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Assessment of solar and wind resource synergy in Australia

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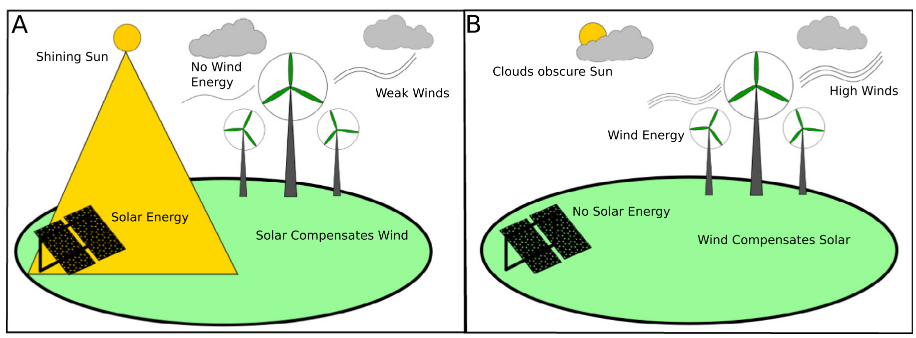
HIGHLIGHTS

- Strong temporal synergy of solar and wind resource exists in Australia.
- Temporal synergy enhanced by 10% with an increase in spatial extent to 465 km.
- Greater synergy characteristics were in close proximity to established transmissions lines.
- South-eastern regions show great potential for future development of solar/wind hybrid systems.

GRAPHICAL ABSTRACT



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ABSTRACT

Solar and wind generated power is expected to increase drastically in the future. Unlike fossil fuels, however, solar and wind resource extraction introduces challenges of variability and intermittency. Several recent studies around the world have shown that since dissimilar climatological factors are responsible for wind and solar resources, they can often operate in tandem to offset lulls in each other. While most research on solar and wind resource interaction has been undertaken over the Northern Hemisphere (America, Europe and China), there is a lack of understanding on how much (or even if) solar and wind resources complement one another in other parts of the world. To partially address this issue in the Southern Hemisphere, this study provides a systematic quantitative analysis of the complementary characteristics of solar and wind resources on the Australian continent. As such, wind power density and surface incident shortwave flux are derived from the hourly Modern Era Retrospective Analysis for Research and Applications (MERRA) product for the entire continent for the period from 1979 to 2014. It was found that the temporal synergy between solar and wind resource is maximum along the western and southern coast of Australia. Tasmania, south-eastern (parallel to eastern Great Dividing Range), and northern regions (Cairns and Kimberley Plateau) of the continent also showed significant synergy (≈40% within a distance of 93 km), which was mostly influenced by hours of daylight when the solar resource is available. Increasing the spatial extent increased the occurrence of synergy characteristics to 50% within a distance of 465 km. These findings are significant because most of the synergy (and intermittency) in solar and wind resources was found in proximity to transmission lines – locations where renewables are likely to be cited going forward. Amongst current large-scale solar and wind farms operating in south-eastern Australia, this study also finds that increased power production is possible by balancing existing assets with complementary solar and wind farms. While these results are limited to a single continent, the

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proposed *approach* (e.g. using similar metrics) can be readily applied to investigate synergies between solar and wind resource in other parts of the world using the global MERRA product.

1. Introduction

Motivated by current carbon emissions causing climate change, worldwide efforts have significantly grown for decarbonisation by increasing the penetration of renewables globally [1,2]. The total renewable energy share in the power generation sector worldwide is therefore expected to grow rapidly based on additional renewable energy targets set by each country on top of the current policies and growth trajectories. According to a recent report by IRENA [3], in 2014 the total renewable energy share (excluding hydropower) in the worldwide power generation sector was 8%, which included the wind having a share of 3% of total power generation and solar photovoltaic < 1%. However, wind's share of worldwide power generation is expected to increase to 14% whereas solar photovoltaic can increase to 7% by 2030 [1]. The top-five renewable energy producing regions by 2030 are expected to include China, USA, the EU, India and Brazil [1]. The EU has already committed to obtaining 35% of gross power consumption from renewables by 2020 and this is expected to increase to 80% by 2050 – with wind and solar photovoltaic generated power as their top priorities [4].

As is the case in many countries [5], solar and wind–derived electrical generation has become increasingly important in the Australian power grid. Over the past five years, solar (including large and small scale) and wind power generation has increased by 128% and 18% per year respectively [6]. With a Renewable Energy Target (RET) scheme designed to ensure that 20% of Australia's electricity comes from renewable sources by 2020 (from ~4.5% today) [6,7], solar and wind power generating systems are being deployed at a rapidly accelerating scale [8].

While engineering and installation firms typically focus on stand-alone solar or wind projects, their intermittency (caused by stochastic climatic and weather conditions) can hinder the performance of these systems [9]. The overall annual quality of both solar and wind resources is largely dictated by fixed (local and global) climate and geographic features. On shorter time-scales, however, solar power is negatively impacted by the movement of clouds [10–12], while wind power benefits from moving weather fronts [13,14]. These variations result in corresponding variations to power generation, and can significantly affect grid scheduling and transmission operations [15,16]. Australia has six climate zones [17] with vast variety of weather conditions affecting solar [12] and wind [18] resources. These climate zones are most commonly represented globally [19], thus the Australian context is indicative of solar and wind resource coupling at a global scale.

1.1. Solar/wind hybridisation

Recent studies show that co-located solar/wind power generation systems represent highly reliable sources of power in comparison to stand-alone systems [20–22]. However, true solar/wind hybrid systems are not well-developed and require more planning and testing [23] than traditional stand-alone systems. Nema, et al. [23] reviewed the design, operation and control requirements of a solar-wind hybrid energy system. They showed that a pre-feasibility analysis and proper sizing of units for optimized performance through simulations is crucial in setting up a solar/wind hybrid system. Although, there are several studies centred on the optimum sizing of hybrid solar/wind power generating systems [9,24–36], relatively little work to date has gone into pre-feasibility studies of the wind and solar resources globally.

Pre-feasibility studies are crucial to predict the performance of how solar and wind will interact at (and across) potential sites using high quality long-term weather data. Several studies conducted in regional locations around the globe have investigated the feasibility of hybrid solar/wind power generating systems through assessments of irradiance and wind speed data [37–42]. Most of these studies show that the extent to which variability in solar and wind resources balance each other is dependent on local climate and weather conditions at various spatial and temporal scales. However, it is clear that enhanced stability (and minimised intermittency) is possible when both wind and solar resources are used in concert [43]. This only does not apply to co-located solar/wind power generation systems, but spatially aggregated solar and wind farms are designed to optimise intermittency resulting from different locations [44].

1.2. Complementary solar and wind resources

Numerous papers have explored the complementary, combined characteristics of wind and solar resources. An extensive review based on analytical techniques used to determine the ability of intermittent renewables like wind and solar power has been reported by Hart et al. [45]. In 1979, Takle and Shaw [46] provided one of the first analyses on the complementary behaviour of solar and wind energy records. Takle and Shaw found higher complementary behaviour on a daily and seasonal scale than on an annual basis. They also found an optimum mix of solar and wind technologies was possible if spatial variability is designed into the system to create a balancing effect on the localised intermittency caused by single sources [46]. Sahin [47] demonstrated the strong anti-correlation between the available solar and wind power potential over a year in north-eastern part of the Arabian Peninsula. In particular, Sahin found strong anti-correlations (≈ -0.75) between the two power potentials on a monthly scale. Heide et al. [48] used meteorological model estimates of a 100% renewable Europe scenario to show that the optimal seasonal mix was 55% wind and 45% solar power generation. Widen [13] assessed correlations between solar and wind energy in a future scenario for Sweden using climatic data of 8 years with hourly resolution. He found negative correlations between solar and wind power from hourly to annual scales, but stronger correlations on a monthly scale. Nikolakakis and Fthenakis [49] showed that by optimising the synergy between solar and wind resources, a maximum penetration of 30% solar and wind energy can be achieved in New York state without adding storage and without having to dump > 3% energy. Li et al. [50] developed an approach to quantify and investigate the impacts of diverse geographical factors on the complementarity of solar and wind using station data over Oklahoma. Li et al. showed that 57% of all sites had an above average complementarity index of wind and solar radiation. Santos-Alamillos et al. [51] looked at the spatiotemporal balancing between solar and wind energy resources in the Southern Iberian Peninsula using daily-integrated solar and wind energy estimates produced from the Weather Research and Forecasting (WRF) mesoscale model. They showed interesting complementary characteristics with anti-correlations of 0.56 (balancing patterns occurred 71% of the time) of solar and wind at marked seasonal and spatial scales in the study region [52]. Liu et al. [53] also found the power output from combining wind and solar resource becomes smoother while investigating the spatiotemporal complementarities between solar and wind using meteorological data over several sites in China. They showed that the aggregate power output from all the wind and solar sites were high at daytime and low in the night time, and the only peak value occurred at 13:00–14:00 for 87.2% of the time. Recently, Jahangiri et al. [54] showed ideal locations of installing solar-wind power stations in the Middle-East using a Boolean model in GIS software.

1.3. The Australian context

In Australia, there have been a plethora of stand-alone resource assessments for solar [8,10,12,55–58] and for wind resources [8,18,59–61], but very few studies have investigated how they might interact [62–65]. As a key research gap, to the author's knowledge no spatio-temporal assessment of the complementary characteristics of solar and wind resource has been conducted across the whole Australian continent. Yi et al. [66] did, however, investigate the complimentary characteristics of solar and wind resources with hourly weather data for a single site in New South Wales, Australia. Yi et al.'s findings do indeed suggest that combining solar and wind resources can effectively deliver energy to the Australian electricity grid during peak load demand. Recently, Kay [67] reported synergy characteristics of solar and wind resource by correlating the dataset derived using the MERRA product, but excluded any spatio-temporal assessment of synergy characteristics. Also, Elliston et al. [68] investigated incremental costs of higher levels of renewable energy in Eastern Australia, suggesting policies promoting rapid deployment and improved integration of wind and photovoltaic may be effective for achieving significant emissions reductions. However, this study excluded any major exploration of synergy characteristics of solar and wind resource all over in Australia. Notably, most research on solar and wind resource interaction has been undertaken over the Northern Hemisphere (America, Europe and China), but there is a lack of understanding on solar and wind synergies in other parts of the world, especially in the Southern Hemisphere. Therefore, the aim of this paper is to assess the complementarity characteristics of solar and wind resources across Australia at various temporal and spatial scales.

2. Data

The quality, coverage, resolution and record length of data often limits solar and wind resource studies. To overcome this, hourly 1/2° (latitude) × 2/3° (longitude) resolution MERRA (Modern Era Retrospective Analysis for Research and Applications) data [69] spanning a period of 36 years (from 0030, 1st January 1979 to 2330, 31st December 2014) over Australia was used for this study. This includes a total of 315,576 hourly data. MERRA was generated with Goddard Earth Observation System GEOS atmospheric model (version 5.2.0) and the associated data assimilation system (DAS). MERRA incorporates observations from satellites and a global network of weather stations, aircraft, and radiosondes to produce a physically consistent picture of the atmospheric state at a global scale. In comparison to other reanalysis products, MERRA offers output frequencies at a higher resolution (other products such as NCEP, ERA-Interim are typically limited to 6-hourly analyses). MERRA produces two-dimensional diagnostics (surface fluxes, single level meteorology, vertical integrals and land states) produced at 1-h intervals at the 1/2° (latitude) × 2/3° (longitude) resolution. More details on the MERRA reanalysis product is described in Rienecker et al. [69]. For the purpose of this study, the key MERRA outputs are Global Horizontal Irradiance (GHI) and Wind Power Density. Note, a large bias in reanalysis data needs correction [70,71], but this requires a high density of sites measuring solar and wind.

2.1. Global horizontal irradiance

Solar resource assessments require analysis of GHI for solar photovoltaic (PV) applications. The products downloaded within MERRA were hourly values of GHI (also known as surface incident shortwave flux (SWGD), surface turbulent flux (IAU 2d) and radiation flux product (called "tavg1_2d_rad_Nx") from the Modeling and Assimilation Data and Information Services Centre [72]. Surface fluxes in MERRA are modelled by Chou and Suarez [73]. Although rarely used for this purpose, this dataset has been validated for solar PV applications in Canada by Richardson and Andrews [74] and was also used by Richardson for solar PV energy modelling [75].

2.2. Wind power density

Wind resource assessments primarily use the wind speed at different heights, but Wind Power Density (*WPD*) is preferable since it combines the effect of changes in air density and is independent of the wind turbine characteristics. It quantifies the amount of wind energy (in Wm^{-2}) available at a site for a wind turbine and is directly proportional to the wind speed [76]. *WPD* can be calculated as:

$$WPD = \frac{1}{2}\rho V^3 \tag{1}$$

where ρ and V are the density of the atmosphere and the wind speed at a point, respectively. For this study, wind speed at a turbine hub-height of 80 m is derived using the MERRA surface turbulent flux as described above available at similar temporal and spatial resolution as the GHI product outlined in Section 2.1. The surface turbulent flux product contains parameters such as friction velocity, surface roughness, surface air density and displacement height. Using the similarity theory of the atmospheric boundary layer (assumed to be neutrally stable), the wind speed at an altitude, V_z, can be calculated as:

$$V_z = \frac{u_*}{k} \ln\left[\frac{z-d}{z_o}\right] \tag{2}$$

where u_* is the friction velocity, k is the Von Karman constant (≈0.40), d is the displacement height and z_o is the roughness length. This approach has been used in previous assessments of the wind resource in the United States [76], Australia [59] and the Arabian Peninsula [77].

2.3. Existing grid and plant data

The Australian Energy Market Operator (AEMO) transmission lines network was downloaded from the Geoscience Australia database and used to calculate the minimum distance of transmission lines from each MERRA grid-point. Also, historical aggregated demand data and the locations of current operational solar/wind farms were downloaded from AEMO [78] and AREMI websites [79].

3. Analysis approach

The metrics used in our assessment of solar and wind resource characteristics are variability and intermittency adapted from Gunturu and Schlosser [76]. The commonly used measures of variability are mean, standard deviation, variance, and range. For this study, the variability in solar and wind resource is captured in terms of Relative Coefficient of Variation ($RCoV$) and the Inter-Quartile Range (IQR). $RCoV$ can be computed with reference to the mean or median, but the latter approach favours distributions with extreme values (long tails) such as WPD [59,76]. Thus, $RCoV$ is calculated as:

$$RCoV = \frac{median(absolute\,deviation\,about\,the\,median)}{median} \tag{3}$$

A lower $RCoV$ indicates lower variability with the resource being highly feasible at the site. However, for two sites with the same median absolute deviation, the one with greater median flux or power density is preferable. On the contrary, for two sites with the same mean flux or power density, the one with lower median absolute deviation is preferable. IQR indicates the possibility of ramps or swings in the solar and wind resource. It is a measure of spread in the data after discarding outliers and a good measure of the amount of backup power needed at potential sites. A lower IQR is preferable for potential sites.

Moreover, intermittency is related to the fluctuations in the resource power density (RPD). Often, solar and wind power is interrupted from the unpredictable nature and dependence on climatic and weather conditions. To quantify these interruptions, a threshold of power density (RPD_{TH}) is used to compute the availability and persistence of the resource. For wind resource, $RPD_{TH} = 240\ \mathrm{Wm^{-2}}$ is used based on the calculation of upper limit of poor wind power class at 80 m, corresponding to wind speeds <5.9 $\mathrm{ms^{-1}}$ [80]. Ideally, $RPD_{TH} = 0$ for the solar resource, since a PV module can theoretically generate some power as long as there is >0 $\mathrm{Wm^{-2}}$ available. However, since the efficiency is low at these levels, the minimum resource (RPD_{TH}) was set to 170 $\mathrm{Wm^{-2}}$ after calculating the lower quartile of all available GHI values for the entire period of study over Australia. Availability measures the reliability (occurrences of efficient resources for power generation) of a system as:

$$Availability\ (\%) = \frac{Number\,of\,Hours\,with\,RPD \geqslant RPD_{TH}}{Total\ number\ of\ hours} \times 100 \tag{4}$$

Thus, the unavailability is calculated when there is no availability. Also, to understand the nature of intermittency, the episode length can be computed as:

$$Episode\,Length = Consecutive\,Number\,of\,Hours\,with\,RPD > RPD_{TH} \tag{5}$$

It is important to note that the Episode Length for solar resource was calculated by filtering out the night hours to show consecutive daytime hours only.

Similarly, the consecutive hours of almost no power generation (referred to as lulls) can be computed as:

$$Lulls = Consecutive\,Number\,of\,Hours\,with\,RPD \leqslant RPD_{TH} \tag{6}$$

The frequency of *Episode Length* and *Lulls* are computed for the whole period in this study. The mean and maximum values of this frequency distribution are also used to characterise the intermittency of the solar and wind resources.

In the past, the Pearson Correlation Coefficient has been used as the metric to assess the complementarity of solar and wind resources [13,51,66,67,75,81,82]. This coefficient is a statistical measure of similarity between two data sources and it ranges between values of −1 to 1. Negative correlations of solar and wind fluxes indicate that they are complementary (e.g. if one resource is not available the other is), whereas positive correlations indicate that they are supplementary (e.g. both resources are either available or unavailable). While this coefficient is indeed a good measure of the relationship between solar and wind resource availability, for this study a framework simply based on the occurrence of solar and wind resource above their respective minimum generation limit was used to characterise their synergy in Australia. A similar framework has been utilized in several studies looking at wind resources [59,76,77]. This method also quantifies the number of hours spent in intermittency mitigation from the solar and wind resource. To study both the case of hybrid solar/wind technology and the case of spatially distributed solar and wind plants, the synergy was conducted at the same (reference) grid points and also for neighbouring grid points to investigate spatial complementarity.

The temporal synergy of solar and wind resources in Australia at a reference grid box is the simplest way of understanding the complementarity characteristic of the resources. This represents a practical solution since stand-alone solar and wind energy systems can easily be added within the perimeter of a MERRA grid box, typically within a maximum corner to corner grid distance of ≈93 km. Within this three different scenarios were explored using the whole period of study:

(a) Wind Complements Solar (WCS):

$$WCS\ (\%) = \frac{Number\,of\,hours\,(WPD > 240\ \mathrm{Wm^{-2}}\,AND\,GHI \leqslant 170\ \mathrm{Wm^{-2}})}{Total\ number\ of\ hours} \times 100 \tag{7}$$

This scenario represents the occurrence of wind resource complementing a solar resource. It shows the capability of a wind farm complementing a non-generating solar farm at the same grid.

(b) Solar Complements Wind (SCW):

$$SCW(\%) = \frac{Number\,of\,hours\,(WPD \leqslant 240 Wm^{-2} AND\,GHI > 170 Wm^{-2})}{Total\ number\ of\ hours} \times 100 \tag{8}$$

This scenario represents the occurrence of solar resource complementing a wind resource. It shows the capability of a solar farm complementing a non-generating wind farm at the same grid.

(c) Wind and Solar Synergy (WSS):

$$WSS\ (\%) = \frac{Number\,of\,hours\,(WPD > 240\ \mathrm{Wm^{-2}}\,XOR\,GHI > 170\ \mathrm{Wm^{-2}})}{Total\ number\ of\ hours} \times 100 \tag{9}$$

This scenario represents the occurrence of wind and solar synergy. It shows the complementary characteristic of a wind and solar farm, where either one complements the other at the same grid.

To investigate the spatial complementary characteristic of the solar and wind resource at the central grid, neighbouring grids (NG) regions of 3×3 (maximum corner to corner distance of ≈279 km) and 5×5 (maximum corner to corner grid distance of ≈465 km) were used in calculating the mean occurrence of synergy periods. It was possible to extend beyond 5×5 grid boxes, but the grid distance was restricted to be within 465 km of the transmission lines. This is more feasible for regions away from the current transmission grid, but this limit still covers 88% of the Australian region. Here four different scenarios were explored with reference to either solar or wind at the central reference grid:

(a) Solar Complements Central Wind (SCCW):

$$SCCW\ (\%) = \frac{1}{NG}\sum_{i=1}^{NG}\frac{Number\ of\ hours\ (GHI_i > 170\ \mathrm{Wm}^{-2} XOR\ WPD > 240\ \mathrm{Wm}^{-2})}{Total\ number\ of\ hours} \times 100 \quad (10)$$

This scenario represents the mean occurrence of the neighbouring solar resource complementing a central wind resource where one resource is in generating power mode while the other is non-generating. It shows the capability of aggregated solar farms on complementing a central wind farm.

(b) Wind Complements Central Wind (WCCW):

$$WCCW\ (\%) = \frac{1}{NG}\sum_{i=1}^{NG}\frac{Number\ of\ hours\ (WPD_i > 240\ \mathrm{Wm}^{-2} XOR\ WPD > 240\ \mathrm{Wm}^{-2})}{Total\ number\ of\ hours} \times 100 \quad (11)$$

This scenario represents the mean occurrence of the neighbouring wind resource complementing another central wind resource where one resource is in generating power mode while the other is non-generating. It shows the capability of aggregated wind farms on complementing another central wind farm.

(c) Solar Complements Central Solar (SCCS):

$$SCCS\ (\%) = \frac{1}{NG}\sum_{i=1}^{NG}\frac{Number\ of\ hours\ (GHI_i > 170\ \mathrm{Wm}^{-2} XOR\ GHI > 170\ \mathrm{Wm}^{-2})}{Total\ number\ of\ hours} \times 100 \quad (12)$$

This scenario represents the mean occurrence of the neighbouring solar resource complementing another central solar resource where one resource is in generating power mode while the other is non-generating. It shows the capability of aggregated solar farms on complementing another central solar farm.

(d) Wind Complements Central Solar (WCCS):

$$WCCS\ (\%) = \frac{1}{NG}\sum_{i=1}^{NG}\frac{Number\ of\ hours\ (WPD_i > 240\ \mathrm{Wm}^{-2}\ XOR\ GHI > 170\ \mathrm{Wm}^{-2})}{Total\ number\ of\ hours} \times 100 \quad (13)$$

This scenario represents the mean occurrence of the neighbouring wind resource complementing a central solar resource where one resource is in generating power mode while the other is non-generating. It shows the capability of aggregated wind farms on complementing a central solar farm.

4. Results

4.1. Variability

The mean and median values of solar and wind resources available over Australia are shown in Fig. 1(a–d). As expected, the solar resource on average is abundant over central Australia (Fig. 1a) ($GHI > 500\ \mathrm{Wm}^{-2}$), but is lower in southern Australia ($GHI < 450\ \mathrm{Wm}^{-2}$), and even lower in Tasmania ($GHI < 350\ \mathrm{Wm}^{-2}$). The mean and median characteristics of solar resource are similar due to the normal distribution of the resource. However, the mean and median do differ in magnitude for the Australian wind resource (Fig. 1b and d respectively) due to skewed distributions of wind power density (which, as shown in Eq. (1), is related to the cube of the wind speed). The wind resource on average is abundant along the southern coast and (to a slightly lesser extent) the western coast of Australia ($WPD > 250\ \mathrm{Wm}^{-2}$), but is lower along the northern and eastern coasts ($WPD < 150\ \mathrm{Wm}^{-2}$). The opposing locations of 'good' mean/median wind and solar resources indicate that there is likely some synergy between them in Australia.

The variability ($RCoV$) of solar and wind resources over Australia is shown in Fig. 1(e and f). Variability associated with solar resource is higher along coastal regions of Australia, except the northwest ($RCoV < 0.6$). South-eastern regions of Australia close to the coast show higher variability ($RCoV > 0.7$), while the greatest variability in solar resource is observed over Tasmania (>0.8). On the other hand, the variability associated with wind resource over Australia is different from that observed for the solar resource, especially in the northwest and inshore southeast ($RCoV > 0.9$). Most of central and, coastal regions of western and eastern Australia show reduced variability in the wind resource ($RCoV < 0.8$).

Moreover, IQR of solar and wind resources over Australia is shown in Fig. 1(g and h). The solar resource is much spread all over Australia, except in eastern and southern coast of Australia ($IQR < 550\ \mathrm{Wm}^{-2}$), and Tasmania ($IQR < 450\ \mathrm{Wm}^{-2}$). Lower spread in solar resource will reduce the dependence for backups. For the wind resource, there is a lower spread over northern, central and south-eastern regions of Australia ($IQR < 250\ \mathrm{Wm}^{-2}$). A higher spread of the wind resource is seen mostly in western and southern Australia ($IQR > 350\ \mathrm{Wm}^{-2}$). These areas will require more backups or reserves since the spread in wind resource varies vastly, thus ramps or swings are common to these regions.

4.2. Intermittency

Solar and wind resource availability over Australia is shown in Fig. 2(a and b) respectively. Solar resource is available mostly in central and northern Australia (where Availability is > 40%) in comparison to southern Australia and Tasmania. On the contrary, the wind resource is highly available in western and southern Australia (where Availability is > 50%) in comparison to central and northern Australia. The wind resource is highly unavailable in the south-

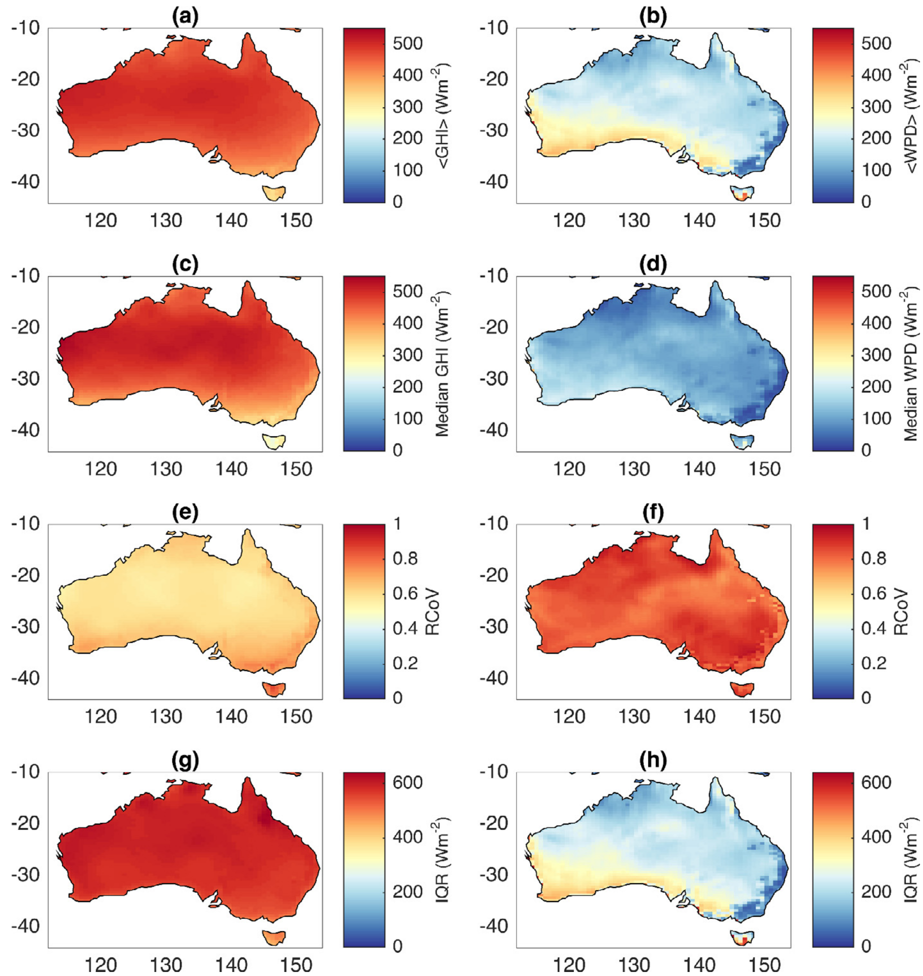

Fig. 1. Variability in solar and wind resource over Australia: (a) mean GHI, (b) mean WPD, (c) median GHI, (d) median WPD, (e) *RCoV* of GHI, (f) *RCoV* of WPD, (g) *IQR* of GHI and (h) *IQR* of WPD.

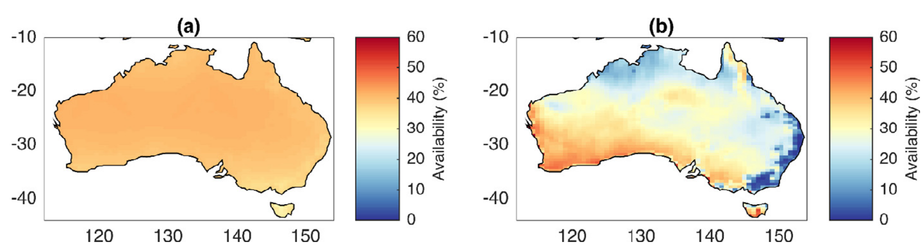

Fig. 2. Availability of (a) solar and (b) wind resource in Australia.

eastern Australia (where Availability is < 10% and where Unavailability is > 90%). Interestingly, regions of high (low) solar Availability show low (high) wind Availability. This also reflects the complementary nature of solar and wind resource in the different regions of Australia.

The nature of intermittent solar and wind resource is shown in Fig. 3(a–d) using the maximum and mean values of Episode Length for solar and wind resource. The maximum Episode Length for the solar resource (Fig. 3a) peaks at 3500 h in the Northern Territory, whereas for wind it peaks at 528 h in northern Queensland. The distribution of maximum Episode Length for wind (Fig. 3b) is more spread over Australia in comparison to solar, but more significant differences can be seen between the mean Episode Length for solar and wind resources. For the solar resource, the mean Episode Length is higher in the central region compared to the southern-eastern region. This is opposite to the mean Episode Length for wind resources, which is higher in the southern region in comparison to central regions in Australia.

Also, the intermittent nature of solar and wind resource using the maximum and mean values of Lulls in the solar (including night hours) and wind resource is shown in Fig. 4(a–d). The maximum Lulls are higher in south-eastern regions of Australia for solar (Fig. 4a) (Lulls > 80 h) and wind (Lulls > 700 h). Northern Australia also shows higher maximum Lulls (>1000 h) for wind resource, whereas solar resource in this region exhibits much lower Lulls (<60 h). The mean Lulls for the wind resource show distinct regional patterns, which are lower in central Australia when

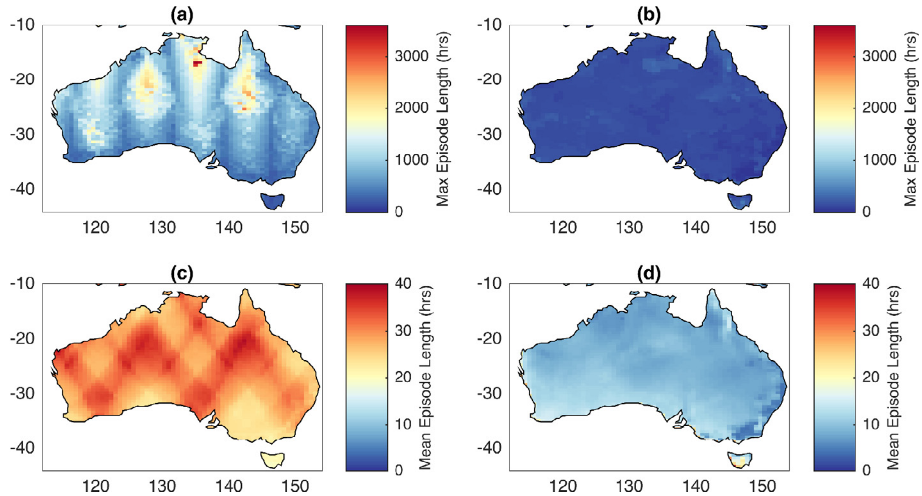

Fig. 3. Observed hours of Episode Length in Australia: The maximum Episode Length of (a) solar, (b) wind and mean Episode Length of (c) solar and (d) wind resource.

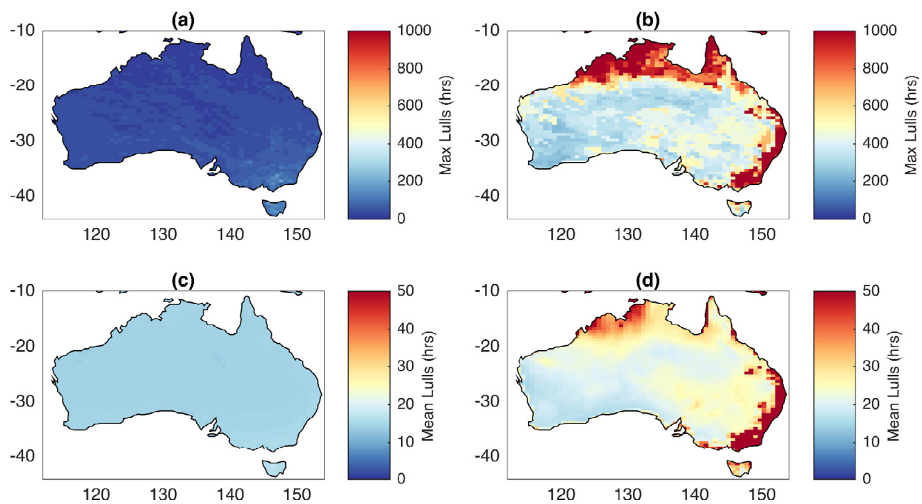

Fig. 4. Observed hours of Lulls in Australia: The maximum Lulls for (a) solar, (b) wind and mean Lulls of (a) solar and (b) wind resource in Australia.

compared to northern and south-eastern regions. For the solar resource, the mean Lulls did not show much variation regionally.

4.3. Synergy

Three different scenarios for the temporal synergy of solar and wind resources in Australia are shown in Fig. 5(a–c). Evidently, wind complements solar (Fig. 5a) in the southern regions of Australia ($WCS > 20\%$), including the south-western region. Tasmania peaks in *WCS* by > 30%. This suggests a wind farm could have generated an additional 94,673 h ($\approx$10 years) of power lost due to loss of solar generation in this region. The north and east parts mostly show weak *WCS* (<5%). Interestingly, opposite regional patterns are seen with the *SCW* scenario. The northern and eastern regions show high *SCW* (>20%), suggesting a solar farm could have made up for an additional 63,115 h of power lost from insufficient generation from a wind farm. The southern regions including the south-west and Tasmania show lower *SCW* (<15%). Clearly, the patterns shown by *WCS* and *SCW* indicate the complementary nature of solar and wind resource in different regions of Australia. This becomes clearer with the overall patterns seen with the *WSS* scenario. Overall, the temporal synergy between solar and wind resource ranges from 25 to 55%, peaking when very close to the western and southern coast. Similarly, south-eastern, northern regions (Cairns and Kimberley Plateau) and Tasmania also show significant synergy between solar and wind resources ($WSS \approx 40\%$). To further explore the *WSS* scenario, the occurrence of synergy characteristics was computed by sorting the entire data on an hourly basis according to Australian Eastern Standard Time (AEST). This is shown in Fig. 6. Clearly, the position of the sun is the dominant factor in affecting *WSS*. During early morning to noon, higher *WSS* exists in the Eastern region, and in the late afternoon higher *WSS* appears along the Northern regions. As daylight ends, wind becomes the dominant factor affecting *WSS*. Throughout the night, higher *WSS* exists close to the western and southern coast.

The synergy characteristics were further investigated by including neighbouring grid points (3×3 and 5×5) to account for spatial complementarity within a distance of 279–465 km. Fig. 7 shows the synergy associated with reference to the wind resource at the central grid. This includes *SCCW* and *WCCW* with neighbouring grid points (3×3 and 5×5). The impact of increasing *NG* from 3×3 to 5×5 does not change *SCCW* significantly. Solar resource has greater autocorrelation within the neighbouring grids, thus there is not much improvement seen in synergy characteristics.

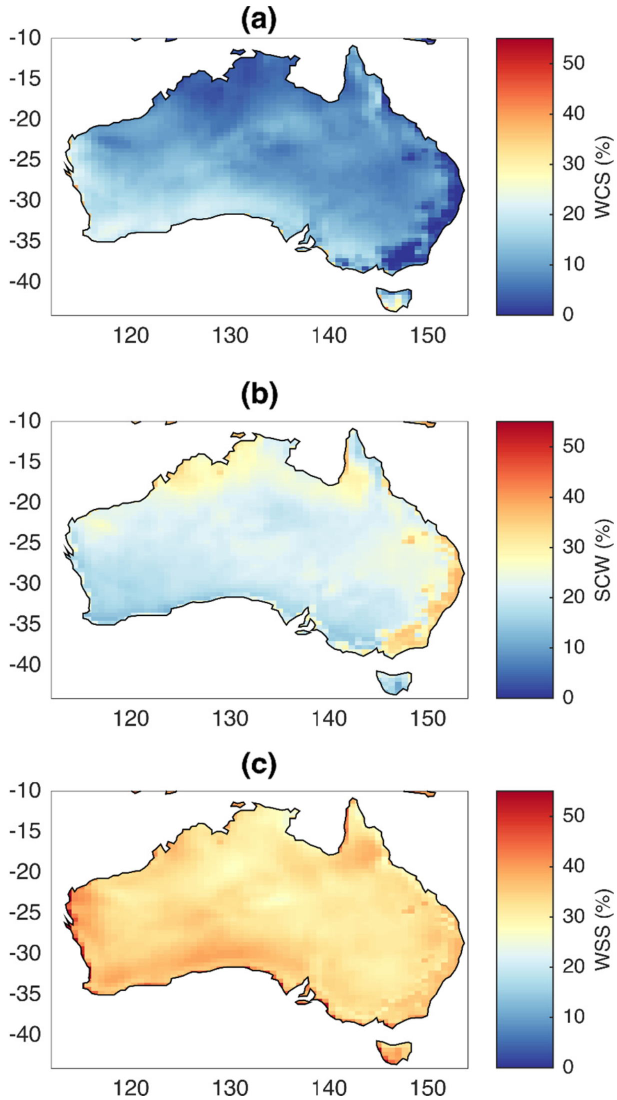

Fig. 5. Temporal synergy of solar and wind resource in Australia: (a) Wind Complements Solar, (b) Solar Complements Winds, (c) Wind and Solar Synergy

However, higher *SCCW* (>35%) exist in coastal regions around Australia, except in the North with only 78,894 h of power generation after spatial aggregation to 465 km. However, increasing *NG* from 3×3 to 5×5 does change *WCCW* significantly in terms of spatial extent and magnitude. Most of this is attributed to the lower auto-correlation of the wind resource within the neighbouring grids. Higher *WCCW* extends more inland from coastal regions, and the magnitude also increases by 5–10%. However, comparison of *SCCW* and *WCCW* shows the greater spatial extent and magnitude ($SCCW > WCCW$) exhibited by solar resource complementing the central wind resource. Generally, a solar farm is expected to complement an existing wind farm more efficiently within a distance of 465 km.

Moreover, the synergy associated with reference to solar resource (*SCCS* and *WCCS*) at the central grid with neighbouring grid points (3×3 and 5×5) is shown in Fig. 8. Increasing *NG* from 3×3 to 5×5 does not change *SCCS* significantly in magnitude (<1%), only enhancing south-eastern region spatially. Similarly, incrementing *NG* had almost no effect on *WCCS* spatially (except in Tasmania), but the coastal regions increased in magnitude by 3–9%. This means setting up a wind farm within *NG* may add at most an extra 28,401 h of generation to existing solar farms. On the other hand, comparison of *SCCS* and *WCCS* showed $WCCS > SCCS$ by 30% at all locations while most differences can be seen near coastal regions of Australia. These differences can also be attributed to day and night differences, where wind resource is available throughout the day and night, and solar resource is only available during the day. Overall, setting up a wind farm within 465 km of an existing solar farm near coastal regions of Australia seem more feasible.

4.4. Proximity to transmission lines

It is evident that variability and intermittency associated with solar and wind resources can seriously undermine the production of stand-alone solar or wind energy systems. While exploring how solar and wind resources complement each other, it is clear that mitigating variability and intermittency is possible, but other factors such as proximity to infrastructure, population and demand may also need to be considered when making crucial decisions of citing renewable energy systems. Ideally, setting up new solar and wind farms further away from the grid is not favourable due to the infrastructure costs incurred in extending the grid. The distance from transmission lines and the location of transmission lines in Australia are shown in Fig. 9. Nearly 88% of MERRA grids shown in Fig. 9 lie within a distance of 465 km from the transmission lines. The relationship of variability and intermittency of solar and wind resource with respect to distance from transmission lines in Australia is shown in Fig. 10(a–d), where the bin size on the axis corresponding to the distance from transmission lines is scaled to MERRA's maximum corner to corner grid distance (≈93 km). The variability (*RCoV*) in solar and wind are more spread within five grid points (≈465 km) from the transmission lines. Similarly, intermittency (Availability) in solar and wind show more spread within 5 grid points from the transmission lines. This indicates variability and intermittency of solar and wind resources are paramount in the proximity of transmission lines, which includes regions that are more populated. On the other hand, greater synergy between solar and wind resources ($SCCW, WCCW, SCCS, WCCS$) are also shown in the proximity of transmission lines (within five grid points) in Fig. 11(a–d), where the bin size on axis corresponding to distance from transmission lines is also scaled to MERRA's maximum corner to corner grid distance (≈93 km). Interestingly, this suggests that the variability and intermittency of solar and wind resource can be mitigated by the synergy of solar and wind resource within a distance of ≈465 km. Especially, in the south-eastern region where most solar and wind farms exists (also shown in Fig. 9) show high variability of solar ($RCoV \approx 0.75$) and wind ($RCoV \approx 0.8$) resources with high intermittency of solar (Availability ≈ 36%) and wind (Availability ≈ 30%) resources can be effectively mitigated by the synergy characteristics of solar and wind resources ($SCCW \approx 35\%, WCCW \approx 15\%, SCCS \approx 3\%, WCCS \approx 40\%$).

Furthermore, synergy characteristics of wind and solar resources may also aid in meeting the energy demand during peak hours. To illustrate this point, the relationship of solar and wind resources, and demand based on hourly averaged values for the year 2010 at a location in the state of Victoria is shown in Fig. 12. Firstly, the complementary nature of mean solar and wind flux is highly evident with a correlation coefficient of ≈−0.95. Interestingly, during morning hours as demand starts to gain momentum, solar complements wind resource since dusk as wind resource declines. During noon, demand peaks with the solar resource, which effectively complements wind resource that is at its minimum at this stage. Similarly, during the afternoon when the demand is still high, the wind resource grows and complements the diminishing solar resource as sunset approaches. This is also true after dawn, where wind resource peaks as demand grow at night, thus effectively complementing for unavailability

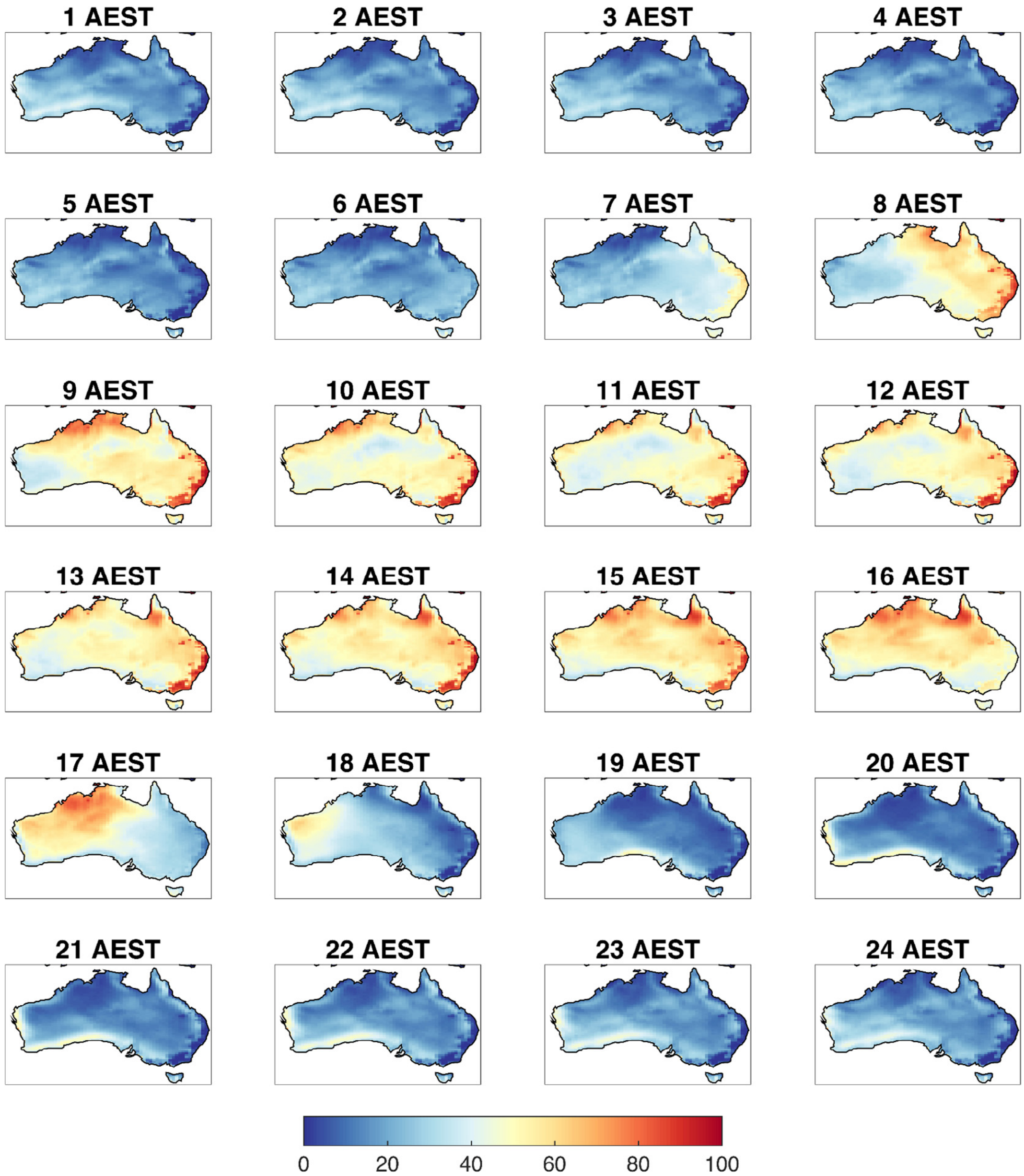

Fig. 6. Hourly synergy characteristics of solar and wind resource in Australia based on local time (AEST).

of the solar resource. This example does not represent all of Australia, but points out an added benefit of matching energy demand while using solar and wind resource in concert to generate power.

4.5. Application to existing solar and wind farms

A hybrid solar-wind power generating system can be initially sited near existing solar and wind farms. The synergy characteristics associated with existing solar and wind farms are listed in Tables 1 and 2, respectively. To complement an existing solar farm, another solar or wind farm can be set up nearby and within proximity of transmission lines. The current locations of solar farms can be complemented by another solar farm with *SCCS* ranging from 1 to 3% within 465 km. On the other hand, current solar farms can be complemented by another wind farm with *WCCS* ranging from 31 to 36% within a distance of 465 km. However, choosing a specific example of an existing solar or wind location in Australia, it was found that the greatest synergy could be achieved with the Royalla Solar Farm with solar complementing 2.72% of the period studied, while wind complements 36.12%. Wind farms are currently more prevalent than solar farms (although a lot of rooftop PV has been installed in Australia which is neglected here), but this analysis shows that the ability of another solar farm can complement the current wind farms with *SCCW* ranging from 29 to 46%. On the other hand, setting up another wind farm within a distance of 465 km can complement current wind farms with *WCCW* ranging from 10 to 26%. From the 40 existing wind farms, *SCCW* peaks for Cathedral Rocks Wind Farm with added 144,155 h of power generation whereas *WCCW* peaks for Bald Hills Wind Farm with added 82,901 h of power generation.

5. Discussion

The variability of solar and wind resources is heavily dependent on large climate drivers (ENSO, monsoon and sub-tropical ridge) and other synoptic (cloud bands, troughs and fronts) features

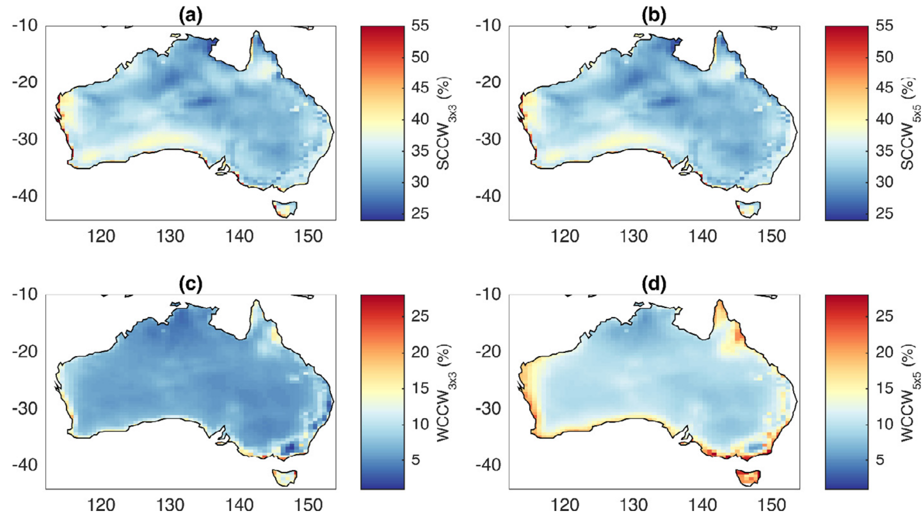

Fig. 7. Spatio-temporal complementary characteristics of solar and wind resource in Australia with reference to central wind resource synergy with (top) solar and (bottom) wind using (left) 3 × 3 neighbouring grids and (right) 5 × 5 neighbouring grids.

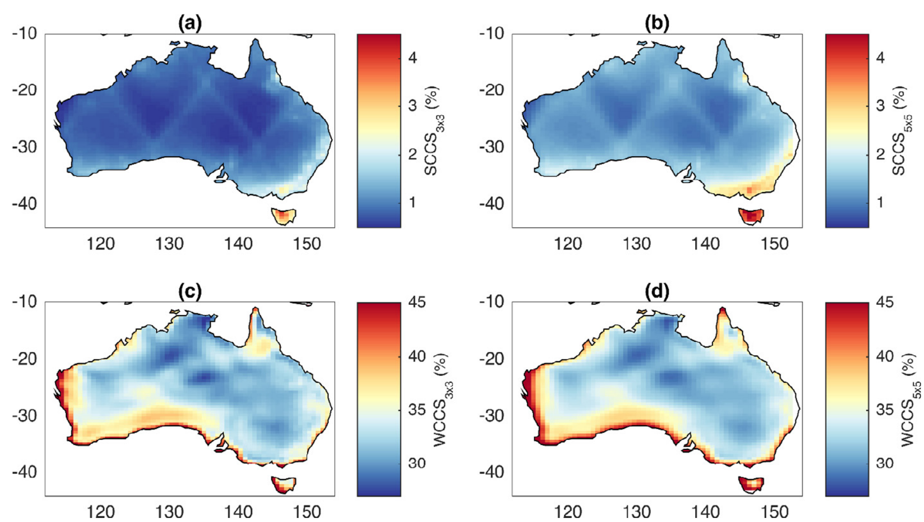

Fig. 8. Spatio-temporal complementary characteristics of solar and wind resource in Australia with reference to central solar resource synergy with (top) solar and (bottom) wind using (left) 3 × 3 neighbouring grids and (right) 5 × 5 neighbouring grids.

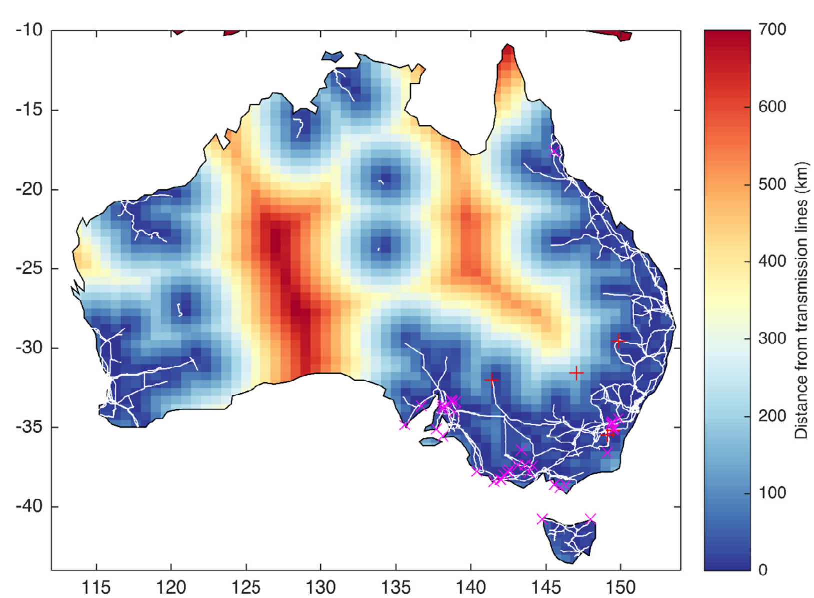

Fig. 9. Current transmission lines (white contours) and locations of solar (+) and wind farms (×). The filled contours show the minimum distance from transmission lines. Nearly, 88% of land area falls within 465 km of the transmission lines.

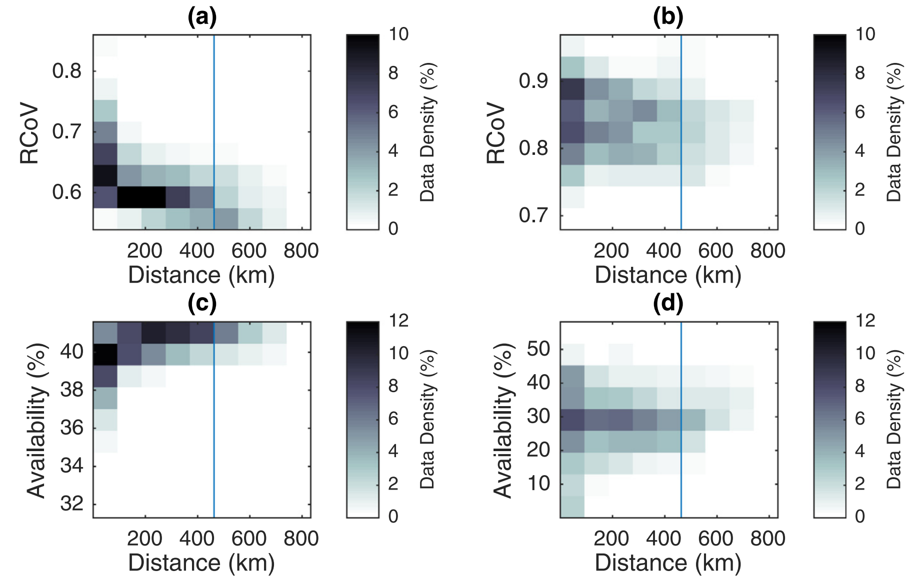

Fig. 10. 2D histogram of (top) variability and (bottom) intermittency calculated from minimum distance from transmission lines for (left) solar and (right) wind resource in Australia. Each bin size on the x-axis corresponds to MERRA's maximum corner to corner grid distance (≈93 km). The vertical reference line in blue shows the distance of 465 km from transmission lines.

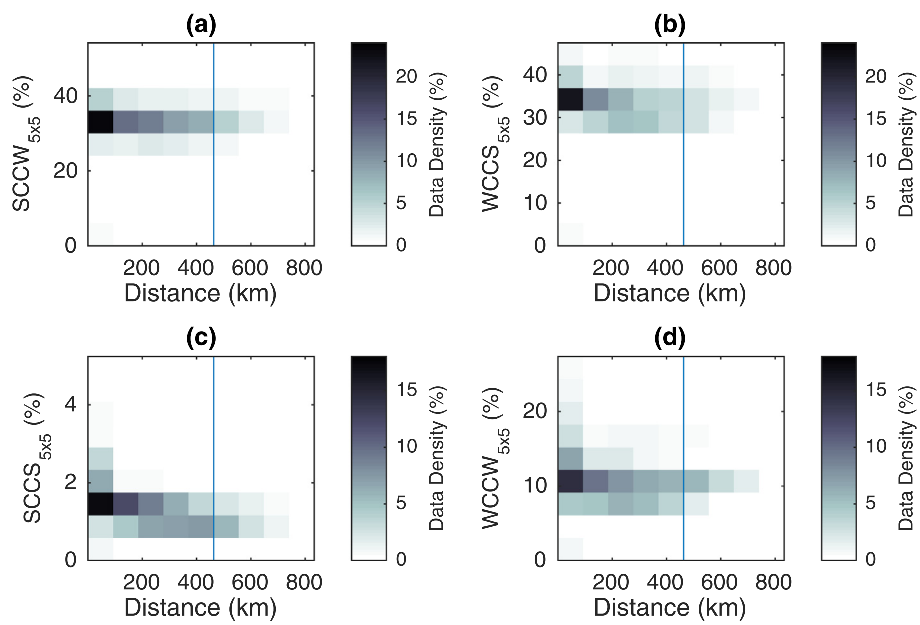

Fig. 11. 2D histogram of solar and wind synergy calculated from minimum distance from transmission lines: (a) *SCCW*, (b) *WCCS*, (c) *SCCS*, (d) *WCCW*. Each bin size on the x-axis corresponds to MERRA's maximum corner to corner grid distance (≈93 km). The vertical reference line in blue shows the distance of 465 km from transmission lines.

common to Australia [12]. MERRA data captures this in terms of patterns seen in the mean GHI and WPD variations. Although using different datasets (mostly satellite retrievals) and timescales, several studies showed very similar changes in variables derived from GHI (such as Direct Normal Irradiance (DNI)) over Australia [10,12]. Similarly, resource maps produced with wind speeds show very similar pattern of mean wind fields and variability as computed from the MERRA dataset [18,60]. Recently, Hallgren et al. [59] used MERRA data to show similar results related to variability and intermittency of the wind resource in Australia. The substantial similarity between studies carried out by other datasets for solar and wind resource in Australia, especially in terms of capturing the variability and intermittency itself validates MERRA dataset, making it credible to be used for the assessment of synergy characteristics of solar and wind resource in Australia.

For this study, the methodology applied in computing the synergy features is robust and is derived from correlation-based studies conducted in the Northern Hemisphere. This allows parallel comparisons to be made from the correlation-based studies. Several studies highlighted that the correlation-based analysis shows a strong relationship of complementary characteristic to the distance from the resource, especially solar resource was highly correlated at a smaller distance, whereas wind show low correlation at larger distances [45,51,53]. This result was also reflected in changes in synergy characteristics observed in Australia when the neighbouring grids were increased (distance increased). Here,

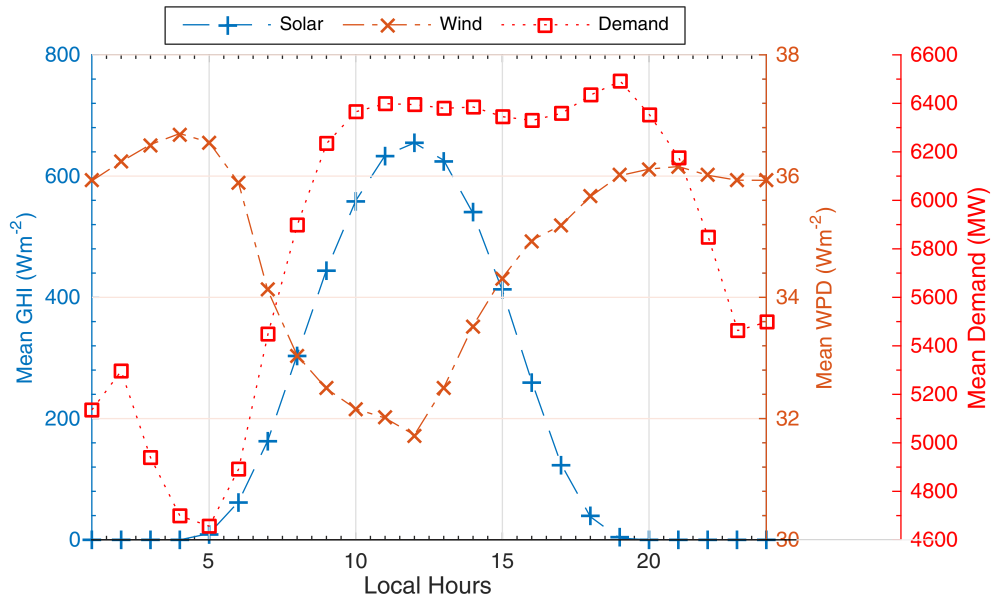

Fig. 12. Illustration of relationship of hourly averaged solar and wind resource with peak demand for the year 2010 for a reference grid point in the state of Victoria.

Table 1
Summary of synergy characteristics for current solar farms.

Scenario	Broken Hill	Capital East	Moree	Nyngan	Royalla
WCCS (%)	32.24	35.22	33.68	31.15	36.12
SCCS (%)	1.35	2.58	1.55	1.43	2.72

Table 2
Summary of synergy characteristics for current wind farms.

Wind farm	SCCW (%)	WCCW (%)	Wind farm	SCCW (%)	WCCW (%)
Bald Hills	41.19	26.27	Mortons Lane	29.87	16.93
The Bluff	32.23	11.02	Mt Millar	33.63	12.35
Boco Rock	37.09	16.94	Musselroe	35.26	24.94
Capital Wind	32.80	18.37	North Brown Hill	32.28	11.02
Cathedral Rocks	45.68	17.82	Oaklands Hill	33.99	12.74
Coonooer Bridge	32.80	10.43	Portland	41.34	22.54
Challicum Hills	32.26	11.46	Snowtown North	32.84	12.33
Clements Gap	34.59	12.30	Snowtown South	34.59	12.30
Codrington	40.89	20.93	Snowtown Units 1&47	34.59	12.30
Cullerin Range	32.80	18.37	Starfish Hill	40.97	22.32
Gullen Range	33.73	19.78	Taralga	35.79	14.80
Gunning	33.73	19.79	Toora	32.64	23.14
Hallett 1	32.23	11.01	Waterloo	31.69	11.23
Hallett 2	32.23	11.01	Waubra	32.25	11.46
Hepburn	34.57	13.58	Windy Hill	34.87	22.02
Lake Bonney	35.43	23.71	Wonthaggi	37.93	21.00
Lake Bonney Stage 2	35.43	23.71	Woodlawn	32.80	18.37
Lake Bonney Stage 3	35.42	23.71	Woolnorth Studland Bay	37.80	23.44
Macarthur	31.21	16.54	Wattle Point	41.63	13.48
Mt Mercer	31.67	18.51	Yambuk	40.88	20.93

the solar resource having greater correlation within the neighbouring grids and the lower correlation of the wind resource within the neighbouring grids explained the major differences observed in the synergy characteristics. Thus, spatial aggregation of solar and wind farms significantly mitigates the intermittency and variability introduced from an individual farm, but complementary characteristics heavily depend on the type of resource farms and the distance between them.

Arguably, a co-located hybrid solar/wind power generation system is an option where greater synergy characteristics exist and especially if transmission grids are not too close. However, spatial aggregation of stand-alone solar and wind farms show greater synergy owing to correlation relationships of the resource with distance. However, increased distance between two complementing power generating systems may require the expansion of the transmission infrastructure [45]. Interestingly, nearly 88% of Australian region is within 465 km of the existing transmission grid. Furthermore, within this distance, maximum synergy characteristics are observed, while resources show higher intermittency and variability. This is perfect for optimising a solar and wind farm operating in concert by generating smooth power output through mitigation of the intermittency and variability introduced from a region already much closer to the transmission grid. Although this study is centred over Australia, the methodology and metrics can be easily applied to other parts of the globe.

6. Conclusion

This paper assessed the spatio-temporal synergy between solar and wind resource in Australia to mitigate variability and intermittency associated with the resources calculated using reduced hourly time averaged diagnostic fields from MERRA reanalysis product for the period 1979–2014.

The variability in solar resource was more pronounced over the south-eastern region, whereas northwest and southeast regions showed greater variability in wind resource. The unavailability in solar resource was complemented by the availability of wind resource in the south of the country, whereas the unavailability in wind resource was complemented by the availability of solar resource in the eastern region. The intermittency of solar and wind resource regarding episodes of time in active energy production show greater persistence over central Australia for solar and southern Australia for wind. On the other hand, the episodes of time for inactive energy production for both solar and wind show greater persistence over south-eastern Australia.

Overall, the temporal synergy between solar and wind resource was higher when very close to the western and southern coast. Also, Tasmania, south-eastern (parallel to the eastern Great Dividing Range) and northern regions (Cairns and Kimberley Plateau) showed significant synergy with an additional capability of 126,230 h of power generation between solar and wind resources mostly influenced by hours of daylight when solar resource is available. Increasing the spatial extent to 465 km increased the occurrence of synergy characteristics by almost 10% with an additional 31,558 h of power generation. It was shown that a solar farm is more preferable over wind due to higher synergy with reference wind farms near coastal regions of Australia. Similarly, a wind farm is more preferable over solar due to higher synergy with reference solar farms near coastal regions of Australia, except the North.

Furthermore, it was shown that the variability and intermittency of solar and wind resources were paramount in the proximity of transmission lines, which included populated regions of Australia. Similarly, greater synergy characteristics of solar and wind resources were shown within the proximity of transmission lines indicating the variability and intermittency caused by the individual resource can be mitigated strongly by combining the two resources, one of which may be already operating in the vicinity of transmission lines. This turned out to be true for Royalla Solar Farm, Cathedral Rocks Wind Farm and Bald Hills Wind Farm. Also, it was illustrated that the complementary nature of solar and wind resource aid in meeting energy demand during peak hours.

This study has shown that assessing synergy characteristics of solar and wind are crucial in deciding future hybrid solar-wind power generating systems, which significantly reduces the intermittency caused by stand-alone solar/wind power generating systems. This inturn will lower costs of energy production, creating more supply from renewables. Although this study is focused on Australia, a similar methodology can be applied to assess complementarity of solar and wind resource in any other country of the world.

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