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Methodology to synthetically downscale DNI time series from 1-h to 1-min temporal resolution with geographic flexibility

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ABSTRACT

In this paper, we present two methods for the synthetic generation of 1-min Direct Normal solar Irradiance (DNI) data from hourly means that can be applied globally without any local adaptation, which are based in the modelling of the stochastic component of DNI, and in the normalization of the daily profiles. The similitude between measured and generated DNI distributions has been evaluated through the Kolmogorov-Smirnov test Integral (KSI), and its performance on the thermal power produced by a parabolic trough (PT) plant has been assessed using the daily normalized root mean square deviations (NRMSD) with respect to site measurements. The generation methods provide, for an annual 1-min synthetic data set, KSI values of ~3.3 W/m^2 and ~12.9 W/m^2 (depending on the generation method used), and daily NRMSD of ~0.9% and ~3.4%, respectively. Sites selected for validating these methods are located at different climates and latitudes, suggesting their global applicability.

1. Introduction

Developers and operators of concentrated solar thermal (CST) plants require Direct Normal Irradiance (DNI) data with high resolution for detailed performance simulations (Gall et al., 2010). However, high resolution DNI data are often limited in duration and location, and typically historical solar resource data are available at hourly scale (Fernandez-Peruchena et al., 2010). DNI series can be calculated at 15-min time intervals from currently operating satellites, but even this resolution may not be sufficient when evaluating a CST system performance (Beyer et al., 2010). Moreover, satellite-derived long time historic DNI series often do not maintain the frequency distribution of the ground measured data (Hammer et al., 2009).

There have been attempts to generate high resolution solar irradiance data. An early example is given by Skartveit and Olseth (1992) where the probability distribution of short-term irradiance data, normalized by transformation to clear sky index data together with the knowledge of the autocorrelation coefficient of these sets form the bases for a scheme of data synthetization. Beyer et al. (2010) generated high frequency DNI series from their cumulative distribution functions. Morf (2013) generated sequences of instantaneous Global Horizontal solar Irradiance (GHI) values dividing the solar radiation into a deterministic and a stochastic component. The deterministic component was related to the Ångström–Prescott regression, while the stochastic component was derived from the cloud cover index. Polo et al. (2011) developed a model to generate synthetic 10-min DNI and GHI data by adding the deterministic contribution of the hourly mean values to the stochastic fluctuation from the mean. This model was improved by Larrañeta et al. (2015) for a more accurate DNI generation, and modified by Grantham et al. (2017) for generating matched pairs of 5-min GHI and DNI values from hourly means. Grantham et al. (2013) previously proposed the use of bootstrapping techniques for generating synthetic 5-min DNI series from hourly means. Ngoko et al. (2014) presented a second-order Markov Transition Matrix (MTM) to generate 1-min synthetic GHI from the daily clearness index. Bright et al. (2015) also used MTM to stochastically determine cloud cover to subsequently generate 1-min DNI, GHI and diffuse irradiance. However, the model requires other meteorological information such as cloud base height, wind speed or sea level pressure. The model was improved including the spatial dimension variation in the synthetic generation without the need of input irradiance data (Bright et al., 2017). Fernández-Peruchena proposed the generation of 1-min resolution DNI series from the daily (Fernández-Peruchena et al., 2014), 3-h (Fernández-Peruchena et al., 2017) and hourly (Fernández-Peruchena et al., 2015) DNI means. The method is based on the generation of a dimensionless high frequency database of daily DNI curves. The same concept was used by Fernández-Peruchena

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Table 1
Location selected for the training the methods.

	Latitude (°N)	Longitude (°W)	Altitude (m)	Climate	Period
Seville	37.4	6.0	12	Mediterranean	2002–2015

Table 2
Locations selected for validating the methods.

	Latitude	Longitude	Altitude (m)	Climate	Period	Radiometric Network
Almería	37.1°N	2.3°E	500	Semi-arid	2013	CIEMAT-DLR
Pretoria	−25.7°N	28.2°W	1410	Sub-Tropical	2016	SAURAN
Payerne	46.8°N	6.9°W	491	Continental	2014	BSRN

data in the 1-min.

and Gastón, 2016 to generate synthetic 1-min GHI from hourly means.

It is worth highlighting that these earlier procedures require high-frequency ground measurements for characterizing the location under study for generating high-frequency solar irradiance series. The models presented in this work use measurements from one location to characterize the cloud transients and generate synthetic 1-min DNI data in any location where hourly DNI data is available, without any local adaptation. Also, they require different degrees of accuracy in the knowledge of local hourly DNI data, thereby facilitating their application:

- The SA (Stochastic Adaptation) method requires high-quality site hourly DNI series and consists on dividing the solar radiation into a deterministic and stochastic component (i.e., the contribution from the hourly mean and stochastic the fluctuation from the mean depending on the sky condition). This method is based on Polo et al. (2011) and Larrañeta et al. (2015).
- The ND (Non-Dimensional) method only requires the site intra-daily characterization of DNI variability and distribution, and thus does not require exact hour-to-hour local DNI series. This method is based on the normalization of high frequency daily DNI profiles by a clear-sky envelope approach, and is based on Fernández-Peruchena et al. (2015).

The models have been applied in three locations with different climatic conditions. The paper is presented as follows: Section 2 presents the measured database used in the work; Section 3 describes the methodologies proposed for generating 1-min DNI data from hourly means. Section 4 shows the results found and in Section 5 discussion, conclusions and future work are drawn.

2. Meteorological database

In this work, an extensive database is used for training the methods proposed (Table 1). This database is composed of 1-min averages values of DNI recorded during 14 consecutive years (2002–2015) for the location of Seville (Spain). The measurements were taken with a sampling and storage frequency of 0.2 Hz. A first class Eppley NIP pyrheliometer mounted on a sun tracker Kipp & Zonen 2AP measured the DNI. The devices are located at the meteorological station of the Group of Thermodynamics and Renewable Energy of the University of Seville and have been periodically calibrated, at least once every two years (Moreno-Tejera et al., 2016).

In addition, the models have been validated in three other locations belonging to different climates and latitudes (Table 2). We have selected these locations as a compromise solution between climate representativeness and availability of high quality 1-min DNI measured data. DNI data of Payerne (Vuilleumier et al., 2014) measured with a first class pyrheliometer Kipp & Zonen CHP1 pyrheliometer, and have been provided by the Baseline Surface Radiation Network (BSRN) (Ohmura et al., 1998); DNI data from Pretoria has been accessed from the Southern African Universities Radiometric Network (SAURAN) (Brooks et al., 2015), and have been measured with a Kipp & Zonen CHP1 pyrheliometer; DNI data from Almeria belong to CIEMAT and DLR meteorological station at the Plataforma Solar de Almeria (PSA), and have been measured with a Kipp & Zonen CHP1 pyrheliometer. Data used in this work have been subjected to quality-control procedures following the BSRN recommendations (McArthur, 2004).

3. Methodology

In the next sections, we briefly describe the two methodologies implemented for the synthetic generation of high frequency synthetic DNI data from hourly means.

3.1. Stochastic adaptation (SA) model

The most recent scheme of this model is based on a methodology proposed by Larrañeta et al. (2015) which in turn improved the model proposed by Polo et al. (2011). In this model, the DNI is divided into a deterministic and stochastic component:

– The deterministic component is generated by the cubic interpolation of the hourly means calculated every 4 h in the high-resolution time scale (Ibn_{i3}^{i}).
– The stochastic component (Ibn_{stoc}^{i}) is dynamically reproduced by using random numbers from the beta distribution curve whose characteristic parameters were fitted for each sky condition, introducing a random sign for the fluctuation.

The synthetic data for the instant i (Ibn_{synth}^{i}) is calculated as the combination of the deterministic plus the stochastic component (Eq. (1)):

$$Ibn_{synth}^{i} = Ibn_{i3}^{i} + Ibn_{stoc}^{i} \tag{1}$$

We aim to generate synthetic data at 1-min resolution for facilitating detailed modelling of Concentrating Solar Power (CSP) performance (Ramirez et al., 2017), even if the original model was designed to generate synthetic 10-min data. This decision implies a new DNI fluctuation characterization and the reassessment of the dynamics of the stochastic component reproduction.

3.1.1. Fluctuations in clear sky equivalent DNI hours

In the previous model (Larrañeta et al., 2015), the decision of whether or not to include fluctuations in the synthetic data was led by a daily index. In many cases, we added fluctuations in clear sky periods because a daily index may not be appropriate to characterize the intra-daily performance of the solar radiation. To solve this weakness, we