A fusion method for creating sub-hourly DNI-based TMY from long-term satellite-based and short-term ground-based irradiation data

Etienne Wey, Claire Thomas, Philippe Blanc, Bella Espinar, Mustapha Mouadine, Moulay Hafid Bouhamidi, Yassine Belkabir

A FUSION METHOD FOR CREATING SUB-HOURLY DNI-BASED TMY FROM LONG-TERM SATELLITE-BASED AND SHORT-TERM GROUND-BASED IRRADIATION DATA

Etienne WEY[1], Claire THOMAS[1], Philippe BLANC[2], Bella ESPINAR[2], Mustapha MOUADINE[3], Moulay Hafid BOUHAMIDI[3] and Yassine BELKABIR[3]

[1] TRANSVALOR S.A, 694 av. Du Dr. Maurice Donat, 06255 Mougins Cedex, France, Phone: +33 492 924 204, Mail: etienne.wey@transvalor.com

[2] MINES ParisTech, CEP – Centre Energétique et Procédés, Sophia Antipolis, France

[3] MASEN, Hay Riad, Rabat, Marroco

Abstract

In order to correctly perform Concentrated Solar Power (CSP) plant electric energy output estimation, a standard approach is to consider Typical Meteorological Year (TMY) as a reference input data in CSP simulation software such as System Advisor Model or Greenius. These TMYs may be built from satellite derived irradiation databases. In order to correctly estimate the CSP electricity production, it is highly recommended to use sub-hourly DNI information. Due to limitation in spatial and temporal resolution of geostationary satellite images, satellite-based irradiation data lack good representativity in term of any sub-hourly temporal variability. To overcome this limitation, we propose an innovative fusion method to combine a one year short time series of ground-based sub-hourly irradiation data and the long-term satellite-based one to create calibrated, sub-hourly and long-term based TMY irradiation data. This method has been successfully applied in the planning of the CSP plant project in Morocco: one year and a half of high quality 10-minute irradiation data from pyranometric ground stations belonging to the Moroccan Agency for Solar Energy (MASEN) has been used with long-term hourly satellite-based irradiation data to create calibrated 10-minute DNI based TMY. The ground-based irradiation data have passed the standard quality check procedure recommended by the Baseline Solar Radiation Network for the World Climate Research Program. The satellite hourly irradiation data has been calibrated on a one year learning period of ground station data and this calibration has been verified on a subsequent half year ground station data. This calibration has been applied to the hourly long-term satellite irradiation time series from which a TMY was computed. The final and innovative step consists in introducing the site specific sub-hourly variability into the whole set of hourly daily profiles of irradiation of the TMY time series, as needed to obtain a better estimation of the CSP producible. The method uses the whole 10-minute measured irradiation data as a store of available days, normalized in terms of time between sunrise and sunset.

Keywords: satellite, irradiation, ground station, DNI, CSP, TMY

1. Introduction

For bankable report or technical and financial feasibility study of a Concentrated Solar Power (CSP) plant, the industry usually performs electric energy output estimation using direct normal irradiance (DNI) and related meteorological data obtained from a Typical Meteorological Year (TMY), using simulation software such as System Advisor Model [1] or Greenius [2]. Ideally, TMY irradiation data are derived from a long-term historical irradiation time series from a ground-based pyranometric station at the exact position of the CSP project. Alternatively – and more likely – these irradiation data can be derived from long-term historical irradiation time series estimated from satellite images and calibrated with short-term reference irradiation data from an *in-situ* dedicated ground station. However, in order to correctly estimate this CSP output, it is highly recommended to use sub-hourly DNI data [3]. Even if geostationary satellites such as Meteosat Second Generation provide images every 15 minutes, its spatial resolution of 3 – 5 km induces a lack of representativity in the derived estimation of irradiation in term of sub-hourly temporal variability inside each pixel. To overcome this limitation, we propose an innovative fusion method meant to combine the short time series of ground-based sub-hourly irradiation data (at least one year) and the long-term satellite-based one to create calibrated, sub-hourly and long-term based TMY irradiation data. This method has been successfully applied for the planning of the CSP plant project in Ouarzazate, Morocco. We explain in this communication the methodology for this data fusion.

2. Ground station measurements and quality check

The three different components of the horizontal irradiation (global horizontal irradiation GHI, diffuse horizontal irradiation DHI and direct normal irradiation DNI) have been measured for almost one year and a half between February 4th 2010 and June 30th 2011, using two different devices at the same location, one rotating shadow-band pyranometer and one "BSRN-like" station equipped with two pyranometers and one pyrheliometer. Due to the very good quality of the pyranometric sensors and the daily maintenance of the ground stations, nearly 100% of the 10-minute irradiation data have passed the standard quality check procedure recommended by the Baseline Solar Radiation Network (BSRN) for the World Climate Research Program [4]. It can also be noted that due to this daily maintenance, there is almost no missing data. We have used, in addition, the latest quality check procedures for the irradiation values resulting from the work in the European ENDORSE project (GA n° 262892, FP7/2007-2013) described in [5].

Ground data has been separated in two groups. The first one, from February 2010 to January 2011, has been used for the calibration of the satellite irradiation data; this is the group of *learning* data. The second one, from February to June 2011, has been used for verification and validation purposes; this is the *test* data.

3. HelioClim-3 (HC3) GHI and DNI calibration

3.1 The Heliosat-2 method and the Helioclim-3 irradiation database

Satellite-based methods for surface solar radiation estimation such as the well known Heliosat method ([6], [7]) represent an operational alternative to interpolation approaches based on meteorological ground stations, as it enables a better spatial and temporal coverage. For instance, the Heliosat-2 algorithm [8] applied to Meteosat Second Generation SEVIRI images is used to update, on a daily basis, the solar resource database HelioClim-3 (HC3). This database covers Europe, Africa, the Mediterranean Basin, the Atlantic Ocean and part of the Indian Ocean with a spatial resolution of approximately 5 km and a temporal resolution up to 15 minutes. The Meteosat Second Generation data are received from Eumetsat and processed in near real time, overnight. This database can be accessed through the SoDa Service (www.soda-is.com).

3.2 Daily GHI and DNI calibration

The procedure for the sub-hourly TMY creation begins by the calibration of the daily time series. The GHI calibration procedure consists of a least square regression of a polynomial-based daily difference model between the clearness indexes derived, on the one hand, from the one-year daily GHI data provided by the ground stations and, on the other hand, the concomitant satellite-based daily GHI data from the HC3 database. Clearness index Kt is defined as the ratio of the surface daily GHI with the corresponding one at the top of the atmosphere (GHItoa).

Using the one-year learning period, the mean bias error of the daily GHI stays unchanged near zero, with respect to the values before calibration, and the corresponding root mean square difference (RMSD) is reduced from 8.7% to 5.3%. In Fig. 1, the scatter plot of the daily GHI comparison between the ground station and HC3 shows the effectiveness of the calibration.

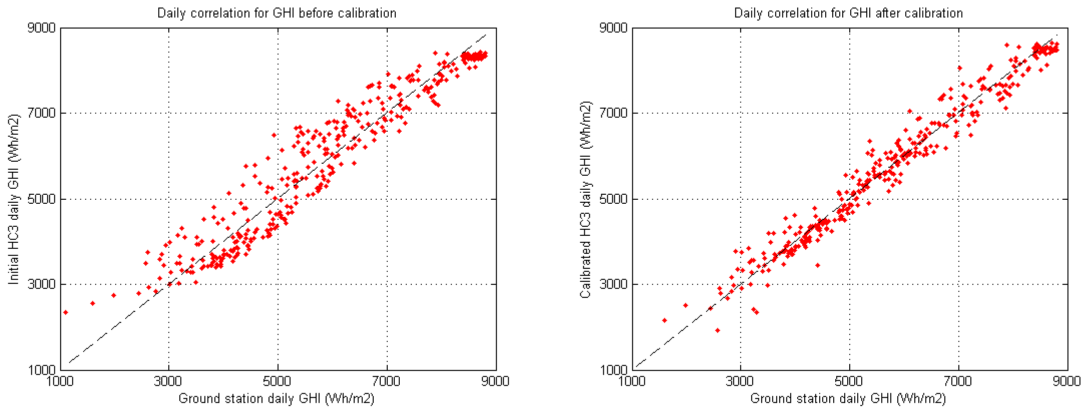

Fig. 1. Scatter plot of the daily GHI comparison between ground station and HC3 before (left) and after (right) calibration.

From the ground-based daily DNI and GHI data, through a non-linear regression, we have determined a site-specific empirical transposition function between Kt and a DNI clearness index. The DNI clearness index, named KDNI, is defined as one minus the ratio of the daily DNI with the corresponding one, at the top of the atmosphere (DNItoa). We have then used this abacus to compute a calibrated daily DNI from the calibrated daily GHI.

On the one-year learning period, the DNI daily bias is kept to nearly zero, with respect to the values before calibration, and the corresponding root mean square difference (RMSD) has been improved by a factor 1.5, from 33% to 22%. With the computation of the Kolmogorov-Smirnov test Integral [9] value (KSI) which is reduced from 124% to 47%, we can confirm that the cumulated distribution function of the calibrated DNI becomes statistically close to the ground station one. The scatter plot of the daily DNI comparison between the ground station and HC3 is shown in Fig. 2.

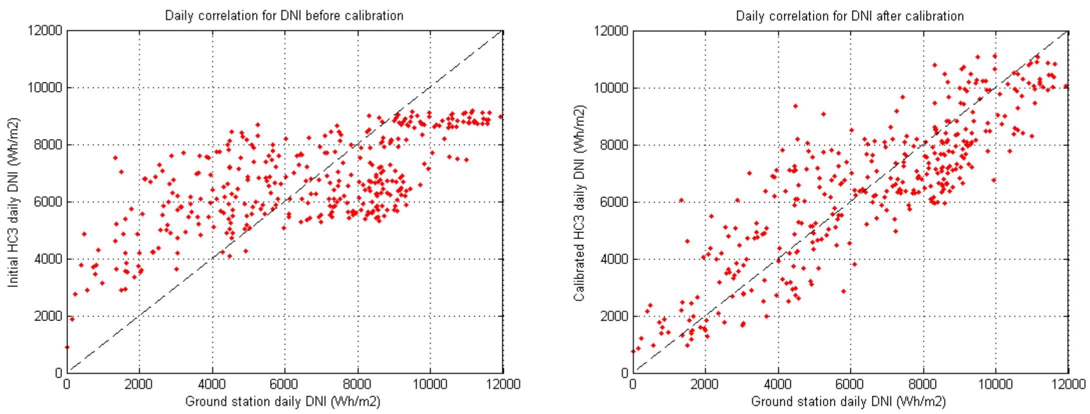

Fig. 2. Scatter plot of the daily DNI comparison between ground station and HC3 before (left) and after (right) calibration.

3.3 Hourly GHI and DNI calibration

The corresponding HC3 hourly time series of GHI and DNI have been calibrated by applying with a scale factor, for each day, the daily calibration factor obtained beforehand. The scatter plot of the comparison between the hourly calibrated HC3 DNI values and the ground station values in Fig. 3 shows the good results obtained with this method. The RMSD is 29.4% and the KSI is equal to 45%.

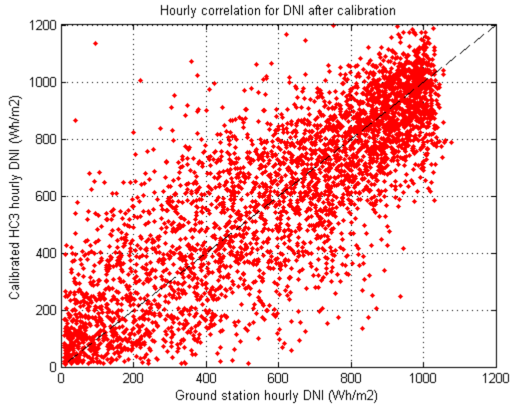

Fig. 3. Scatter plot of the hourly DNI comparison between ground station and calibrated HC3.

This calibration procedure has been then applied to the long-term hourly HC3 time series.

For validation purpose, we have applied the calibration parameters to the HC3 data for the test period from February 1st 2011 to June 30th 2011. The comparison results for this period are quite similar to the one-year learning period. This result confirms the reliability of the calibration procedure.

4. Creation of the hourly TMY

A P50 and a P90 TMY have been computed from the long-term hourly calibrated irradiation time series. A P50 and a P90 correspond respectively to a median and a pessimistic annual scenario. For the generation of TMY, for each month of the year, the set of this same month of the year for the whole long-term time series is considered. For example, for searching the month January which will be chosen as the month January in the TMY, all the monthly sum of DNI for all Januaries of the long-term time series are considered, and so on for the rest of the months of the year. For the P50-TMY, that is the median TMY, the selected month will be the one whose monthly DNI is the closest to the median value of the different corresponding monthly sums of DNI in the long-term series. Similarly, for the P90-TMY, that is the pessimistic TMY scenario, the month whose monthly DNI is the closest to the percentile 10% will be chosen.

5. A fusion method to create sub-hourly TMY

The final and innovative step consists in introducing the site specific sub-hourly typical variability into the whole set of hourly daily profiles of irradiation of the P50- and P90-TMY time series. The method uses all the 10-minute measured daily profiles of irradiation as a "store" of available days, normalized in terms of time between sunrise and sunset. Based on time-normalized 1-h daily profiles of the DNI, for each day of the TMY, the algorithm searches for the closest day in term of Euclidean distance in the DNI daily profile store, in a temporal window of plus or minus 20 days. The selected 10-min daily profile of DNI is then fitted to the real daylight duration and its daily sum is slightly scaled to fit the real one. The resulting 10-min daily profile of DNI is then inserted in the TMY. It is important to note that this method is not directly applicable to GHI data series due to the effect of the declination angle which would change too much the maximum value of the GHI in the time window of plus or minus 20 days. A selection based on Euclidean distances on clearness index can be a solution in that case.

We can see in Fig. 4 an illustration of the method with the different irradiation curves (blue: 1-h daily profile of DNI in the TMY, red: ground-based 1-h daily profile of DNI for the matching day, green: resulting 10-min daily profile of DNI in the TMY extracted from store of ground-based 10-min daily profiles for the matching day)

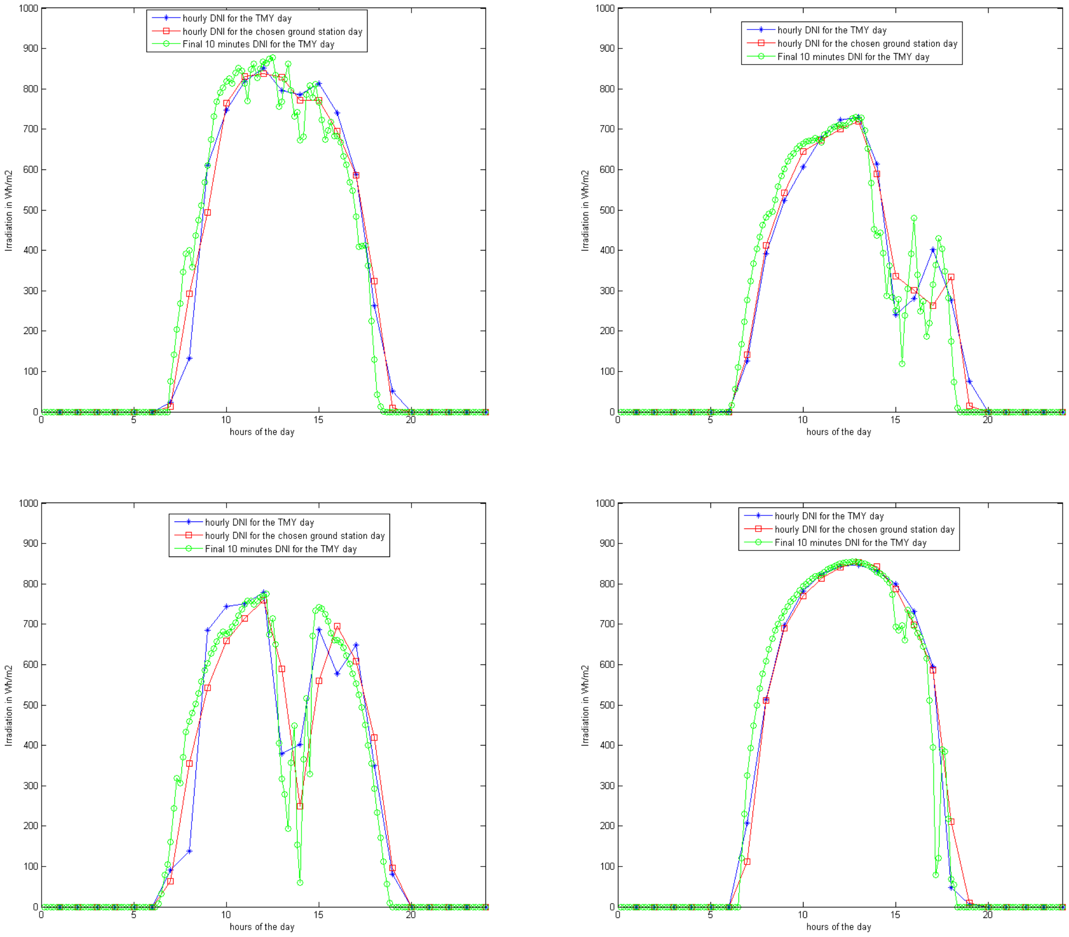

Fig. 4. Examples of the application of the fusion method for some days of a TMY time series.

To check the consistency of the method, we have statistically compared the time series of the TMY, in hourly resolution, before and after the fusion of the sub-hourly 10-min temporal variability. We have checked that the fusion method does not introduce any bias. The hourly RMSD is limited to 18.6% and the KSI is 71%, proving that statistically the two time series may come from the same distribution. This shows that our choice of "matching days" was correct and did not significantly change the distribution of the hourly irradiation values of the TMY.

Conclusion

Within the scope of an industrial CSP project irradiation assessment, we have presented a method to combine a short period ground-based measured irradiation and a long-term satellite based irradiation data to produce a sub-hourly calibrated TMY time series with a 10-minute temporal resolution. We have used an original fusion method to introduce the site specific sub-hourly typical variability into the hourly TMY created from the calibrated satellite irradiation data.

We will continue to work on this subject mainly with an extensive validation based on long-term high quality ground-based irradiation measurements from the BSRN network.

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