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Predicting intra-hour variability of solar irradiance using hourly local weather forecasts

Jing Huang *, Robert J. Davy [1]

CSIRO Oceans and Atmosphere Flagship, Yarralumla, ACT, Australia

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ABSTRACT

A linear regression model is proposed that relates outputs of weather model forecasts to the variability of solar irradiance at ground level. In combination with numerical weather prediction modelling, this simple model provides up to day ahead forecast of short-term variability in solar irradiance and its performance tends to decrease with forecast horizon time. A measure of intra-hour solar irradiance variability is constructed, and a regression is formed against many candidate predictors from the weather model. The model is refined using a stepwise algorithm. The method is demonstrated using observations over two summers at Melbourne airport, Australia. The hourly clear sky index and the 500–850 hPa geopotential thickness together form useful predictors for the sub-hourly variability in irradiance ($R^2 = 0.47$ for two hours advance forecasts). The relationship with hourly clear sky index k_t changes at a threshold near $k_t = 0.79$. The variability index was found to be inversely related to the 500–850 hPa geopotential thickness, a relationship that may be due to cloud type variations. Further analysis indicates that improvements in the weather model forecast of hourly clear sky index would substantially increase the ability to infer the intra-hour solar variability, increasing the R^2 value to 0.7 if there was a perfect hourly forecast.

1. Introduction

The variable nature of solar power generation requires forecasting of solar irradiance so that corrective measures can be taken to keep generation and load in balance. Essentially, accurate energy production forecasts for renewable energy systems allow the electricity grid to accommodate more renewable energy, and enhance security of supply (see Chapter 6 in Perez et al., 2016). In Germany, where solar energy penetration can be high, solar energy forecasting has become integral to the operation of the energy supply system (Lorenz et al., 2011, 2012; Wirth et al., 2015). For networks with high penetration of solar photovoltaic (PV) power, sudden changes in solar power generation can cause undesirable variations in voltage, and in theory it is possible for instability to occur when the penetration of solar PV within a small area exceeds 40 per cent (Yan and Saha, 2012; Karimi et al., 2016). This provides the motivation to assess the predictability of short-term solar fluctuations.

Solar energy forecasting has generally taken the form of longer term weather prediction models with time horizons of a few days (e.g. Mathiesen and Kleissl, 2011; Perez et al., 2013), together with statistical models based on satellite cloud motion for time horizons of a few hours (e.g. Hammer et al., 1999; Jang et al., 2016). For very short-term forecasts, it is possible to use ground-based sky imaging where it is available (e.g. Chow et al., 2011; West et al., 2014). A key feature of forecast models with time horizons beyond one hour is that they tend to focus on half hourly or hourly averaged time series. It is difficult to predict solar irradiance using physically based numerical weather prediction (NWP) on the timescale of minutes. This is because dynamic processes in the atmosphere result in phenomena that are essentially stochastic from minute to minute at a given location. In addition, reflections from the sides of cumulus clouds can locally enhance the solar radiation in ways that are inherently unpredictable (Laird and Harshvardhan, 1997). Therefore, a question remains as to how to deal with the sub-hourly fluctuations, which can be considerably large.

Given the unpredictable nature of minute-level fluctuations, the next best approach is to attempt to forecast a measure of the variability in solar irradiance over some interval using empirical methods. Previous research indicates that intra-hour variability of solar irradiance is related to the hourly clear sky index – that

* Corresponding author at: CSIRO Oceans and Atmosphere Flagship, Wilf Crane Crescent, Yarralumla, ACT 2601, Australia.

E-mail address: jing.duke@gmail.com (J. Huang).

[1] Now at: CSIRO Information Management and Technology, Yarralumla, ACT 2601, Australia.

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is, the fraction of clear sky radiation that reaches the ground (Skartveit and Olseth, 1992; Tovar et al., 2001). Also, empirical models for the short-term variability based on hourly satellite-derived irradiance have been developed (Perez et al., 2011). Intuitively, it is to be expected that when the hourly clear sky index is high (very clear skies), or low (overcast skies), the intra-hour variability of the clear sky index will tend to be small. Larger fluctuations in the instantaneous clear sky index are likely to occur under partly cloudy conditions. There is the potential to further refine the understanding of the relationship between the variability of solar irradiance using other properties of the atmosphere, such as temperature, pressure, humidity and cloud properties. If such a relationship is established, and if those atmospheric properties can be forecast using NWP, it is then possible to predict the variability of solar irradiance.

It should be noted that the prediction of solar variability is a fundamentally difficult problem because errors could arise from modelling solar variability using specific predictors as well as forecasting these predictors. Huang et al. (2014) modelled the daily variability of solar irradiance using meteorological variables selected from the ERA-Interim reanalysis as predictors for four sites across Australia and the resultant R^2 is around 0.55, which could serve as a benchmark for the performance of the model to be developed in this paper. Lauret et al. (2016) investigated the relationship between the daily clear sky index and the intraday variability for twenty locations across North America and tropical regions. In order to obtain a simple yet effective and actionable model, the locations were categorised into two groups based on their prevailing cloud formation regimes and corresponding lookup tables were produced to match the daily clear sky index with the mean and the standard deviation of the intraday variability. It was also shown how the lookup tables can be applied to day-ahead forecasts of solar irradiance from the European Centre for Medium-Range Weather Forecasts (ECMWF) model.

Following the philosophy of Lauret et al. (2016) to propose a parsimonious approach, the aim of this work is to form a statistical regression model for the intra-hour solar irradiance variability using hourly modelled meteorological variables as predictors. Firstly, a measure of the intra-hour variability in solar clear sky index is derived. This is applied to the global horizontal irradiance as measured at ground level at Melbourne airport, Australia, and some of the properties of this quantity are described. Next, a regression model for this quantity is built using hourly quantities from the Bureau of Meteorology's operational forecast model as predictors. The predictors retained in the model provide some insight into the process of solar irradiance variability. Also, this model can potentially provide a few hours to day ahead warning of short-term variability of solar irradiance.

2. Data description

Solar radiation has been measured at one-minute time intervals at Melbourne airport, Australia since 1999 (Lat: −37.67, Lon: 144.83). The thermopile pyranometer instruments (Kipp & Zonen CM11) are regularly maintained and the measurements undergo stringent quality control. Measurements consist of global horizontal, direct beam and diffuse irradiance. Measurements are taken each second and the data is aggregated at the minute level. The station also has instruments which measure wind speed, wind direction, air temperature, dewpoint temperature and humidity.

Melbourne is a coastal city in southeastern Australia characterised by its variable weather conditions. The temperature gradient between the cool southern ocean and the hot inland can lead to the formation of strong cold fronts in summer, which in turn are responsible for various cloud types and heavy rains. Common cloud types include low-level cumulus, mid-level altocumulus and high-level cirrus (see e.g. Gregory et al., 2012). As such, it is not an ideal location for solar thermal plants. However, it is Australia's second-largest city, with significant uptake of rooftop solar PV in recent times, providing sufficient motivation to study this location. Because solar PV is the prime concern, only the global horizontal irradiance component is used in the present study.

The Australian Community Climate and Earth-System Simulator (ACCESS) model is an operational forecast model run over a number of spatial domains and temporal resolutions by the Australian Bureau of Meteorology. For the ACCESS model being used, its atmospheric component is version 7.6 of the Unified Model (UM) by the United Kingdom Meteorological Office (UKMO), which uses 70 vertical atmospheric levels reaching about 40 km above the mean sea level (National Meteorological and Oceanographic Centre, 2013a). Its cloud scheme and radiation (both long-wave and short-wave) scheme are based on Smith (1990) and Edwards and Slingo (1996), respectively. The ACCESS city model has 4 km spatial resolution with hourly forecast output, which is nested inside the coarser regional ACCESS model. The city model's initial conditions are provided by dump files of the regional model, which in turn uses four-dimensional variational data assimilation (4DVAR) over a 6-h window to produce global analyses (National Meteorological and Oceanographic Centre, 2013b). As such, the city model is run four times a day at Hour 00, 06, 12, and 18 UTC, respectively. A number of quantities from the model were selected as candidate predictors for the solar irradiance variability during the daytime hours. These are shown in Table 1. They include many of the quantities which are related to the exchange of energy at the earth's surface, as well as a number of upper air (pressure level) quantities. The quantities were taken from the model grid point that is nearest to Melbourne airport. In addition to these variables, the clear sky irradiance was derived for the location at Melbourne airport using the NREL Bird clear sky radiation model (Bird and Hulstrom, 1981).

Since the ACCESS city model in its current form has been running since October 2013, and there are data missing from end 2013 to early 2014, this study is restricted to about two years. Of these, the summer months are used since that is when solar irradiance is highest, combined with a potential for large rapid fluctuations. To be precise, the period under study is the union of December 2014–February 2015 and December 2015–February 2016. Note that there is no major upgrade to the ACCESS city model during this period.

3. A measure of variability in solar irradiance

Previous authors developed a wavelet-based measure of solar power variability and used it to analyse the frequency and duration of fluctuation events (e.g. Woyte et al., 2007; Lave et al., 2013). In this work, it is required to produce a single measure of intra-hourly variability in one-minute irradiance, so a wavelet approach is not needed. The measure of intra-hour solar irradiance variability was developed as follows. Firstly, the clear sky index was calculated by taking the ratio of the one-minute measured global solar irradiance to the clear sky global irradiance. Then the hourly standard deviation of the clear sky index was calculated, which is similar to the calculation of solar variability used in Hoff and Perez (2010) and Lave and Kleissl (2010). Since the distribution of this standard deviation is heavily skewed towards zero, a square root transform was applied ($y = \sqrt{\sigma(k_t^m)}$ where y is the hourly solar variability index, k_t^m is the minute-level clear sky index and σ represents the operation of standard deviation). In doing so, the distribution of the solar variability index becomes more uniform so that asymptotic properties of linear regression can be applied more readily.