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Spatio-temporal characterisation of extended low direct normal irradiance events over Australia using satellite derived solar radiation data

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A B S T R A C T

As part of an on-going program to develop technological scenarios for 100 per cent renewable generation within the Australian National Electricity Market (NEM), we explore the degree to which concentrating solar thermal (CST) power might reliably contribute to the generation mix. We analyse satellite-derived hourly direct normal irradiance data provided by the Australian Bureau of Meteorology for Australia over a 13-year period. This large data set covers sufficient time to enable us to characterise the frequency and duration of rare events such as extended periods of heavy cloud cover and hence low solar insolation over regions of Australia. The results highlight those regions with both the highest and lowest occurrence of extended periods of low DNI. They also identify regions whose correlated climatic characteristics would reduce overall CST generation variability if the plants were distributed across them. As such, the findings may assist both project developers, and long-term system planning for reserve generation capacity in future high renewable generation mixes.

1. Introduction

The question of what role solar generation might usefully play in low carbon future electricity industries is receiving growing attention given recent technological progress and cost reductions. At present, the Australian National Electricity Market (NEM) produces around one third of total Australian greenhouse gas emissions, and its predominantly coal-based fuel mix has the highest emissions intensity of any electricity industry in the OECD, and one of the highest in the world [9]. The current climate science suggests that developed countries must aggressively reduce greenhouse gas emissions over the next several decades to a point of near-zero emissions by 2050 in order to avoid global warming of more than 2 °C [12]. If aggressive emissions reduction targets are to be achieved, electricity industries worldwide will need to be transformed over the coming decades to zero carbon electricity sources.

The primary concern for the integration of solar electricity into power systems at high penetration is the variability of solar radiation over various time scales [4]. At short time scales, seconds to minutes, variability creates difficulties for balancing, frequency control, and voltage control. Variability on time scales of hours to a day ahead influences the commitment of other generating units to maintain adequate supply reserves. On even longer time scales of days to weeks and beyond, variability influences decision making for power system dispatch and security issues including production scheduling of hydro, fuel contracting and scheduled generator maintenance [6].

Solar generators have some particular advantages over other variable renewable sources such as wind and wave power. In particular, the solar resource is more evenly and widely distributed than these options. Wind and wave power machines must be built to withstand forces far in excess of what is typically encountered in the field. However, an unexpected lack of solar energy availability outside normal statistical parameters is of concern for power system planning and operation. Photovoltaic (PV) and CST plants have rather different characteristics in this regard. In particular, CST requires (DNI) to achieve effective solar concentration while PV will provide some power as long as there is some sunlight. However, CST also has some inherent energy storage through its heat collection and transfer system, and there are straightforward options to add additional heat storage. Still, if an extended period of

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low irradiance occurs, there must be sufficient generating capacity, energy storage or demand-side response available in the power system to cover demand without significant solar contribution.

As part of previous efforts to characterise the solar radiation resource, it has been common to quantify the annual frequency of runs where solar radiation does not exceed a threshold value. This has typically been done using daily insolation measurements and usually only from a single location [7,2]. In this paper, we use satellite-derived hourly solar irradiance data for Australia over the period 1998–2010 inclusive, to characterise the frequency and duration of runs of extended low DNI at a spatial resolution of 5 km × 5 km across the entire Australian continent. Although the DNI threshold that is required to begin producing electrical power from a CST plant varies with the plant design, a value of 400 W/m^2 has been chosen for this work as broadly representative across a range of CST power plants in existence today [23,8]. The results presented will answer the following questions:

- How long are periods of DNI below 400 W/m^2 across different locations within Australia?
- How frequently do these low DNI events occur, and what are the synoptic situations causing these events?
- The location and time of year we see these events occurring.

The rest of the paper first provides some context for assessing likely CST performance. The method used in this study to assess CST performance is described in Section 3. Section 4 presents the findings and analysis by examining the spatial relationship of these historical periods of extended low DNI, while Section 5 concludes with showing how geographic diversity of concentrating solar power stations can help minimise the impact of these periods.

2. Context for concentrating solar power

The frequency and duration of extended periods of low DNI is of particular interest for modelling the operating performance of CST power plants because these periods will characterise the duration of what is essentially a forced outage. Like the forced outage of a conventional thermal power plant, it is necessary to plan sufficient reserve generating capacity to meet this contingency.

For CST power plants, steam production declines rapidly once direct normal irradiance falls below a critical threshold. Depending on the CST design in use, this threshold can be the level of irradiance required to first overcome power losses in the receiver and then to achieve the minimum turbine load. Fig. 1 shows the non-existent electrical power being produced by a 100 MW parabolic trough plant without storage, as simulated by the System Advisor Model [14], during a three day period of extended low DNI. The reason for this extended low irradiance period was a severe dust

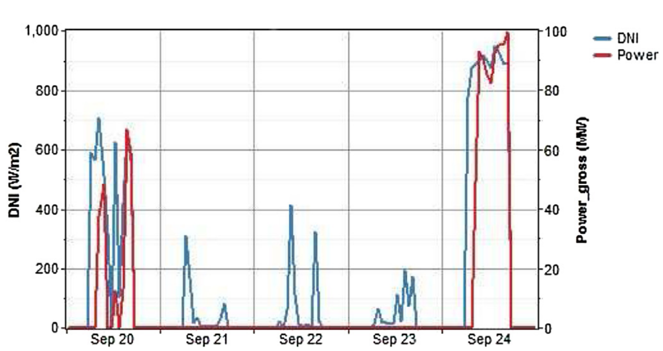

Fig. 1. Simulated 100 MW trough plant in Cobar, New South Wales, September 2009.

storm that developed in central South Australia and travelled across to Eastern Australia in the following three days. In a CST system with thermal storage, a protracted period that is much longer than the number of full-load hours covered by the thermal storage will exhaust all stored energy.

A range of CST plant designs are in operation today. Some, such as the SEGS plants in California, have no added thermal energy storage. Others, such as Andasol-I and Gemasolar in Spain are equipped with between 7.5 and 15 full-load hours of thermal energy storage respectively. This storage enables the plants to continue operating through short periods of low irradiance. However, less common, extreme extended low irradiance events lasting several days cannot be overcome by the thermal energy storage. It is clearly uneconomic to incorporate enough thermal storage to withstand such events.

3. Methodology

We have completed an exhaustive analysis of satellite-derived surface solar irradiance data provided by the Australian Bureau of Meteorology. The data span a 13 year period from 1998 to 2010 inclusive and represent the most comprehensive historical record of solar irradiance for the Australian continent. First, the data set will be described. We then describe how extended periods of low DNI were located in a computationally efficient way.

3.1. Surface solar irradiance data

The National Climate Centre at the Bureau of Meteorology produces two gridded irradiance products: one for global horizontal irradiance and one for DNI. The estimates of global horizontal irradiance are made using satellite images collected from three satellites over the past 13 years: GMS-5 (Japan Meteorological Agency), GOES-9 (U.S. National Oceanic and Atmospheric Administration), and MTSAT-1R (Japan Meteorological Agency). A physical model progressively developed by Refs. [21,22] is in operational use at the Bureau of Meteorology based on earlier work by Refs. [5,10]. Any anomalous grids within the satellite images are discarded.

Feedback adjustments to the model from a limited number of ground station pyranometer readings are used to eliminate bias due to sensor calibration errors, biased estimates of water vapour from the numerical weather prediction model and aerosol effects [22]. It should be noted that positional accuracy can also be a source of error with some images having errors of several kilometres. However, the corrections made, are on average, less than 1%. With these corrections applied, the satellite-derived data is comparable in uncertainty to good quality pyranometers and can be considered sufficiently accurate to use for finding periods of irradiance below a certain threshold.

The DNI data provided by the Bureau of Meteorology is derived from global horizontal irradiance using an adapted version of a diffuse fraction model by Ref. [20]. The data set will be briefly described here, but full details are available in a metadata document that accompanies the data sets [16].

The spatial extent of both data sets includes the entire Australian continent (10.05 °S to 43.95 °S, 112.05 °E to 153.95 °E). The spatial resolution is 0.05° × 0.05°, or approximately 5 km × 5 km.

The temporal resolution of the data is 1 h and the range is shown in Table 1. No data are available from July 1, 2001 to June 30, 2003 due to a long transition from the GMS-5 satellite imagery to GOES-9 imagery. Up to date grids are being produced as images become available. The data includes up to 18 hourly grids per day. Hours 12 to 17 (UTC) are excluded for brevity, as these grids are dark on every day of the year. Additional grids may be missing due to absent or poor quality images.