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High frequency generation of coupled GHI and DNI based on clustered dynamic paths

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Abstract

This Brief Note presents a general and efficient clustered-based methodology for the generation of high-frequency coupled global horizontal irradiance (GHI) and direct normal irradiance (DNI) series, based on the envelope clear sky and Dynamic Paths concepts. The procedure for generating 1-min synthetic irradiance data assumes that the effect of passing clouds on the fluctuations of both GHI and DNI can be dynamically reproduced using local variability patterns characterized by a 1-year ground measurements. This work presents for the first time synthetically generated 1-min GHI and DNI coupled datasets (156 months, from 1999 to 2011) generated from their corresponding low frequency series and local solar irradiance dynamics. The statistical parameters used for compare the measured and generated series perform well: mean absolute deviation is negligible, with averaged values of ~0.3% and ~0.2% for GHI and DNI, respectively. The KSI (%) values for DNI and GHI are lower than 100% in average. KSI (%) values of GHI series (in the range of 51.5-70.1% for averaged daily KSI (%) values at each month) are lower than the respective KSI (%) values of the DNI series (in the range of 75.0-110.8%). Finally, the generated 1-min solar irradiance series has the same autocorrelative structure as the observed, according to the similitude of their Ramp Rates.

Keywords: Dynamic Path; High-frequency; Variability; Synthetic generation

1. Introduction

Concentrating solar thermal power technologies show a nonlinear response to Direct Normal solar Irradiance (DNI) governed by various thermal inertias owing to their complex response characteristics. The accurate modeling and analysis of transient processes in these technologies requires the availability of high-frequency (1-min) DNI series. Similarly, large irradiance fluctuations can cause ramps in solar energy power generation outputs, these power fluctuations can result in electrical problems and supply/demand issues such as over voltages in PV laden distribution grids (Widén et al. 2015). Notwithstanding, the time resolution of modeled solar irradiance datasets are typically 15-min (or lower frequencies). Unfortunately, the use of low frequency solar irradiance series hinders the management and integration of power output from solar plants, and consequently new models are emerging trying to improve the time resolution of modeled gridded datasets (Bright et al. 2015, Larrañeta et al., 2015; Munkhammar et al. 2016, Nielsen et al. 2016).

Prevailing winds and cloud motion patterns can affect both spatial and temporal variability throughout distances from few kilometers. In particular, solar irradiance correlations decrease with increasing sites spacing and higher time resolution data integration periods, and consequently their short-term fluctuations (due to passing clouds or cloud fronts) are expected to be smoothed when the whole plant layout is taken into account.

This paper presents an improvement of the methodology for increasing the temporal resolution of solar irradiance series for any location based on the envelope clear sky and local measured solar irradiance (Gómez Camacho et al. 1990; Wey et al. 2012), previously presented separately for GHI (Fernández-Peruchena et al. 2016) and DNI (Fernández-Peruchena et al. 2015). This improvement consists in the coupled generation of high-frequency GHI and DNI series, as well as the categorization of GHI and DNI Dynamic Paths into clusters for an efficient and consistent generation.

2. Data and Methodology

The methodology presented requires local ground measurements (commonly required in solar resource assessments for energy projects) as it has been proven that the high-frequency (1-min) solar irradiance distributions are site-dependent (Fernández-Peruchena et al. 2015), even if hourly distributions show universal properties (Collares-Pereira et al. 1992). To capture the high-frequency solar irradiance dynamics at a site, dimensionless measured high-frequency GHI and DNI curves (both in time and energy) are used. To non-dimensionalize the temporal axis (the axis of abscissas in Fig. 1), the time from sunrise is divided by the total day span, i.e., the time between sunrise and sunset. To non-dimensionalize the solar irradiance axis (the axis of ordinate in Fig. 1), their measured values are divided by the corresponding extraterrestrial horizontal solar irradiance and clear-sky DNI profiles values of that particular day. This transformation can be undone, however, by multiplying the x-dimension by a different day span and the y-direction by a different clear day envelope. Thus, high-frequency GHI and coupled DNI series are converted into Dynamic Paths in this non-dimensional space can be re-dimensioned for reproducing actual high-frequency DNI dynamics of each day (accordingly to extraterrestrial horizontal solar irradiance and clear-sky DNI profiles calculated for that particular day) (Fernández Peruchena et al. 2017). It is worth to remark that the Dynamic Paths of both GHI and DNI computed from a given measured day must be applied simultaneously in the generation of a high-frequency solar irradiance day (otherwise, generated GHI and DNI would not be coupled).

In the search of an efficient and consistent methodology for the generation of solar irradiance series, all days available (both ground measured and low resolution modeled) are assigned to groups ("clusters") so that observations within each group are similar to one another with respect to variables or attributes of interest and the groups themselves stand apart from one another. The clustering method used in this work is the K-medoids algorithm, and the calculation of the number of clusters (groups) in the daily series is carried out through the gap statistic method (Tibshirani et al. 2001).

Clustering is useful for two main reasons: summary (deriving a reduced representation of the full data) and discovery (looking for new insights into the structure of the data). This allows for a most appropriate selection of days for generating new high frequency days (within the same cluster), and also reduce computational effort. In this work, the following parameters have been analyzed to characterize individual days (Peruchena et al. 2016): daytime average ambient temperature; daily cumulative DNI value; sum of the product of $DNI \cdot cos(SZA)$, being SZA the solar zenith angle expressed in radians; a category variable as a function of maximum wind speed value.

By doing so, in the generation of solar irradiance series for a given day, only Dynamic Paths belonging to the same cluster are used (Fig. 1), ensuring the reproduction of local weather patterns representative of that day. Also, an additional restriction may be imposed relative to the use of Dynamic Paths generated from a day similar (in terms of day length) to the one to be generated, so that the duration of the cloud events is similar on both days.

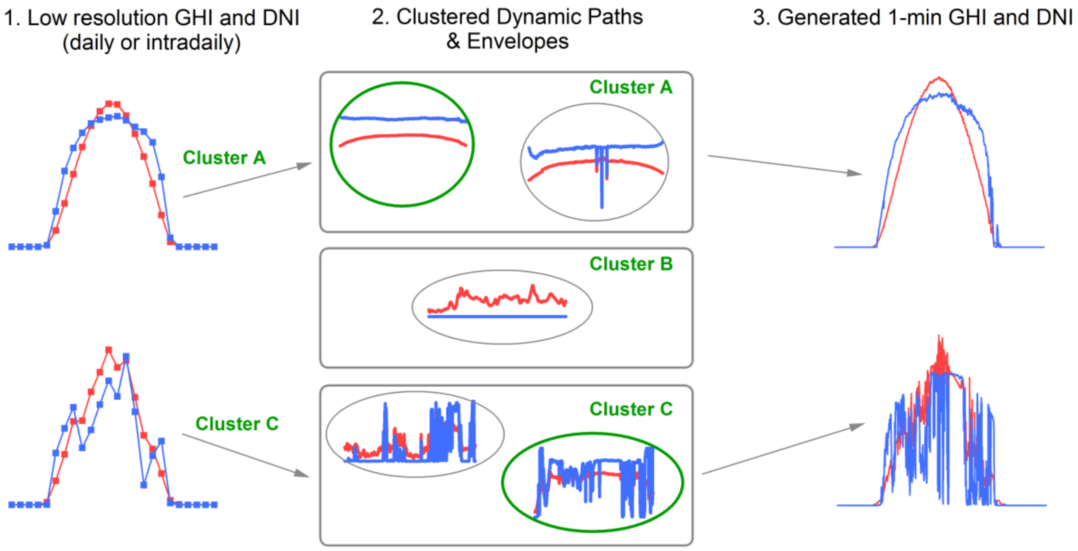

Figure 1. Resume of the generation procedure: low frequency inputs are assigned to Dynamic Paths from the same cluster for the coupled high-frequency generation.

To carry out this study, we have chosen GHI and DNI measurements from Carpentras radiometric station belonging to the Baseline Surface Radiation Network (BSRN) (Ohmura et al. 1998) (Table 1). GHI and DNI datasets in the selected station were collected by a Kipp & Zonen CM21 pyranometer and a Kipp & Zonen CH1 Pyrheliometer, respectively. In this work, only validated data according to BSRN tests (Ohmura et al. 1998) measured at solar elevations above 5º are used.

Table 1. BSRN radiometric stations selected for this study.

Station	Country	Coordinates	Altitude (m)	Years	Climate
Carpentras	France	44.083 N 5.059 E	100	1998-2011	Mediterranean

The measurements of the first year available (1998) have been used for characterizing the 1-min solar irradiance variability, while the rest of the period available (1999-2011) has been used for testing the methodology.

The statistical performance indicators proposed for validating the high-frequency solar irradiance generation method are listed below, grouped according to their nature:

- Dispersion:
  - Relative bias (%), normalized with respect to the measured mean solar irradiance.
  - Ratio of Standard Deviations (RSD), between generated and measured 1-min series.
- Distribution similitude:

    - The KSI (Espinar et el. 2009) is defined as the integrated absolute differences between the cumulative distribution functions (CDF) of two data sets.
    - OVER (Espinar et el. 2009) describes the relative frequency of exceedance situations when the normalized distribution of modeled data points in specific bins exceeds the critical limit that would make it statistically undistinguishable from the reference distribution.
- Autocorrelation:
    - Ramp Rate (RR), calculated as the differences in solar irradiance from one 1-min time period to the next 1-min time period, minus the corresponding values for solar irradiance under clear sky conditions (calculated using CAMS McClear (Lefevre et al. 2013)), such that the remaining value is the variation from expected irradiance (Lave et al. 2010).

3. Results

Fig. 2 shows generated 1-min GHI and coupled DNI series of mostly clear (first day) and mostly cloudy (second day). This figure illustrates that the generation procedure preserves the natural GHI to DNI relations at 1-min time scale, in a wide variety of sky conditions.

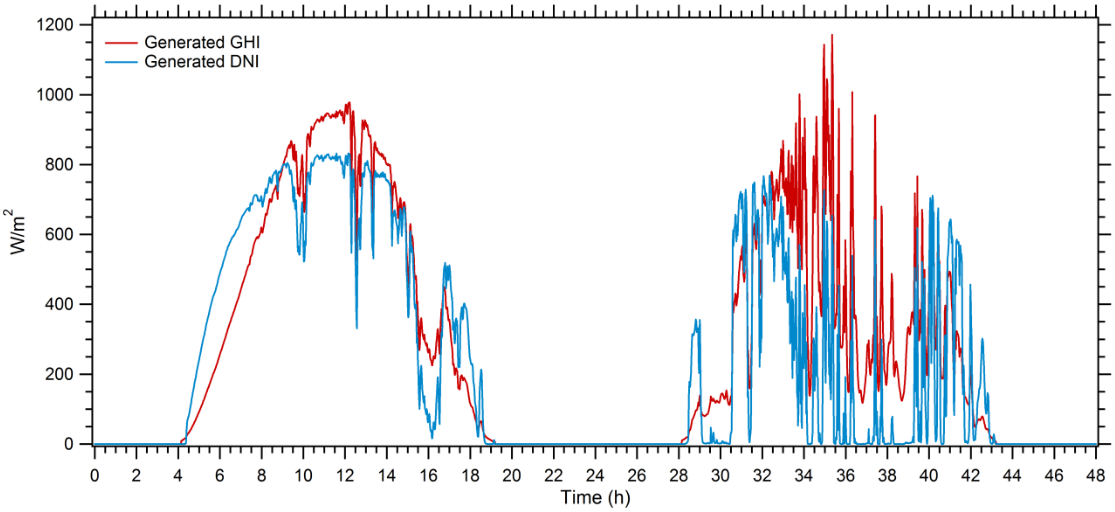

Figure 2. An example output of 1-min generated GHI and DNI coupled series.

Relative bias is low both for GHI (0.3%) and DNI (-0.3%) measured and generated series (as this condition is imposed in the generation). The RSD is close to 1 in both GHI (0.99) and DNI (0.96), indicating a similitude between the variability of both datasets.

Table 2 presents the daily averages for each month (out of 156 months, from 1999 to 2011) of the statistical estimators of the 1-min synthetically-generated DNI data compared to ground measurements (2,955,326 1-min data).

Table 2. Daily averages (in %) of the statistical indicators calculated for each month (from 1999 to 2011) comparing the 1-min measured and generated GHI and DNI series.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
DNI	KSI	75.0	108.3	96.9	102.2	110.8	98.8	102.2	98.7	97.5	99.6	84.7	80.4	96.3
	OVER	27.1	45.1	37.5	44.8	48.0	38.6	41.8	37.5	38.4	39.4	31.2	28.9	38.2
GHI	KSI	63.4	64.3	70.1	69.6	70.0	53.7	51.5	56.0	59.4	64.1	62.4	65.7	62.5
	OVER	15.3	15.3	18.9	20.3	20.8	12.3	11.5	12.7	14.0	13.9	14.3	16.8	15.5

KSI and OVER averaged values for DNI and GHI keep lower than 100%. Notwithstanding, KSI averaged values are higher than 100% in several months (February, May and July), reaching up to 110.8%. On the contrary, monthly averaged KSI values for GHI keep lower than 100%, being ~1.6 times lower than the corresponding KSI values for DNI. OVER values for GHI are in the range of 11.5-20.8%, and the corresponding values for DNI are in the range of 27.1-48.0%.

Fig. 3 shows the Empirical Cumulative Distribution Functions (ECDF) of 1-min measured and generated GHI (left) and DNI (right) series for daytime (from sunrise to sunset) periods, which shows similarity between measured and generated series, most marked in GHI. This figure, along with the results of distribution similitude parameters, confirms the better performance of generated GHI series with respect to the DNI ones, which can be attributed to their lower short-term variability with respect to the DNI.

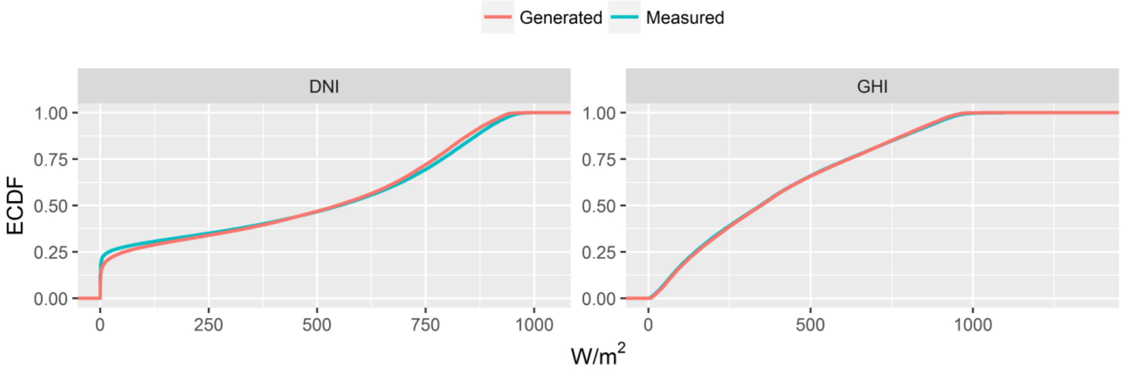

Figure 3. Empirical Cumulative Distribution Function (ECDF) of the measured 1-min solar irradiance series for daytime data compared to the corresponding ECDF of the generated ones, for both DNI (left) and GHI (right).

Figure 4 shows ECDF of absolute values of daytime measured and generated RRs, both for DNI (left) and GHI (right). Higher RRs are found in DNI than in GHI (~1.6 higher in average), reflecting its higher high-frequency variability. Measured and generated RRs show similar statistical properties: the difference of the absolute RRs is slightly higher in measured than in generated series (8.9 and 4.8 W/m^{2}min for DNI and GHI, respectively). Skewness of measured and generated RRs is similar (being between 0 and 0.1 W/m^{2}min in all cases), and kurtosis is slightly higher in generated series, being also higher for GHI RRs (61 and 73 for measured and generated RRs GHI, and 41 and 57 for measured and generated RRs DNI).

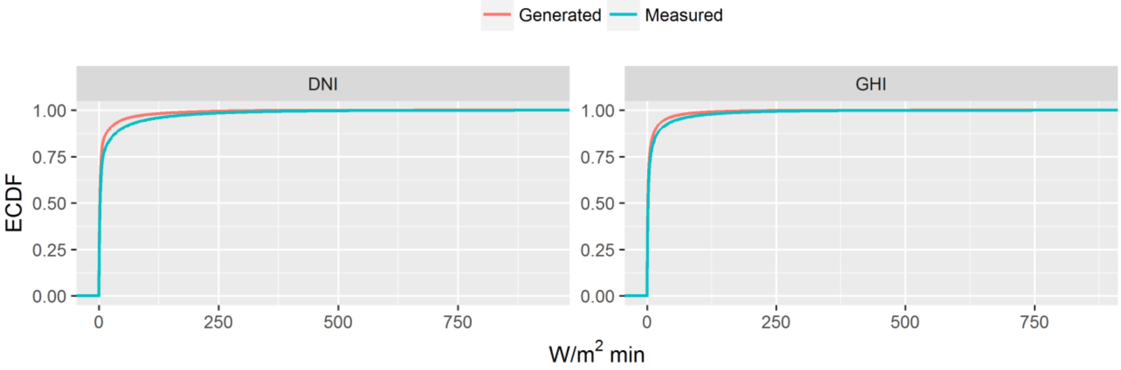

Figure 4. Empirical Cumulative Distribution Function (ECDF) of absolute values of 1-min Ramp Rates series for daytime data compared to the corresponding ECDF of the absolute value of generated ones, for both DNI (left) and GHI (right).

5. Conclusions

In this study, an enhancement to an existing method for increasing the temporal resolution of solar irradiance series is presented. In particular, a general and efficient clustered-based methodology for the generation of high-frequency coupled GHI and DNI series has been developed based on the envelope clear sky and Dynamic Paths. The procedure for generating solar irradiance data assumes that the effect of passing clouds on the fluctuations of both GHI and DNI can be dynamically reproduced using local variability patterns characterized by a 1-year ground measurements. This work presented for the first time the synthetic generation of 1-min GHI and DNI coupled datasets from their corresponding low frequency series and local solar irradiance dynamics (calculated from 1 year of measurements, 1998). To test the methodology, several statistical parameters related to variability, distribution similitude and autocorrelation have been applied to measured and generated series. The statistical parameters used for compare the measured and generated series perform well, showing a better performance in GHI series. Therefore, if both GHI and DNI at 1-min are required in a specific solar resource assessment, as in a site with Concentrating Solar Power (CSP) and photovoltaic (PV) planned, the new extension of previous methodologies presented in this paper is applicable.

Notwithstanding, these outcomes are worse than the corresponding ones obtained with the application of the methodologies separately. Consequently, if the objective pursued in a solar resource assessment is just one of solar components (let GHI or DNI), it is recommended the use of the previous methodologies.

The methodology is also open for development. The methodology presented in this article, focused on a pin-point location, does not include this spatial aggregation effect and consequently its applications are oriented to characterize the high frequency irradiance in a single location. Further works are required to describe this spatial aggregation phenomenon in the size of CSP plants especially in transient situations. Also, other future works will include the link of the envelope clear sky and Dynamic Paths with additional atmospheric information, as focusing on intra-daily segments according to their Variability Classes (Schroedter-Homscheidt et al. 2017), which may represent a complementary approach for assuring the use of specific site information of close similar conditions in the generation of a specific day. Finally, the application of this methodology with no local ground measurements available will be explored using Dynamic Paths generated in different climate zones.

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