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 Bosphorus 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
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 relatively 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 $\sim30\%$, an amount well outside the uncertainty shown by the black whiskers in figure 1 (reflecting an uncertainty range of $\pm95\%$ in the extractable wind power). Note that the variation in LCOE reflected in the $\pm95\%$ 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 whikers 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.
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 $8 \times 10^3$ MWh y$^{-1}$. This produces variations in turbine capacity factor from $\sim$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 $>8 \times 10^3$ MWh y$^{-1}$. Tasmania, a strongly viable region for future energy production (figure 1) is also a region where EWP exceeds $8 \times 10^3$ MWh y$^{-1}$ in the current climate. In contrast, regions north of $20^\circ$S, and most of Queensland east of $140^\circ$E, have low EWP ($3\times10^3$ MWh y$^{-1}$). The eastern side of the Cape York Peninsular in Northern Queensland does display current EWP of $8\sim10 \times 10^3$ 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 $0.25 \times 10^3$ 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 $\sim 0.5 \times 10^3$ MWh y$^{-1}$ ($\sim 6\%$ decline). For proposed regions, Tasmania enjoys an increase in EWP in the near ($\sim 1\%$) and far ($\sim 3\%$) 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 ($0.05\sim0.5 \times 10^3$ MWh y$^{-1}$ or up to a $\sim 5\%$ 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 affects 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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