CASE STUDY FACT SHEET

ELECTRICITY SECTOR CLIMATE INFORMATION PROJECT

# The impact of extreme heat on Variable Renewable Energy (VRE) generation

## Introduction

Increasing risk from exposure to changes in temperature, wind and solar irradiance associated with climate change may have implications for the safe and efficient operation of Australia's electricity networks. These risks should be assessed and strategies for mitigation and adaptation should be integrated with ongoing planning and operational decision-making frameworks.

This Electricity Sector Climate Information (ESCI) case study explores the projected change impacts on Variable Renewable Energy (VRE) generation.

The case studies are designed to demonstrate the use of the ESCI Climate Risk Assessment Framework and the choice and application of appropriate climate information for long-term risk decision-making for the sector. This case study is also presented as a Summary Case Study Fact Sheet, along with other ESCI Case Study Fact Sheets, on the ESCI website.

This case study and other case studies from the project can be found at: www.climatechangeinaustralia.gov.au/en/projects/esci/esci-case-studies

## Overview

The purpose of this case study is to demonstrate the application of the ESCI climate risk framework to exploring the vulnerability of variable renewable energy (VRE) generators to projected changes in temperature, solar irradiance and wind speed.


Figure 1 ESCI Climate Risk Assessment Framework, based on International Standard ISO 31000 'Risk Management' and Australian Standard AS 5334 'Climate change adaptation for settlements and infrastructure'.

The Electricity Sector Climate Information (ESCI) project was funded by the Department of Industry, Science, Energy and Resources (DISER) and was a collaboration between the Bureau of Meteorology (BOM), the Commonwealth Scientific & Industrial Research Organisation (CSIRO) and the Australian Energy Market Operator (AEMO). The ESCI website is at: www.climatechangeinaustralia.gov.au/esci

Australian Government Department of Industry, Science, Energy and Resources

Australian Government Bureau of Meteorology

CSIRO

AEMO AUSTRALIAN ENERGY MARKET OPERATOR

DISCLAIMER: This case study is intended as a guide for conducting a climate change risk assessment, not to provide information for use in operational decision-making as every organisation, location, and portfolio of risks is different and should be assessed in that context.

## Understand context

VRE generation sources driven by wind and solar energy are making an increasing contribution to the supply of electricity in the National Electricity Market (NEM). Their electrical and mechanical power system components are, however, vulnerable to extreme heat. Extreme heat is also a major driver of customer demand and so outages during high demand periods leave consumers vulnerable and can incur large societal impacts.

Solar and wind farms can be adversely affected by variability in temperature, solar irradiance and wind speed, with potential disruption to generator output and system reliability. If generator output declines against expectation, either on average or during peak demand periods, owners and investors may receive less revenue than expected, potentially reducing the viability of new projects or the profitability of existing projects. As well as this, the reliability of the system may be reduced, increasing the risk of unserved energy needs.

### Relevant stakeholders

VRE investments are unregulated and therefore investment decisions are primarily driven by the financial business case, that is revenue generation. Therefore, investors, insurers and operators of VRE are interested in understanding how climate change may affect VRE output. Similarly, AEMO and electricity consumers would benefit from understanding how exposed they might be to any potential changes to reliability. Accordingly, electricity retailers have an enhanced obligation for the contracting of available capacity during peak demand periods (Retailer Reliability Obligation).

## Identify historical climate risks

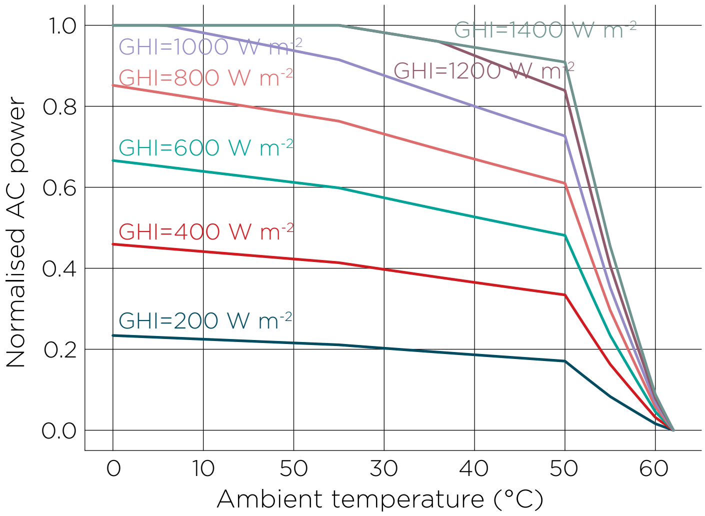
High temperatures are a known hazard for solar farms. VRE output is also dependent on solar irradiance and wind speed. This case study sought to quantify the risk that projected temperatures, solar radiation and wind speed might present to both solar and wind farms.

For this case study, a large-scale solar farm model[1] was employed that describes the relationship between weather variables and generator output for typical installations. A wind farm 'power conversion model' was developed by AEMO for this case study which used input from the observed performance of numerous operational wind farms (Figure 2). The solar farm model describes normalised AC power output variation with temperature for different levels of Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI) and wind speed at 10 m. The wind farm model describes output as a function of wind speed at 150 m and temperature. The output of the solar or windfarm is normalised (described on a scale from 0 to 1) as the actual output will depend on the size, make and number of the panels.

Depending on the level of solar energy input (GHI) the normalised power output for the solar farm declines slightly with increasing temperature up to about 50 °C, at which point the power output falls rapidly (Figure 2, top). For the wind power model (Figure 2, bottom), power output increases with wind speed up to 20 ms-1 and then declines (due to automatic protections in the turbines against damage at high wind speed); power output also responds to temperature with response capacity highest up to 37.5 °C, but reduced at higher temperatures.[2]

1 Developed in the PVLIB (Holmgren et al. 2018) and PVWatts (Dobos 2014) models assuming a single axis tracking installation using SMA Sunny Central 850CP XT inverter and a DC-to-AC ratio of 1.2.

2 The assessment assumes no changes to generator specifications over time; this process can be repeated if specifications change. Individual turbine design response may be available from the manufacturer.



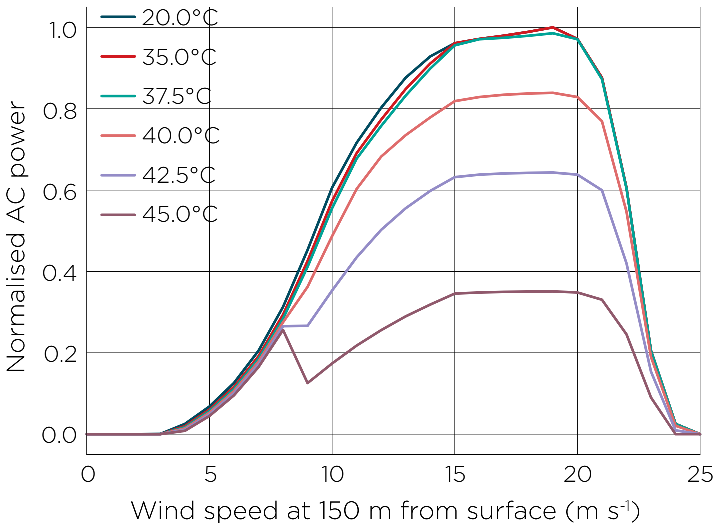




Figure 2 Indicative power conversion models used in this case study: Solar farm output (top) as it varies with temperature (horizontal axis) and Global Horizontal Irradiance (GHI, coloured lines). The wind farm model (bottom) describes output varying with wind speed (150 m from surface; $ms^{-1}$, horizontal axis) and temperature (coloured lines).

## Assessment locations

This analysis focused on four Renewable Energy Zones (REZ) located in Victoria (VIC) and New South Wales (NSW) (Figure 3). These four sites are where VRE generators are currently located, or likely to be, based on the 2020 draft ISP forecasts.[3]

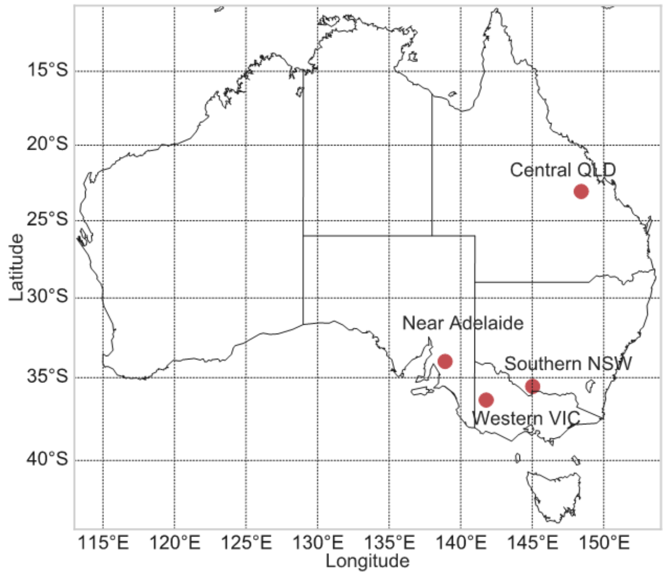



Figure 3 Renewable Energy Zones (REZ) sites used for this analysis.

# Analyse future climate risks

## Analysis period

The investment case for most VRE is 25 years, therefore the temperature trends were analysed out to 2060 to include the time frame of most interest to VRE stakeholders.

## Climate variables and time resolution

High temperature has been identified as the hazard of interest, with wind speed and solar irradiance also important climate variables considered here.

Due to the very high volatility in power prices typically driven by the customer response to high temperatures, the time of day at which the power is generated is important to the business case with the risk highest during peak demand periods. For this reason, sub-daily time-series data (30-minute temporal resolution) are required for this assessment.

3 Australian Energy Market Operator (2020). Draft 2020 ISP Archive. https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp/draft-2020-isp-archive

### Future climate scenarios

Future climate scenarios are influenced by three main sources of uncertainty which should be considered in any assessment:

1. Future greenhouse gas emissions pathways
2. Regional climate model responses to a given emission scenario
3. Natural variability at timescales ranging from hours to decades

#### *Greenhouse gas emissions pathways*

For the VRE case study, a high emissions pathway (RCP8.5) was assessed (noting for a more thorough assessment of future risk, it is strongly recommended that a range of concentration pathways are used to assess potential best and worst cases).[4]

#### *Regional climate response*

The project recommends climate projections are drawn from a range of models: for this case study, six GCMs were used to represent the plausible range of future climate pathways (ACCESS1.0, CanESM2, CNRM-CM5, GFDL-ESM2M, MIROC5, NorESM1-M). As this assessment of generator output requires sub-daily data (see above), downscaling of global circulation models (GCMs) using CSIRO's CCAM model (McGregor and Dix 2008) was undertaken (this CCAM regional climate model provides projections of both daily and 30-minute simulations of 'future weather'). The analysis was carried out for each model in order to preserve the projected interaction between weather variables, and then results combined to give an ensemble range of possible future risks.

For this case study, the climate data used to assess historical performance is drawn from CCAM downscaled ERA-interim re-analysis, not observed data. (Climate model history preserves the distribution of historical variables while not necessarily simulating the exact conditions that occurred.)

### Confidence in the climate projections and sources of uncertainty

Levels of confidence in projections rely on consideration of multiple lines of evidence, drawn from understanding of the underlying physical processes that influence weather and climate. This project is undertaking careful assessment and presentation of these processes as they vary for different climate variables across the different regions in Australia. Temperature projections can be given with very high confidence while projections for solar irradiation are linked to rainfall projections, about which there is lower confidence than projections for temperature.[5]

## Evaluate climate risks

### Potential impact on VRE output on average

To assess the impact of changes in the respective climate variables to VRE output on average (annual mean), 30-minute time-series of temperature, solar radiance and wind speed derived from six GCMs (RCP8.5; downscaled using CCAM modelling) were applied to the generator output model (Figure 4).

4 See ESCI Key Concepts—choosing representative emissions pathways (RCPs).

5 See ESCI Key Concepts—climate projection confidence and uncertainty.

From these mean annual time-series and underlying analyses we can note:

- Annual mean temperatures are predicted to increase in all regions with a high level of agreement amongst the GCMs.
- The annual mean levels of solar irradiance may increase slightly in the southern regions although there is not strong agreement amongst the GCMs. Solar resources are highest in the South Australian (SA) and Queensland (QLD) example sites.
- Annual solar farm output predominantly follows the trends in solar irradiance, showing that possible increases in irradiance have a larger impact on annual output compared to temperature.
- Annual mean wind speed is projected to remain reasonably steady with high levels of agreement amongst the GCMs. The SA and VIC example sites have the highest wind speeds.
- Annual wind farm output shows no trend in response to climate variables. The high level of agreement amongst the GCMs for temperature and wind speed results in a high level of agreement for stationary output over the prediction horizon.

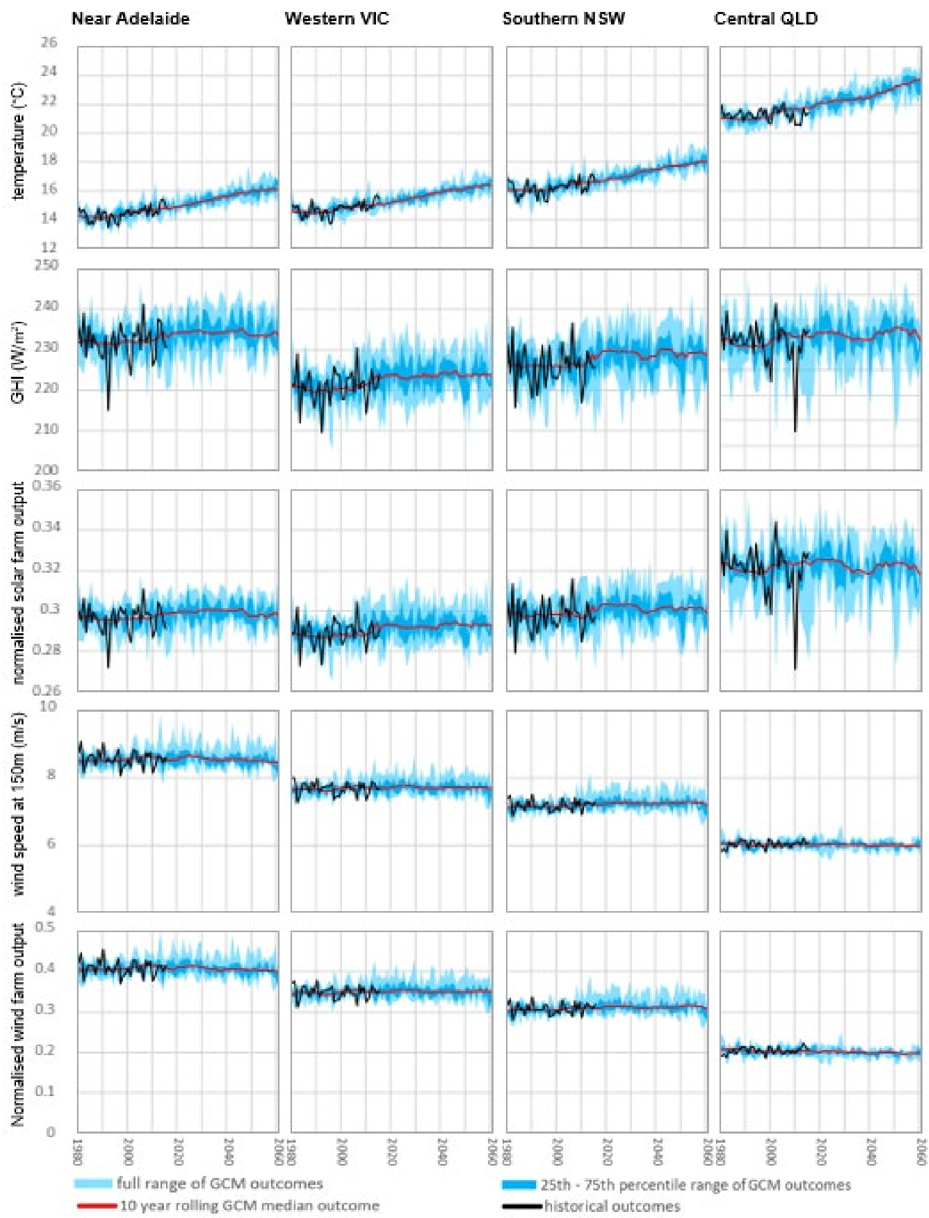



Figure 4 Time-series (30-minute) for key variables (left column: temperature (°C), solar irradiance (GHI; W/m²), normalised solar farm output, wind speed at 150 m, normalised wind farm output) from 1980 to 2060. The light blue shade is bounded by the 10th and 90th percentiles of the 6-GCM ensembles in individual years. The dark blue shade is bounded by the 10th and 90th percentile for the 10-year moving averages of the 6-GCM ensembles. The thick red line is the median of 10-year moving averages of the 6-GCM ensembles. The thin black line is the 10-year moving average of ERA interim results (observations).

## Potential impact on VRE output through peak demand periods

While changes in annual mean values did not have a significant impact on the performance of renewable energy assets, it is potentially of more interest to understand the impact through times of extreme heat; that is, periods where prices are more likely to be high due to either decreased supply or increased demand.

In an initial assessment of potential changes to VRE output, a simple model was developed that assesses the projected change in output that results from changes in high temperatures. The 1-in-10 year ARI (average recurrence interval, i.e. the temperature that is expected to be exceeded one in every ten years) was used as an indication of extreme temperature to which VRE plants are exposed (Table 1). Here, the power conversion models, described in Figure 2, are used to assess projected change in output under high temperature conditions.

Thus, for a solar farm in Western Victoria, with an historic (1961–2020) 1-in-10-year temperature of 46 °C, has projected temperatures of 48 °C in the 2021–2060 period. Given the relationship between temperature and power output in the solar model described above (assuming GHI of 1000 W/m$^2$) maximum output on a 1-in-10 ARI temperature sunny day would drop from historic output of ~74 per cent of capacity to ~72 per cent in the future. For a wind farm in a similar location output would drop from ~15 per cent to zero (assuming wind speed of 15 m/s).

Table 1 Changes in 1-in-10-year temperatures and the associated changes in power output at that temperature for wind and solar farms for each REZ. Power output values are calculated using the models shown in Figure 2.

| | Near Adelaide | Western VIC | Southern NSW | Central QLD |
|---|---|---|---|---|
| Historical: 1961–2020 | | | | |
| 1-in-10-ARI Temperature (°C) | 44 | 46 | 44 | 42 |
| Maximum Wind Farm Output | ~40% | ~15% | ~40% | ~65% |
| Maximum Solar Farm Output | ~76% | ~74% | ~76% | ~78% |
| Future: 2021–2060 | | | | |
| 1-in-10-ARI Temperature (°C) | 48 | 48 | 48 | 44 |
| Maximum Wind Farm Output | ~0% | ~0% | ~0% | ~40% |
| Maximum Solar Farm Output | ~72% | ~72% | ~72% | ~76% |

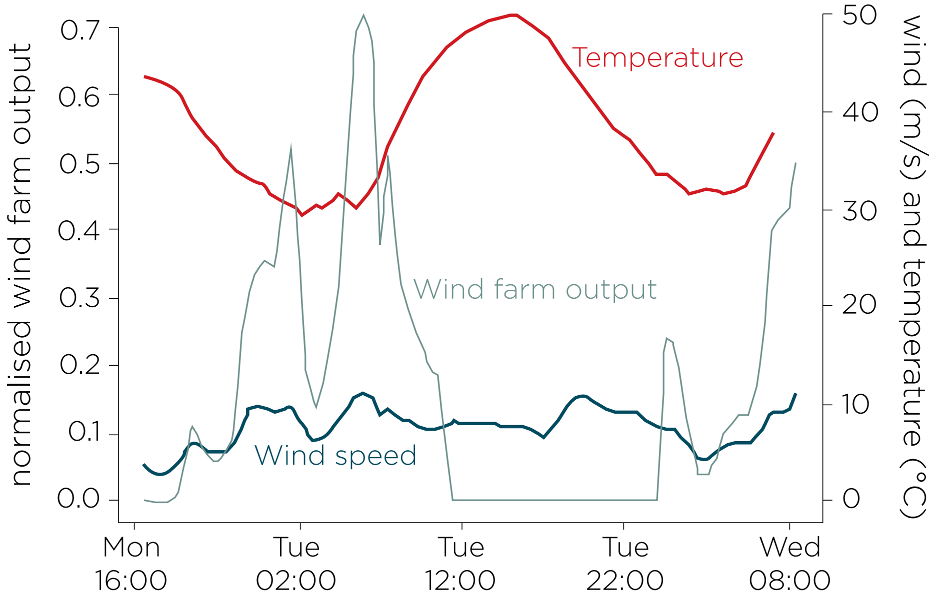



Figure 5 Thirty-minute simulation of wind farm output (black line) for varying temperature (red line) and wind speed (blue line) in Western Victoria.

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Figure 5 shows a simulation of wind farm impact on one of the hottest days in the sample at Western Victoria. Mean output during the identified peak demand (1200 to 1900) period is zero.

To assess the impact on VRE output during **peak demand**, the 30-minute modelling was filtered to analyse the impacts. For this study, peak demand periods were defined as the top five hottest days per year between 1200 and 1900 AEST, a time period likely to capture the timing of daily maximum temperature and the timing of maximum electricity demand. The 30-minute weather input and VRE generation output was then analysed for the peak demand period (average of 70 30-minute market periods per year) (Figure 6).

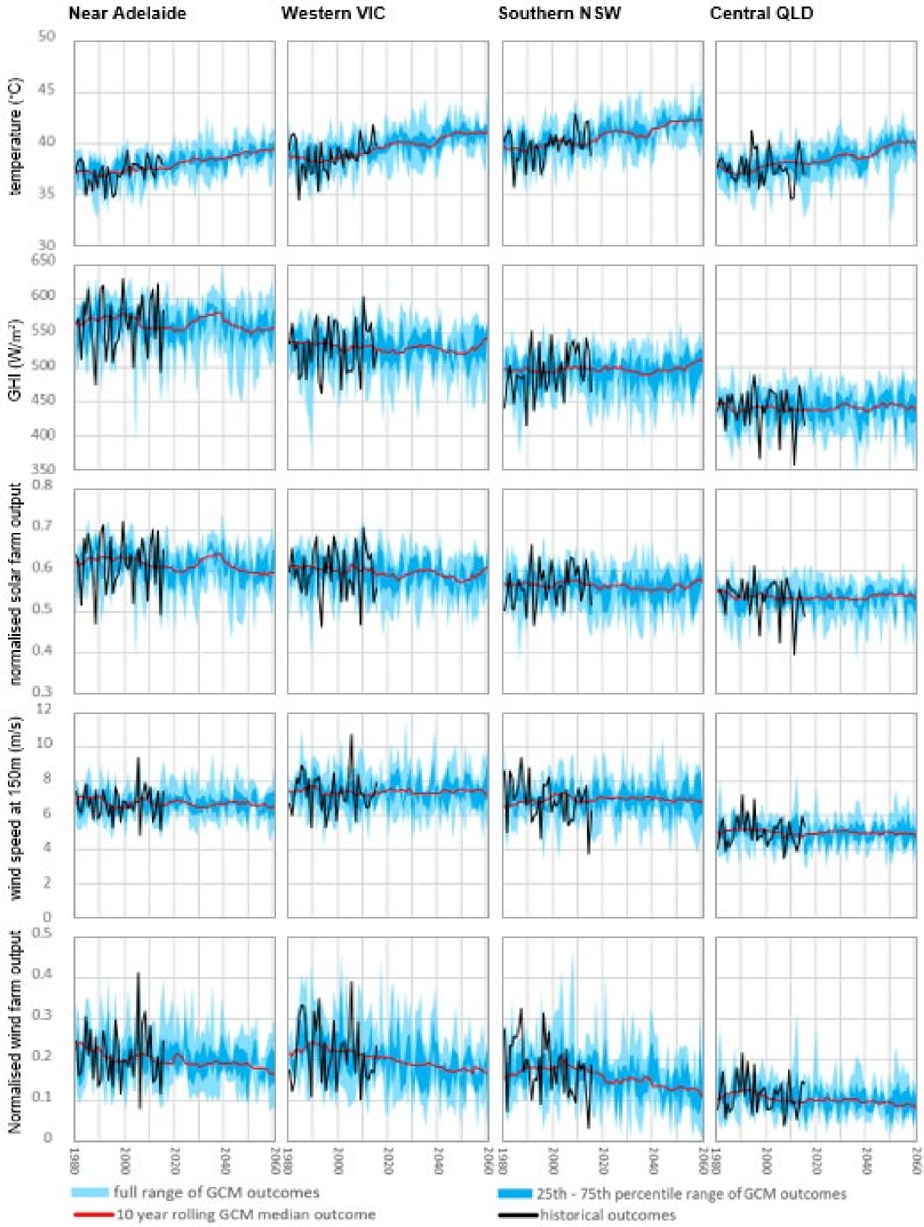


Figure 6 Thirty-minute time-series during the peak period mean (i.e. 1200 to 1900 in local standard time) for the hottest five days in a year for a range of variables (left column: temperature (°C), solar irradiance (GHI; W/m²), normalised solar farm output, wind speed at 150 m). The light shade is bounded by the 10th and 90th percentiles of the 6-GCM ensembles in individual years. The dark shade is bounded by the 10th and 90th percentiles of 10-year moving averages of the 6-GCM ensembles. The thick red line is the median of 10-year moving averages of the 6-GCM ensembles. The thin black line is the 10-year moving average of ERA interim results (observation).

Considering the peak period analysis (Figure 6) we can note:

- Temperatures during peak demand periods are predicted to increase in all regions with a high level of agreement amongst the GCMs. Peak temperatures are higher in VIC and NSW.
- The level of solar irradiance during this period is higher than the annual average and there is disagreement amongst the GCMs about how this may change.
- Solar farm output during peak demand periods shows a slight downward trend
- Mean wind speed during peak demand periods is predicted to remain steady with expected year to year variability demonstrated by the GCMs.
- Wind farm output during peak demand periods shows a distinct downward trend. While the GCMs show high levels of expected year-to-year variability, there are high levels of agreement regarding the trend, with steepest trends in the regions with the hottest maximum temperatures.

## Analyse future climate risks

Wind power generation had the greatest output reductions under extreme temperatures, for example 1-in-10-year event in the simple modelling experiment used in this case study. Solar de-rating was relatively limited, compared with wind, for the four case study locations.

While long-term solar output may increase in some locations due to possible increases in irradiance, it was also confirmed that without changes to generator specifications, wind farm output during peak demand periods is likely to fall, even if average outputs are likely to remain unchanged.

### Investment risk

To ascertain the relevance of these findings, a number of VRE project developers were interviewed. These interviews largely validated the analysis but also indicated that investment risks were likely to be immaterial under current market rules and conventions. For developers and owners, the heat impacts on projected revenue was deemed small relative to other revenue risks like price and marginal loss factor volatility. There may however be growing financial incentives to increase generator availability during peak demand periods to adhere to the Retailer Reliability Obligation.

Climate risks that result in the destruction of the asset or their insurability, like floods, fire and wind events, were perceived to be of more significance. In the case of solar developers, projected increases in solar irradiance may increase output.

### Reliability risk

Further interviews were conducted with AEMO and other industry representatives to ascertain the materiality of system reliability projections. Medium-term and long-term system reliability is considered in AEMO outputs including the Electricity Statement of Opportunities (ESOO) and the Integrated Strategic Plan (ISP). Year-to-year volatility in the combined peak demand contribution of VRE generators is well-considered, however the uncaptured downward trend in this contribution is likely to result in an overestimation in the reliability of the electricity system on extremely hot days.

### Risk treatment

In future periods where VRE generators collectively supply larger portions of total energy, this overestimation is material, particularly for wind. To address this risk, the identified mitigation options will need to be considered including:

- increasing the robustness of VRE specifications to heat
- including on-site energy storage to support VRE output
- procuring additional dispatchable capacity, or demand side participation
- increasing transmission connections to improve the support of regional energy transfers

Further work would be required to identify the lowest cost option, whether that be enhanced VRE specifications or the procurement of additional capacity. Cost–benefit analyses would then need to be conducted to identify the lowest cost pathway for mitigation.

Maps of ARI temperatures, and time-series of multiple variables for a suite of different climate models and emissions scenarios are available on the ESCI website.

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## Further information

This ESCI case study is accompanied by a Technical Report which covers the analysis and implications in more detail.

## References

Australian Energy Market Operator (2020). Draft 2020 ISP Archive. https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp/draft-2020-isp-archive

Dobos AP (2014). PVWatts Version 5 Manual. NREL Technical Report. https://www.nrel.gov/docs/fy14osti/62641.pdf

Holmgren WF, Hansen CW, and Mikofski MA (2018). 'PVLIB python: a python package for modeling solar energy systems' Journal of Sustainable Studies. DOI: 10.21105/joss.00884

Huang J, Jones B, Thatcher M, et al. (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 12:046501. DOI: 10.1063/5.0012711

McGregor J and Dix M (2008). 'An updated description of the conformal-cubic atmospheric model' in K Hamilton and W Ohfuchi (eds), *High Resolution Numerical Modelling of the Atmosphere and Ocean*. Springer, New York, 51–75.