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Abstract

In order to accurately simulate the behavior of a solar thermal power plant, it is necessary to carry out an adequate evaluation of the available solar resource. To that end, it is important to know the cumulative Direct Normal solar Irradiation (DNI) values and their dynamic behavior. Only by knowing this information with accuracy, it will be possible to predict the solar thermal power plant behavior and to establish an adequate operation strategy.

Sites with high cumulative DNI values are not necessarily the best locations for solar thermal power plants. Variability of the solar resource and its impact on the management of the plant may cause that sites with similar or lower DNI values can present a higher electricity production.

Current solar radiation models based on hourly data series do not allow fairly evaluating the plant behavior or analyzing with the required detail different possible operation strategies. So as to overcome this limitation and to have a more accurate knowledge of the solar resource it is necessary to increase the sampling frequency of the data, what will enable to simulate with higher accuracy certain aspects of the operation like transient effects. For that purpose, this paper presents a new global-to-direct irradiance conversion methodology, based on 1-minute frequency series, which will improve results of solar thermal power plants simulations.

Keywords: Direct Normal Irradiance (DNI), Global Horizontal Irradiance (GHI), Aerosol Optical Depth (AOD).

1. Introduction

Solar thermal power plants can be used for baseload generation as well as peak power generation since the use of thermal energy storage and different hybridization concepts enable scheduling energy production. However, for this prediction to become real, better plant designs and operation procedures are needed. These better designs and procedures should be based on the optimization of plant configurations, the improvement of components and sub-systems and the design of more effective O&M strategies. As testing at commercial-scale has prohibitive cost, it is essential to have appropriate simulation and design tools, which must be fed with a certain range of input variables such as site, meteorological data, etc. One of the most important inputs to be provided is the Direct Normal solar Irradiation (DNI). Slight variations on this input can lead to very different results on the simulation, so it is important to have an accurate record of the solar resource that takes into consideration its dynamic evolution.

Instantaneous flickering nature of DNI (Fig. 1) has a considerable impact on the behavior of solar energy conversion systems. Due to the variable nature of its input, the non-linear solar generation (especially CSP without energy storage) can affect power system operations in several ways [13].

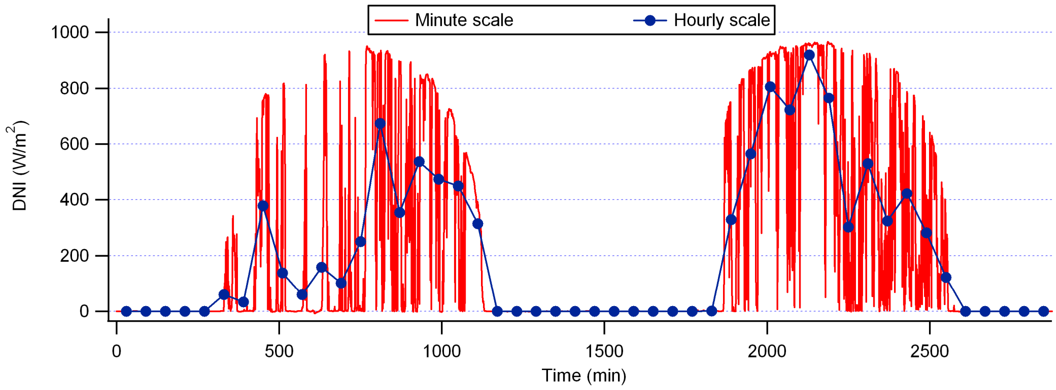

Fig. 1. DNI at minute (red trace) and hour (blue trace) scale. Source: CENER BSRN radiometric station

The irregularity in electricity generation is driven by the variability of the solar resource. Therefore, a model that estimates irradiance values at short time scales is a key first step in estimating solar plant output.

Field measurement campaigns designed to analyze solar resource on a specific site commonly lack the whole DNI series, due to tracker issues or other problems. This fact is still more pronounced for remote sites, where maintenance operations are more difficult to accomplish. As a consequence, models are generally used to estimate DNI as an alternative to on site measurements to rebuild incomplete DNI measured series.

There are mainly two types of solar radiation models available in the literature used for the prediction of DNI: parametric models and decomposition models [1]. Parametric (or atmospheric) are based on physical processes including complex radiative transfer models, and they require detailed atmospheric information [2-4]. On the other hand, decomposition models provide direct and diffuse irradiance from Global Horizontal Irradiance (GHI) values, using regressions between two dimensionless indices: the clearness index, kt (GHI to extraterrestrial horizontal irradiance ratio) and either the direct solar transmittance, kb (DNI to extraterrestrial irradiance ratio) or the diffuse fraction, kd (diffuse horizontal irradiance to GHI ratio). These models have been usually developed in hourly scale [5-12].

This work presents a new methodology for the estimation of DNI from Global Horizontal Irradiance (GHI) based on 1-minute data. This methodology and the results of the analysis are described in detail in the current paper.

2. Description of the methodology

The Louche [9] model is a decomposition model derived for hourly series, and it is one of the most common models used for the estimation of DNI values. This model calculates DNI from direct transmittance values, whereas most of other typical models (Orgill and Hollands, Erbs, etc.) calculate DNI from the diffuse fraction.

However, the methodology here proposed for the calculation of DNI values has demonstrated to procure better adjusted DNI values than the Louche model at one minute scale. This new methodology applies different strategies for clear and cloudy sky conditions, as detailed next.

2.1. Clear sky conditions

The methodology proposed calculates DNI from Aerosol Optical Depth (AOD) derived from GHI, using the model proposed by P. Ineichen [15].

Under clear sky conditions, the atmospheric water vapor column and aerosol content are the atmospheric components that provide the highest attenuation of the solar radiation. The first can be evaluated from ground temperature and relative humidity measurements with a satisfactory precision, while the second, due to the lack of measurements, has to be taken from climatological data banks or calculated from GHI measurements [14].

To estimate DNI data from GHI on minutely basis, the clear sky model proposed by P. Ineichen has been used [15]. This model is a simplified version of the Solis clear sky model, and it has been chosen due to its simplicity and accuracy with respect to Solis model. The Solis model [16] is a spectrally resolved physical model developed within the European project Heliosat-3, based on radiative transfer models (RTM) using atmospheric parameter information retrieved from the MSG satellite (clouds, ozone, water vapor) and the ERS-2/ENVISAT satellites (aerosols, ozone).

The P. Ineichen model is based on a modified Beer-Lambert equation, whose parameters are analytically calculated. The use of this model requires both aerosol optical depth at 700 nm (AOD_{700}) and water content of the atmosphere (*w*). First, *w* can be measured, or retrieved from ground measurements of the ambient temperature and the relative humidity [17]. Then, AOD_{700} is numerically solved, for example, by means of Newton–Raphson method through the clear sky model, *w* and GHI value. Through derived AOD_{700} and w values, the same clear sky model is used to determine DNI data (Fig. 2).

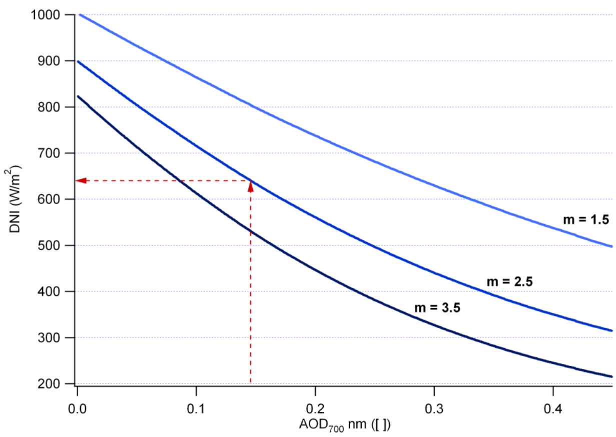

Fig. 2. DNI determination from AOD_{700} and optical air mass (m) values, for atmospheric water content of 1.5 cm.

The range of values used for atmospheric parameters and altitude of the model are shown in the Table 1.

	AOD_{700} [ ]	**w [cm]**	**Altitude [m]**
Minimum value	0	0.2	Sea level
Maximum value	0.45	10	7000

Table 1. Parameters range for the simplified version of the Solis clear sky model.

As it can be observed in Fig.2, this methodology makes it possible to calculate DNI values through a relatively simplified way. In Section 3, the validation of the methodology is carried out in parallel with a comparison with data obtained with the Louche model.

2.2. Cloudy conditions

Even if the methodology proposed has demonstrated a better adjustment of the DNI data under clear sky conditions, it has not been yet developed under cloudy conditions. Under cloudy conditions, the Louche's model [9] is proposed to be applied by now.

The model proposed by Louche has been selected for the estimation of the DNI in cloudy conditions because of the reasonable results obtained by it [5]. Future works will be focused in developing improved methodologies also for DNI estimations under cloudy conditions.

3. Methodology preliminary validation

The analysis of the results obtained is focused on the comparative between measured AOD and DNI data and estimated AOD and DNI data by means of the proposed methodology, as well as the DNI values calculated with the Louche model.

In order to carry out a preliminary validation of the proposed methodology, data from two Baseline Surface Radiation Network (BSRN) stations have been used: Carpentras and Pamplona. A future validation of the complete methodology will be carried out in further works by taking data from several BSRN stations located at different latitudes.

The BSRN is comprised of groups of researchers from around the world dedicated to the long-term, accurate measurement of surface radiative fluxes at the highest possible accuracy with well-calibrated state-of-the-art instrumentation, under the auspices of the World Meteorological Organization (WMO) World Climate Research Program (WCRP). Main parameters of the station selected are shown in the Table 2. The period selected for the analysis is June 2008 (Carpentras) and July 2011 (Pamplona).

Network	Latitude (+N)	Longitude (+E)	Elevation (m)	Surface type	Topography type
BSRN Carpentras	44.0830º	5.0590º	100	cultivated	hilly, rural
BSRN Pamplona	42.8160	-1.6010	471	asphalt	mountain valley, urban

Table 2. BSRN radiometric stations selected.

Also, aerosol data from AERONET database are available for the first location chosen: Carpentras. (Table 3) This data has been also used to verify AOD_{700} and *w* calculations. The AERONET (AErosol RObotic NETwork) program is a federation of ground-based remote sensing aerosol networks established by NASA and PHOTONS (University of Lille 1, l'agence française de l'espace, and the Institut national des sciences de l'Univers). The program provides a long-term, continuous and readily accessible public domain database of aerosol optical, microphysical and radiative properties for aerosol research and characterization, validation of satellite retrievals, and synergism with other databases.

Network	Latitude (+N)	Longitude (+E)	Elevation (m)
AERONET (Carpentras)	44.08333º	5.05833º	100

Table 3. AERONET Carpentras station selected.

4. Results

4.1. AOD_{700}

The methodology presented in the current paper takes from starting point the determination of AOD_{700} from GHI records, in a first step, in order to calculate the DNI value. Fig.3 (left side) shows AOD_{700} series recorded by AERONET in Carpentras (red plot) and calculated values from GHI records (blue plot). It is remarkable that both series follow a similar trend, increasing and decreasing at the same time. Fig. 3 (right side) also shows a graphic with the dispersion of both series, where a certain underestimation can be observed for values calculated from AOD_{700} in comparison to values recorded. This trend is more pronounced for AOD_{700} values greater than 0.1.

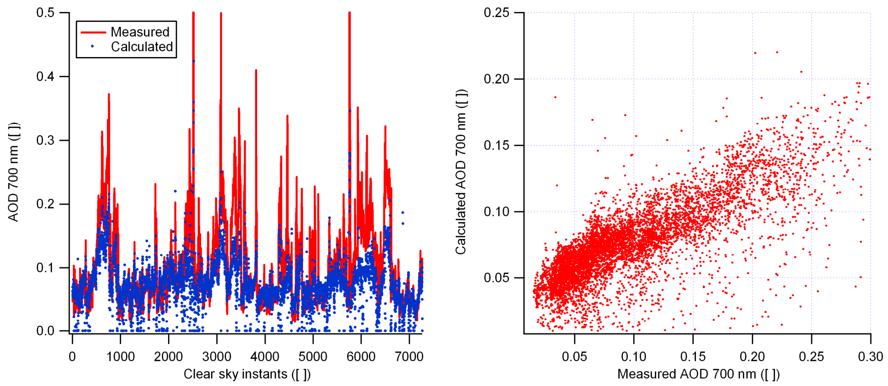

Fig. 3. Left, measured (red trace) and calculated with the proposed methodology (blue trace) AOD_{700}. Right, dispersion plot between measured and calculated AOD_{700}.

The same analysis has not been possible to carry out for the location of Pamplona, as no data are available in AERONET.

4.2 DNI

After the determination of the AOD_{700} values, which was the first step of the procedure here explained, the DNI values have been estimated according to the model proposed by P. Ineichen, already explained in Section 2. Fig.4 shows measured DNI (red plot) and estimated DNI (blue plot) obtained as a result of the analysis, for the location of Carpentras.

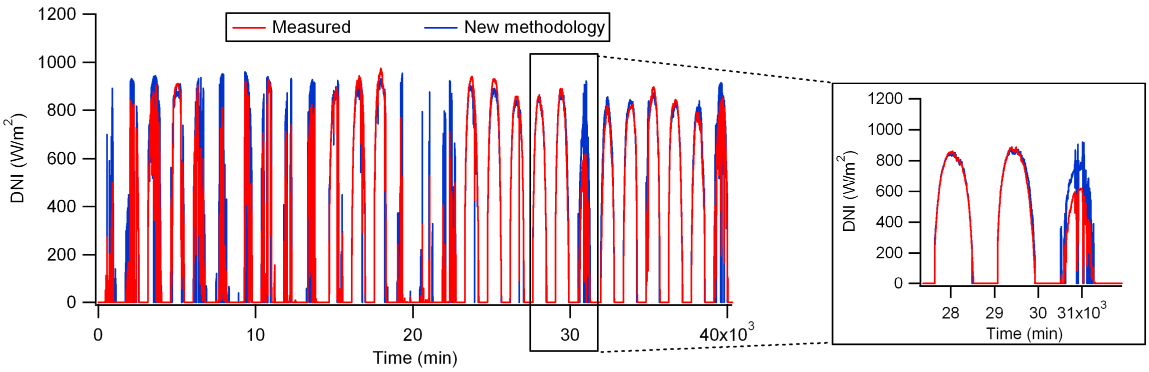

Fig. 4. Measured (red plot) and calculated (blue plot) DNI data for Carpentras (July 2011).

A good adjustment between registered DNI values (red plot) and calculated DNI values (blue plot) can be observed for clear sky moments. However, for cloudy moments, there is a wider dispersion between both series.

A comparison between DNI values calculated with the proposed methodology and DNI values calculated with the Louche model has been performed. Similarities between measured values and calculated values for clear sky moments are noticeable in Fig. 5. It is remarkable that registered values (red plot) show a higher degree of similarity with DNI values calculated with the proposed methodology (blue plot), than with values calculated with the Louche model (green plot), for the cited clear sky conditions.

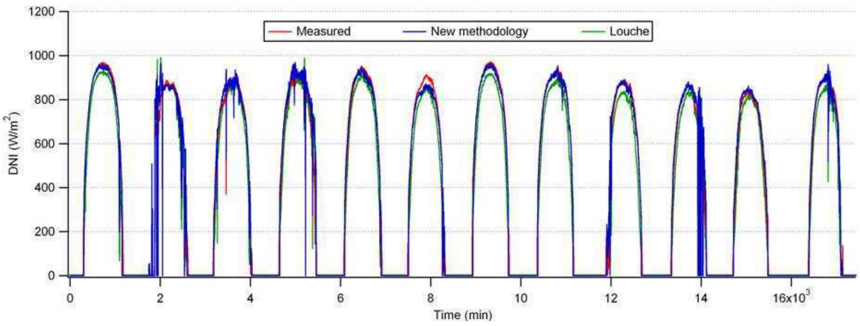

Fig. 5. Measured (red trace), calculated with the proposed methodology (blue trace), and calculated with Louche model (green trace) DNI data under clear sky conditions, in Pamplona.

Table 4 shows Mean Bias Error (MBE), relative Mean Bias Error (rMBE), Root square Mean Bias Error (RMBE) and relative Root square Mean Bias Error (rRMBE) of calculated, with the proposed methodology and Louche model, and measured DNI series. These statistical parameters have been calculated for clear days (even if they present instants of flickering in DNI) (7680 data).

	Carpentras (n = 12960)		**Pamplona (n = 17433)**	
Statistical parameter	**DNI (proposed methodology)**	**DNI (Louche model)**	**DNI (proposed methodology)**	**DNI (Louche model)**
MBE	-0.57 W/m^2	1.44 W/m^2	1.61 W/m2	-21.12 W/m2
rMBE	-0.08 %	0.20 %	0.32%;	-4.24%
RMSE	32.35 W/m^2	65.52 W/m^2	40.64 W/m2	63.13 W/m2
rRMSE	4.53 %	9.17 %	8.16%	12.67%

Table 4. Statistical parameters of agreement for calculated values with the proposed methodology vs. measured DNI series, and calculated values with Louche model and measured DNI series.

From Table 4, it can be stated that DNI values calculated with the proposed model adjust better to measured values, as errors calculated are lower than those obtained with the Louche model. The Louche model seems to present a certain deviation in the central hours of the day. This behavior can be observed in Fig.6 and Fig.7, where a dispersion plot between measured and calculated DNI, for clear moments, is shown for each of the stations. On the right side of these figures, dispersion between values obtained with the Louche model and the corresponding registered values are represented, whereas on the left side, a similar graph is shown with values obtained from the model and registered values.

It can be observed that, for both cases studied, for low DNI values (< 600 W/m^2 approximately) most of the values provided by the Louche model are underestimated, as they are below the reference trace with slope 1. On the other side, for higher DNI values this trend decreases gradually. Even, in the case of Carpentras, most of the DNI values obtained by the Louche model above 700 W/m^2 are overestimated. These areas described are remarked with a circle.

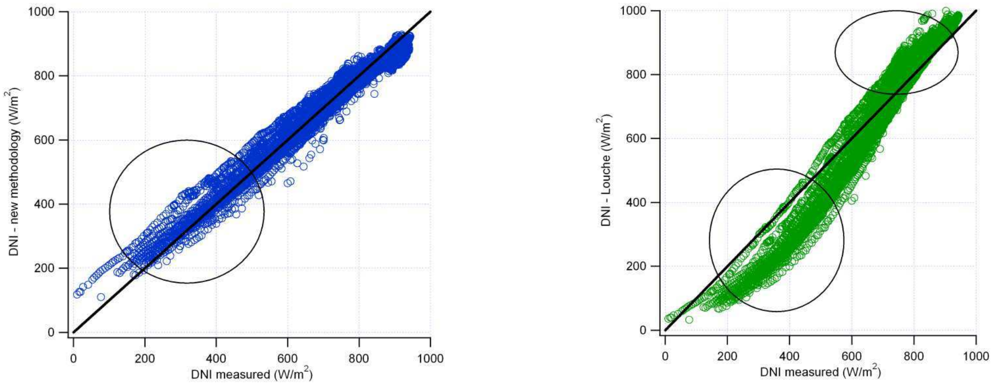

Fig. 6. Left, dispersion plot between calculated values with the proposed methodology and measured DNI values under clear sky conditions. Right, dispersion plot between calculated by means of Louche model and measured DNI values under clear sky conditions. Case: Carpentras.

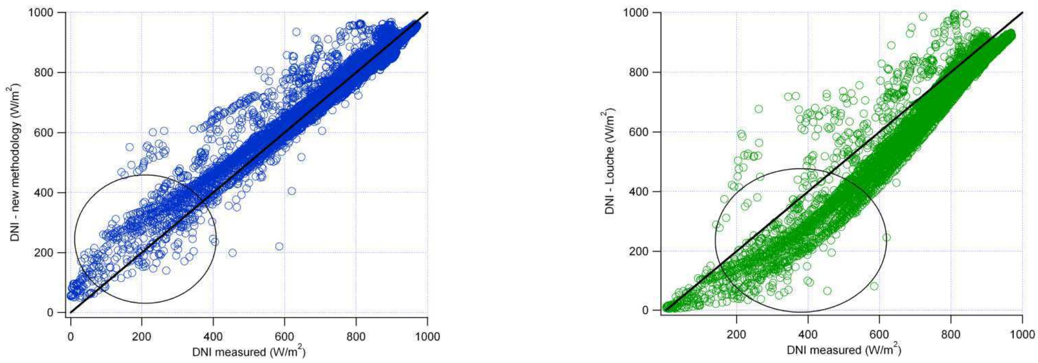

Fig. 7. Left, dispersion plot between calculated values with the proposed methodology and measured DNI values under clear sky conditions. Right, dispersion plot between calculated by means of Louche model and measured DNI values under clear sky conditions. Case: Pamplona.

Results obtained with the methodology presented show a certain overestimation for low DNI values (< 400 W/m2 approximately), area remarked with a circle in the dispersion plot. However adjustment obtained with higher DNI values is very precise, as observed in Fig.6 and Fig.7. For both studied cases, the new methodology gets DNI values closer to the measured.

This analysis thus suggests that the methodology here detailed calculates with a higher accuracy the DNI values for clear sky conditions than the Louche model. Results obtained are even better for cases with clear atmosphere (AOD_{700}<0.1), as it has been demonstrated in subsection 4.1., with the case of Carpentras.

5. Conclusion

The new methodology here presented shows a high concordance between calculated values and measured data, only considering data under clear sky days. Still for the data analyzed, the proposed model has shown an adjustment between estimated and measured data more than 50% better than the Louche model, in terms of MBE and RMSE.

However, the current methodology does not entirely represent the real range data series, as in this preliminary validation cloudy days have not been considered. In future developments, a complete validation of the methodology is expected to be done, considering not only measured data from several BSRN stations located at different latitudes, but also analyzing the behavior of this methodology under cloudy conditions.

Development of kb-kt relations at one minute scale for cloudy conditions, or the establishment of relations between GHI, cloudiness and DNI at one minute scale are promising approaches. This future work will make it possible to have a reliable methodology for the estimation of the DNI at higher frequencies, for the accurate simulation of solar thermal power plants.

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