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Increasing the temporal resolution of direct normal solar irradiance series in different climatic zones

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Abstract

A precise knowledge of the high-frequency variation of the incoming Direct Normal solar Irradiance (DNI) is required for an accurate design and operation of Concentrating Solar Thermal Power (CSTP) plants. The time resolution of the numerical weather prediction models or satellite derived solar irradiance data are typically limited to 1-h (at best 15-min). Unfortunately, this resolution is not sufficient in the design and performance of a CSTP plant, which shows a nonlinear response to DNI governed by various thermal inertias due to their complex response characteristics. In this study, a new methodology has been developed to increase the temporal resolution of DNI series from 1-h to 1-min. This methodology is based upon the nondimensionalization of the daily DNI curve by the clear-sky envelope approach and uses the solar radiation data obtained in the one-year measurement campaign to characterize the DNI high-frequency dynamics at a given site. The evaluation of the method with 2 years of measured data in different climatic zones has resulted in KSI(%) (Kolmogorov–Smirnov test Integral parameter) and normalized root mean square deviation values below 23% and 22% respectively for each month, with negligible bias. Indicators of overall performance show an excellent agreement between measured and modeled 1-min DNI data for each month: average values for Nash–Sutcliffe efficiency, Willmott index of agreement and Legates coefficient of efficiency are found to be 0.90, 0.97 and 1.0, respectively.

Keywords: Direct normal irradiance; Synthetic generation; Enveloping scheme; High-frequency

1. Introduction

Direct Normal solar Irradiance (DNI) exhibits a great variability at high-frequency due to the dynamic effects of passing clouds (Cebecauer et al., 2011; Grantham et al., 2013). This variability is an issue of high relevance for the design and performance analysis of a Concentrating Solar Thermal Power (CSTP) plant, which shows a nonlinear response to DNI governed by various thermal inertias due to their complex response characteristics (Beyer et al., 2010). DNI series of sub-hourly frequency resolution permit an accurate modeling and analysis of transient processes in some CSTP technologies. For example, parabolic troughs with direct steam generation could be particularly sensitive to the cloud transients (Eck and Hirsch, 2007; Montes et al., 2009), and, therefore, better analyzed using DNI series with frequency resolutions much lower than 1-h (Meyer, 2010).

Historical solar resource data are frequently available at hourly scale (Fernández-Peruchena et al., 2010, 2009). As the statistical properties of instantaneous solar irradiance series differ considerably from hourly or daily series

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(Aguiar and Collares-Pereira, 1992; Bartoli, 1983; Fernández-Peruchena and Bernardos,, 2015; Liu and Jordan, 1960; Suehrcke and McCormick, 1988), new DNI products are currently being developed. Especially for Europe, Africa and the Middle East, the Meteosat Second Generation satellite is now able to provide the necessary inputs to radiative models at 15-min time intervals. Unfortunately, this resolution is not sufficient when analyzing a CSTP system (Beyer et al., 2010). Moreover, recent results indicate that satellite derived data does not accurately reproduce the frequency distribution of DNI (Hammer et al., 2009). In parallel, several models have been proposed in literature to synthetically generate high-frequency DNI series of similar statistical characteristics to the typically measured series. Skartveit and Olseth (1992) proposed modeling the probability distribution and lag-1 autocorrelation of short term irradiance data. Beyer et al. (2010) developed a method to generate high-frequency DNI series from their cumulative distributions functions and time series characteristics. Polo et al. (2011) proposed a method for generating synthetic irradiance at 10-min intervals from the hourly mean values by means of adding a random fluctuation to the hourly interpolated values. Wey et al. (2012) proposed a fusion method to combine a one-year short time series of ground-based 10-min irradiation data and the long-term satellite-based series to create calibrated, sub-hourly and long-term based TMY irradiation data. Grantham et al. (2013) presented a method where 5-min DNI series from one location were used to develop synthetic variations in the hourly data from another location. Finally, Fernández-Peruchena et al. (2014) proposed a method for generating 1-min DNI data from daily DNI values.

This paper presents a methodology for generating synthetic DNI time series at 1-min temporal resolution from 1-h DNI series. This methodology is based upon the nondimensionalization of the daily DNI curve by the clear-sky envelope approach (Gómez Camacho and Blanco, 1990) and uses the solar radiation data obtained in the one-year measurement campaign to characterize the DNI high-frequency dynamics at the given site. From this characterization, it is possible to generate compatible DNI series at a temporal frequency up to the measured values compatible with low-frequency (from sub hourly to daily temporal resolution) DNI series at the site. The methodology proposed is validated by comparing the statistical characteristics of the synthetically generated DNI series to those of the ground measured ones in four locations with different climatic conditions.

2. Procedure and data

2.1. Experimental procedure

The methodology for increasing the temporal resolution of solar DNI series takes advantage of a recently developed technique for the nondimensionalization of measured high-frequency daily solar DNI curves (Fernández-Peruchena et al., 2014). This nondimensionalization technique makes the transformation of high-frequency measured daily solar DNI curves possible for the generation of new daily curves of high-frequency solar DNI data.

The steps followed in the construction of the synthetic series are detailed below:

Step 1. Calculation of the clear-sky DNI envelopes of the location. This is calculated by appropriately adjusting the two parameters (E_0, κ) of the clear-sky ASHRAE exponential model (MacPhee, 1972) so that the curve defined by the model is the tightest possible upper boundary of the cloudless measured DNI values for the given day. The ASHRAE exponential model is defined by the following expression:

$$DNI = E_0 \cdot \exp\left(\frac{-\kappa}{\sin(\alpha)}\right) \qquad (1)$$

where α is the solar elevation, E_0 the apparent extra-terrestrial irradiance, and κ the overall extinction parameter. ASHRAE model has been selected due to its simplicity and flexibility. Its mathematical formulation allows a simple and robust analysis, and the combination of its parameters facilitates the generation of a remarkable variety of daily clear-sky DNI envelopes (Fig. 1).

Therefore, the use of the ASHRAE model in this methodology does not intend to characterize a unique set of parameters (E_0, κ) for a given location, but the generation of any enveloping DNI curve in the location through the combination of those parameters.

Step 2. Calculation of the dimensionless DNI curves of the location. The nondimensionalization of measured high-frequency daily DNI curves is based on the nondimensionalization of the temporal scale by dividing the elapsed Universal Time (UT) since sunrise by day length and on the nondimensionalization of the solar DNI scale by dividing each actual solar DNI value by the corresponding DNI value of the clear-sky DNI envelope curve. As shown in Fig. 2, this nondimensionalization scheme transform every daily high-frequency DNI curve into a dimensionless curve where the dimensionless time scale goes from 0 to 1 and the dimensionless DNI scale goes also from 0 to 1.

Step 3. Generation of high-frequency DNI series on a given day. Since once they are transformed, all dimensionless daily DNI curves in a year have the same horizontal and vertical scales, and any day may be replaced by any other day. Regarding time, there are 365 different possibilities, since the duration of each day along the year is fixed for a given location. However, regarding the selection of clear-sky DNI envelopes, the possibilities are countless: for every day of the year the values of the pair (E_0, κ) are not deterministically fixed. To