The Impact of Climate Change on Wind Energy

Nicholas Smykowsky

2024

1 Graphical Abstract

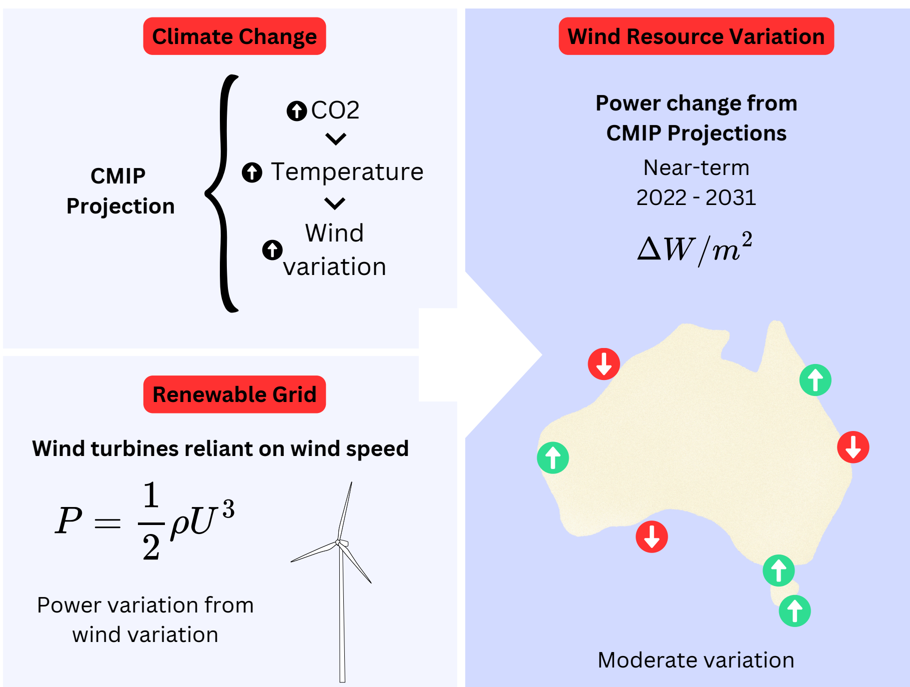

Figure 1: Graphical Abstract

2 Introduction

2.1 Problem

As the power grid transfers to a 100% renewable energy it becomes more reliant on the weather (Fournier et al., 2023). Solar panels are reliant on sunshine reaching the Earth and are impacted by clouds. Wind farms can also be substantially effected by change and distribution of wind velocity (Martinez and Iglesias, 2024). As the net-zero transition occurs in Australia in the coming decades it will be critical to understand how the weather changes.

Climate change is predicted to have a major impact on how the wind velocities will change in the future (Fournier et al., 2023). Wind turbines are difficult to move and their locations are selected based on their potential power output. The average wind velocity may change over time, this is especially a concern when large levels of climate change is predicted. These changing wind speeds will in turn have a large impact on power generation. This is an issue as consistent electricity is a key element of any modern economy. Predicting future wind speeds is crucial for mitigation of these effects.

2.2 Purpose

This report attempts to find the extent of wind velocity variation and therefore power output from wind farms due to climate change. The climate models we have project future climates based on a number of CO2 emission pathways. Using Coupled Models of Inter-comparison (CMIP) we can have estimates of wind velocities and convert these into energy availabilities (Fournier et al., 2023) . This is of great use to governments and private companies wanting to invest in and build infrastructure for wind farm projects. It will help to find the best available locations for offshore wind farms in Australia and how these locations may change under different climate change scenarios. These climate change scenarios may differ depending on future CO2 emissions. Outcomes will inform grid design and potential backup sources or firming of the grid.

2.3 Scope

There are many current and future wind farm projects in Australia (AEMO, 2022). We will be looking at climate projections for the rest of the century to see how wind velocities and the best locations for wind farms will change. The years from 2050 onward will be the most interesting as that is when Australia is due to move to a net-zero grid (AEMO, 2022). Assumptions made will be that the wind energy sector grows in Australia and that the grid is reliant on it (Evans et al., 2018). This report will not cover future energy prices and how that relates to viability of wind projects. It's main output is wind velocity converted to power density and it's distribution through time and space under the influence of climate change.

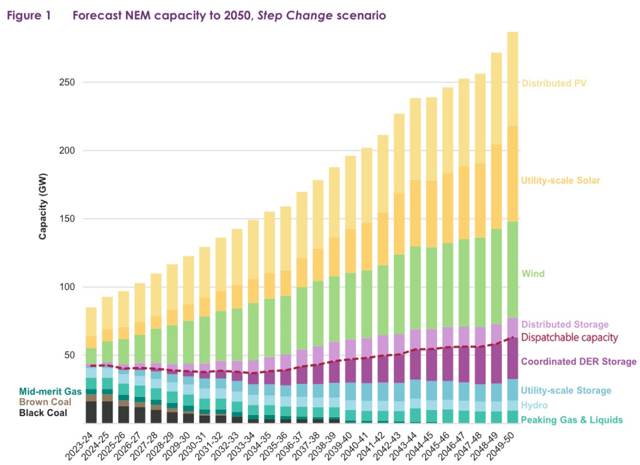

Figure 2: AEMO 2050 energy mix
(AEMO, 2022)

3 Current Understanding

3.1 Renewable Grid

To analyze the problem accurately we should have context of power generation in the current grid system and how it may evolve. The Australian Energy Market Operator (AEMO) has a plan for a net-zero grid in 2050 and it it relies heavily on wind and solar (Figure 2). If we assume the future set out in the AEMO net-zero report (AEMO, 2022) we can see that our economy and energy system will be much more reliant on wind velocity.

3.2 Energy Availability

Availability of wind energy is a crucial measurement to determine where the best locations for wind turbine placement (Martinez and Iglesias, 2024). Figure 3 can be used as a baseline for how the power will change in the future. It is represented in power per unit area of potential wind energy, this is the standard for how different locations are compared. Using Figure 4 we can find the wind power available on average. We may note that the velocity term is cubed meaning that the power output will vary greatly with only a small wind velocity variation (Hdidouan and Staffell, 2017). This is important when considering wind velocity fluctuations in the future due to climate change.

There is also the fact that wind turbines can not make extra power from higher wind velocities if it reaches a certain limit (Hdidouan and Staffell, 2017). Meaning they are susceptible to decreased wind speeds and cannot utilize excessive wind speeds in some circumstances. Making variation of wind speed an undesirable outcome for power generation.

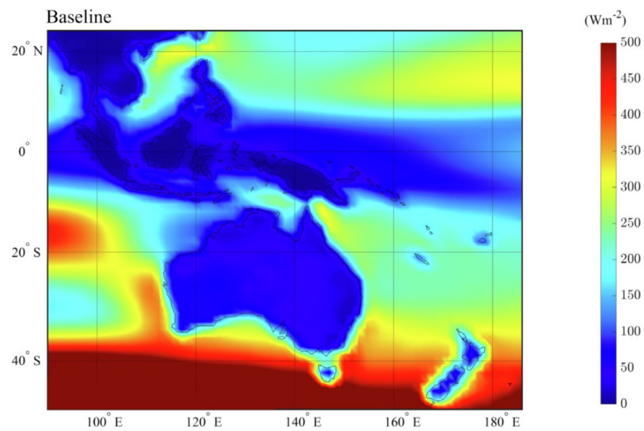

Figure 3: Baseline wind energy (Fournier et al., 2023)

$$P = \frac{1}{2}\rho U^3$$

Figure 4: Power equation for wind velocity (Hdidouan and Staffell, 2017); U: wind velocity, P: power output, ρ: density of air

3.3 Climate Model Projections

To determine the future wind velocities and their distributions climate models will be used. These models have many outputs about future weather conditions predominantly temperature and precipitation (Hdidouan and Staffell, 2017). However, their outputs can be used to predict future wind velocities on a daily time scale. Climate projections exist for the whole world and until the end of the century, with the certainty continually decreasing the further the project into the future.

These models are based on CO2 emissions increasing and causing global warming through altering the energy balance on Earth. We can't predict human behavior and how much CO2 will continue to be emitted. This is dealt with by modeling a number of scenarios corresponding to moderate (SSP 4.5) and extreme (SSP 8.5) CO2 emissions. We will take this into account.

3.4 Wind Variation

The variation of mean wind power density for Australia is projected to experience a decrease of less than 5% over the 21st century(Fournier et al., 2023). This decrease is slightly greater in a high emissions scenario (SSP 8.5) compared to a moderate emissions scenario (SSP 4.5). The reason the whole country average change is small is mainly due to Australia being a large area and the mean value

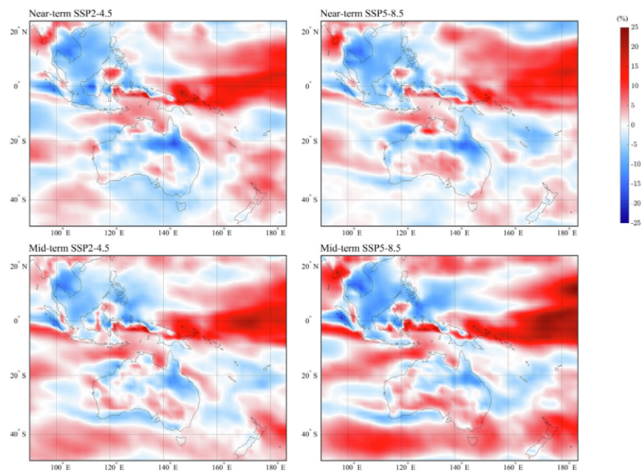

Figure 5: Power variation under different climate change scenarios (Fournier et al., 2023)

evens out across the whole country. This does not occur when analyzing smaller countries and can skew country to country comparisons.

There are more significant local changes that should be considered as they are large and become more extreme with higher CO2 emission. Changes in the near-term are up to -20% and +20% depending on which location you look at in Australia (Figure 5) (Fournier et al., 2023). This variation is greater when looking at a higher emissions scenarios from -20% to +40%. Considering the change in power density varying across the whole country we must consider which wind farms will need to handle an increase in capacity to counteract a decrease in other locations. The overall power available to Australia does not change in a great manner but its location does. With a distributed grid these effects may be offset. A large part of these output variations are due to large scale atmospheric circulation changes (Fournier et al., 2023).

Observing these trends in conjunction with Figure 3, we can see that many offshore and coastal locations still retain a high energy density even when the variations are taken into account. Seasonal variation plays a major role in the overall variance of the power density. Certain months experience an increase (September - November) and others seeing a decrease (December - May) (Fournier et al., 2023). The different emissions scenario causes certain months to increase or decrease with a low emissions scenario causing power density to decrease and high scenario causing an increase in the months June, July and August (Fournier et al., 2023). This is crucial to our understanding of how a future grid should be built. The monthly variation should be considered with the fact that a power grid energy supply must match energy demand at all times. These intra-annual variations could be a critical failure point to a grid that relies on wind power.

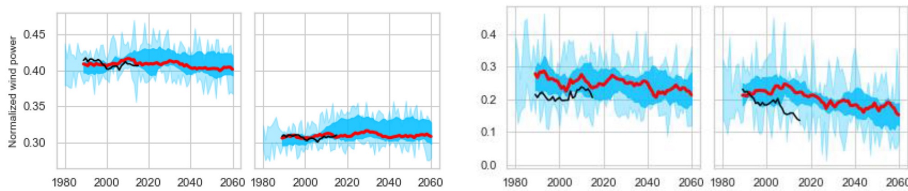

Figure 6: Wind power output; left averaged, right peak days (Huang et al., 2020)

Temperature variation has a large influence on wind farm power output as well. This has been studied at two on-shore sites using past data and future climate projections. Although the averaged output of energy does not change greatly (Figure 6.), days with peak heat the power output does vary greatly (Figure 6). This is a large issue due to the fact that on hot days there is a much greater power demand (Huang et al., 2020), this is especially true in Australia. This study is only for a particular site and does not have a general application for all of Australia. However, it does show us how important extreme events can be on the power grid. This study also predicts that periods of high wind may cause the turbines to shut off for safety reasons. Sever weather may also pose a risk to offshore wind sites especially tropical cyclones causing mechanical failure of turbines. Tropical cyclones are predicted to increase in climate change scenarios. This has been modeled in the South China Sea and may cause a moderate increase in damage to wind turbines (Wen et al., 2024). This has not been studied in Australia but is relevant to future study of offshore tropical regions of Australia.

3.5 LCOE

Levelised cost of energy (LCOE) is a measurement of the cost per unit energy over the lifespan of the power generating asset (Evans et al., 2018). This is the key driving factor for what energy supplies are cheapest and the best choice for new development and government investment decisions. With levels of uncertainty in the climate projects overall power density changes and the variance in location and time of power production the resilience of projects LCOE is worth considering. A worst case scenario of overall power output in Australia decreasing may be mitigated by other effects. The decreasing cost and increasing efficiency of wind turbines is predicted to more than compensate for the deceased production level (Evans et al., 2018). However, this does not solve the problem of intra-annual variance.

4 Knowledge Gaps

The challenges facing this report are generally due to the uncertainty of climate models and the lack of data surrounding local wind variations for the entire country. Climate models until recently lacked the temporal resolution necessary for accurate daily wind predictions so this is a relative new area of research (Fournier et al., 2023). Majority of climate model outputs must be reanalyzed for site specific predictions, which is time consuming and requires more data.

There is no control group for these studies that are conducted using climate models. This is due to there only being one Earth where we can observe changes due to increasing CO2 and consequential temperature increases. This makes it hard to conduct studies and tease apart causes. All we can do is make predictions and observe how they turn out in the future. This is a key area for future study and should be focused on potential future sites outlined in Australia's renewable energy plan (AEMO, 2022).

Wind farms have been shown to alter micro-climate characteristics of the location they are placed. They can alter the daily temperature of the sites they are built at (Liu et al., 2023). This is an added uncertainty to how these locations will change in the future. This may be less important in offshore projects.

5 Recommendations

Wind energy is still one of the cheapest forms of renewable electricity and the yearly mean for the whole country will only slightly decrease in the future. The key takeaway from this report should be that climate change will cause wind at particular locations to vary greatly, especially during days that experience peak heat or storms. The particular locations increase or decrease from these climate model outputs is important and useful but not certain. This finding should be used to ensure that the power grid can handle these variations of supply and demand through extra storage or over sizing.

Over sizing is where the capacity of renewables is overbuilt so that they can supply significant power during non-peak production periods. During peak periods of power generation the excess power will be unused and shed. It may seem wasteful but this solution has been identified as decreasing the need for battery storage and a cost effective way of providing electricity at a large scale(Rey-Costa et al., 2023).

What may turn out to be an important outcome is finding that demand at certain times of day is more important than the average demand. Focus should be placed on how power changes on peak demand days and how this can be addressed through grid design. Energy generation companies prefer steady power generation through the year and climate change will effect this. Government policy may be required to mitigate this.

Australia should begin to invest in research to determine where the best locations for wind farms are. The temporal distribution of wind power should be further researched to determine how supply can best meet demand while limiting the need for energy storage. This may be more important than producing more power.

References

Hdidouan, D., & Staffell, I. (2017). The impact of climate change on the levelised cost of wind energy. *Renewable Energy*, *101*, 575–592. https://doi.org/10.1016/j.renene.2016.09.003

Evans, J. P., Kay, M., Prasad, A., & Pitman, A. (2018). The resilience of australian wind energy to climate change. *Environmental Research Letters*, *13*(2), 024014. https://doi.org/10.1088/1748-9326/aaa632

Huang, J., Jones, B., Thatcher, M., & Landsberg, J. (2020). Temperature impacts on utility-scale solar photovoltaic and wind power generation output over australia under RCP 8.5. *Journal of Renewable and Sustainable Energy*, *12*(4), 046501. https://doi.org/10.1063/5.0012711

AEMO. (2022, June 30). *2022 integrated system plan ISP*. Australian Energy Market Operator. https://aemo.com.au/-/media/files/major-publications/isp/2022/2022-documents/2022-integrated-system-plan-isp.pdf?la=en

Fournier, A., Martinez, A., & Iglesias, G. (2023). Impacts of climate change on wind energy potential in australasia and south-east asia following the shared socioeconomic pathways. *Science of The Total Environment*, *882*, 163347. https://doi.org/10.1016/j.scitotenv.2023.163347

Liu, N., Zhao, X., Zhang, X., Zhao, J., Wang, H., & Wu, D. (2023). Remotely sensed evidence of the divergent climate impacts of wind farms on croplands and grasslands. *Science of The Total Environment*, *905*, 167203. https://doi.org/10.1016/j.scitotenv.2023.167203

Rey-Costa, E., Elliston, B., Green, D., & Abramowitz, G. (2023). Firming 100% renewable power: Costs and opportunities in australia's national electricity market. *Renewable Energy*, *219*, 119416. https://doi.org/10.1016/j.renene.2023.119416

Martinez, A., & Iglesias, G. (2024). Global wind energy resources decline under climate change. *Energy*, *288*, 129765. https://doi.org/10.1016/j.energy.2023.129765

Wen, Z., Wang, F., Wan, J., Wang, Y., Yang, F., & Guo, C. (2024). Assessment of the tropical cyclone-induced risk on offshore wind turbines under climate change. *Natural Hazards*, *120*(6), 5811–5839. https://doi.org/10.1007/s11069-023-06390-3