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LETTER

The resilience of Australian wind energy to climate change

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Abstract

The Paris Agreement limits global average temperature rise to 2 °C and commits to pursuing efforts in limiting warming to 1.5 °C above pre-industrial levels. This will require rapid reductions in the emissions of greenhouse gases and the eventual decarbonisation of the global economy. Wind energy is an established technology to help achieve emissions reductions, with a cumulative global installed capacity of ~486 GW (2016). Focusing on Australia, we assess the future economic viability of wind energy using a 12-member ensemble of high-resolution regional climate simulations forced by Coupled Model Intercomparison Project (CMIP) output. We examine both near future (around 2030) and far future (around 2070) changes. Extractable wind power changes vary across the continent, though the most spatially coherent change is a small but significant decrease across southern regions. The cost of future wind energy generation, measured via the Levelised Cost of Energy (LCOE), increases negligibly in the future in regions with significant existing installed capacity. Technological developments in wind energy generation more than compensate for projected small reductions in wind, decreasing the LCOE by around 30%. These developments ensure viability for existing wind farms, and enhance the economic viability of proposed wind farms in Western Australian and Tasmania. Wind energy is therefore a resilient source of electricity over most of Australia and technological innovation entering the market will open new regions for energy production in the future.

Introduction

Wind energy is an established source of renewable energy with the potential to exceed present total energy needs (~18 TW) by between 5 and 100 times [1–3]. As a consequence of both the need to cut global greenhouse gas emissions and the utility of wind power generation, rapid growth has occurred such that wind power capacity installed globally met less than 1% of electricity demand at the end of 2006, but rose [4] to ~4.3% at the end of 2015. In Australia, a country with significant wind resources [5–7], wind generation increased by 12% in 2014–2015 while generating 33% of renewable electricity. All renewable electricity accounted for a 5% share of total electricity generation [8]. Current projections point to further wind power generation in the future as technological innovation, manufacturing technologies, more flexible operational systems, and changing social preferences, advantage wind power generation over other sources of power [9].

An underlying concern around the long-term future of large-scale wind energy generation is its vulnerability to climate change. Wind is generated by pressure gradients in the atmosphere, combined with thermal gradients and orographic characteristics, which means the potential for wind energy is site specific. Wind energy generation is vulnerable to changes in synoptic patterns, large-scale weather features such as low and high pressure systems, and modes of variability but is also vulnerable to changes in extreme wind speeds associated with cyclones or storms that can exceed the design limits of a wind turbine [10]. Consequently, previous analyses have pointed to strongly regionally contrasting future potential for wind energy. In Europe, projections point to increases in wind power potential by the end of the 21st century by 10%–20% including increases over Northern Europe, the Aegean Sea and the Bosporus but decreases over the Mediterranean region and the Atlantic Ocean [11–14]. There has been an overall increasing trend in wind speed over the historical period in the USA [15] with increases projected in the future using regional model simulations [16]. Over Australia, observations point to a decline in wind speeds [17] and wind power potential [7] over the historical period.

A number of these studies used regional climate models to investigate wind power. Pryor *et al* 2009 [18] used several sources, including regional climate models, to investigate the past trend in wind power over the USA. They found conflicting trends in the various data sources and recommended the use of multiple sources when analyzing wind climates. Pryor and Barthelmie 2010 [19] also highlighted the large inter-model variability with respect to the climate change signal, and again suggesting that the use of multiple sources is required.

Wind energy requires long-term investment. Wind farms of a nationally significant scale, and the connection of these farms to a national grid, is a multi-million dollar investment with large up-front costs. For example, the Boco Rock Wind farm located 175 km south of Canberra was completed in 2015 and has a total capacity of 113 megawatts at a cost of $361 million. The Taralga Wind Farm, located in the southern tablelands of New South Wales, was commissioned in 2015 with a capacity of 107 megawatts at a cost of $275 million [20].

Given projected changes in climate, current locations with economically viable wind power generation may not be viable in the future. Regions that are currently non-viable may become viable in the next few decades. We therefore examine the viability of current wind farms in the near (2020–2040) and far (2060–2080) future using an ensemble of dynamically downscaled climate model projections [21] (see Methods). Using multi-model ensembles helps assess the uncertainty inherent in climate models [22–25]. We cross-reference our results with proximity to current transmission infrastructure to determine which regions remain optimal locations for wind farm investment, without the need to build new transmission infrastructure. We also examine the impact of advances in wind turbine technology, relative to any changes in climate, to explore whether new regions will emerge as optimal for wind energy generation. By combining a model ensemble approach with established dynamical downscaling techniques, and by incorporating both existing and future technologies we provide the most reliable assessment of the future viability of wind energy generation across Australia and identify regions where future investment might be prioritized.

Methods

Regional climate projections: We use a regional climate ensemble [29] and separately downscale four global climate models (MIROC3.2 medres, ECHAM5, CCCMA3.1, and CSIRO-Mk3.0) using the weather forecasting and research (WRF) modeling system [26] version 3.3. Each global climate model was downscaled three times, with the representation of the planetary boundary layer, cumulus and radiation schemes varied in WRF. These configurations were chosen based on a minimum level of performance and independence of the model errors [27–29]. Details of the model configurations are given in the supplementary material available at stacks.iop.org/ERL/13/024014/mmedia. This created a 12 member ensemble for three time periods: present (1990–2009), near future (2020–2039), and far future (2060–2079) [19, 30]. All future simulations used the Special Report on Emission Scenarios A2 emissions scenario [31]. The wind speed was extracted from the atmospheric winds at model height 80 m (to match wind turbine hub height) at 3 hourly resolution. WRF simulations, nested in each climate model, were performed at 50 km resolution over the Australian continent, with lateral boundary conditions provided geographically distant from land.

Extractable wind power (EWP): The EWP is the amount of power that can be extracted from the wind turbines at particular locations. The wind speed at the turbine hub height is converted into EWP using a standard modern turbine power curve by fitting a cubic polynomial to this data. The EWP has been modelled on the power curve for the VESTAS V90-3 MW (see supplementary figure 1) which is technology currently installed at some locations in Australia. This turbine has also been installed in 34 countries providing over 13GW of installed generation.

Levelized Cost of Energy (LCOE): LCOE is the most commonly used tool for measuring and comparing different electric power generation costs [35]. It reflects the minimum cost of energy at which a generator must sell the produced electricity in order to break even. It is equivalent to the long-run marginal cost of electricity at a given point in time because it measures the cost of producing one extra unit of electricity with a newly constructed electricity generation plant. The calculation of LCOE is for a 100 MW wind farm, and the assumptions used are based on the Australian Energy Technology Assessment reports [32, 33]. This wind farm consists of approximately thirty-three 3 MW turbines and the assumptions used include the competition among these turbines for the winds available kinetic energy which has been found to decrease power extraction by ~8.5% [34]. The lifetime given for most turbines is 20 years (based on the manufacturers warranty), with a discount rate of 0.1. The other key inputs are the capital cost of onshore wind farms, set at $2530 per kW, the net plant

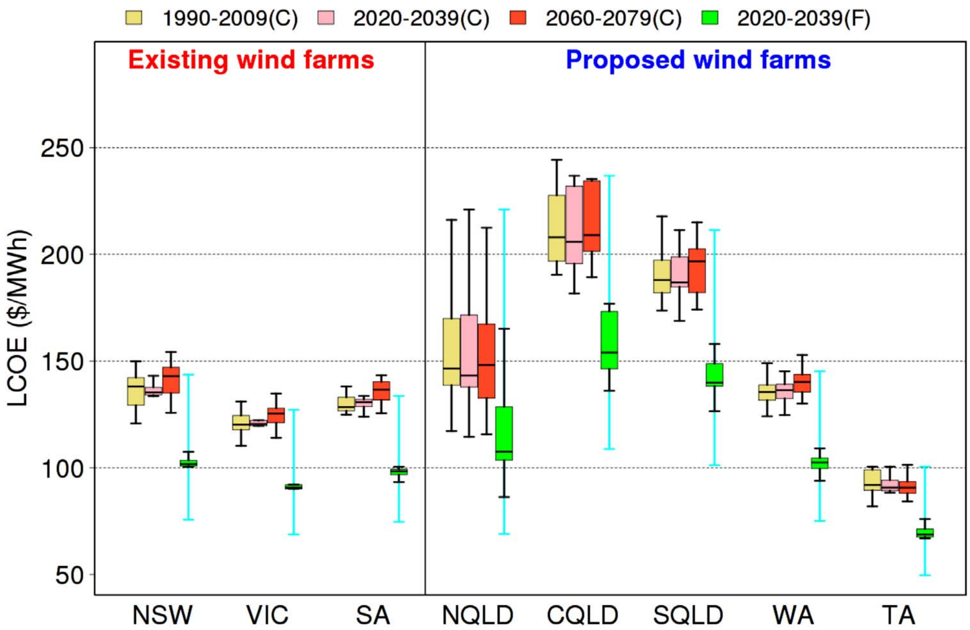

Figure 1. Boxplot of the levelized cost of energy (LCOE) over 12 ensemble model members for current (*c*) and future (*f*) technology. Results are shown for the present day (1990–2009), the near future (2020–2039) and the far future (2060–2079). The *x*-axis provides the broad region where wind farms either do, or are planned to exist (see figure 2(*b*)). They are New South Wales (NSW), Victoria (VIC), South Australia (SA), North Queensland (NQLD), Centre Queensland (CQLD), South Queensland (SQLD), West Australia (WA) and Tasmania (TA). C in the legend represents current and F indicates future. The extended cyan whiskers indicate the range including the uncertainty in future technology and economic outcomes contained within Wiser *et al* 2016 [35].

output, which is based on the Vestas 3 MW turbine, the electricity generation, which is based on the calculated EWP, and assuming 80% of the investment cost is incurred in the first year and 20% in the second year. The fixed operation and maintenance is \$32 500 per MW y^{-1} and the variable operation and maintenance is \$10 per MWh.

Future projections of wind farm efficiency: We used the outcomes from an expert elicitation survey of 163 individuals for future technology developments to update some key assumptions in the estimation of LCOE for the near future (2030). The capacity factor of wind plants is forecast to increase by 10% due to raising the height of the wind turbine hub height to 115 m, and increasing the rotor diameter. The required capital investment costs will decrease 12% and the operation cost of wind farms will decrease 10% by 2030 with the development of technology and changes in the energy market. We therefore used these assumptions to re-calculate the LCOE for the near future, including future winds calculated at 115 m height.

Results

The viability of existing wind farms in Australia is examined in figure 1. These locations were chosen as representative of the top wind generating locations in each state [36]. Focusing first on the recent past (1990–2009) the levelized cost of energy (LCOE) ranges from a median cost of around \$140 per MWh (NSW) to \$120 per MWh (VIC), which is in line with past studies [37]. The range shown in figure 1 reflects the uncertainty due to four CMIP global climate models used to provide the lateral boundary conditions for the dynamical downscaling (see Methods). For each region shown in figure 1, the median LCOE increases in the near future (2020–2040) and far future (2060–2080) but the increase is negligible and in all cases the changes are reasonably close to the median (the box shown in figure 1). In contrast, if we account for advances in future technology, the median LCOE decreases by ~30%, an amount well outside the uncertainty shown by the black whiskers in figure 1 (reflecting an uncertainty range of ±95% in the extractable wind power). Note that the variation in LCOE reflected in the ±95% ranges shown in figure 1 are relatively small, and remain small under future technology; this points to relatively low uncertainty due to the uncertainty in extractable wind power and thereby relatively low investment risk. That is, for each of NSW, Victoria and South Australia the impact of future changes of wind energy due to climate change, and associated impacts on LCOE are negligible, while the impact of future technology enhances the economic value of wind energy by significantly decreasing costs and not increasing risk. There is, however substantial uncertainty concerning the future technology and economic outcomes. This additional uncertainty is estimated based on the high and low scenarios given in Wiser *et al* [35] and is embodied in the cyan whiskers in figure 1. These results indicate that in the worst case scenario LCOE will remain similar to today, while in the best case scenario the LCOE could decrease by around 50% by 2030.

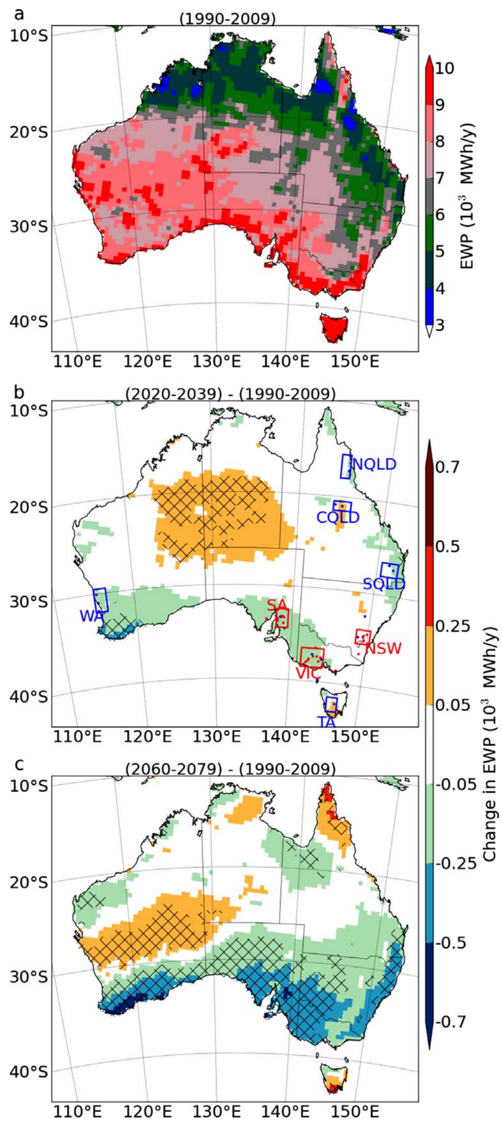

Figure 2. The EWP with current technology for (*a*) the present day (1990–2009); and the differences from the present day for (*b*) the near future (2020–2039) and (*c*) the far future (2060–2079). Red boxes shown in (*b*) are the existing wind farms and blue boxes are the proposed wind farms using the same key as in figure 1. Note: MWh y^{-1} = MW∗24∗365 (hours per day ∗ days per year). The EWP values have been calculated for each grid point corresponding to the model output. Hatching shows regions that are statistically significantly different using a student's *t*-test with a significance level of 5%. These maps were created using Python 2.7.13 (www.python.org/downloads/release/python-2713/).

A series of future wind farms have been proposed over other regions of Australia. These include regional Queensland (currently being developed by industry), Western Australia and Tasmania. Both Western Australia and Tasmania have a significant wind resource, comparable to existing wind farm locations. Figure 1 shows the LCOE for the present, near and far future for these regions. Tasmania is overall the most promising region for wind energy in Australia, with average wind speeds greater than 8 m s^{-1} due to the region's proximity to storm tracks [38]. This region will remain the most promising, with LCOE costs lower than elsewhere now and around half those elsewhere when accounting for new technology. Central and Southern Queensland are less viable regions for wind energy with LCOE exceeding those of existing regions even when accounting for new technology. For Northern Queensland, the median LCOE is similar to NSW, but the range is extremely high pointing to considerable uncertainty and high levels of associated investment risk. Northern Queensland is also prone to cyclones and since current wind turbines are not engineered to survive cyclones, any trends in the magnitude and frequency of cyclones would add significant investment risk. Finally, figure 1 shows Western Australia to be a similar environment to NSW in terms of LCOE in the present and future, and the impact of new technology.

The impact of near and far-future climate change on the extractable wind power (EWP) is shown in figure 2 (median wind speed is shown in the supplementary material). There is a strong regional variation in the present with most regions' EWP commonly exceeding 8–10 × 10^3 MWh y^{-1}. This produces variations in turbine capacity factor from ∼40% in the high EWP regions, to as little as 15% in the lowest EWP regions. Regions of current and proposed wind farms are shown in figure 2(*b*) and all existing wind farms are co-located with regions with > 8 × 10^3 MWh y^{-1}. Tasmania, a strongly viable region for future energy production (figure 1) is also a region where EWP exceeds 8–10 × 10^3 MWh y^{-1} in the current climate. In contrast, regions north of 20 °S, and most of Queensland east of 140°E, have low EWP (3–6 × 10^3 MWh y^{-1}). The eastern side of the Cape York Peninsular in Northern Queensland does display current EWP of 8–10 × 10^3 MWh y^{-1} although we note this region is susceptible to tropical cyclones.

Most current regions with wind farms (boxes, figure 2(*b*)) show a decrease in EWP in the near future. However, the reductions are small and rarely exceed 0.25 × 10^3 MWh y^{-1} (of order 3% decline). This does increase in the far future (figure 2(*b*)) over all current generating regions but only reaches ∼0.5 × 10^3 MWh y^{-1} (∼6% decline). For proposed regions, Tasmania enjoys an increase in EWP in the near (∼1%) and far (∼3%) future assuming current technology. Southern Queensland experiences a weak decrease while Central Queensland experiences an increase in the near future and no change in the far future. Northern Queensland, and in particular Cape York Peninsular, is projected to experience a quite large increase in EWP (0.05–0.5 × 10^3 MWh y^{-1} or up to a ∼5% increase) in the far future. Overall, regions with current wind farms are projected to experience small decreases in EWP in the future, and some proposed regions an increase, but in all cases the magnitude of the changes in EWP are small. The increases in some regions of Queensland (figures 2(*b*) and (*c*)) are simply too small to offset the low EWP in the current climate (figure 2(*a*)).

While many factors may influence the most profitable location for wind farms, low LCOE today and

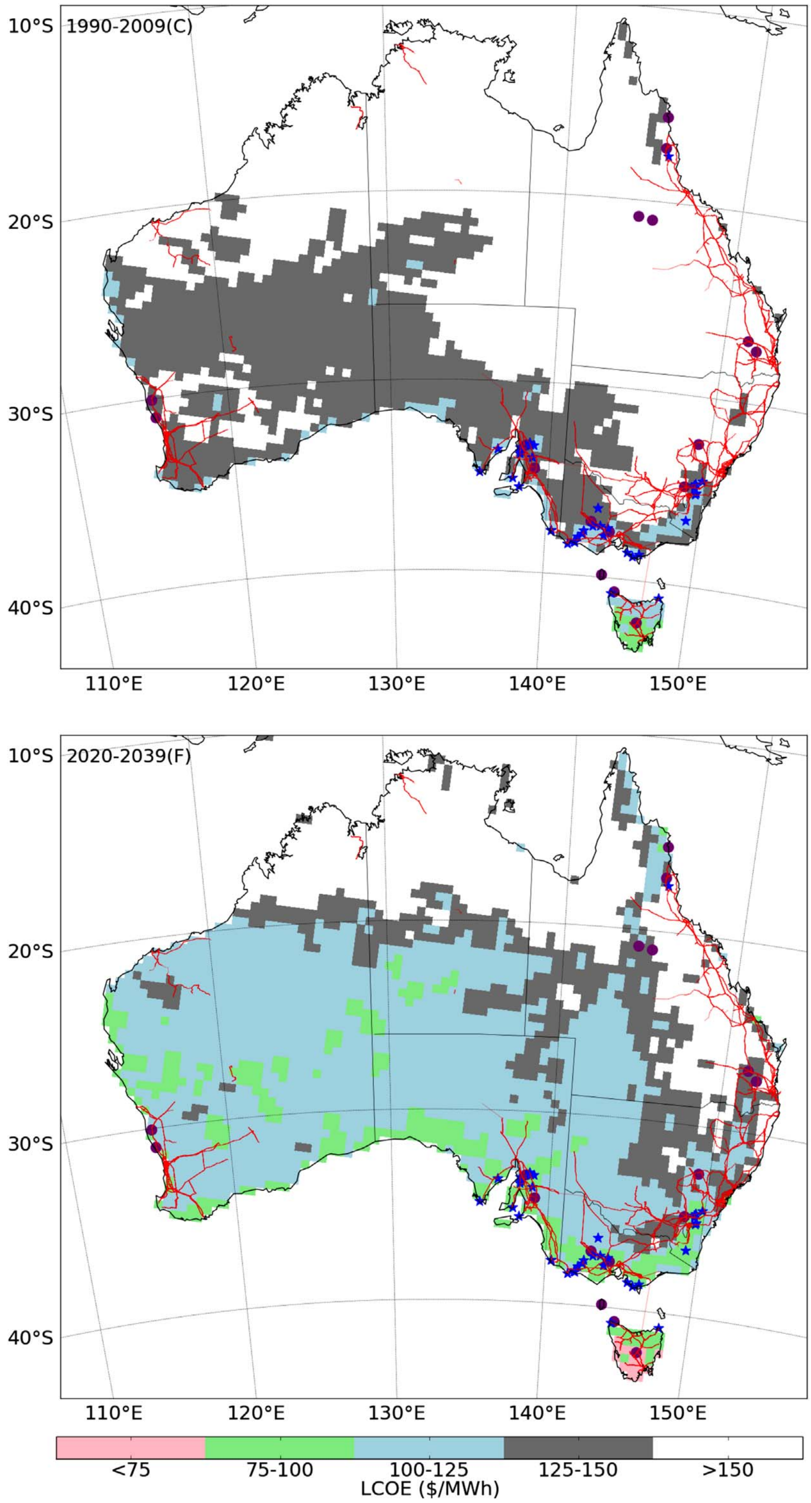

Figure 3. The current (top panel) and future (bottom) levelized cost of energy (LCOE) for the present day (1990–2009) and near future (2020–2039). The red lines represent current transmission line. Blue star points represent the existing and purple circles represent proposed wind farms. These maps were created using Python 2.7.13 (www.python.org/downloads/release/python-2713/).

in the future indicates regions with relatively low costs and good potential for profitability. Additional factors such as proximity to current energy transmission lines are also important considerations. Figure 3 shows the LCOE in the present and near future, the existing transmission lines and the locations of current and proposed wind farms. Most existing wind farms are located close to existing major transmission lines but two major omissions are apparent. There are large regions of Tasmania and Western Australia where the potential for wind farms exist, where the transmission grid already exists and the LCOE is low. Although the transmission lines across Tasmania may need to be upgraded to accommodate increased wind energy, this energy would be independent of water supply and hence resilient to drought conditions which effects the hydropower facilities supplying most of Tasmania's current energy supply. In addition, a surplus of supply could be exported to the mainland via the high-capacity Bass link connector, which is able to transmit 500 MW of energy continuously to mainland Australia [39]. In each case, the LCOE decreases into the near future. Proposed wind farms in Victoria and South Australia are also close to the existing transmission grid and in regions where the LCOE is likely to decrease in the future. In contrast, proposed developments in Queensland appear less likely to benefit from changes in EWP and from associated declines in LCOE. As noted earlier, these regions of Queensland are also geographically coincident with the highest cyclone risk.

Discussion and conclusions

Wind farms are an established technology for renewable energy. Our results point to this continuing over most regions of Australia through to the end of the 21st century even without technological innovation. The projected changes in wind, associated with climate change, are small compared to the benefits from expected technological innovation. The most ideal regions for wind energy production will remain similar in the future, but Tasmania and parts of Western Australia, already possible locations, will provide particularly good future opportunities. In contrast, proposed developments in Queensland will remain less viable, and once risks associated with tropical cyclones are accommodated are not likely to be competitive with the more southern states.

The deep cuts to emissions of carbon dioxide required to meet the Paris agreement highlights the need to invest in low-carbon energy production. Wind energy is already a major supplier of renewable energy but concerns have been expressed around its long-term viability due to climate change. Our results do not support these concerns, at least over Australia. Wind energy production appears resilient to the projected small decreases in wind energy potential, and once technological innovations are taken into account wind energy remains a viable source of energy at least to the end of this century.

Data availability

The NARCliM regional climate projection data that support the findings of this study are available through the New South Wales government Climate Data Portal—https://climatedata.environment.nsw.gov.au/, and from the corresponding author upon reasonable request.

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References

[1] Lu X, McElroy M B and Kiviluoma J 2009 Global potential for wind-generated electricity *Proc. Natl Acad. Sci.* **106** 10933–8

[2] Marvel K, Kravitz B and Caldeira K 2012 Geophysical limits to global wind power *Nat. Clim. Change* **3** 118–21

[3] Barthelmie R J and Pryor S C 2014 Potential contribution of wind energy to climate change mitigation *Nat. Clim. Change* **4** 684–8

[4] Wiser R and Bolinger M 2015 *Wind Technologies Market Report* (Oak Ridge, TN: US Department of Energy) (https://energy.gov/sites/prod/files/2016/08/f33/2015-Wind-Technologies-Market-Report-08162016.pdf)

[5] Australian Energy Market Operator 2016 Electricity Statement of Opportunities: For the National Electricity Market (www.aemo.com.au/Electricity/Wholesale-Electricity-Market-WEM/Planning-and-forecasting/WEM-Electricity-Statement-of-Opportunities)

[6] Prasad A A, Taylor R A and Kay M 2017 Assessment of solar and wind resource synergy in Australia *Appl. Energy* **190** 354–67

[7] Hallgren W, Gunturu U B and Schlosser A 2014 The potential wind power resource in Australia: a new perspective *PLOS ONE* **9** e99608

[8] Department of Industry, Innovation and Science 2016 *Australian energyupdate 2016* (Canberra) (www.industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/aes/2016-australian-energy-statistics.pdf)

[9] Mitchell C 2016 Momentum is increasing towards a flexible electricity system based on renewables *Nat. Energy* **1** 15030

[10] Vose R S *et al* 2014 Monitoring and understanding changes in extremes: extratropical storms, winds, and waves *Bull. Am. Meteor. Soc.* **95** 377–86

[11] Hueging H, Haas R, Born K, Jacob D and Pinto J G 2013 Regional changes in wind energy potential over europe using regional climate model ensemble projections *J. Appl. Meteorol. Climatol.* **52** 903–17

[12] Reyers M, Pinto J G and Moemken J 2015 Statistical-dynamical downscaling for wind energy potentials: evaluation and applications to decadal hindcasts and climate change projections *Int. J. Climatol.* **35** 229–44

[13] Tobin I, Vautard R, Balog I, Bréon F-M, Jerez S, Ruti P M, Thais F, Vrac M and Yiou P 2015 Assessing climate change impacts on European wind energy from ENSEMBLES high-resolution climate projections *Clim. Change* **128** 99–112

[14] Tobin I *et al* 2016 Climate change impacts on the power generation potential of a European mid-century wind farms scenario *Environ. Res. Lett.* **11** 034013

[15] Holt E and Wang J 2012 Trends in wind speed at wind turbine height of 80 m over the contiguous United States using the North American regional reanalysis *J. Appl. Meteorol. Climatol.* **51** 2188–202
[16] Liu B, Costa K B, Xie L and Semazzi F H M 2014 Dynamical downscaling of climate change impacts on wind energy resources in the contiguous united states by using a limited-area model with scale-selective data assimilation *Adv. Meteorol.* e897246
[17] McVicar T R, Van Niel T G, Li L T, Roderick M L, Rayner D P, Ricciardulli L and Donohue R J 2008 Wind speed climatology and trends for Australia, 1975–2006: capturing the stilling phenomenon and comparison with near-surface reanalysis output *Geophys. Res. Lett.* **35** L20403
[18] Pryor S C, Barthelmie R J, Young D T, Takle E S, Arritt R W, Flory D, Gutowski W J, Nunes A and Roads J 2009 Wind speed trends over the contiguous United States *J. Geophys. Res.* **114** D14105
[19] Pryor S C and Barthelmie R J 2010 Climate change impacts on wind energy: a review *Renew. Sustain. Energy Rev.* **14** 430–7
[20] Stark C, Martin K and Penney K 2011 *Major Electricity Generation Projects* (Canberra: Bureau of Resources and Energy Economics)
[21] Evans J P, Ji F, Lee C, Smith P, Argüeso D and Fita L 2014 Design of a regional climate modelling projection ensemble experiment-NARCliM *Geosci. Model Dev.* **7** 621–9
[22] Rasmussen D J, Holloway T and Nemet G F 2011 Opportunities and challenges in assessing climate change impacts on wind energy—a critical comparison of wind speed projections over California *Environ. Res. Lett.* **6** 0240008
[23] Pryor S C, Barthelmie R J and Kjellström E 2005 Potential climate change impact on wind energy resources in northern Europe: analyses using a regional climate model *Clim. Dyn.* **25** 815–35
[24] Pryor S C, Barthelmie R J and Schoof J T 2006 Inter-annual variability of wind indices across Europe *Wind Energy* **9** 27–38
[25] Pryor S C, Nikulin G and Jones C 2012 Influence of spatial resolution on regional climate model derived wind climates *J. Geophys. Res. Atmos.* **117** D03117
[26] Skamarock W C, Klemp J B, Dudhia J, Gill D O, Barker D M, Wang W and Powers J G 2008 A description of the advanced research WRF version 2 *NCAR Technical Note* NCAR/TN-475+STR p 123
[27] Evans J, Ekström M and Ji F 2012 Evaluating the performance of a WRF physics ensemble over South-East Australia *Clim. Dyn.* **39** 1241–58
[28] Ji F, Ekström M, Evans J P and Teng J 2014 Evaluating rainfall patterns using physics scheme ensembles from a regional atmospheric model *Theor. Appl. Climatol.* **115** 297–304
[29] Evans J P, Ji F, Abramowitz G and Ekström M 2013 Optimally choosing small ensemble members to produce robust climate simulations *Environ. Res. Lett.* **8** 044050
[30] Olson R, Evans J, Di Luca A and Argüeso D 2016 The NARCliM project: model agreement and significance of climate projections *Clim. Res.* **69** 209–27
[31] Nakicenovic N and Swart R 2000 *Special Report on Emissions Scenarios: a Special Report of Working Group III of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)
[32] Australian Energy Technology Assessments 2012 (www.industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/aeta/australian_energy_technology_assessment.pdf)
[33] Syed A 2013 *The Australian Energy Assessment 2013 Model update* (Canberra) (www.industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/aeta/AETA-Update-Dec-13.pdf)
[34] Jacobson M Z, Delucchi M A, Cameron M A and Frew B A 2015 Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes *Proc. Natl Acad. Sci.* **112** 15060–5
[35] Wiser R, Jenni K, Seel J, Baker E, Hand M, Lantz E and Smith A 2016 Expert elicitation survey on future wind energy costs *Nat. Energy* **1** 16135
[36] Geoscience Australia and BREE 2014 *Australian Energy Resource Assessment* 2nd edn (Canberra: Geoscience Australia)
[37] Foster J, Wanger L and Bratanova A 2014 LCOE models: a comparison of the theoretical frameworks and key assumptions *Project 3: Economic and Investment Models For Future Grids* (Brisbane, University of Queensland: CSIRO)
[38] Hoskins B J and Hodges K I 2005 A new perspective on southern Hemisphere storm tracks *J. Clim.* **18** 4108–29
[39] Details of the Basslink interconnector (www.basslink.com.au/basslink-interconnector/)
[40] Meinshausen M *et al* 2009 Greenhouse-gas emission targets for limiting global warming to 2 °C *Nature* **458** 1158–62
[41] Rogelj J *et al* 2011 Emission pathways consistent with a 2 °C global temperature limit *Nat. Clim. Change* **1** 413–8