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Operational performance analysis of distributed PV systems in Australia

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Abstract

Accurate estimations of distributed PV generation performance have potentially significant planning and operational value. With 5.3 GW of small scale PV installed across Australia, there has been no comprehensive assessment of how well these PV systems are performing compared to expectations. In this paper, the daily energy yield from more than 2000 distributed PV systems across Australia are analysed and compared to PV performance estimates modelled using the publicly available simulation platform known as Renewables.ninja and the PV_LIB simulation package with RMY and TMY weather files for Australia. The average daily yields of the PV systems were also compared to available estimates of PV performance from the Clean Energy Regulator and the Clean Energy Council. The results revealed that a subset of the PV systems selected on the basis of having appropriate orientation and tilt without shading, generally generated more power than the estimate from the Clean Energy Regulator. In comparison, the estimates from both the Clean Energy Council's and the PV_LIB simulation were found to more closely align with the measured PV performance data. The estimates from the Renewables.ninja platform were generally found to overstimate performance because of it's dependence on NASA MERRA weather data which has been shown to overestimate insolation in Australia.

1. Introduction

Worldwide capacity of Photovoltaics (PV) has increased dramatically over the past decade reaching an installed capacity of 227GW at the end of 2015. Indeed, PV systems represented more than 18% of all added electrical generation capacity in 2015 (REN 2016). Australia has played an important role in this deployment, as the seventh country in the world in terms of added PV capacity, and tenth in terms of total PV capacity as of the end of 2015. More strikingly, some 80% of its 5.3GW of installed PV capacity consists of over 1.5 million small scale PV (less than 10kW). Further, around 30% of dwellings in Queensland and South Australia, and 15% of all Australian dwellings currently have PV installed on their rooftops (APVI 2016). The high and increasing penetration of distributed PV systems within Australia's electricity generation portfolio highlights the fundamental importance of better understanding and estimating the actual operation performance of distributed PV systems.

A range of models for estimating actual performance are available, and comparisons between modelled and real PV system performance across different locations and climates have been undertaken (Stein et al., 2010) (Phinikarides et al., 2015) (Kurtz et al., 2013) (Cameron et al., 2008). The PV performance models have been shown to be reasonably accurate for appropriately designed, installed and well maintained PV systems. Distributed PV systems, however, pose particular challenges for modelling based estimates as their installation is often compromised by the available residential and commercial buildings roof arrangements, while the PV systems are not carefully monitored nor maintained. This makes it difficult to achieve ideal operational conditions, resulting in PV performances below ideal estimates. In other studies, authors have tried to understand the performance mechanisms of distributed PV systems, identifying the primary causes of non-ideal performance linked to shading, module orientation, outages, and weather condition (Lonij, et al 2012).

For the study reported in this paper, we evaluate the daily energy yield of more than 2000 small-scale distributed PV systems across Australia, sourced from the publicly available website PVOutput.org (PVoutput.org 2016). These measured yields were compared against available estimates of PV performance for the capital cities across Australia based on a range of modelling tools and databases. The findings of this study may help a range of different stakeholders to better understand the expected performance of PV systems in different locations across Australia and hence assist in planning and operations. As the installation conditions of the distributed PV systems within the PVOutput.org database cover a diverse range of configurations (Haghdadi et al,. 2015), this data source captures the real-world diversity of distributed PV systems across Australia.

2. Database

2.1. Distributed PV systems in Australia

System specifications and energy generation from approximately 5000 PV systems were sourced from PVOutput.org. The PV system specifications available within PVOutput.org are input by PV system owners/installers and include standard system configuration details such as the location's postcode, the systems' tilt and orientation angles, shading status, and inverter and module capacity. The locations of PV systems available within PVOutput.org are shown in Figure 1 with the percentage of systems in each state. The majority of the PV systems are located along the East coast of Australia, coinciding with the most densely populated regions of the country.

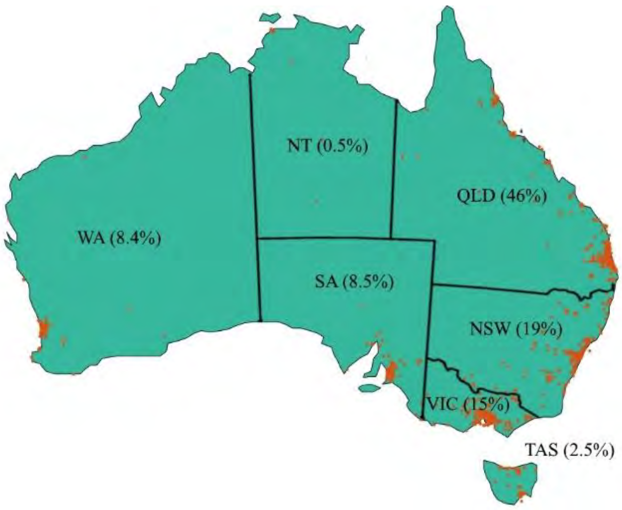

Figure 1. Location of PV systems in PVOutput.org

To achieve the maximum annual energy from a PV system in southern hemisphere, it should ideally be oriented towards north with the tilt angle close to the latitude angle. However, due to several reasons, including building roof slopes and orientations, distributed PV systems are often installed at non-ideal orientations and angles. Figure 2 shows the distribution of orientation angles (left) and shading status (right) of the PV systems within the PVOutput.org database. More than half of the systems are installed at the correct orientation, and the majority of them are reported to be unshaded. Figure 2 (right) shows the distribution of orientation angle of PV systems.

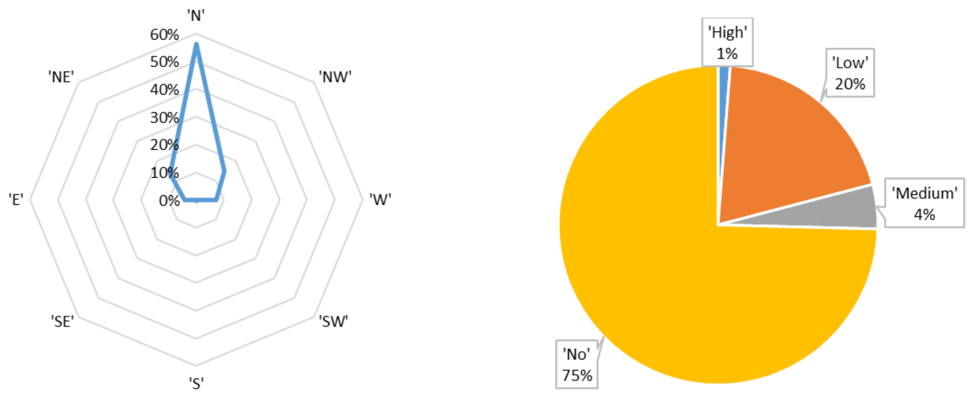

Figure 2. Distribution of self-reported orientation of PV systems (left) and shading status of them (right)

Figure 3 shows the distribution of tilt angles (left) and distribution of difference between tilt and latitude angle (right). As observed, most of the systems are installed in tilt angle between 15° and 30° (most likely due to the most common roof slope) and in average around 10° lower than the optimal tilt angle.

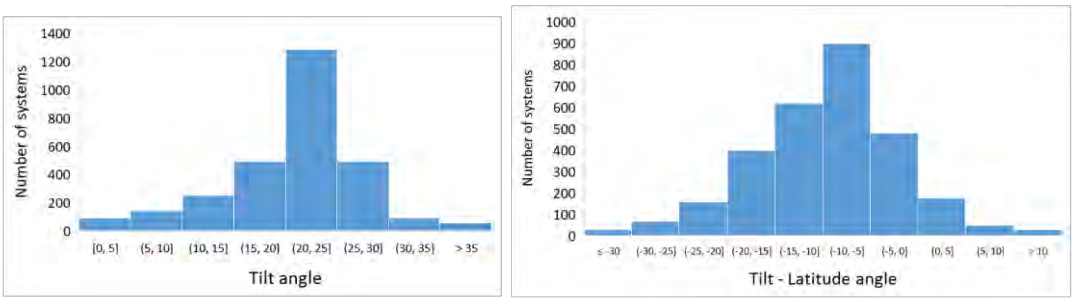

Figure 3. Distribution of tilt angle of PV systems. left: distribution of absolute tilt value, right: distribution of tilt offset from (ideal) latitude

In regions with a low frequency of high levels of instantaneous irradiance (i.e. > 1000 W/m^2) the capacity of inverter (AC size) can be sized slightly below the standard test condition rating of the array (DC size) as the expected output power will rarely reach the DC nameplate capacity; hence a smaller (and therefore generally cheaper) inverter would be sufficient for such a location. However, for locations where a higher frequency of instantaneous irradiance > 1000 W/m^2 are expected, then the generated power of the DC array can exceed the inverter rated maximum power, resulting in the clipping of power during these time periods. Therefore, depending on the expected distribution of the solar resource and hence the PV output, undersizing the system inverter may or may not be appropriate.

Figure 4 presents the DC to AC ratio of the PV systems within the PVouput.org database grouped by inverter size range (left) and by state (right). The results indicate that the highest DC to AC ratios occur for inverters grouped in the 4kW category (4kW≤AC size<5kW). This result is likely related to the residential PV installation regulations. In different states, QLD has the highest observed DC to AC ratios. A preliminary look at the PV systems output patterns, reveals that a considerable number of PV systems in QLD experienced inverter clipping during the middle of the day during summer. The underlying reason for such trend in QLD is likely to be the network requirements for PV installations as until September 2015, residential PV systems with an inverter capacity ≤5kW gained automatic approval to connect to the network, with no restriction on higher module capacity. Restrictions on export and ineligibility for feed in tariffs also applied to systems with inverters >5kW installed in QLD at different times.

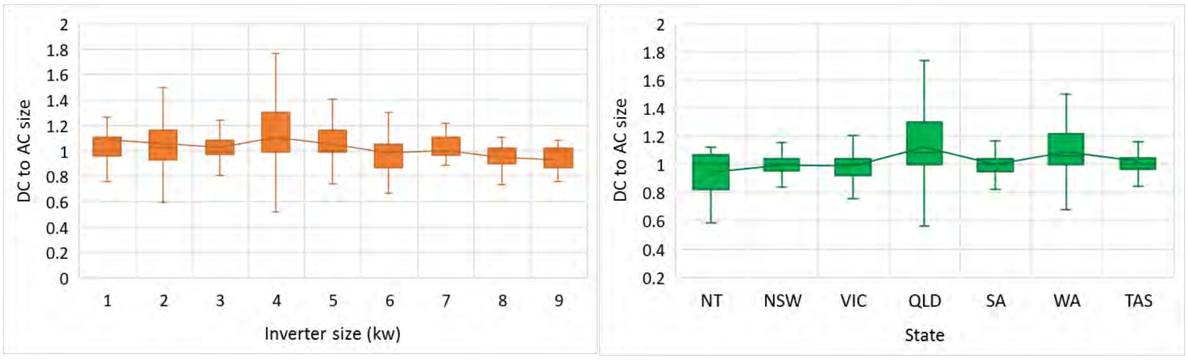

Figure 4. Module to inverter (DC to AC) capacity ratio. Left: for different inverter size ranges, right: for different states

The average performance of the PV systems within the PVOutput.org database, which were found to be located within a 30km radius from the centre of each capital city across Australia and had more than one year worth of data (total ~2000 systems for all capital cities out of ~5000 systems in all Australia), were considered to represent the typical performance of the PV systems within these cities. Because distributed PV systems are not always installed at ideal conditions, a subset of the PV systems which were found to have system configurations within an optimal range (tilt angle within ±10 degrees from latitude angle, orientation toward north, with no reported shading) were selected for separate analysis. This subset will be referred to as the ideal subset, and is useful for comparison with projections of performance where ideal mounting angles are assumed. The PV system data used in this study are for years 2012 to 2015. Figure 5 shows the average daily solar exposure in these years compared to the long-term average sourced from Australian Bureau of Meteorology (BOM) website (Bureau of Meteorology 2016).

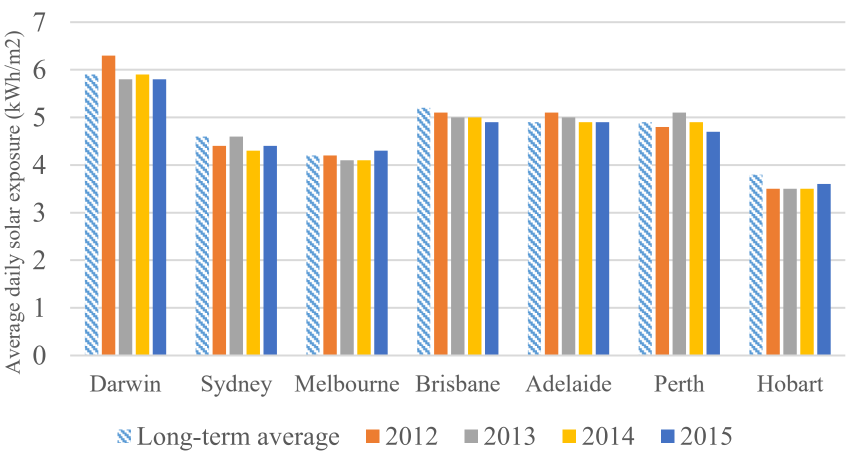

Figure 5. Comparison of average daily solar exposure in capital cities compared to the long-term average

The figure shows that these four years are reasonably similar to the long-term average and hence the average performance of the PV systems can be used as an indicator for typical performance. However, in Hobart the solar exposure in recent years appears to be slightly lower.

2.2. Simulated PV system using publicly available weather data

The performance of a typical PV system, for any location, can be modelled using both commercial and publicly available simulation platforms. Typical inputs for such modelling are the weather parameters of Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), temperature, and wind speed. The input weather data can be historical data for a specific period of time, a typical meteorological weather file developed from long term observations of real historical data or a synthetically generated weather file. Other essential inputs include coordinates of the location, and the PV system configuration, such as the array maximum power temperature coefficient, tilt and orientation in addition to the inverter efficiency.

2.2.1. Available historical weather data

A variety of historical weather data sources exist for Australia which can be used to simulate the performance of a PV system. These weather data sources range in quality, and period of availability. The BOM has a range of data available including, standard meteorological variables like temperature and wind speed from their network of Automatic Weather Stations (AWS) (~500 stations across Australia); One minute solar irradiance data for a small collection of ground measurement locations (20 stations across Australia covering various time periods from 1 to 20 years of data); and the hourly gridded satellite derived irradiance data available across the entire continent for a period of ~25 years (Bureau of Meteorology 2016).

NASA has also range of different products including gridded datasets (NASA 2016a) and the Modern-Era Retrospective Analysis for Research and Applications reanalysis (MERRA/2) data (NASA 2016b). These NASA datasets are publicly available and therefore can be used freely for distributed PV modelling. In this paper we used the Renewables.ninja web application (Pfenninger et al,. 2016), which utilises MERRA as the input weather data source for the region of Australia, to produce hourly profiles of PV performance for a typical PV system, for each of the capital cities across Australia. The typical PV system is defined with an optimal tilt and orientation angle for each location with assumed system losses of 20%.

2.2.2. RMY data and PV_lib

Representative Meteorological Year (RMY) weather files for each of the capital cities were sourced from EnergyPlus[1] (US-DOE 2013). The hourly output power, for the typical PV system in each capital city, was then modelled using SANDIA's PV Performance Modelling Collaborative modelling package, PV_Lib developed in MATLAB (SANDIA 2016). Specifications of the simulated PV system are detailed in Table 1.

[1] Representative Meteorological Year is based on multiple years' data to reflect the long-term average, but does not comply with the standard method for creating a TMY. Note that the acronym RMY is also used for the different climate data type "Reference Meteorological Year".

Table 1. Specification of the typical PV system used for simulation

Module technology	**C-Si**	
MPP temperature coefficient	-0.436	
Array STC power	12*220 W	
Cell temperature parameters	α	-3.56
	β	-0.075
	ΔT	3
Inverter Pdc	2640 W	
Inverter Pac	2500	

2.2.3. TMY data and PV_lib

Typical Meteorological Year (TMY) weather files are also available for the location of BOM weather stations in Australia. This weather file is based on the ground measurement irradiance and temperature data. The TMY data for the Darwin, Melbourne, and Adelaide is sourced from (AREMI 2016) and the same simulation is done for a typical PV system using TMY weather files for these cities.

2.3. Publicly available estimates

Owners of PV systems ≤10kW in Australia receive Small-scale Renewable Energy Certificates (SRECs) as an investment incentive. The number of certificates (based on the amount of renewable energy deemed to be generated by the system) depends on the size and location of the PV system. The Clean Energy Regulator (CER) has partitioned Australia into four climate zones, Figure 6, where each zone is allocated a different REC multiplier (Clean Energy Regulator 2014). The REC multiplier is equivalent to the average expected number of MWh of energy generated by a 1kW PV system in each zone.

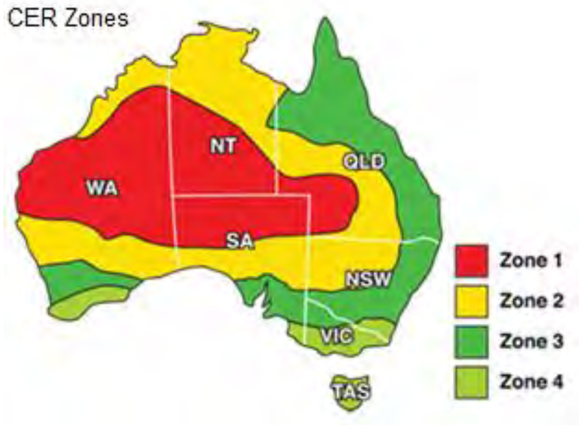

Figure 6: Clean Energy Regulator climate zones

The Clean Energy Council (CEC) has also published a guide for installing PV in Australia, which provides estimates of the of annual yield for typical PV systems installed across the Australia (Clean Energy Council 2014). The estimated yield for each of the capital cities across Australia were sourced from both the CER and the CEC. These values were compared against the annual average yield calculated from the reported outputs of the PV systems located within PVOutput.org.

3. Performance comparison

In order to evaluate the different estimates of PV system performance, the average measured performance of the PV systems located within each of the capital cities were compared against (1) the output from the publicly available Renewables.ninja web based modelling platform (Pfenninger et al., 2016); (2) the PV_LIB simulation results using the publicly available RMY and TMY weather files for Australia; and (3) the available PV performance estimates from the CEC and CER.

3.1. Average daily energy

The distributions of the measured PV system yields (kWh/kWp/day) for each of the capital cities and for the full PVouput.org dataset are presented in Figure 7. The figure illustrates significant differences in the distributions across each of the capital cities, theorised to be driven by the differences in the distribution of the solar resource across Australia. For example, the combined results for all of Australia appears to adhere to a normal distribution, whilst for the capital city of Brisbane the distribution indicates a positive skew in the distribution likely driven by the higher frequency of clear sky days in this location. In comparison, the distribution for Hobart shows the reverse result.

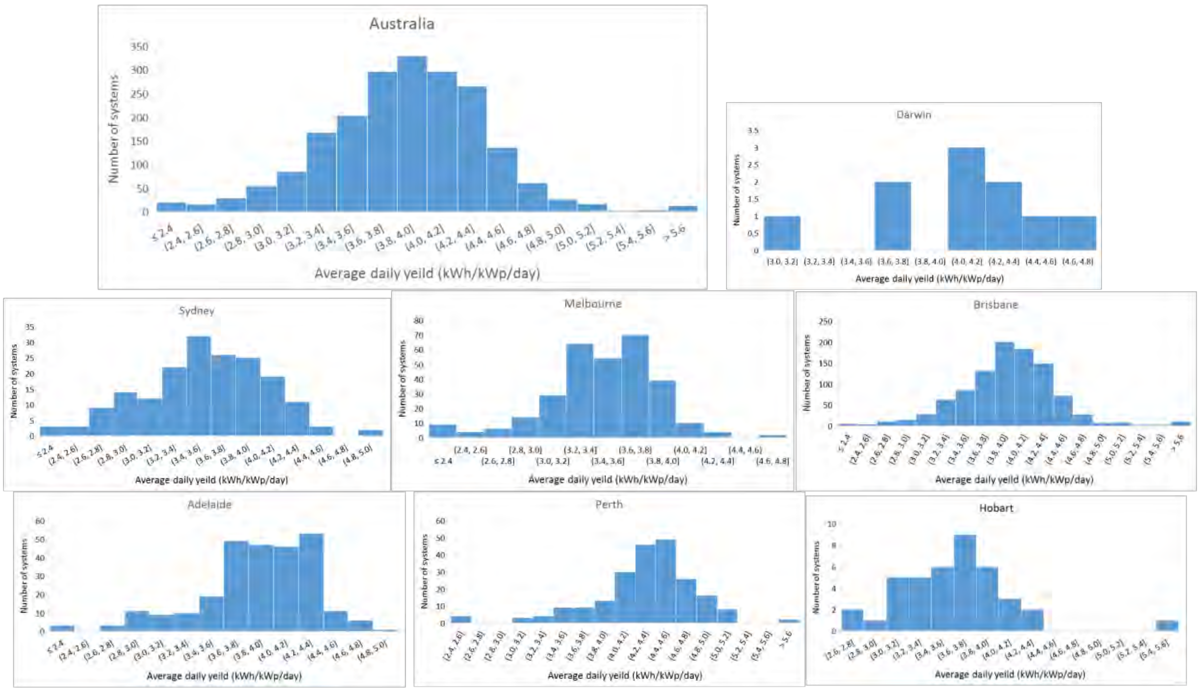

Figure 7. Distribution of average daily energy for Australia and its major cities

3.2. Monthly comparison

The monthly average daily yield (kWh/kWp/day) of the PV systems in each capital city are presented in Figure 8. Results are presented for (1) the median performance from all systems within the PVOutput.org database; (2) the interquartile range of all systems; (3) the median of the ideal subset of the PVOutput.org database; (4) the simulated performance using the RMY weather files; (5) the simulated performance using the TMY weather files, and (6) the Renewables.ninja application (RN), which is based on the 2014 MERRA data. The figures contained within the brackets indicate the sample size i.e. the number of PV systems within the PVOutput.org database for each capital city.

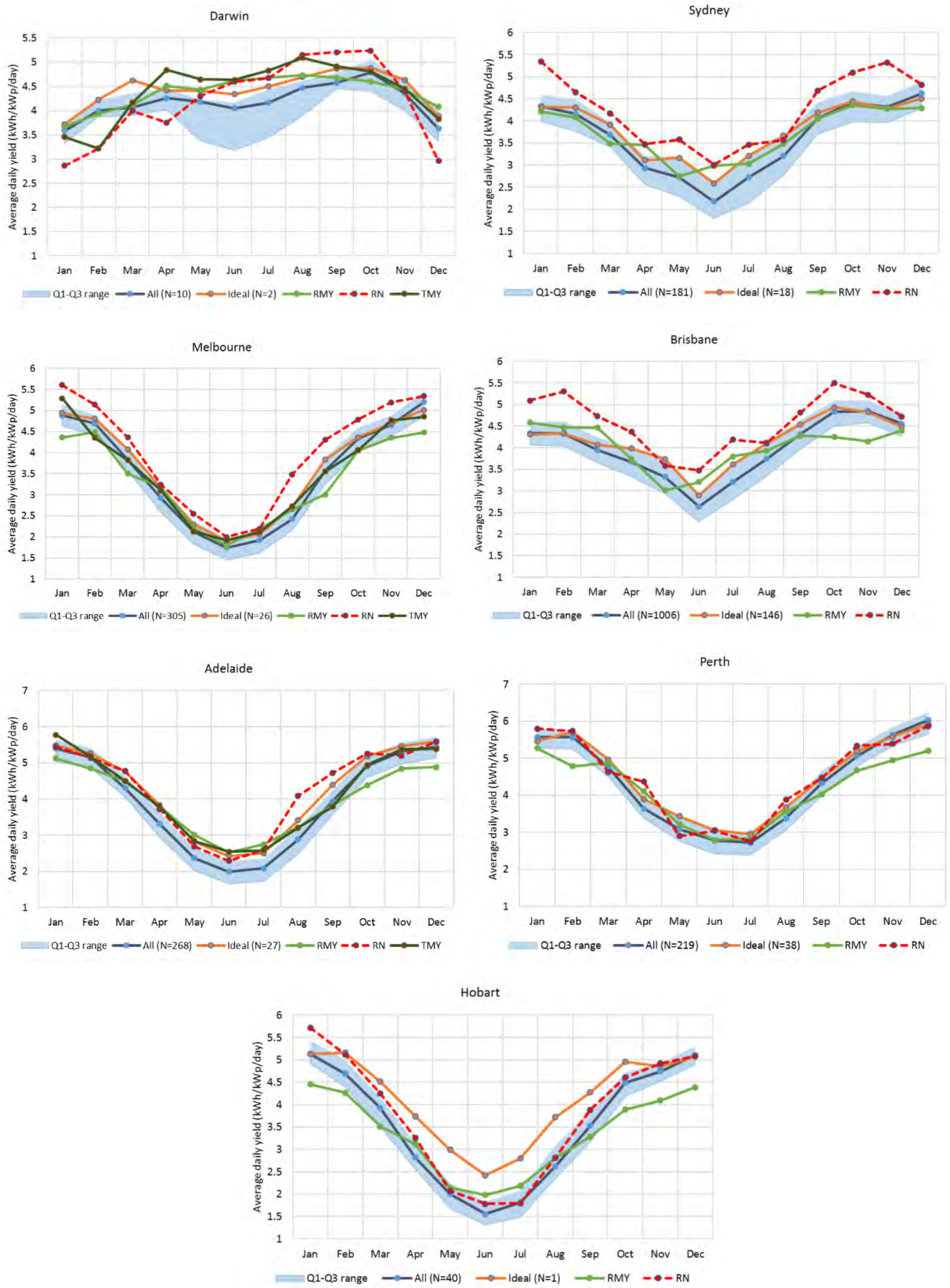

Figure 8. Monthly value of average daily energy for PV systems. Range of 25% to 75% is marked with blue shade.

The results indicate that the averaged measured performance of the PV systems are lower than the modelled estimates of performance. In particular, the estimates from Renewables.ninja appear to overestimate the performance for the majority of the locations analysed. This result was not unexpected given that the input weather data within the Renewables.ninja platform across Australia are based on NASA's MERRA reanalysis data set, which been shown to significantly overestimate the level of irradiance across Australia (Zhang et al., 2016).

The performance estimates generated using the RMY weather files, visually appear to achieve improved correlations with the measured performance. In particularly, the results indicate better agreement with the ideal subset of the PV systems, rather than the full measured dataset, which is as expected, given that an optimally tilted PV system is modelled. Of the locations analysed, Sydney and Darwin have the highest variation in performance estimates particularly in winter months. In Darwin, Melbourne, and Adelaide, where TMY data is available, the performance of modelling using this weather file seems to be better aligned with the observed performance of PVOutput.org systems. Compared to RMY, TMY appears to be specifically better in summer month in Melbourne and Adelaide.

3.3. Annual comparison

The average annual measured daily yields of PV performance are compared against the available estimates of annual PV performance in Figure 9 and Table 2. The results once again suggest that the RN platform generally overestimates the performance (excluding the locations of Darwin and Hobart); whereas the simulated performance with the RMY weather files are more reflective of the observed yields of the ideal subset. Similarly, the results indicate that the performance estimates from the CEC are more correlated with the ideal subset, while the CER estimates are more correlated to measured estimates from the full PVOutput.org dataset. Table 2 also shows the comparison between the estimated and measured values of the ideal subset.

The Mean Bias Deviation (MBD) and Mean Absolute Deviation (MAD) are calculated based on the observed deviation from ideal subset weighted by the sample population for each state. Therefore, due to larger sample in Brisbane, the result is likely to be impacted by the performance in this city. The individual figures are also provided for each city in the table. On average RN overestimates the annual performance on the order of 3%, the CEC and RMY overestimates the performance on the order of 1%, the TMY and the CER underestimate the performance on the order of 2% and 9% respectively when compared to the ideal subset. Although in terms of absolute deviation, TMY with the absolute deviation less than 2% and CER with more than 9% are best and worst estimates respectively.

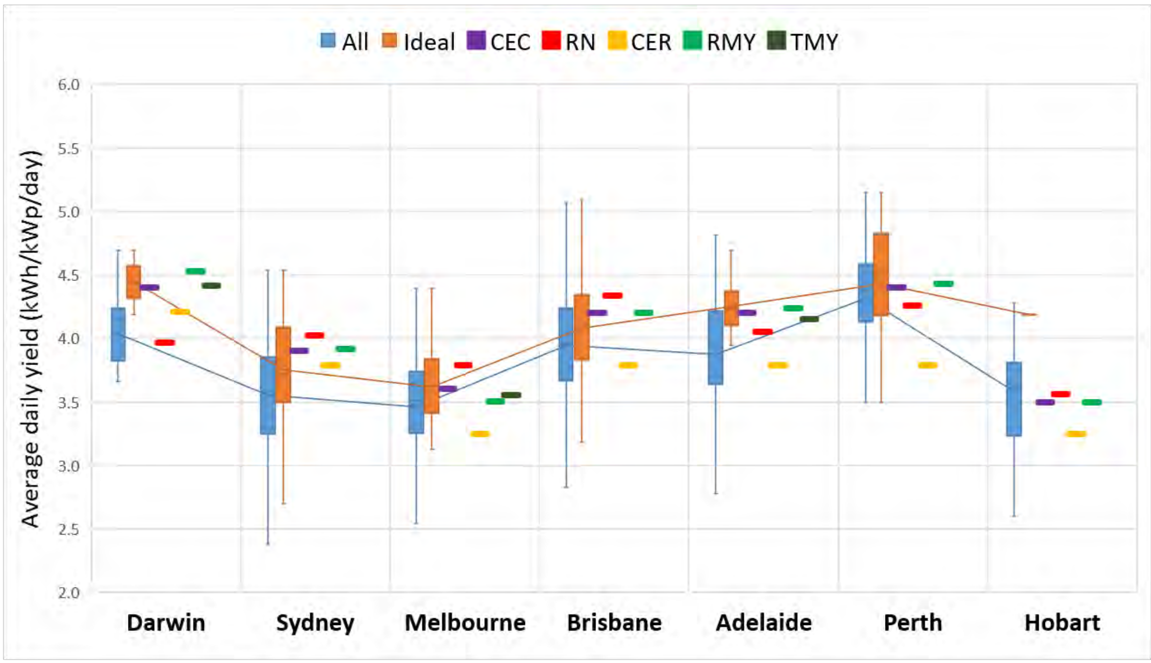

Figure 9. Comparison of observed with estimated performance of PV systems in major citis of Australia

Table 2. Average daily yield and bias from the median of ideal subset

City	Average daily yield (kWh/kWp/day) CEC	RN	CER	RMY	TMY	All	Ideal	N all	N Ideal
Darwin	4.40	3.97	4.21	4.53	4.41	4.15	4.44	10	2 (20%)
Sydney	3.90	4.03	3.79	3.91	-	3.59	3.72	181	18 (10%)
Melbourne	3.60	3.79	3.25	3.50	3.55	3.51	3.62	305	26 (9%)
Brisbane	4.20	4.33	3.79	4.20	-	3.95	4.11	1006	146 (15%)
Adelaide	4.20	4.05	3.79	4.23	4.15	3.94	4.24	268	27 (10%)
Perth	4.40	4.26	3.79	4.43	-	4.38	4.51	219	38 (17%)
Hobart	3.50	3.56	3.25	3.49	-	3.60	4.18	40	1 (3%)
							Sum	2029	258 (13%)

City	Bias from the median of ideal subset CEC	RN	CER	RMY	TMY
Darwin	-0.9%	-10.7%	-5.3%	2.0%	-0.6%
Sydney	4.9%	8.3%	1.8%	5.3%	
Melbourne	-0.6%	4.6%	-10.4%	-3.3%	-1.9%
Brisbane	2.3%	5.5%	-7.8%	2.3%	
Adelaide	-0.9%	-4.4%	-10.7%	-0.1%	-2.0%
Perth	-2.4%	-5.6%	-16.0%	-1.7%	
Hobart	-16.3%	-15.0%	-22.4%	-16.5%	
min	-0.6%	-4.4%	1.8%	-0.1%	-0.6%
max	-16.3%	-15.0%	-22.4%	-16.5%	-2.0%
MBD	1.05%	2.76%	-8.94%	1.05%	-1.91%
MAD	2.20%	5.60%	9.19%	2.36%	1.91%

Conclusion

This paper summarised the distributions of PV system configurations, (tilt, orientation and DC/AC ratio) of the PV system reporting within the PVOutput.org database. In addition, the average performance of all the PV systems as well as an ideal subset of the systems with near optimal system configurations, were calculated and compared to the simulated performance of a typical PV system across the capital cities of Australia. The results revealed that the ideal subset generally generated more power than the performance estimate from the Clean Energy Regulator. The performance estimates from the Clean Energy Council and the RMY weather files were found to more closely aligned with the observed measured data. Finally, the Renewables.ninja estimates, based on NASA's MERRA reanalysis data, were shown to significantly overestimate the PV performance. While some caution is required in extrapolating from PV systems voluntarily reporting to PVOutput.org to the much larger number of distributed PV systems across Australia, the database still provides useful insights into the likely spread of performance across those 1.5 million systems.

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