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Changes in solar resource intermittency and reliability under Australia's future warmer climate

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ABSTRACT

The dependency of photovoltaic (PV) power generation on meteorological parameters can impact power production due to weather-induced variability. During the day, fluctuations in radiation introduce intermittency in power generated, raising reliability and grid stability issues at higher penetration levels. Long-term future resource assessment provides an effective tool for estimating resource reliability and future intermittency essential for pre-feasibility site assessments around the world. Australia has high solar power capacity, with several solar farms in operational and developmental stage. Using Australia as a case study, this research aims to understand Australia's solar resource distribution and variability using regional climate model projections under a high emission scenario. Results indicate an abundance of solar resource power density in Australia, especially in the North (450-500Wm^{-2}). The solar resource will be more reliable in Eastern Australia in the future with ∼ 5% increase in resource density. Results suggest reduction in intermittency (∼20-minute lull periods) in the East with increase in clear-sky days/year in the future (∼20 days/year). Resource assessment of Sun Cable and New England solar farm located in Australia, revealed the future scope of increase in clear-sky days at the sites. This long-term future solar variability analysis can help identify regions in Australia where PV systems will be least susceptible to losses due to intermittency. Furthermore, this study will help in critical decision-making processes like planning storage systems, site selection, opportunities to create hybrid solar farms with the co-existence of solar and wind technology, etc., to mitigate the risks associated with future intermittent PV power generation.

1. Introduction

Large-scale deployment and integration of renewable energy into the electricity grid is one of the predominant ways to regulate global carbon emissions and mitigate climate change. Solar Photovoltaic (PV) energy is a substantial part of the renewable electricity sector, and there has been rapid growth in the deployment of PV plants worldwide over the last decade. Australia is experiencing a rapid transition towards substantial integration of renewable technologies in its energy systems to meet its large-scale Renewable Energy Target. Solar PV contributed ∼10% to Australia's total electricity generation in 2020 [3], with >4.5 GW of new installations. To meet the net zero emission target, Australia will need an increase in 30 GW solar PV capacity by 2026 [21] and another 72 GW by 2050 [10]. However, the sensitivity of PV to weather-induced variability increases uncertainty, and its intermittent nature limits its reliability [59]. With the increase in PV penetration levels into the electricity grid, the weather-induced variability in PV power output negatively impacts the utility grid stability due to fluctuations in the grid voltage and frequency [25]. Even though this issue can be partially solved by power storage, geographic dispersion, load control, and irradiance forecasting, it still poses a challenge to grid integration and stable grid regulation [7,32]. Therefore, it is crucial to estimate the PV system

Abbreviations: PV, photovoltaic; GHI, global horizontal irradiance; CMIP5, Coupled Model Intercomparison Project 5; RCP, representative concentration pathway; DNI, direct normal irradiance; ENSO, El-Nino Southern Oscillation; IOD, Indian Ocean Dipole; CORDEX, Coordinated Regional Downscaling Experiment; RCM, Regional Climate Model; GCM, Global Climate Model; sSOLIS, simplified SOLIS; MERRA2, Modern-Era Retrospective analysis for Research and Applications Version 2; ERA, European Centre for Medium Range Weather Forecasts (ECMWF) Re-analysis; εORA, the observed range adjusted error (W/m^2); RCoV, relative coefficient of variation (unitless); RPD, resource power density (W/m^2); DCI, daily clearness index (unitless).

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performance and resource variability as a part of the pre-feasibility site assessment and long-term management of solar PV farms [6,41]. Besides the solar resource's magnitude, knowledge of the solar resource uncertainty at any given location is important for precise analysis of optimal system design, financial viability, and integration of solar energy.

Solar radiation variability is caused by overpassing clouds and has been previously studied using in-situ observations at several specific locations across the world: Colorado [28], several locations across the United States [30,39], Spain [33], Estonia [55], Hawaii [18] and Finland [26]. These studies have highlighted the impact of high-frequency solar radiation variability on PV output at specific locations. Lave et al. [27] used satellite-derived Global horizontal irradiance (GHI) to define GHI variability zones across the United States and determine its impact on distribution grid voltage and transformer tap change operations. The GHI variability leads to voltage fluctuations, which increases the use of regulation equipment like on-load tap changers to ensure power output is at the rated voltage. Further, variations in solar radiation during the day can introduce intermittency in the PV power generated [7] and raise reliability and grid stability issues at higher penetration levels. Considering substantial future investments planned in PV technology, most studies have highlighted the predicted long-term changes in radiation patterns and PV power production [5,14,37;43,50,58], with limited studies focusing on future PV system reliability. Multidecadal changes in solar radiation have been discussed by [35;57,57] using long-term observational radiation records where coherent periods pertaining to decline and incline in solar radiation have been detected worldwide that accord with air pollution patterns. Several studies using global climate model (GCM) projections and regional climate model projections predict an increase in future PV energy yield over Europe and China, a decrease over the USA, Africa and slight decrease over Australia [5,14,19,36,37,50,58]. A recent study using Coupled Model Intercomparison Project 5 (CMIP5) projections [59] reveals the heterogeneous relationship between mean solar radiation trends and future power supply, emphasizing that power reliability is more sensitive to variations in solar radiation in hot arid regions. It is expected that future PV power intermittency will increase in Europe and the Arabian Peninsula under intermediate emission representative concentration pathway (RCP) 4.5. At the same time, regions in North America and Australia may experience stronger intermittency during winter [13].

Even though Australia has one of the largest potentials for the solar energy generation [46], it faces PV reliability issues due to cloud-induced intermittency [24]. Previous studies over Australia have emphasized the pronounced seasonal variability of GHI and direct normal irradiance (DNI) [43,44] due to changes in cloud cover. The cloud cover patterns over Australia are influenced by the large-scale climate drivers (like El-Nino Southern Oscillation (ENSO), monsoon, and sub-tropical ridge) and synoptic features (like cloud bands, troughs, and fronts) [43]. ENSO and Indian Ocean Dipole (IOD) can account for ~10% of the changes in the solar energy resources over Australia during winter with no-to-little effect during the summer [7]. Prasad et al., [43,45] studied the synergy of solar energy with wind energy and battery systems to discuss the co-existence of hybrid renewable technologies in Australia using reanalysis data. These studies suggest Australia has higher solar resource variability in the Southern regions. At the same time, the North is more susceptible to high intermittency due to the influence of clouds in these regions. Even though their study suggests the complementarity of solar PV with other renewable technologies, it does not discuss the plausible impacts of future climate change on the solar resource feasibility in the region. Global studies using GCMs on future PV energy yield in a warmer world have predicted a negligible effect on solar PV productivity in Australia [5,14,58]. Due to the inability of GCMs to capture small-scale regional processes, high-resolution regional climate model projections are recommended for impact and resource assessment studies [60,61]. Recent studies by [20,42] are devoted to understand the impact of climate change on future PV potential based on dynamically downscaled RCM projections. They predict a decrease in the future PV potential over Australia due to climate change. Poddar et al., [42] discuss the future PV cell efficiency losses in Australia due to the anticipated rise in cell temperatures. However, given the importance of solar PV in mitigating climate change in Australia, a comprehensive assessment of future solar feasibility in Australia is lacking using high-resolution regional climate model projections. Further, there has been no research to date predicting the changes in solar resource intermittency and reliability in Australia under a future warmer climate.

Therefore, this research aims to understand the solar radiation variability Australia-wide using high-resolution regional climate model projections. This study examines several metrics (such as availability, episode length, lulls, and daily clearness index (DCI)) to understand the future changes in PV reliability and intermittency due to climate change across Australia. Further, we classify daily weather to analyze the future changes in clear and cloudy days to gain insight into the daily net productivity and how it may vary in the future under a high emission scenario (RCP8.5). We use these key metrics for the solar resource assessment of two large-scale PV farms under development and estimate the influence of climate change on the reliability of the energy generated at these sites.

To the best of our knowledge, this comprehensive and detailed analysis of solar variability will offer national policymakers and stakeholders a valuable resource to comprehend the impact of climate change and gain a deeper understanding of project related uncertainties in the long-term decision-making process. Furthermore, several climate zones within Australia are affected by many modes of climate variability [48]. This proposed framework is standardized and can be applied to study the feasibility of future solar plants, including intermittency and energy storage estimation for different climate regions of the world, in order to promote the worldwide integration of solar energy into the electricity grid. This study is organized as follows. Section 2 describes the data and methods. Section 3 presents the results and discussions on validation of CORDEX-Australasia solar radiation data, solar resource distribution in Australia, reliability and intermittency along with case studies on two future solar plants in Australia. Section 4 concludes the main findings of this study.

2. Data and methods

2.1. Regional climate model projections

This study uses regional climate model simulations from the Coordinated Regional Downscaling Experiment (CORDEX) for Australasia [12]. Several GCMs from CMIP5 have been downscaled by RCMs for future scenarios under CORDEX experiments by the contributing modelling groups. Not every GCM is downscaled by every RCM leading to a sparse matrix (Table 1) and a 15 member ensemble [12]. Seven GCMs from the CMIP5 were downscaled using five RCMs to obtain the climate projections over the CORDEX-Australasia region. The climate

Table 1
CORDEX-Australasia GCM-RCM combinations analyzed in this study. The climate projections from these pairs were available for the historical and future periods under the RCP8.5 scenario. The highlighted boxes indicate the available GCM-RCM pairs [12].

	WRF J	WRF K	CCLM	REMO2015	RegCM4.7
ACCESS1.0					
ACCESS1.3					
CanESM2					
MPI-ESM-LR					
MPI-ESM-MR					
NORESM1-M					
HadGEM2-CC					

projections obtained using 5 RCMs and 7 GCMs pair create a 15-member ensemble for historical and future periods (Table 1). The details of the different parameterization schemes used for downscaling the RCMs, their resolution and the contributing modelling group are listed in Table 2. The CORDEX-Australasia future simulations are obtained for the high-emission RCP8.5 scenario. The RCP8.5 scenario projects a surface warming up to 4.8 °C by the end of the 21st century [23]. The CORDEX Australasia simulations have been evaluated over Australia and shown to provide an overall good representation of the climate of Australia [9,12] and to add value to the GCM projections [8]. In this study, the time periods 1976–2005, 2030–2059 and 2070–2099 are investigated as historical, near future and far future periods respectively. In this research, we have used shortwave downward radiation at three-hourly intervals to perform relevant analysis. Results obtained from the intermediate scenario (RCP4.5) are included in the appendix (figure A1-A6, table A3) and are not discussed in the main results due to data availability from only 6 ensemble members (refer to table A2 for ensmeble member). We have obtained the clear sky radiation using the simplified SOLIS (sSOLIS) clear sky model [22]. sSOLIS clear sky model performs the best for the region with the least mean bias and root mean square error (RMSE) compared with other clear-sky models (refer to Appendix, Table A1).

2.2. Reanalysis and observational datasets

The different ensemble members are evaluated using two reanalysis datasets: Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA2) and European Centre for Medium Range Weather Forecasts (ECMWF) Re-analysis (ERA5). The details of these datasets used in this study are listed in Table 3. The 3-hourly shortwave downwelling solar radiation from the reanalysis datasets is used for the period 1980–2005 to evaluate the historical CORDEX-Australasia ensemble members. All three datasets have been re-gridded to a spatial resolution of 0.5°X0.5° using bilinear interpolation. We also evaluate the ensemble mean of shortwave downwelling radiation using ground observation data from the eight weather stations maintained by Australian Bureau of Meteorology (BOM) from 1994 onwards. These stations have at least 10 years of data recorded during the historical period. The detailed description of the stations and data availability period along with the mean bias is shown in Table 4. The model validations are done considering daytime values.

The mean radiation values can differ among these reanalysis datasets due to difference in physical parameterizations of numerical models, observational data used for assimilation and the assimilation schemes [17,47]. The range given by these reanalysis datasets gives an approximation of the observational uncertainty. Therefore, we consider the observation by these datasets as a range for each grid point instead of a single value to estimate the model bias. We use observation range-adjusted error (εORA) to estimate bias in CORDEX-Australasia simulations. The observation range adjusted error is calculated as:

Table 3
Description of reanalysis data sets used in model evaluation.

Name	Native Resolution	Analysis Period	Variable name	Reference
ERA5	0.25° lat X 0.25° lon	1980–2005	msdwswrf	[17]
MERRA2	0.5° lat X 0.625° lon	1980–2005	SWGDN	[47]

$$\varepsilon_{ORA} = \begin{cases} 0, & \min(O_i)\langle M < \max(O_i) \\ M - \min(O_i), & M < \min(O_i) \\ M - \max(O_i), & M > \max(O_i) \end{cases} \tag{1}$$

where O_i are the reanalysis estimates, and M is the modeled value. The mean bias and RMSE are then calculated using the ε_{ORA}.

If a model estimate falls within the range of the two observational estimates or equals to either of them, then it is regarded to have zero error. If the model estimate lies beyond the observational range, then the model error is calculated as the distance from the model value to the nearest observational estimate [11].

2.3. Resource assessment metrics

This section presents the details of the various metrics analyzed to understand the solar resource variability, reliability and intermittency in Australia. All the calculations are done for daytime only.

2.3.1. Variability

It is most desirable to have a stable energy-generating source with minimum variability. In this study, the variability in the solar resource is estimated using the relative coefficient of variation (RCoV). A lower RCoV implies lower variability, indicating that the resource is highly feasible at the site. RCoV is the ratio of the median absolute deviation of irradiance and median irradiance [15,43].

$$\mathrm{RCoV} = \frac{\text{median (absolute deviation about the median)}}{\text{median}} = \frac{\text{median}\,|(\mathrm{X_i} - \widetilde{\mathrm{X}})|}{\widetilde{\mathrm{X}}} \tag{2}$$

2.3.2. Reliability

The reliability of solar resources in Australia was determined using the two metrics: availability and episode lengths. Availability is defined as the frequency of occurrences of efficient resources for solar power

Table 2
Parameterization schemes of the RCMs used to generate the CORDEX-Australasia ensemble members [12]. The abbreviations used for Mellor-Yamada-Janjic, Yonsei University, WRF Double-Moment 5, Noah Land Surface Model are MYJ, YSU, WDM5, and Noah LSM respectively.

RCM	WRFJ	WRFK	CCLM	REMO2105	RegCM4.7
Institution	UNSW	UNSW	CLMCOM	GERICS	ICTP
Grid resolution	0.44°x0.44°	0.44°x0.44°	0.44°x0.44°	0.22°x0.22°	25Km × 25Km
Map Projection	Rotated pole lat-lon	Rotated pole lat-lon	Rotated pole lat-lon	Rotated pole lat-lon	Oblique Mercator
Vertical levels	30	30	35	27	23
Planetary Boundary Layer	MYJ	MYJ	Prognostic turbulent	Turbulent surface kinetic energy	Holtslag PBL
Cumulus	Kain-Fritsch	Betts-Miller-Janjic	[2]	Tiedtke [54] with modification from [38,40]	[54]
Microphysics	WDM5	WDM5	Seifert and Beheng, [51], reduced to one moment scheme	[31]	SUBEX
Radiation	Dudhia/ RRTM	Dudhia/ RRTM	[49]	[34]	CCSM
Land Surface	Noah LSM	Noah LSM	CLM3.5	Surface runoff scheme with vegetation phenology	CLM4.5

Table 4
Solar radiation data from the Australian Bureau of Meteorology (BOM) weather stations used for comparison with the CORDEX-Australasia mean radiation along with their available time periods. The mean bias observed in each station is also listed below.

Sl No	Station Name	Data Availability	Data Missing	Mean Radiation (Wm^{-2})		Mean Bias (Wm^{-2})
				CORDEX-Australasia	BOM	
1	Alice Springs	1994–2005	–	341.93	384.47	−42.54
2	Broome	1996–2005	–	349.27	384.84	−35.57
3	Darwin	1994–2005	05/1997–06/1997	320.37	368.27	−47.9
4	Learmonth	1996–2005	04/1999–07/1999	354.9	406.41	−51.51
5	Mildura	1996–2005	–	295.85	339.92	−44.07
6	Mt. Gambier	1994–2005	–	244.46	274.58	−30.12
7	Rockhampton	1996–2005	–	312.72	352.95	−40.23
8	Tennant Creek Airport	1996–2005		349.56	390.85	−41.29

generation. Availability is estimated as:

$$Availability\ (\%) = \frac{No\ of\ hours\ with\ RPD > RPD_{TH}}{Total\ no\ of\ hours} \times 100 \tag{3}$$

The RPD and RPD_{TH} refers to the resource power density and threshold resource power density. Solar resource power density is the amount of solar power available per unit area. It can be affected by geographical location and atmospheric constituents like aerosols and clouds. The RPD_{TH} represents low solar radiation values when the solar power generation is minimum. Even though a PV panel can generate power whenever radiation is >0 Wm^{-2}, the efficiency of the panel and the amount of power generated reduces at low insolation levels. Hence, we consider the lower quartile range of solar radiation data over Australia for the historical period to calculate the RPD_{TH} [43]. The RPD_{TH} is set to be 180 Wm^{-2} over Australia.

The episode length is estimated as the consecutive hours the RPD is greater than the RPD_{TH}.

2.3.3. Intermittency

The intermittency of the solar resource is characterized using lulls. Lulls are defined as periods of no power generation. They are computed as the consecutive hours when the RPD is lower than the RPD_{TH}. The abrupt cloud movements during the day can cause sudden drops in energy production and negatively affect the daily energy production rates. Therefore, it is essential to estimate the cloudiness in the sky using the DCI. The DCI can be estimated according to the following equation [20]:

$$DCI = \frac{\sum_{i=1}^{n} GHI_i}{\sum_{i=1}^{n} GHI_{CS_i}} \tag{4}$$

The DCI can be used to discriminate between the different weather conditions of the day. Under clear sky conditions, the value of DCI is close to one. It has a significantly lower value on an overcast day. We identify clear, intermittent, and cloudy days as per the classification by Huang et al. [20]. When the DCI values are<0.5, it is identified as a cloudy day. We identify an intermittent day when DCI varies between 0.5 and 0.95. Similarly, when DCI values are beyond 0.95, it is considered a clear day.

2.4. Significance test

We examine the statistical significance of the results with Student's *t*-test and use the convention of [52] to identify the regions with statistically significant change. Student's *t*-test at 5% significance level ($p < 0.05$) is performed at each grid point, to determine the significance of the mean change in each ensemble member. Following the convention by [52], we represent the results as areas with significant agreement, insignificant agreement, and significant disagreement.

- The areas with significant agreement in the change are denoted by color and stippling. These are the grid points where at least half of the model ensemble show a significant change, and at least 70% of those members agree on the sign of change. These regions have higher confidence in future change.
- The areas with insignificant agreement are denoted in color. Grid points at these regions have less than half of the ensemble members with significant change. These regions have lower confidence in future change.
- The areas with significant disagreement are denoted in white. Grid points at these regions have at least half of the ensemble members with significant change, and<70% of those members agree on the sign of change. These regions have limited confidence in future change with significant model disagreement.

3. Results and discussions

3.1. Model validation

CORDEX-Australasia ensembles have been previously evaluated for the historical period and are found to reproduce the spatial pattern in various surface variables like minimum temperature, maximum temperature and precipitation [12,53]. According to Evans et al., [12] the CORDEX-Australasia ensemble mean shows a small positive bias for minimum temperature (up to 2°C) and small negative bias for maximum temperature (up to −2°C). In this study, we have additionally evaluated the surface downward shortwave radiation in the CORDEX-Australasia ensemble with the two reanalysis datasets: MERRA2 and ERA5 (Fig. 1), for the period 1980–2005. We also evaluate the CORDEX-Australasia mean radiation with the BOM station data (Table 4).

Fig. 1 shows that the CORDEX-Australasia ensemble mean captures the spatial pattern and magnitude of mean solar radiation for most of the continent (Fig. 1a-c). The Observation Range Adjusted (ORA) mean bias and RMSE for the ensemble mean is shown in Fig. 1d-e. The simulated radiation has a positive bias almost throughout the continent except near Western and Northeastern Australia, with a very small negative bias (∼5 Wm^{-2}). Further, the ORA-RMSE is highest for Northern and Eastern Australia (>110 Wm^{-2}). These slight differences between the CORDEX-Australasia radiation and the reanalysis are generally smaller than the difference between the evaluated reanalysis products used in this study [42]; supplementary figure s3) indicating good performance. The ORA mean bias and RMSE for the different ensemble members shows the spread among them (Fig. 1f). Further, it seen that there is a negative mean bias between the CORDEX-Australasia ensemble mean and the ground observations (-30 to −50 Wm^{-2}) (Table 4). These validation results with both reanalysis and observation data show that the mean bias in the model data is <15%. Thus, this concise evaluation of the surface solar radiation and the previous evaluation of CORDEX-Australasia variables in the above-mentioned studies add confidence in using these simulation results to estimate the solar resource feasibility during the future periods over Australia.

3.2. Solar resource distribution

To assess the solar resource distribution and variability over

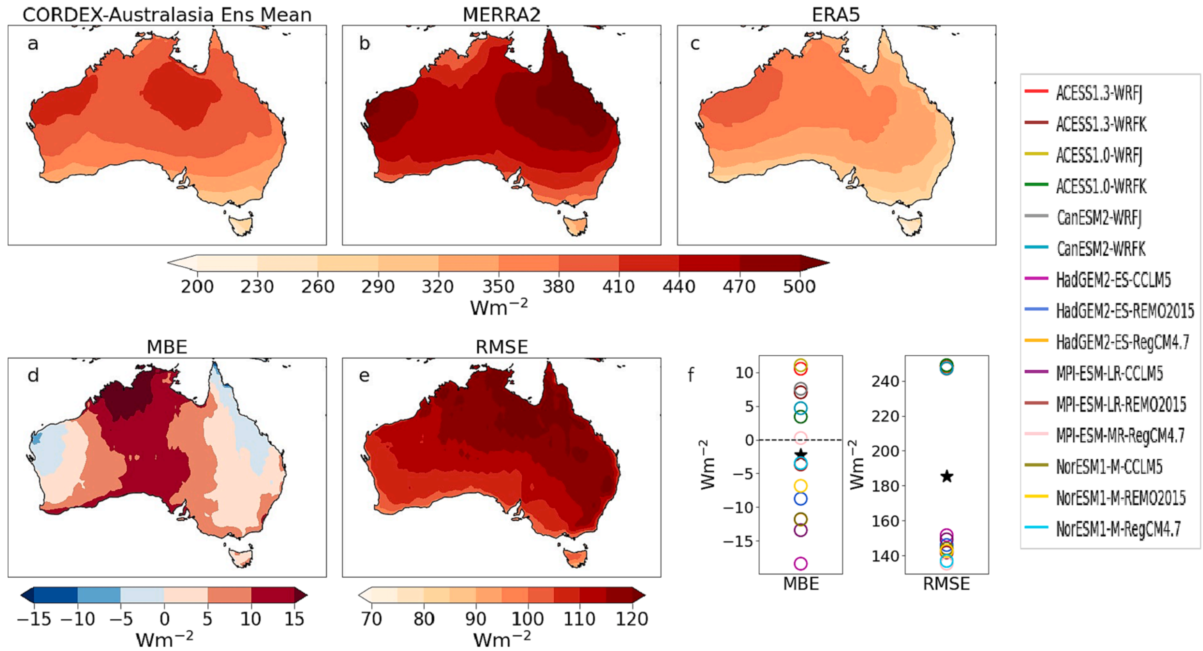

Fig. 1. CORDEX-Australasia mean solar radiation validation with two reanalysis products: MERRA2 and ERA5. The mean solar radiation from 1980 to 2005 is shown for a) CORDEX-Australasia ensemble mean, b) MERRA2 c) ERA5. Panel d and e represents the mean bias error and RMSE calculated using εORA. Panel f represents the MBE and RMSE for each ensemble member of CORDEX-Australasia calculated using εORA. The black star mark in panel f represents the ensemble mean MBE and RMSE.

Australia, we estimate the mean radiation and RCoV for the historical (1976–2005) period and changes in the future periods, near future (2030–2059) and far future (2070–2099) (Fig. 2). The average solar resource is high in Australia, especially in central and Northern Australia (>440 Wm^{-2}) during the historical period. The average solar radiation during the historical period is lowest in the southern regions of Australia (<400 Wm^{-2}) (Fig. 2a). The geographical location of these regions in higher latitude accounts for lower insolation levels. In order to estimate the influence of climate change on solar resource distribution, the future changes in mean solar radiation is analyzed with respect to the historical

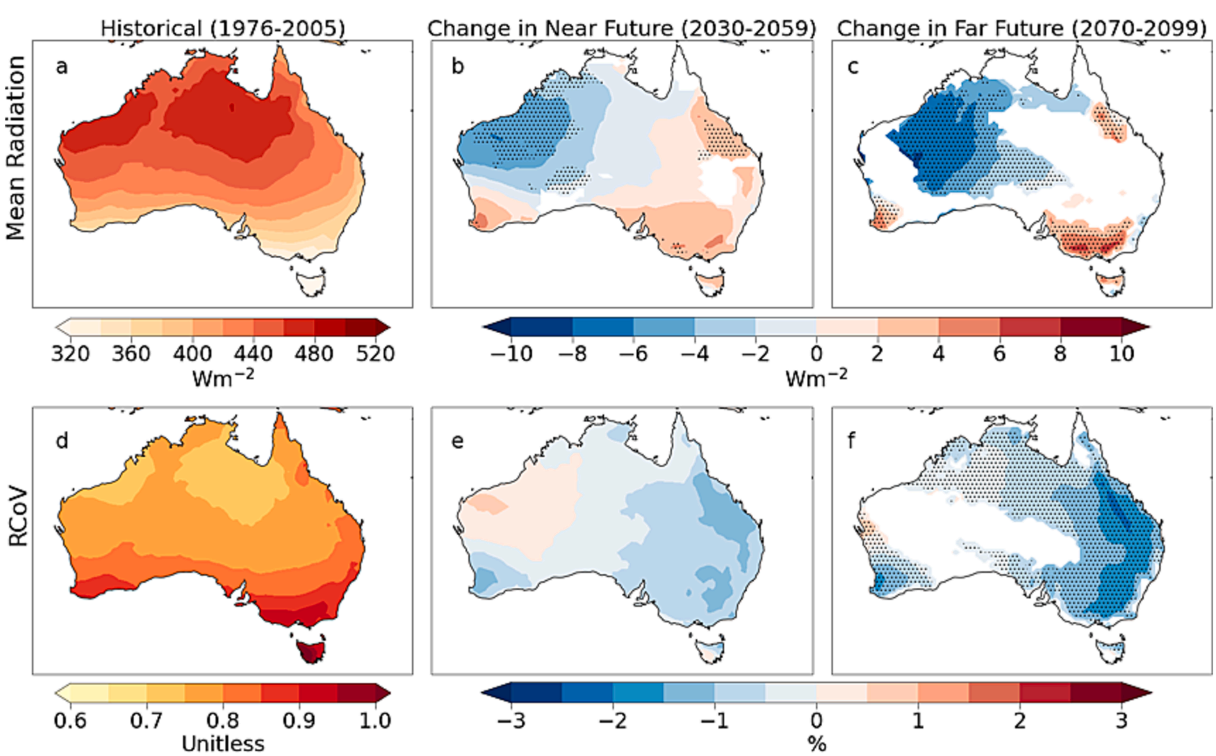

Fig. 2. Solar Resource Power Density and variability across Australia. Panel a) presents the mean solar radiation for the historical period (1976–2005). Panel b) and c) presents the future changes in the mean solar radiation for the near future (2030–2059) and far future (2070–2099) periods under RCP8.5. Panel d) presents the RCoV historical period (1976–2005). Panel e) and f) presents the relative percentage change in the RCoV for the near future (2030–2059) and far future (2070–2099) periods under RCP8.5. Stippling represents a significant change (according to method 2.4).

period. The mean solar radiation is expected to decrease in Western and Northern Australia (~6 Wm^{-2}) while increasing in Eastern Australia (~6 Wm^{-2}) during the near future period (Fig. 2b). During the far future period, the magnitude of the mean solar radiation intensifies further with ~10 Wm^{-2} decline in the Western Australian region and ~8 Wm^{-2} increase in some parts of Eastern and Southern Australia (Fig. 2c). The changes in the future solar radiation patterns can be largely attributed to the cloud cover changes in the future over this region. The cloud cover changes can be indicated by the future changes in DCI in these regions (Fig. 4b-c). It is predicted that the DCI will increase in the East and reduce in the West in the future. Other cloud properties like cloud optical depth can also play a role in these changes. However, detailed analysis of the cloud properties responsible for solar radiation changes is beyond the scope of this paper and should be carried out in the future. The mean variability (RCoV) of the solar resource in Australia is shown in Fig. 2d for the historical period. The future changes in the RCoV concerning the historical period is shown in Fig. 2e-f. Solar resource variability is highest near Southern and Eastern coastal Australia (>0.85) and least near Central Australia (~0.65) during the historical period. In the near future, the variability decreases for most of Australia (~2%) with a slight increase in the West (0.5–1%). However, during the far future period, there is a further decline in the variability over most of Eastern Australia (~3%).

It is desirable to have solar farms located in regions with high solar resource power density for maximum power generation. A higher resource variability in a region indicates more weather-induced intermittency. Considering the influence of solar power variability on the electricity grid and the economic implications on power generation and distribution, it is desirable to build solar farms in regions with low RCoV of solar power. The site with lower variability is preferred for two sites with the same resource power density. However, when two sites have the same variability, the site with higher resource density is preferred as a potential future solar farm [43].

3.3. Reliability

Reliability metrics measure the consistency of the solar resource for power generation. The reliability of solar resources is assessed using

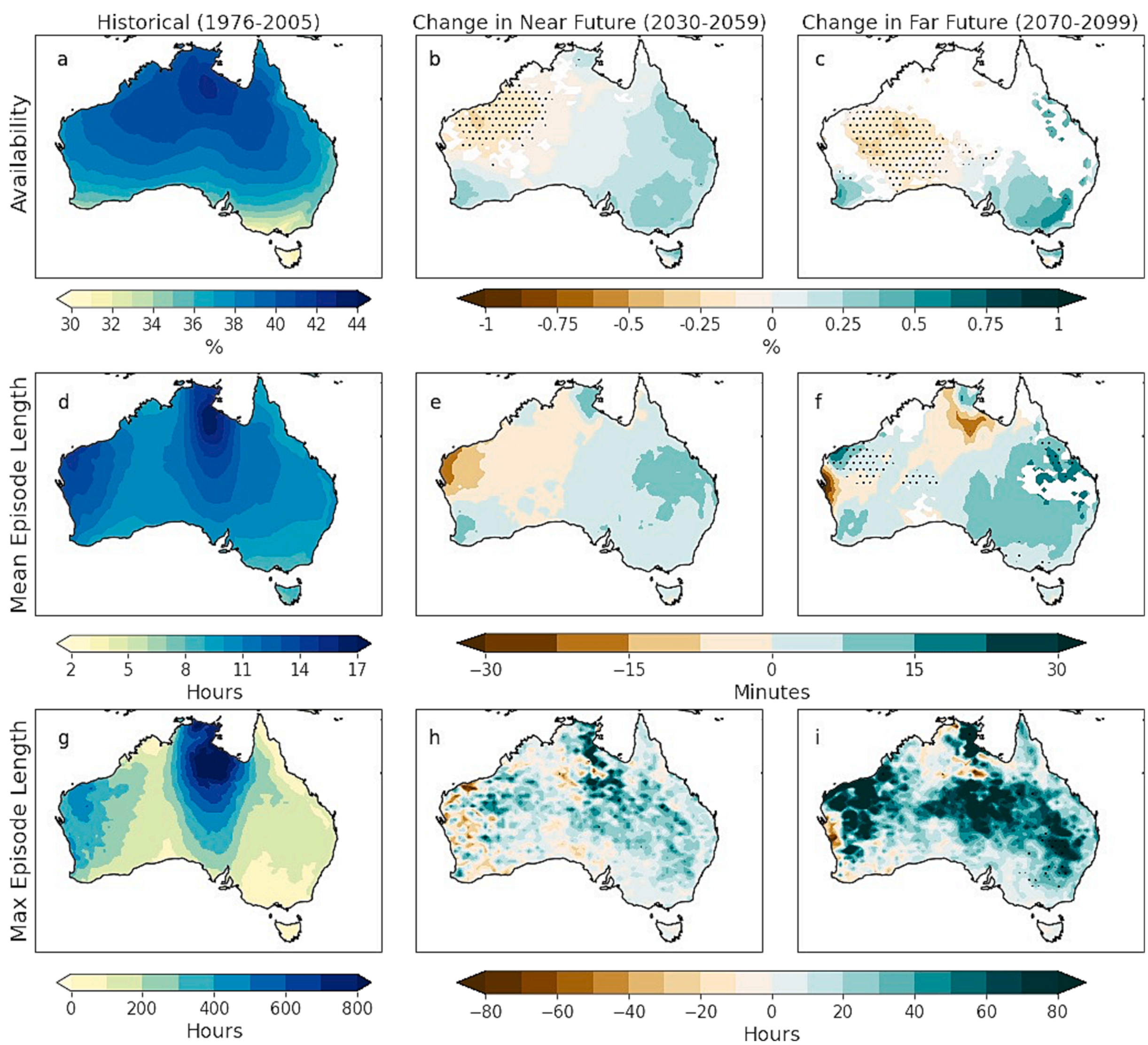

Fig. 3. Solar resource reliability across Australia. Panel a) presents the mean solar availability for the historical period (1976–2005). Panel b) and c) presents the future changes in the mean availability for the near future (2030–2059) and far future (2070–2099) periods under RCP8.5. Panel d) presents the mean episode length during the historical period (1976–2005). Panel e) and f) presents the future changes in mean episode length for the near future (2030–2059) and far future (2070–2099) periods under RCP8.5. Panel g) presents the maximum episode length during the historical period (1976–2005). Panel h) and i) presents the future changes in maximum episode length for the near future (2030–2059) and far future (2070–2099) periods under RCP8.5. Stippling represents a significant change (according to method 2.4).

availability and episode length (Fig. 3). The mean solar resource availability for the historical period is shown in Fig. 3a, and the mean change in the availability is shown in Fig. 3b-c for the near and far future periods. Solar resource availability is highest in Northern Australia (>40%) during the historical period. Northern Australia has a higher availability due to higher incoming shortwave solar radiation than the rest of the country (Fig. 2a). The availability will increase for most of the continent during the near future period except for a slight decrease in Western Australia (~0.25%) (Fig. 3b). However, during the far future period, the availability increases are confined to the southwest and southeast regions (up to 0.75%; Fig. 3c).

Episode lengths represent the consecutive periods when the resource is highly feasible for power generation. Fig. 3d shows the mean episode lengths over Australia for the historical period, while the future changes in mean episode length is demonstrated in Fig. 3e-f. Western and Northern Australia have the highest episode length (>14 h), with the lowest episode lengths for the Southern region and Tasmania (~9 h) during the historical period. These regional differences in episode length are largely due to differences in the cloud cover. The mean episode length is expected to increase for most of Australia (~15 min), but it will decrease in parts of Western Australia (~30 min) (Fig. 3e). The mean episode length increases uniformly for most regions during the far future period except for a decline over some parts of Northern and Western Australia (~15–20 min). The maximum episode length is highest for the northern Australia (>600 h) during the historical period (Fig. 3g). The maximum episode lengths shall increase in the central part of Australia for both the future periods (Fig. 3h-i). Increases in availability and episode length in Eastern Australia during the future periods suggest that solar resource reliability will increase in those locations. This would indicate the probability of more stable power generation across these regions.

3.4. Intermittency

Intermittency in the solar resource can impact the supply–demand ratio significantly. This is usually caused by cloud movements during the

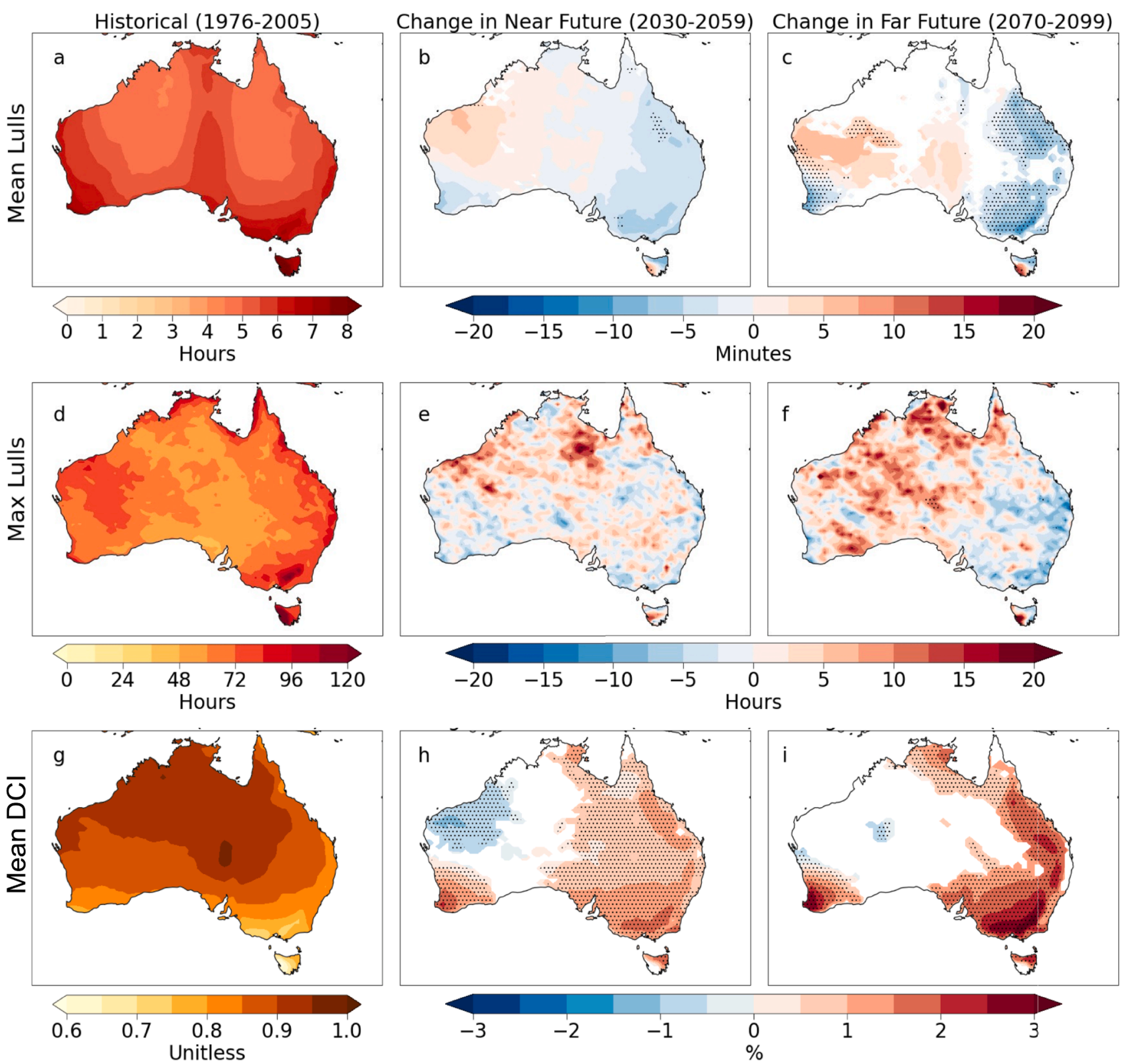

Fig. 4. Solar resource intermittency across Australia. Panel a) presents the mean lulls for the historical period (1976–2005). Panel b) and c) presents the future changes in the mean lulls for the near future (2030–2059) and far future (2070–2099) periods under RCP8.5. Panel d) presents the maximum lulls during the historical period (1976–2005). Panel e) and f) presents the future changes in maximum lulls for the near future (2030–2059) and far future (2070–2099) periods under RCP8.5. Panel g) presents the daily clearness index (DCI) during the historical period (1976–2005). Panel h) and i) presents the future changes in the DCI for the near future (2030–2059) and far future (2070–2099) periods under RCP8.5. Stippling represents a significant change (according to method 2.4).

day that leads to drops in the amount of energy extracted. The intermittent nature of the solar resource over Australia is assessed using two critical metrics: lulls and the number of clear sky, intermittent and cloudy days. Fig. 4a represents the mean lulls for the historical period over Australia, while Fig. 4b-c represents the future changes in the mean lulls for the near future and far future periods. The mean lulls are highest for the Southern part of the continent (>6.5 h), with minimum lull periods near Northern and Central Australia (<5 h) during the historical period. The lulls are highest for Southern regions due to the frequent occurrence of clouds in these regions. High cloud cover leads to more frequent intervals of resource power density lower than the threshold. In the near future, the mean lulls are expected to undergo only slight changes, with a decrease in the East and an increase in the west. The mean lulls further increase during the far future period and are more widespread across almost all parts of the continent than in the near future period. The Eastern and South-Western Australian regions are expected to have a reduction in the mean lulls during the far future period.

The maximum lulls indicate the extreme periods where there can be a subsequent reduction in energy generation. Fig. 4d shows the maximum lulls for the historical period and the future changes in the maximum lulls are depicted in Fig. 4e-f. During the historical period, the maximum duration of lulls occurs along Australia's Eastern and coastal regions (>80 h). Unlike the mean lulls, the future changes in the maximum lulls don't have a clear spatial pattern. However, it is expected that regions of Northern and Central Australia will have an increase in the maximum lull durations (15–20 h) with a decrease near the Eastern coastal region by the end of the century. Further, the relative change in the future DCI (Fig. 4h-i) shows a substantial increase in the DCI over Eastern Australia when compared to the historical period (Fig. 4g). This indicates that intermittency shall reduce in the East, suggesting the possibility of fewer ramping events. Ramps are sudden fluctuations in the PV power generated due to abrupt cloud movements during the day [62]. They can lead to voltage flicker issues and severely threaten electric-grid stability [29]. Sudden changes in the power generated by the PV systems introduce variations in the amplitude of the

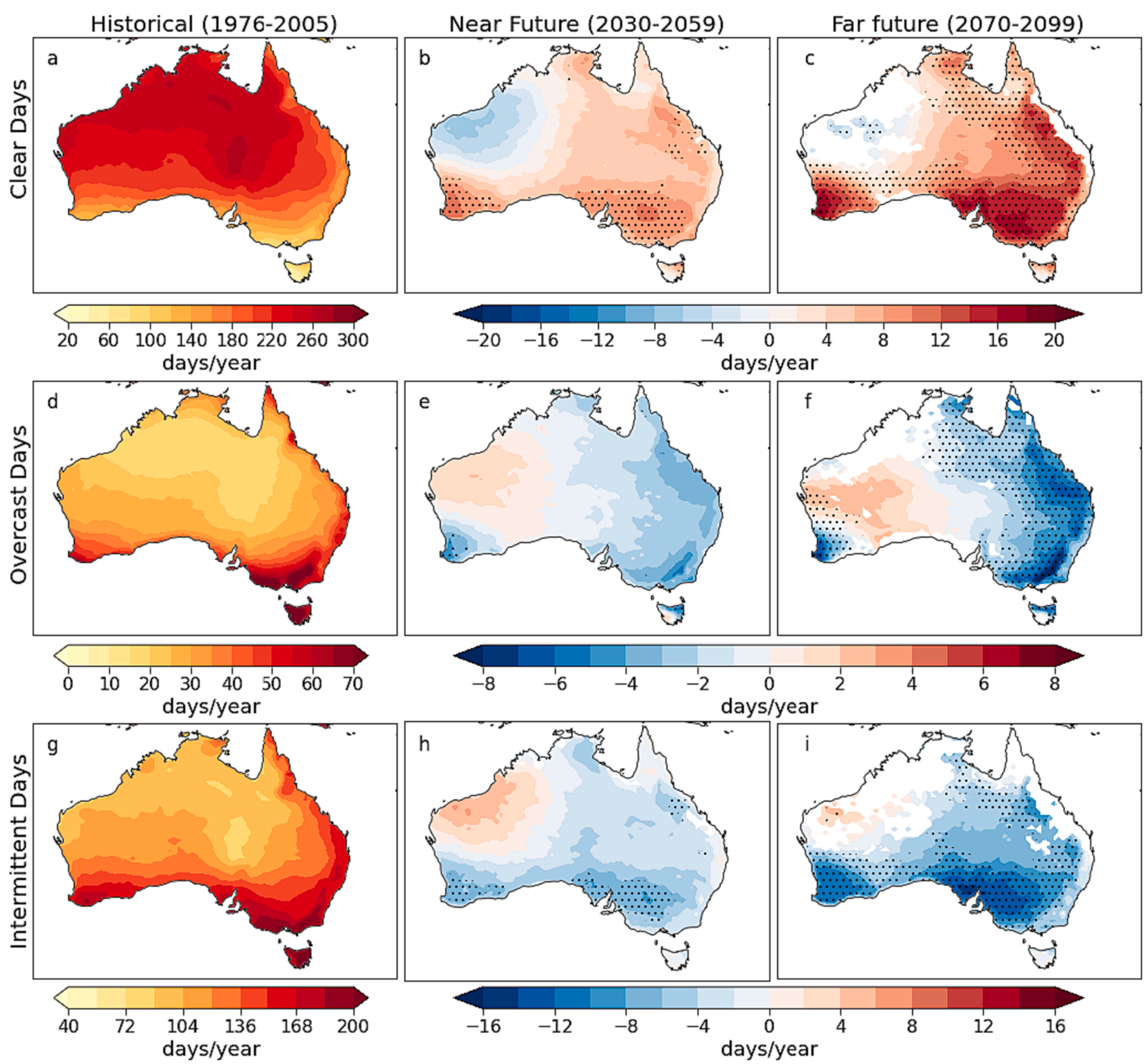

Fig. 5. Clear, overcast and intermittent days across Australia. Panel a) presents the clear-sky days/year for the historical period (1976–2005). Panel b) and c) presents the future changes in the clear-sky days/year for the near future (2030–2059) and far future (2070–2099) periods under RCP8.5. Panel d) presents the overcast days/year during the historical period (1976–2005). Panel e) and f) presents the future changes in overcast days/year for the near future (2030–2059) and far future (2070–2099) periods under RCP8.5. Panel g) presents the intermittent days/year during the historical period (1976–2005). Panel h) and i) presents the future changes in intermittent days/year for the near future (2030–2059) and far future (2070–2099) periods under RCP8.5. Stippling represents a significant change (according to method 2.4).

voltage waveform supplied to the grid, widely known as voltage flicker. Deviations from the acceptable voltage range during power supply can lead to power outages and blackouts. The mean clear-sky, overcast and intermittent days/year over Australia are shown in Fig. 5a, d and g, respectively. In contrast, Fig. 5b-c, 5e-f and 5 h-i represent the future changes in the clear-sky, overcast and intermittent days/year over Australia. It is evident that the Northern part of the country has more clear days (>200 days/year). In comparison, the Southern and Eastern coastal regions of Australia are more prone to overcast (>40 days/year) and intermittent days (>130 days/year) during the historical period. The number of clear-sky days/year is expected to increase throughout the country except for Western Australia. Further, it is likely that there shall be a reduction in the number of overcast and intermittent days/year for most of the country, with the most significant reductions in the east. This indicates the probability of harvesting higher PV power in the future periods.

Solar radiation patterns in the atmosphere are directly affected by clouds and atmospheric aerosols. The changes in radiation patterns due to cloud cover changes have been reported in previous studies for different regions of the world [1,16,57]. The spatial pattern of the number of clear days is consistent with the solar radiation and other metrics analyzed in this paper, suggesting that changes in future radiation patterns are largely dominated by regional cloud cover conditions. Our results suggest that Western regions of Australia shall experience more cloudy days which leads to a reduction in solar radiation in those regions, with subsequent decreases in resource availability and episode lengths. These regions shall experience more extended future lulls, while Eastern Australia will experience shorter future lulls. A detailed analysis of the change in cloud types and their patterns could not be performed with the available CORDEX data due to the limited variables available. It is recommended to perform an in-depth study on the future changes in the cloud properties and its influence on future radiation patterns in Australia using regional modelling simulations. Previously the impact of different clouds and cloud properties on plane of irradiance has been only studied for the historical period using satellite and reanalysis data [63]. The regional model projections from CORDEX-Australasia do not consider changes in aerosols in the future; hence the results in this study are dominated by the impact of cloud cover changes on the radiation. It is recommended that future work consider the impact of changing aerosols on solar radiation in Australia.

In this paper, we discuss the results of the CORDEX-Australasia ensemble mean. However, it should be noted that each ensemble member has individual characteristics in the future due to its parameterization schemes and driving GCMs, giving a range of future possibilities. The internal physics of RCMs is a crucial element contributing to the range of uncertainty for variables influenced by local processes [52]. Hence, we have included a similar analysis of all the metrics from each RCM-GCM pair to understand the wide range of future possibilities (refer to appendix section 3, figures A7-A26). Results reveal that even though most ensemble members show similar types of future change, few of the members show the possibility of having precisely opposite changes in the future. This emphasizes the importance of having multiple ensemble members to quantify the level of confidence in future projections. Further, the uncertainties between the model simulations are large when considering dynamically downscaled RCM simulations. This is due to the difference in parameterization schemes, the different parent GCMs used to downscale from, initial boundary conditions and resolution of the models [1]. To adequately sample this future change uncertainty in dynamically downscaled projections, the GCM ensemble selected should include a range of future changes.

The ensemble mean projections of this study indicate that there will be an increase in solar energy in the country's eastern regions in the future with reduced intermittency in energy generation. This is important to the solar energy industry and national policymakers to achieve net zero emissions. However, the wide range among the ensemble members should be considered during PV system design and planning storage to achieve a stable and reliable power supply during all times of the day. It is essential to plan maximum storage capacity during a solar farm's planning and developmental stage, considering the future scenarios and uncertainties amongst the individual ensemble members, to avoid energy deficits during intermittent energy generation periods.

3.5. Case study: Sun-Cable solar farm and New England solar farm

Sun Cable is developing the largest solar farm in the world in the Northern Territory, Australia, with at least 14GW solar power generation capacity and plans to construct a 5000 km transmission system to supply electricity to Darwin and Singapore generated from reliable renewable energy sources. Similarly, the New England solar farm is the second largest in Australia, currently under construction, located near Ullara, New South Wales and is expected to generate 720 MW of electricity. Therefore, we demonstrate the long-term resource assessments for these sites in different climate regions (Fig. 6) to understand the implications of climate change on future generation capacity and reliability.

The time series representing anomalies of mean radiation/year, clear-sky days/year, overcast days/year, intermittent days/year, availability and maximum lulls are shown in Fig. 7a-f and 8a-f for Sun Cable and the New England solar farms, respectively. The ensemble spread is wide for all variables (blue and red shading). This suggests that different modelled futures can produce diverse PV power generation rates in the future, and thus emphasizing that one should be cautious when interpreting the results obtained using one single climate model. Here we can also see that while trends are apparent in several variables, the ensemble spread always includes the "no change" case. Thus, the ensemble mean trends are discussed below.

In terms of the ensemble mean, there will be a decrease in the mean solar radiation at the Sun Cable solar farm (~10 Wm^{-2} or 2%) by the end of the century (Fig. 7a). Since the power generation capacity of a plant is directly dependent on the amount of solar radiation at that location, a decline in radiation can directly impact the amount of net energy generated. Based on the solar radiation decline of ~2% (Fig. 7a), it is estimated that Sun Cable solar farm can have ~280 MW loss in the total PV generation capacity by the end of the century. This estimation does not account for the future expansion in the solar farm production capacity, technology selection, temperature and wind effects on the generation rate. It is also predicted that Sun Cable shall experience a reduction in mean and maximum episode lengths, indicating a reduction in the periods of reliable power output.

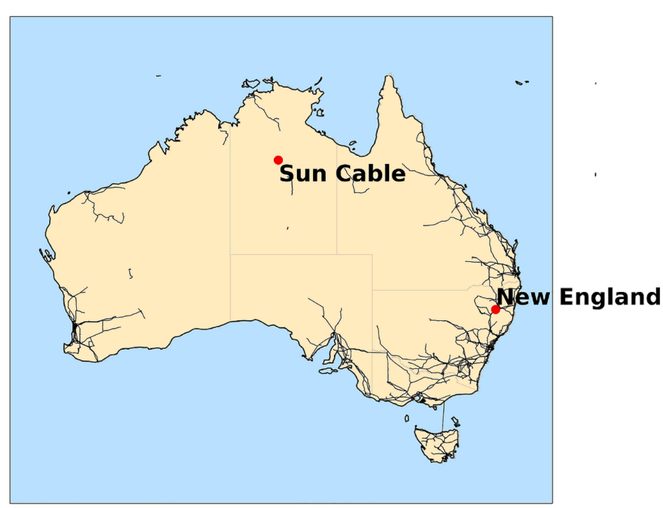

Fig. 6. Location of the two solar farms: Sun Cable, Northern Territory and New England, New South Wales used in the case study. The black lines in the background represent the electricity transmission lines.

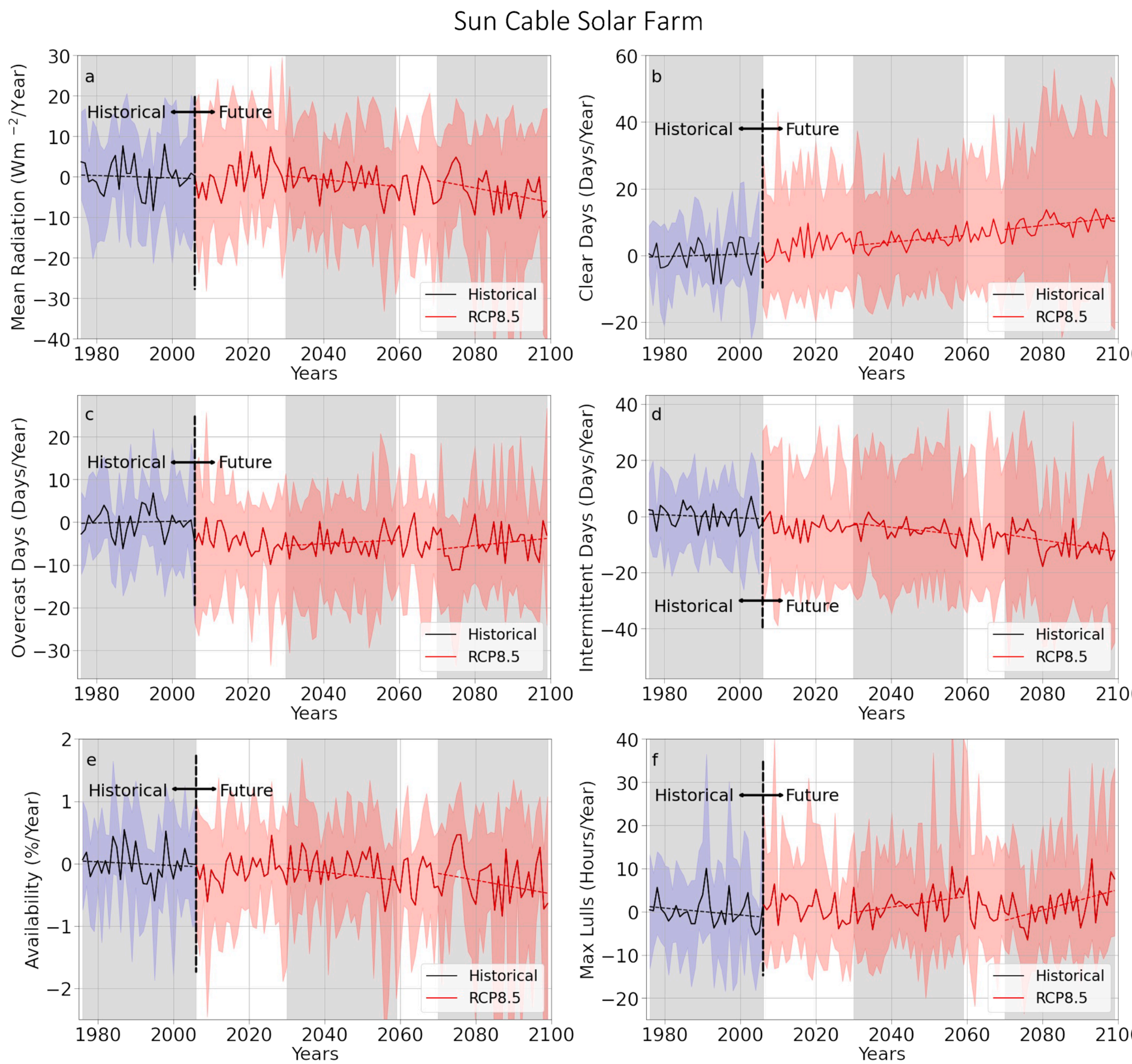

Fig. 7. Time series of mean radiation, clear-sky days, overcast days, intermittent days, availability and maximum lull anomalies per year for the Sun Cable solar farm in Northern Territory, Australia. The black and red lines present the anomalies observed in the ensemble mean for the historical and future periods under RCP8.5. The shading in the blue and red represent the interquartile range of the different metrics evaluated in the ensemble members for the historical and future. The black and red dashed lines represent the trend line for the historical and future (near future and far future) periods. The grey shading presents the historical period (1976–2005), near future period (2030–2059) and far future period (2070–2099).

Further, the increase in future lull duration suggests intermittent power generation in the future (Fig. 7f). This highlights that there might be periods during the day when the power produced will be lower than the optimum capacity. However, the DCI is expected to increase at the site in the future with an increase in the frequency of the clear sky days/year (Fig. 7b). At the same time, the frequency of the overcast and intermittent days/year is expected to decrease in the future (Fig. 7c-d). Even though the possibility of daily net production increases due to more frequent clear-sky days in the future, the power generated can be highly variable throughout the day due to increased lull periods. This can cause severe grid instability issues and impact the supply–demand ratio during the day. The results highlight the requirement for storage facilities at the Sun Cable site to deal with intermittency and power curtailment issues in the future.

On the contrary, the New England solar farm is expected to have an incremental increase in the mean radiation by the end of the century ($\sim$7Wm^{-2}) (Fig. 8a). This indicates a net increase in the long-term power generation capacity of the site in future. Due to climate change, the New England solar farm is estimated to have a surplus of up to 1.6 MW of energy generation capacity by the end of the century. This is estimated assuming no future installations at the location. Also, the New England solar farm location is highly favorable for more reliable energy output, as indicated by the increase in the episode length and reduction in lulls in future periods (Fig. 8f, Table 5). This suggests that there will be a reduction in power curtailment and expected ramps during the day at the site in future. Curtailment refers to the reduction in the power output during periods of excess generation than the load requirements. Ramps are defined as sudden fluctuations in solar radiation or the PV power generated due to sudden cloud movements during the day. Ramps introduce instability within the electricity grid. Further, this site may experience an increase in the frequency of clear-sky days/year, ensuring the chances of higher net daily productivity (Fig. 8b). The surplus power generated in the future can be stored for future use during the peak demand hours when there is an imbalance in the supply–demand ratio. The results indicate that future conditions are conducive to reliable power generation from the New England solar farm. This analysis highly recommends proper planning and installation of energy storage systems at both locations.

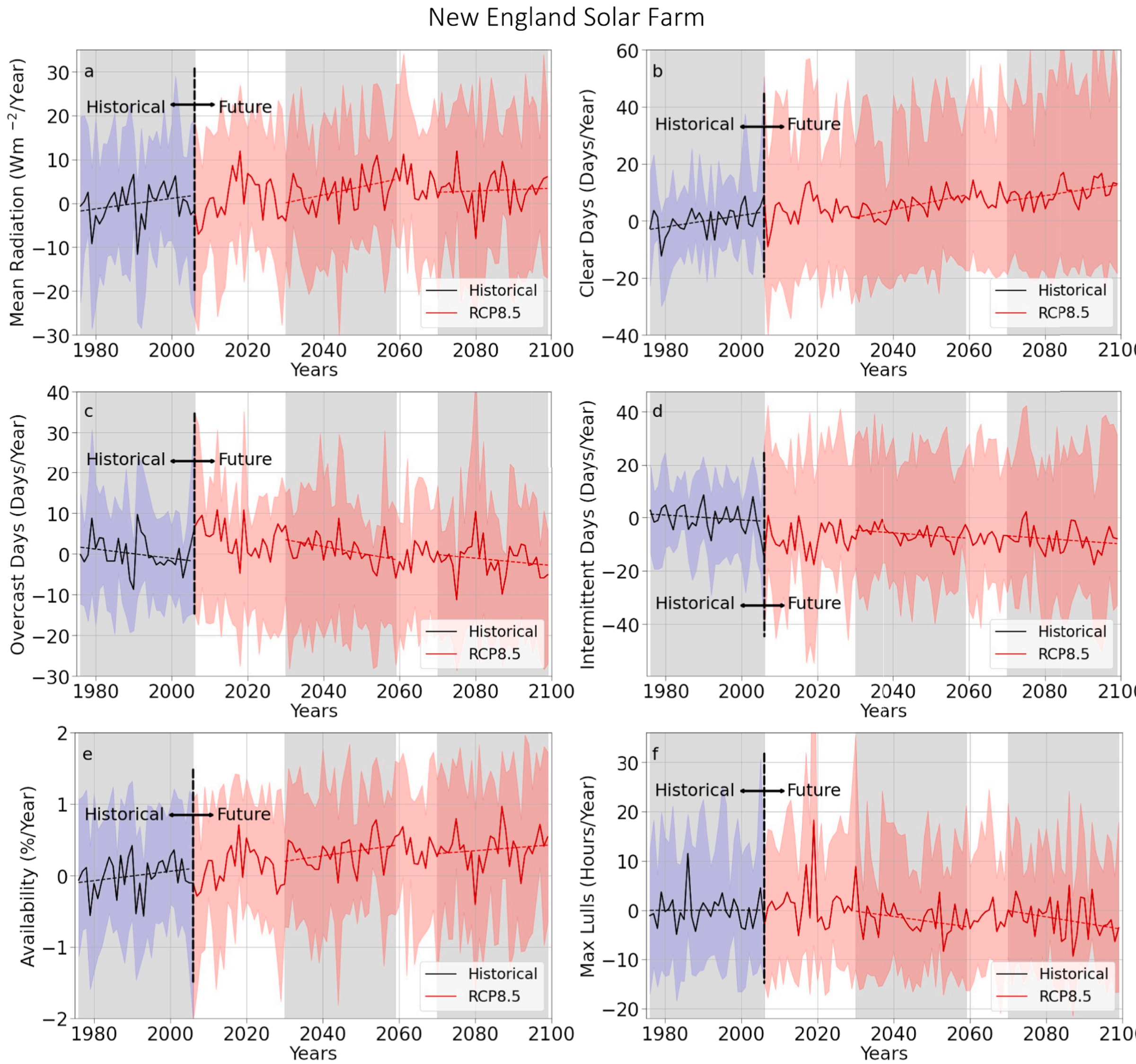

Fig. 8. Time series of mean radiation, clear-sky days, overcast days, intermittent days, availability and maximum lull anomalies per year for the New England solar farm in New South Wales, Australia. The black and red lines present the anomalies observed in the ensemble mean for the historical and future periods under RCP8.5. The shading in the blue and red represent the interquartile range of the different metrics evaluated in the ensemble members for the historical and future. The black and red dashed lines represent the trend line for the historical and future (near future and far future) periods. The grey shading represents the historical period (1976–2005), near future period (2030–2059) and far future period (2070–2099).

4. Conclusion

Solar PV technology is one of the rapidly growing renewable energy technologies in the world and is expected to expand further over the 21st century across the globe with several technological developments. With the increasing integration of solar PV plants into the electricity grid, the operation and planning of the power distribution system are subject to increased risk of uncertainty due to climate-induced variability. As the installation capacity of PV increases in the future, managing solar power fluctuations will be a escalating problem globally. Hence, understanding the dynamic characteristics of irradiance will be of utmost importance. Site characterization and solar resource assessment are vital for planning appropriate storage requirements and electricity dispatch to the grid. Further, it is of crucial importance to consider changes in resource distribution and intermittency the future due to climate change while selecting sites for the deployment of future PV plants across the world.

Australia has one of the world's largest solar resource densities and several large-scale solar PV plants in the operational and developmental phases. It has the world's largest proposed solar plant: Sun Cable solar farm, in the planning and development phase that will supply electricity to Singapore and Australian markets. Further, it is foreseen that the solar PV capacity will increase Australia-wide by ~90 GW by 2050 to meet the net zero commitments [4,10]. However, dependency of the solar resources on weather and climate can impact the viability of future low-carbon energy supply systems in Australia. In this regard, we have assessed the key metrics for future solar resource assessment in Australia. The expected future changes in resource distribution, reliability and intermittency under a high-emission scenario are presented using the regional climate projections from CORDEX-Australia simulations. The solar resource power density is projected to increase for the Eastern regions of Australia during both future periods, with a decline near the western regions of Australia. It is further expected that the solar resource variability will decrease in the future almost throughout the continent, thus indicating higher feasibility of solar energy extraction in the future. Results reveal that Eastern Australia shall experience an increase in solar resource availability and episode length in the future, ensuring a more stable and reliable future energy output. This region is predicted to experience a reduction in the lulls and frequency of

Table 5
Future changes in the key resource assessment metrics calculated for the near future (2030–2059) and far future (2070–2099) periods under the RCP8.5 scenario with respect to the historical period (1976–2005) for the Sun Cable and New England solar farms. Maximum episode length and maximum lulls in the table below represent the changes in the maximum values during future periods.

Metrics	Sun Cable Solar Farm		New England Solar Farm	
	Near Future Change	Far Future Change	Near Future Change	Far Future Change
Radiation (Wm^{-2})	−1.45	−4	2.8	4.7
RCoV (%)	−0.54	−1.09	−1.22	−1.88
Availability (%)	−0.08	−0.25	0.29	0.38
Mean Episode Length (minutes)	−2	−4	6.50	13.21
Maximum Episode Length (hours)	−2	−8	15	22
Mean Lulls (minutes)	1.21	5.50	−4.71	−6
Maximum Lulls (hours)	3.25	5.80	−2.5	−3.2
Daily Clearness Index (%)	0.29	0.80	1.08	2.40
Clear Sky Days (days/year)	4.50	9.50	5	10
Overcast Days (days/year)	−1.50	−5	1	−4
Intermittent Days (days/year)	−4	−9	−6.25	−8.50

intermittent and overcast days in the future, highlighting reduced future intermittency. On the contrary, some regions in Western Australia may experience increased intermittency issues, a key challenge for Australia's future energy systems. Hence it is highly recommended to implement energy storage options to ensure grid stability in these regions. This also suggests exploring the spatio-temporal complementarity of renewable energy resources to maximize energy generation in these regions. Furthermore, an investigation of the two developing solar farms, Sun Cable and New England, revealed increments in clear-sky days at the sites in future. New England solar farm will have highly favorable conditions in the future to generate optimum PV power. However, future climate change can introduce intermittency issues at the Sun Cable solar farm in future. This suggests the need for storage systems and solar resource forecasting for Sun Cable solar farm.

This work lays the foundation for resource assessment of future PV plants in Australia. Future work is expected to explore the implication of these findings in PV plant design and storage estimation. Further, this research can be extended to different regions of the world using high-resolution climate projections for analyzing future solar resource variability and site feasibility. One of the biggest problems in the solar power sector is maintaining grid stability due to fluctuations in the energy generated at various timescales. This work can be valuable in investigating the grid operation extensively by including multiple power sectors for power generation, storage, transmission, distribution and technology development for risk assessments and various mitigation strategies. Future intermittency and reliability discussed in this study, along with the projected changes in the cloudy and intermittent days, can be valuable in planning solutions for grid stability and maintenance of the supply–demand ratio. It is also recommended that trends in different PV technology and future degradation rates be considered in resource feasibility assessments for future solar farms. This would ensure the maximum productivity of the solar farms with well-planned systems to ensure grid stability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solener.2023.112039.

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