wind speed and demand for the years 2010-12 by State

		Demand					Wind Speed				
		QLD	NSW	VIC	SA	TAS	QLD	NSW	VIC	SA	TAS
Demand	QLD	1.00									
	NSW	0.79	1.00								
	VIC	0.74	0.87	1.00							
	SA	0.63	0.76	0.84	1.00						
	TAS	0.49	0.73	0.72	0.54	1.00					
Wind speed	QLD	0.21	0.27	0.28	0.25	0.21	1.00				
	NSW	0.19	0.17	0.14	0.02	0.12	0.12	1.00			
	VIC	0.04	0.07	0.05	-0.06	0.02	-0.00	0.44	1.00		
	SA	0.21	0.16	0.13	0.02	0.08	0.12	0.41	0.53	1.00	
	TAS	-0.04	-0.01	-0.03	-0.13	-0.08	-0.11	0.32	0.68	0.24	1.00

(c) Difference between table (a) and table (b) that is table (a) less table (b)

		Demand					Wind Speed				
		QLD	NSW	VIC	SA	TAS	QLD	NSW	VIC	SA	TAS
Demand	QLD										
	NSW	0.04									
	VIC	0.01	0.02								
	SA	0.04	0.05	0.01							
	TAS	0.05	-0.01	0.06	0.04						
Wind speed	QLD										
	NSW	-0.08	-0.09	-0.07	0.03	-0.02					
	VIC	-0.09	-0.15	-0.10	0.00	-0.02		0.00			
	SA	-0.29	-0.32	-0.29	-0.09	-0.23		-0.07	0.11		
	TAS	0.08	-0.05	-0.01	0.07	0.04		-0.01	-0.21	0.00	

In summary, when compared with our results, the results in Bannister and Wallace (2011) downplays the potential advantages of wind power for the NEM based on all three above-mentioned quadrants. This leads them to conclude a lesser role in increasing interconnector capacity to avail the NEM of wind power advantages.

The following factors help explain the difference between Bannister and Wallace (2011) and our study. The motivation for their study was the negative prices and volatility in SA with its large penetration of wind power relative to State demand. They use 10 years of half-hourly loads adjusted for a linear trend in demand over 10 years. In contrast, we use actual demand data for the year 2010 to 2012. They use wind data based on 2½ years of half hourly data. We use half-hourly wind data for the years 2010 and 2012. Hence, our correlations are likely to be more accurate for the years 2010 to 2012.

Our study uses more recent data than Barrister and Wallace (2011). Hence, a structural change in the NEM's electricity demand profiles could account for the differences in our results. The following structural changes are consistent with the disparity between our results. The large increase in solar water heating and unscheduled solar PV and decline in manufacturing load has altered the overall daily profile of electricity demand. The midday demand peaks shift later into the afternoon and early evening. The resulting changed demand profile more closely matches the power profile of wind. Both the decline in demand by the manufacturing sector and increase in displaced demand by solar PV and solar hot water are likely to continue. Bell, Wild and Foster (2013) discuss this transformative effect of unscheduled solar PV and wind generation and solar water heating on "total" demand in detail. This demand transformation effect illustrates the advantage of a portfolio approach to renewable energy. However, portfolio optimisation needs considering if the NEM to minimise spillage and maintain reliability. The requirement for portfolio optimisation will become more pressing as the proportion of renewable energy increases.

For instance, assuming the NEM's existing level of reliability and moderate carbon prices, Elliston, MacGill and Diesendorf (2013) simulate four least cost portfolios of renewable energy consisting onshore wind 34-41%, solar PV 24-34%, CST with storage 7-13%, hydro 4-5%, pumped hydro 2% and bio-fuelled gas turbine 19-23%. Depending on the portfolio, there is spilled energy of between 7 to 27 TWh. They also find 100% renewable electricity portfolio cheaper on an annual basis than replacement by fossil fuel generation.

5. Conclusion

The paper investigates wind speed and electricity demand correlation to determine the ability of wind turbine generators to meet electricity demand in the NEM without the aid of energy storage.

We find that lower wind speed correlations between the peripheral states of Queensland, South Australia and Tasmania should assist in system balancing. This assumes sufficient transmission structure to accommodate the transport of surplus wind power between these peripheral States via New South Wales and Victoria. Notable positive electricity demand-wind speed correlations were found between Queensland, New South Wales and South Australia and too a less extent between Queensland, New South Wales and Victoria. These positive correlations point to the ability of wind generation to provide capacity capable of meeting increases in demand, thus indicating potential network benefits from wind generation. In contrast, Tasmania has negative electricity demand-wind speed correlations that might require some supplementation with energy storage in order to meet peak demand. The electricity demand-wind speed correlations in Victoria and South Australia are similar to Tasmania but to a lesser extent.

Maximising the benefits of wind power for the NEM requires further augmentation of the interconnectors to the NEM's peripheral States Queensland, South Australia and Tasmania but the State scope of the transmission companies and self-interest groups within NSW and Victoria act as barriers to implementation. The findings in our transmission congestion report (Bell et al.

2015) confirm that the interconnector capacity is hampering the NEM's ability to gain the full benefit of wind power.

We also found that the combined effect of increasing penetration of solar PV and solar water heating are unwittingly improving wind power's ability to meet electricity demand without storage via a portfolio effect. However, an optimal portfolio of onshore wind and other renewable energy requires some planning and the requirement for optimal portfolio planning becomes more pressing as the penetration of renewable energy increases. The decline of the manufacturing sector makes household consumption relatively larger that also improves wind power's ability to meet electricity demand.

One useful avenue for further research would be to test whether the half-hourly electricity demand-wind speed correlations findings hold using five-minute interval data. This would require developing five-minute demand profiles to match the existing five-minute wind speed profiles.

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