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Measurements and Model Evaluations of Direct Normal Irradiance in Central Spain

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Abstract

The availability of hourly irradiance data is very important in the assessment of solar energy resources. This quantity is estimated for hourly global solar irradiance recorded in most radiometric stations. Measurements of global, diffuse, direct normal irradiance (*DNI*) and meteorological variables have been recorded and evaluated in an rural area northwest Spain. Daily solar radiation data show a large annual cycle with a maximum in June when the influences of summer solstice occur. Maximum hourly and daily direct normal irradiance occurs in June 2011, 1006.5 W m^{-2} and 43.70 MJ m^{-2}, respectively. Daily clearness index varies between 0.79 from June to August and 0.2 in winter. It has been observed that *DNI* tends to show much variability than global solar irradiance in December and January months as consequence of cloudy weather associated with low-pressure systems. The most representative statistical *DNI* indices (mean, median, standard deviation, maximum, minimum, quartile, percentiles coefficient of quartile variation) has been evaluated. In addition four models have been selected for predicting hourly direct normal solar irradiance from global solar irradiance. Model validation has been performed by comparison with experimental data by means of two statistic estimators, root mean square error and mean bias deviation.

Key-words: direct normal irradiance; clearness index; *DNI* modeling; model validation

1. Introduction

The main energy source for the Earth-atmosphere system is solar radiation. One important component of incident radiation is direct normal solar irradiance, *DNI*, which is the maximum amount of solar radiation received per unit area by the Earth's surface. Solar radiation at ground level depends on geographical and astronomical factors such as, latitude, (Oña et al. 2013), Earth-Sun distance, solar altitude, and interaction with atmospheric components such as aerosol, ozone, clouds, water vapour, and gases. Under cloudless conditions, one of the main factors impacting *DNI* is atmospheric aerosol, the effect of which on *DNI* depends on the aerosol amount, its absorption, and its scattering, (Bilbao and De Miguel 2010; De Miguel et al. 2011).

The knowledge of *DNI* arriving at the earth's surface is important for designing solar energy applications, heating and cooling loads as well as simulations of long-term process operations. In addition, concentrating solar thermal power requires clear skies and strong sunlight for solar applications, in this case the solar resource is measured as direct normal irradiance (*DNI*) which is the energy received on a tracking surface perpendicular to the sun rays. Locations whose latitude ranges between 45º S and 45º N are within the "solar belt", and are the most suitable areas for *DNI* applications if their mean solar *DNI* resources are above 5 kWh m^{-2} day^{-1}, (Meyer at al. 2011)

Long data sets of *DNI* are rarely available at the location of interest because of problems with maintenance and the high cost of solar sensors. Available data series are frequently typical reference year data series, TRY, (Bilbao et al. 2003, 2004). For these reasons *DNI* must be estimated from other variable recorded at the place.

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Nowadays there are different method and models for simulating *DNI* data and they can be classified as a) radiative transfer models (Bilbao et al. 2011; Ineichen, 2009; Kaskaoutis and Kambezidis, 2008) and b) decomposition models (López et al. 2000). The first ones are based on interactions of solar direct with the atmosphere, as scattering by air molecules, water and mineral dust (aerosols) and absorption by gases (ozone, water vapor, CO_2). The decomposition models relate *DNI* with other solar radiation variable. Some authors have estimated *DNI* from diffuse and global solar irradiance and other methodologies evaluate *DNI* from global solar irradiance (Bilbao et al. 2004; Gueymard, 2009). Diverse authors have proposed different relationships between *DNI* and atmospheric and meteorological variables and as consequence model algorithms have been developed, (López et al. 2000; Perez at al. 1990).

Several research groups have evaluated solar radiation using remote sensing data, (Espinar et al. 2009; Hammer et al. 2003) and different authors are involved in different campaigns for monitoring changes in *DNI* (Islam et al. 2010).

The aim of this paper is to analyze the *DNI* characteristics, select and evaluate different algorithm models at some stations and assess the agreement between measured and estimated values. The results have been compared to decide with model could be recommended as the best for the continental Mediterranean region.

Section 2 provides detailed information about site description, sensors, data collection and quality are shown. Methodology is given in section 3 and results and discussion obtained in the study are provided in section 4. And finally, section 5 summarizes the main results and findings.

2. Location, Instruments and data

The Solar Radiometric Station (SRSUVA) is located in a rural area free from obstructions, at Villalba de los Alcores, 40 km NW of Valladolid city (Spain). The geographical coordinates are: 41º48´50'' N, - 4º55’48'' W and 840m a.s.l. The climate is continental, but is also influenced by the Mediterranean, with dry and warm summers and cold and wet winters. Cloudless skies predominate in summer while cloudy skies are more frequent in autumn and winter. Typical annual rainfall averages about 476 mm, (Oña et al. 2013). SRS is equipped with numerous radiometric and meteorological sensors. Direct normal solar irradiance measurements were recorded using a solar tracker (Solys-2 from Kipp & Zonen) which has a CHP-1 pyrheliometer with a 2% calibration accuracy, 14 $\mu V/W\ m^{-2}$ sensitivity, a 200 to 4000 W m^{-2} irradiance range, and a 280-5000 nm spectral range. Global and diffuse solar irradiance were recorded each ten minutes by two CMP21 (Kipp & Zonen) pyranometer, (Bilbao et al. 2011). The instrument has a flat spectral response from 305 to 2800 nm, and is well calibrated each two years. The expanded uncertainty (95% confidence) of the measurements obtained by the CMP21 instrument is about 2% (given by Kipp & Zonen).

All sensors are connected to two CR23X Campbell dataloggers which are programmed to record measurements each 10 minutes as an average of 10-second values. The *DNI* data used were recorded between January 2010 and December 2012 and a quality control data were performed prior to data use. Hourly and daily data were evaluated and a series of 57,537 global solar and 57,643 direct normal 10-minute data values were analysed. Meteorological variables such as temperature, relative humidity, and pressure are recorded by a HMP35AC probe (Vaisala) and a RPT410F Barometric Pressure sensor (Campbell Scientific), respectively. Also hourly data series for the period 2002-2010 from State Meteorological Agency (AEMET), in Madrid (Universitary City 40º27'06'' N, 3º43'27'' W and 664m a.s.l.), Cáceres (39º28'17'' N; 6º20'20'' W 394 m a.s.l.) and Valladolid (41º39'00'' N, 4º46'00'' W and 735m a.s.l.) have been used.

3. Methodology

A statistical study of the most representative indices have been evaluated and the following parameters were assesses: arithmetic average, standard deviation, maximum, minimum, first and third quartile, coefficient of quartile variation, which is defined by the expression: $V = 100(Q_3 - Q_1) / (Q_3 + Q_1)$ and $P5$ and $P95$ percentiles.

The cloud effect was interpreted by the cloud modification factor, *CMF*, defined by the following expression:

$$CMF = \frac{I_{meas}}{I_{cls}} \quad \text{(eq. 1)}$$

where I can be DNI; I_{meas} is the measured irradiance and I_{cls} is the calculated irradiance under cloudless conditions. The CMF meaning is related to cloud transmittance.

Four algorithms were selected for simulating *DNI*, Maxwell,(Maxwell,1987), Skarveit and Olseth (Skarveit and Olseth, 1987) and Erbs, Klein and Duffie (Erbs et al.1982) and RR-model (Perez-Burgos et al. 2015). They will call as EK&D, S&O, Maxwell and RR models in this study. The Maxwell is a “quasi-physical” and combines a physical clear sky with experimental fits for other conditions. EK&D was selected because it has been used by the International Energy Agency, (Perez et al. 1990). The algorithms were selected because some of them had been the most accurate by the International Energy Agency. Inputs for all models consists of global irradiance and solar zenith angle, *SZA*. A statistical study of the most representative *DNI* indices for each month of the year has been evaluated. Global solar irradiance and solar zenith angle, *SZA* and the clearness index, K_T are the variables used (De Miguel et al. 2011).

4. Results

This section aims to evaluate daily *DNI* values and analyse the distribution characteristics of energy levels, following the daily evolution at different times of the year at the SRSUVA. An initial analysis of *DNI* data characteristics, global irradiance was performed as functions of time of year, and *DNI*, global irradiance, and the clearness index frequency distributions are reported. Some previous results about *DNI* modelling are also included.

4.1 Maximum hourly direct normal irradiance and daily irradiation

Hourly and daily *DNI* values were calculated from 10-min recorded data. It can be observed that maximum hourly *DNI* ranges between 1006.5 W m^{-2} and 100 W m^{-2}. Daily values show a high symmetry around June when irradiance reaches maximum values, while it decreases in spring and autumn and reaches its minimum in winter

Daily *DNI* follows the variation of the day length, both being maxima in summer and minima in winter. Maximum daily *DNI* irradiation was reached on June 21st, 2011 and it was around 43.70 MJ m^{-2}. The results can be explained taking into account the symmetry relation between the summer and winter solstices. The strong fluctuations in the evolution of hourly and daily values are mainly due to the presence of clouds, which reduce direct irradiance.

4.2 Monthly maximum and mean daily DNI irradiation

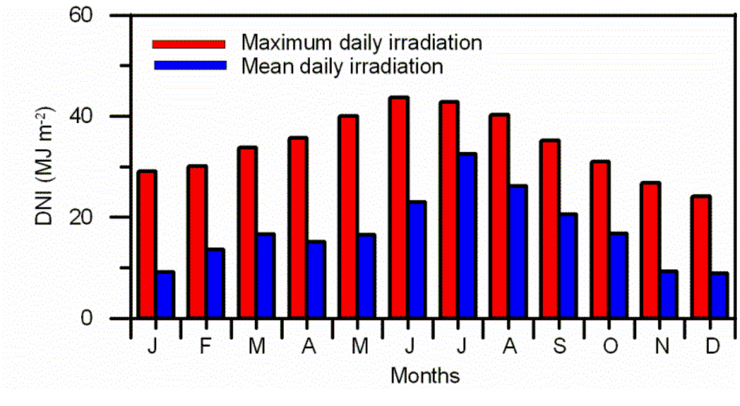

Fig. 1: Annual evolution of maximum and monthly mean daily direct normal irradiation for the period 2010-2012 at Villalba de los Alcores, Valladolid (Spain).

Monthly mean *DNI* values show greater fluctuations in winter and spring due to clouds (Fig. 1) the maximum occurring in July, 32.50 MJ m^{-2}. A relative maximum is shown in March, 17.30 MJ m^{-2} and a minimum in January, 9 MJ m^{-2} (blue lines).

4.3 DNI and global irradiance frequency distributions

An initial analysis of data was performed on the basis of the frequency histograms for 10-min solar data of *DNI* and global irradiance levels. Fig. 2 shows *DNI* frequency distribution, which can be assumed to be a linear combination of three distinct Beta probability functions: exponential, uniform, and asymmetric (Assunçao el al. 2003). The exponential range ($DNI < 100$ W m^{-2}) corresponds to atmospheric conditions in which direct normal solar irradiance is low and frequency is high. These low *DNI* values are due to measurements under low solar altitudes (near sunrise and sunset). The other factor increasing the frequency of low *DNI* values is clouds.

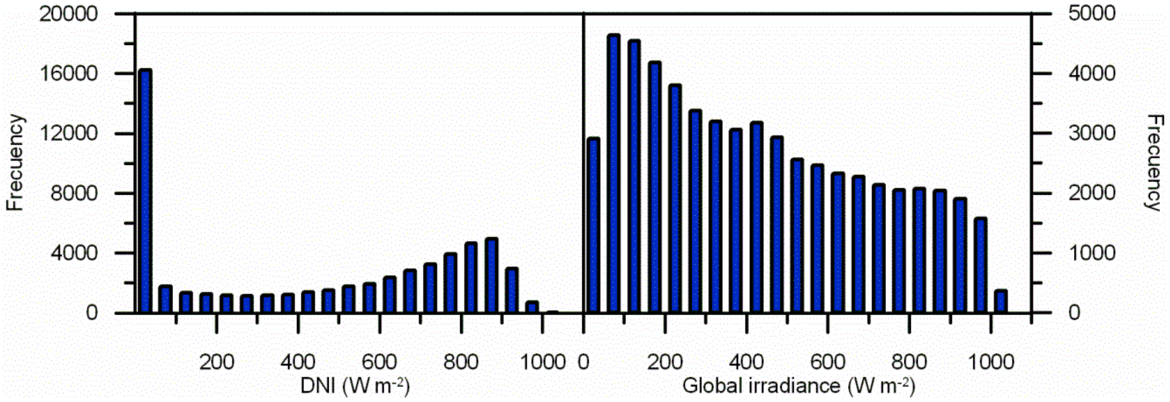

Fig. 2: Direct normal and global solar irradiance frequency distribution for the period 2010-2012 at Villalba de los Alcores, Valladolid (Spain).

Fig. 2 also shows the frequency distribution of global solar irradiance. There is almost a normal distribution with a positive tail, the low irradiance values corresponding to cloud conditions, which have a weaker effect on global than on direct normal irradiance. Frequency decreases as energy increases. The authors found that the bimodal character of the frequency distribution becomes more distinct as the optic air mass increases (Assunçao et al. 2003). In our work, all data have been included, and the study requires an air mass classification which will be taken into account in future research.

4.4 Sky clearness index

Clearness index, K_T, is defined as the relation between global and horizontal solar extraterrestrial irradiation during the same period of time. Taking into account (Iqbal,1975), the sky can be considered as clear ($K_T \geq 0.7$), partly cloudy ($0.3 \leq K_T < 0.7$), or very cloudy ($K_T < 0.3$). From this index, skies can be classified into clear, partly clear, and all sky conditions.

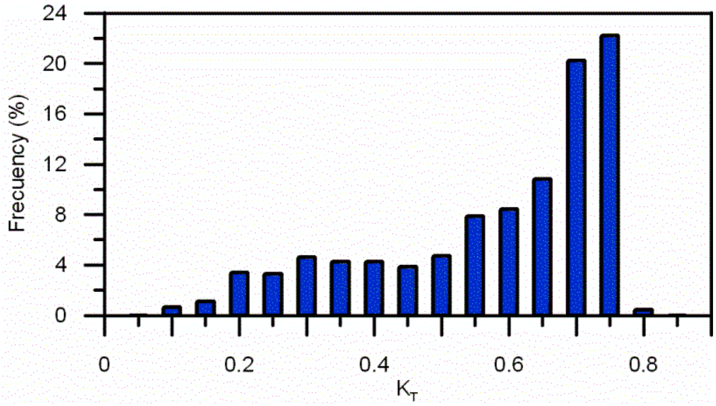

Fig. 3: Clearness index frequency distribution for the period 2010-2011 at Villalba de los Alcores, Valladolid (Spain)

The clearness index at SRSUVA varies between 0.78 and 0.45 in summer time, and in winter, December-March, between 0.7 and 0.25. In our region, clouds affect the clearness index more than any other factor. Clouds may block the sun and thus reduce the clearness index below the unit. Comparing these results with, (Islam et al. 2010), it can be seen that in summer time clear skies are more frequent at SRSUVA than in lower latitude stations; this difference might be explained by the environmental conditions of atmospheric visibility and by the influence of nearby deserts. The frequency distribution of the observed hourly clearness index was evaluated and plotted in Fig. 3. The choice of 0.05 wide clearness index bins demonstrates that this distribution in our region has a maximum mode close to 0.75 clearness index, even though cloud traces and even variations in pressure, ozone, humidity, turbidity, albedo certainly contribute to widen this mode. Fig. 3 also shows that 46% of K_T are above 0.7, meaning that 46% of measurements correspond to clear sky. Compared to other locations, *DNI* reaches high values in Spain during summer, other countries accumulating more hours with moderate *DNI* values, (Islam et al. 2010).

4.5 Statistical characteristics of monthly and yearly average DNI values

The yearly *DNI* average value was 18.03 MJ m^{-2} and the standard deviation 12.50 MJ m^{-2}; maximum daily monthly *DNI* was reached in June, 43.70 MJ m^{-2}, at Villalba de los Alcores solar station (Spain). *DNI* variability has been studied by means of the coefficient of quartile variation V. From this, it can be seen that it fluctuates between 94.64 in January and 16.77 in July. The monthly average values are between the first and third quartile. The frequency histograms for 10-min solar data of *DNI* and global irradiance levels can be assumed to be a linear combination of three distinct Beta probability functions: exponential, uniform, and asymmetric (Assunçao et al. 2003).

4.6. DNI and databases

Tab: 1: Monthly mean daily DNI measured and model values for Villalba de los Alcores station, Valladolid (Spain)

Month	*DNI* (kWh m^{-2} day^{-1})	
	Ground Measured	NASA-SSE model
January	1.79	3.20
February	3.12	4.23
March	3.58	5.36
April	5.44	5.41
May	6.37	6.00
June	8.48	7.38
July	8.16	7.55
August	6.34	6.82
September	6.08	5.83
October	5.02	4.05
November	1.91	3.26
December	2.75	2.83

In addition, there are databases data that provide *DNI* values for different places and time intervals. These databases use different kinds of input data (satellite data, ground measurements) and different procedures to estimate *DNI* values. In this study the measured *DNI* values have been compared with NASA-SSE database, https://eosweb.larc.nasa.gov/project/sse/sse_table.The results are shown in Table 1 and the differences between measured and database values implied an error (relative deviation) of 4.8% in Villalba de los Alcores station, Valladolid (Spain), which means that database overestimates *DNI* and the error in Madrid was -2.5%, the lowest value. As a conclusion, it can be thought that it is difficult to get reliable *DNI* data because database shows different value and there is a source of uncertainty, Table 1 and Table 2. After our study we have observed that the lack of *DNI* data and the availability of global solar irradiance have make interesting to find the most appropriate procedure and model to obtain *DNI* from global solar irradiance in order to know if places are favourable for the use of concentrator solar systems, (Pérez-Higueras et al. 2012).

Tab. 2: Annual DNI values for four Spanish locations (kWh m-2).

Location	Measured	NASA-SSE
Cáceres	2102	2197
Madrid	2029	1978
Valladolid	1806	1880
Villalba de los Alcores	1795	1883

4.7 Simulation DNI 10-min values

Four different algorithms were selected, (Erbs et al. 1982, Maxwell 1987, Skartveit and Olseth 1987, and Perez-Burgos et al 2015) for evaluating *DNI* 10 minutes values. Inputs to all models were the global irradiance, the solar zenith angle and the clearness index. Model performance has been evaluated by the observations of trends in scatter plots (not shown) and by the two statistical estimators *RMSE* and *MBE* taking into account the *DNI* irradiance measurements. For cloudless sky conditions ($K_T \geq 0.7$) and low zenith angle range (0º - 35º), the Maxwell model obtains the lowest values of *MBE* and *RMSE* errors. The comparison between the estimated (Skarveit and Olseth 1987 model) and measured *DNI* values shows a linear fit with a correlation coefficient of 0.969; the study shows that the algorithm proposed by Maxwell (1987) performs better than those proposed by Erbs, Klein and Duffie and Skarveit and Olseth respectively, although each model performs better depending on the atmospheric and climatic characteristics of the place, (Perez et al. 1990).

For clear sky ($K_T \geq 0.70$) Erbs and Skarveit models obtain the lowest *RMSE* (10%). For all data Skartveit and Erbs models obtain *RMSE* of 15%. Under cloudy conditions (K_T = 0.20 - 0.45) all models obtain *RMSE* of 80% except RR model that obtains 50% at Villalba de los Alcores (Spain).

Fig. 4 shows that *RMSE* ranges between 80% and 9%, depending on clearness and for all data, Skarveit, Maxwell and Erbs model gives the best results and also for clear skies, low panels. *RMSE* increases for low values of K_T (0.20 - 0.45). Erbs model does not give good results for k low and intermediate values; Erbs is a model for clear and all sky values.

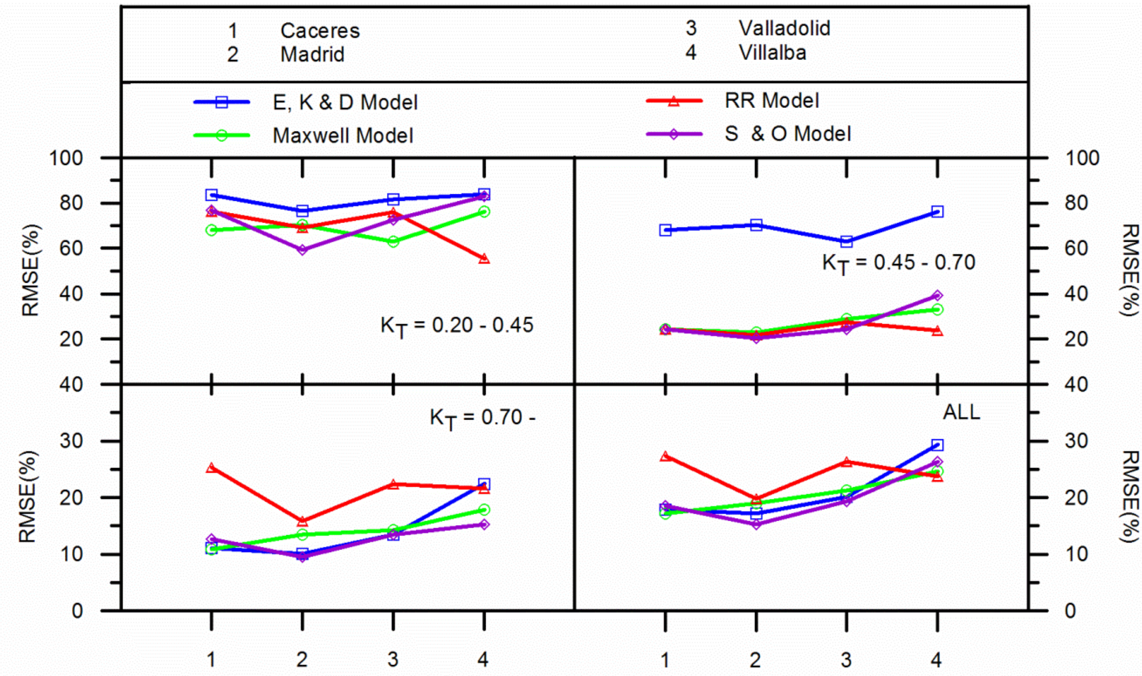

Fig. 4: Model *RMSE* variations as a function of location and clearness index for four different models.

5. Conclusions

Direct normal and global irradiance and meteorological data monitored during the period June 2010 to December 2012 at a radiometric station near Valladolid, Spain were analyzed. Maximum hourly *DNI* ranges between 1006.5 W m^{-2} and 100 W m^{-2}. Daily *DNI* follows the variation of the solar altitude angle and day length, and reaches a maximum in summer and a minimum in winter. Maximum daily *DNI* irradiation occurs on 21 June 2011 with 43.70 MJ m^{-2}.

Measurements were compared to modelled data of the 22-year average of the NASA EES model, the results showing that modelled values are higher than measured ones except in summer months, although yearly mean results are similar in the two series.

When clearness index results are compared to the corresponding values at lower latitudes near desert areas, it was observed that Spanish K_T index values are higher in summer time due the possible presence of desert dust aerosol at lower latitudes. The clearness index results confirm the mostly clear sky conditions, although they are affected by convective evolution clouds during the central hours of the day. In conclusion, it might be said that skies are clearer in the studied region.

Solar *DNI* irradiance was simulated by three different models and the comparison of measured and simulated values shows that the statistical errors increase when the clearness index and solar zenith angle increase.

The findings from this study are interesting for gaining insights into the potential solar energy received in central Spain and for climatology, as well as radiative interaction in the atmosphere, and concentrating solar energy systems.

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