Solar Energy 137 (2016) 46–54

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

High resolution characterisation of solar variability for two sites in Eastern Canada ☆

Alexandre Gagné *, Dave Turcotte, Naveen Goswamy, Yves Poissant

CanmetENERGY, Natural Resources Canada, 1615 Lionel-Boulet, Varennes, QC J3X 1S6, Canada

ARTICLE INFO

Article history:
Received 8 April 2016
Received in revised form 19 July 2016
Accepted 23 July 2016

Keywords:
Solar variability
Variability Index
Irradiance
Photovoltaics

ABSTRACT

The characterisation of solar resource variability is important to understanding the impacts of PV grid-integration. A total of 41 monitoring units were distributed at two sites in Eastern Canada, collecting irradiance data with a recording period of 10 ms. The solar variability was quantified using the Variability Index and distribution using the daily Clear-Sky Index, allowing grouping of the days measured at each site into four discrete categories. The Variability Score was also computed to facilitate comparisons with other similarly characterised sites. The effect of recording period on these metrics suggests that using a recording period longer than 400 ms would lead to underestimating variability in many cases. The dependence of observed variability on geographic dispersion is also examined, demonstrating a relationship between cloud speed, footprint area, and the averaged Variability Index.

1. Introduction

The output power of PV plants depends on the incident solar irradiance which can fluctuate as clouds pass overhead. As PV generation capacity is predicted to increase steadily over the coming years, concerns have been raised regarding impacts to the grid due to short-timescale changes in output (PVPS-T10, 2009; Passey et al., 2011). Quantifying and characterising the solar variability at a given site can help inform decisions regarding site specificity and implications for grid impacts. The present article aims to characterise the solar variability measured at two sites in Eastern Canada using networks of ground-level high frequency irradiance sensors.

Similar characterisations of solar variability have been previously conducted elsewhere. Irradiance variability from three sites in the United-States were compared in Stein et al. (2012), where the irradiance was characterised on a daily basis. The Variability Index was introduced as a metric to quantify the fluctuations at a 1 min timescale allowing comparisons between sites and days. The Clear-Sky Index was also used in combination with the Variability Index to group the days into categories.

In Lave et al. (2015), the Variability Score is introduced as another metric to quantify the variability based on the cumulative distribution of ramp rates. The Global Horizontal Irradiance variability was characterised at recording periods ranging from 1 s to 30 s. Also, the Variability Score was shown to be nearly proportional with the Variability Index.

The present work employs the Variablity Index, Clear-Sky Index, and Variability Score, and uses them to compare the two Eastern Canadian sites of Alderville and Varennes with results from the academic record. Temporal and spatial dispersion of variability is examined using a base timescale of 10 ms and spatial resolution of up to 10.3 sensors/ha (1 ha = 10,000 m^2). As shall be demonstrated for the two sites being studied, changing the temporal or spatial resolution can lead to modifying the results of the metrics used to characterise them.

The experimental set-up used to record irradiance datasets is described in Section 2. After some definitions about the metrics used in this article, the variability characterisation is presented for both sites in Section 3. A brief analysis of spatial and temporal resolution on observed variability follows in Section 4.

2. Experimental set-up

The studied datasets were collected using sensor networks composed of a total of 41 units that measured the solar irradiance at two sites in Eastern Canada. The first system is located in Varennes, Québec, and the second in Alderville, Ontario. The latter is co-located within a 1 MW sub-array of the 5 MW Alderville First Nations Solar Farm (Alderville First Nation, 2013).

☆ © Her Majesty the Queen in Right of Canada, as represented by the Minister of Natural Resources, 2016.

* Corresponding author.

E-mail address: alexandre.gagne@canada.ca (A. Gagné).

http://dx.doi.org/10.1016/j.solener.2016.07.042

2.1. Monitoring units

The irradiance sensors are LI-COR LI-200S photodiode-type pyranometers installed on wirelessly-communicating and autonomously-powered remote units. Each unit has two pyranometers: the first for global horizontal irradiance, and the second for the in-plane irradiance. The sensors allow measuring solar variability at ground level over a given surface and are shown in Fig. 1.

The monitoring units were designed for high-speed acquisition, tolerance to low temperature, and low cost. Each unit takes measurements every millisecond, averages them over a period of 10 ms, and saves the data when it changes by more than 5 W/m^2 since the last saved value. In addition, data is saved at 1 min intervals. This strategy is used in order to reduce the amount of recorded data (empirically determined to be approximately 99.6% less data than if saving data each 10 ms continuously), and also serves to eliminate unwanted noise in the signal. Noise inherited from the monitoring system has an amplitude of approximately 1 W/m^2. Such fluctuations are not recorded, however, due to the 5 W/m^2 saving threshold.

The units are synchronised using a Global Positioning System (GPS) system to ensure that the unit-to-unit skew time is limited to 1 ms. The typical calibration uncertainty of these silicon-diode pyranometers is about 5% (LI-COR Inc., 2015), which is sufficient given that the objective is to capture the relative irradiance fluctuations and not so much to acquire an accurate measurement of the irradiance itself. In addition, the response time of 10 µs is sufficiently low to perform adequate measurements at high frequency. Note that higher accuracy thermopile pyranometers (such as the Eppley SPP) would not have been acceptable for high frequency measurements because of their slower response time, which is approximately 5 s (The Eppley Laboratory, Inc., 2015).

2.2. Studied sites

The locations of the monitoring units at each site are presented in Fig. 2. The irradiance time-series have been recorded since November 2013 in Varennes, and since December 2014 in Alderville. The focus for this study will be on the data collected in 2015, when both sites were operational.

The two sites are about 400 km apart and have similar meteorological conditions, as shown in Table 1. The Köppen-Geiger climate classification for both sites is *Dfb* (i.e., humid continental with mild to cool summers), common to the central and northeastern portions of North America, as well as locations in Europe and Asia (Kottek et al., 2006).

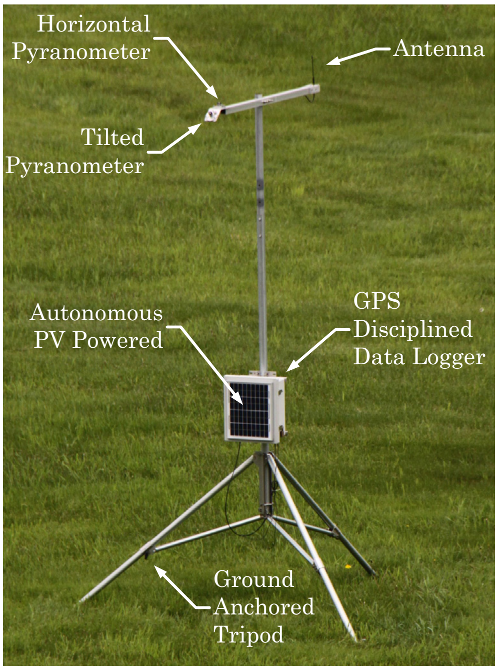

Fig. 1. Monitoring unit on a tripod showing its main components.

3. Variability characterisation

To characterise variability based on time-series data, two main metrics have been used: the Variability Index and the Variability Score. In addition, the daily Clear-Sky Index is used to quantify the cloud-free sky fraction for the day. The following sections will present these metrics and indices in greater detail and show how they can be used for categorising days and comparing sites.

3.1. Variability Index

Introduced by Stein et al. (2012), the Variability Index represents the ratio of irradiance time-series curve length over the clear-sky irradiance curve length on a daily basis. Eq. (1) gives the Variability Index *VI*, where GHI_k is the Global Horizontal Irradiance (in W/m^2) taken at time t_k (in min). CSI_k represents the clear-sky Global Horizontal Irradiance (in W/m^2), and n the number of data points collected during the day from the start of morning civil twilight to the end of the evening civil twilight. The clear-sky model used is derived from Ineichen and Perez (2002). The *VI* has no physical interpretation; it is intended for comparison between days and sites. For a given day, more irradiance fluctuations will result in a higher Variability Index. A clear-sky day should have a Variability Index close to unity.

$$VI = \frac{\sum_{k=1}^{n-1}\sqrt{(GHI_{k+1}-GHI_k)^2+(t_{k+1}-t_k)^2}}{\sum_{k=1}^{n-1}\sqrt{(CSI_{k+1}-CSI_k)^2+(t_{k+1}-t_k)^2}} \tag{1}$$

3.2. Daily Clear-Sky Index

The daily Clear-Sky Index K_T is a metric used to quantify the amount of available solar radiation that reaches the ground. Taken from Stein et al. (2012), it represents the ratio of the area under the Global Horizontal Irradiance curve divided by the area under the clear-sky Global Horizontal Irradiance curve. It is computed using Eq. (2), where the trapezoidal rule of integration has been applied to approximate the total irradiation H_{GHI} and H_{CSI}. A clear-sky day has a value of K_T close to 1. The more a given day is cloudy, the lower its daily Clear-Sky Index will be.

$$K_T = \frac{H_{GHI}}{H_{CSI}} = \frac{\sum_{k=1}^{n-1}\left(\frac{GHI_{k+1}+GHI_k}{2}(t_{k+1}-t_k)\right)}{\sum_{k=1}^{n-1}\left(\frac{CSI_{k+1}+CSI_k}{2}(t_{k+1}-t_k)\right)} \tag{2}$$

3.3. Variability distribution

A scatter plot of K_T with *VI* can be used to describe the distribution of cloud-covered days. Days with similar K_T-*VI* relationships present similar cloud cover conditions. The resulting graph is referred to as an "arrow head" plot in Stein et al. (2012), due to its shape. To compare results adequately with Stein et al. (2012), the irradiance time-series from this study were averaged and downsampled to 1 min.

The variability distribution for Varennes and Alderville are presented in Fig. 3 where each of the 365 points represents a day in