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Abstract

Observations and estimations of solar radiation at ground level deal most frequently with global horizontal irradiance (GHI) while direct irradiance is crucial notably for Concentrated Solar Technology (CST) such as solar energy conversion systems: parabolic through, solar towers, parabolic dish or concentrated photovoltaic. Several global-to-direct irradiance conversion schemes are proposed in the literature. They are obtained by regression of an empirical parametric function with global and direct irradiance measurements made at few stations over a time period. These schemes are well suited to the climatic region where they have been designed, but not likely to other climatic regions. A new method is proposed. A general shape of the relationship between the clearsky index (Kc) and the ratio of the diffuse to global irradiance (fD) is derived from literature and analysis of several data sets of ground measurements. This analytical function needs two parameters. One is defined by the case of the overcast skies; the other is changing depending on the clear-sky conditions for the location and time under concern. A clear-sky model provides the Kc and fD for the clear-sky conditions. The new method was validated against ground measurements made by BSRN ground stations located in Carpentras, Sede Boqer and Tamanrasset. It reveals itself accurate compared to other methods. Indeed, for the data sets used, the bias amounts to 0%, -9% and 10%, the root mean square deviation (RMSD) to 16%, 19% and 21% and the correlation coefficient to 0.98, 0.96 and 0.95. The proposed method is interesting because it is flexible, adaptive and does not rely on empirical parameter.

Keywords: clearsky index, diffuse fraction of irradiance, direct irradiance

1. Introduction

The direct or beam irradiance is the irradiance coming directly from the sun disk, and the diffuse irradiance is the part that undergoes several scattering before reaching the ground. Compared to other meteorological parameters, measuring the beam normal (and horizontal) irradiance (BNI and BHI) is relatively complex and more expensive process. Therefore, observations of solar radiation at ground level deal most frequently with global horizontal irradiance (GHI) and BHI measurements are available only for a limited number of locations. Long term direct irradiance measurements is essential for quantifying CST (Concentrated Solar Technology)-related solar resource potential at a given location. Direct irradiance is also necessary for the evaluation of global irradiance on inclined surface which is needed for photovoltaic systems. Obtaining datasets of direct irradiance is an issue which is often resolved by the application of empirical global-to-direct models. Several models are proposed in the literature. They are obtained by a regression of an empirical parametric function with respect to concomitant measurements of GHI and BNI made at few stations. These models are well suited to a given climatic region but none is found highly accurate overall [1]. Indeed, the limitation of this type of empiric approach is that such transposition models have been established by the mean of a regression on a limited number of ground stations over a limited time period that enable only a scarce coverage in space and in time. Moreover, these transposition models do not have any specific in time and space information about the optical transparency of the atmosphere.

In this paper we propose a new approach for transposition models where local information about the optical transparency of the atmosphere is provided by an irradiance model under clear-sky condition. This should be obtained with physics-based algorithms, with little or no empiricism. From the analysis of the behavior of diffuse fraction of irradiance in all-sky condition, we propose a new method. We then compare it accuracy to that of 7 others found in the literature, against BSRN (Baseline Surface Radiation Network) ground measurements made by BSRN pyranometric ground stations located in Carpentras (CAR), Sede Boqer (SBO) and Tamanrasset (TAM) sites.

2. Variation of the diffuse fraction of irradiance with the clearsky index

The diffuse fraction fD of irradiance is defined as the ratio of the diffuse horizontal (DHI) with the concomitant GHI. The clearness index Kt, respectively the clear-sky index Kc, is defined as the ratio of the GHI with the irradiance at the top-of-atmosphere, respectively with would be measured if the sky is clear (i.e. irradiance under clear-sky condition). The more the scattering due to particles in the atmosphere, the more the diffuse fraction.

The vast majority of existing models are linear or exponential fitting function which link the clearness index (Kt) to the diffuse fraction of irradiance (fD) [1] [2]. The problem of using Kt for direct and diffuse irradiance separation is that with Kt the effects of clouds, aerosols and sun zenith angle (SZA) on solar radiation are mixed up and cannot be discriminated. But the ability of these parameters to scatter the solar radiation is not the same. E.g. when the atmosphere is getting cloudy, the attenuation of irradiance (decrease of Kt) goes with an increase of fD which reaches 1 for cloud optical depth (COD) around 5. The diffuse fraction fD also increases with SZA, but cannot reach 1 in a cloudless and non dusty sky. The advantage of using a relation between Kc and fD is that the Kc is more related to the attenuation due to clouds. The Kc offers the advantage to be able to better discriminate air mass and aerosols effects from the pure cloud attenuation effects.

In order to establish the relationship between fD and Kc, several ground measurements have been analyzed. The figure 1 is made from hourly irradiance measurements at Sede Boqer, for the period 2005 - 2008. It shows that the variation of fD due to Kc can be modeled by the following sigmoid function:

$$fD = 1/(1+\exp(a*Kc + b)) \qquad (1)$$

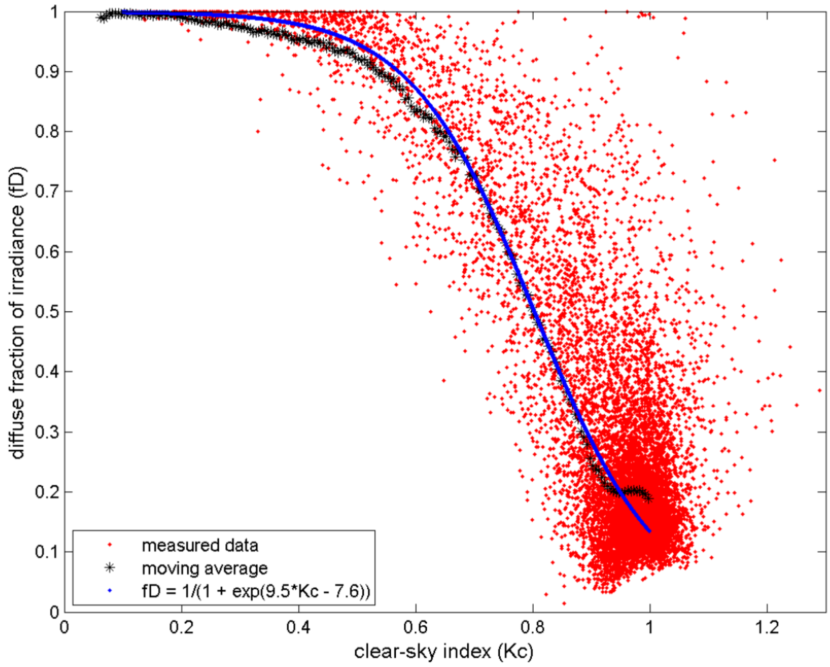

Fig. 1. Diffuse fraction as a function of clearsky index at Sede Boqer

The optimal sigmoid – which corresponds to the minimum root mean square deviation on fD – has as parameters *a* = 9.5 and *b* = -7.6. The moving average is made for an average window of length *N* (number of points) = 10. The figure depicts that the optimal sigmoid has the same shape as the moving average. We also see that the moving average is less or equal to 0.95 when *Kc* is less than 0.3, and is close to, the moving average for *Kc* less than 0.95.

Similar shapes, with different values for *a* and *b*, are obtained at Tamarasset (desert region) and Carpentras (rural area). The parameters *a* and *b* slightly change from a month to another, but remain around 10 for *a* and -8 for *b*.

3. The proposed Global-to-direct method

From the above-mentioned observations, a new method is proposed. The parametric function is still the one defined by eq. 1. A similar function has already been proposed in model [2], but with fixed parameters. This function requires two parameters. We define one from experiment, for the overcast skies, where we fix fD to 0.95 when Kc is less than 0.3 or GHI less than 150 W/m^2. The other parameter is changing depending on the clear-sky conditions for the location and time under concern. Knowing fD for overcast skies and fD for clear skies, the parameters *a* and *b* are estimated in a monthly basis using a linear regression.

fD = 0.95, if Kc < 0.3 or GHI < 150 W/m^2

fD = 1/(1+exp(a*Kc + b)) if Kc > 0.3 and Kc < 1 (2)

fD = fDcs if the sky is clear

fDsc is the ratio of the DHI in clear sky to the GHI in clear sky. A clear-sky model provides the Kc and fD for the clear-sky conditions. The clear-sky irradiances used are derived from the so-called McClear method [2]. This method aims at producing direct and diffuse components of the radiation with accuracy close to that of the LibRadTran radiative transfer model (www.libradtran.org) and on operational basis. It takes as inputs the advanced optical properties of the atmosphere derived within the MACC (Monitoring Atmosphere

Composition and Climate) project. The McClear method is free of empirical data, and can therefore be easily applied to any climatic location. Its validation over 11 BSRN stations worldwide [3] showed high performances on hourly GHI: MBE (mean bias error) = 1 - 8%, RMSD (root mean square deviation) = 5 - 11%.

4. Ground measurements

The ground measurements used are provided by Baseline Surface Radiation Network (BSRN). BSRN (www.bsrn.awi.de) is a project of the Radiation Panel from the Global Energy and Water Cycle Experiment under the umbrella of the World Climate Research Program, aiming at detecting important changes in the Earth's radiation field at the Earth's surface which may be related to climate changes. The network has a about forty stations in contrasting climatic zones, covering a latitude range from 80°N to 90°S. Global direct and diffuse irradiances and other atmospheric parameters are measured with instruments of the highest available accuracy (1 to 3% on irradiances). The time interval for the radiation data compilation is mostly 1 min. A few sites provide data every 3 or 5 min.

We use the BSRN stations Carpentras, Sede Boqer and Tamanrasset (Table 1) for validation. Sede Boqer and Tamanrasset are interesting because there are desert region (where BHI is high), and Carpentras is used to verify the soundness of the method in a continental area.

	Latitude	Longitude	Country	Elevation	Surface type	Period
Carpentras	44.083°	5.059°	France	100 m	Cultivated	2005 – 2008
Sede Boqer	30.905°	34.782°	Israel	500 m	Desert, rock	2005 – 2008
Tamanrasset	22.78°	5.51°	Algeria	1385 m	Desert, rock	2005 – 2008

Table 1. BSRN stations used for validation.

The BSRN data are filtered out using the algorithm by [4]. Only are kept data which obey the following constraints:

$$(DHI + BNI \cos(SZA)) / GHI = 1 +/-8\% \text{ if } SZA <= 75° \quad (3)$$

$$(DHI + BNI \cos(SZA) / GHI = 1 +/-15\% \text{ if } SZA > 75°$$

SZA is sun zenith angle. For this analysis, because we want to avoid non coherent and low GHI, we consider only the cases were solar zenith angle less than 80° and GHI greater than 100 W/m^2

A second filter is applied on the results of Eq 3 to select clear-sky instants. The criteria are the following:

1. for a given instant t, expressed in min, at least 30% of the observations made every 1 min in the intervals [t-90, t] and [t, t+90] respectively should obey these constraints,
2. the variability of the irradiance should be low in order to avoid cases of broken clouds: the standard-deviation of the modified Kt (Kt') in the interval [t-90, t+90] is less than 0.02. Kt' is computed according to [5]:

$$Kt' = Kt / [1.031 \exp(-1.4 / (0.9 + 9.4 / am)) + 0.1] \quad (4)$$

am is the air mass given by [6].

5. Validation of estimated direct irradiances with ground measurements

In order to assess the performances of these methods, the global measurements provided by BSRN are filtered – as described above - to eliminate cases where the 3 irradiance components (global, direct and diffuse) mismatch. Secondly, Kt and Kc are computed at each time step. Then, the GHI, Kt and Kc are averaged every hour. Afterwards they serve as inputs to each method. The estimated BHI are compared to the measured values. All sky data are used, the period is 2005 - 2008. The results are presented in table 2.

	Carpentras mean BHI: 333 W/m^2			**Sede Boqer** mean BHI: 445 W/m^2			**Tamanrasset** mean BHI: 429 W/m^2		
	MBE (W/m^2)	RMSD (W/m^2)	r	MBE (W/m^2)	RMSD (W/m^2)	r	MBE (W/m^2)	RMSD (W/m^2)	r
New method	**1** (0%)	**52** (16%)	**0.978**	-41 (-9%)	83 (19%)	**0.963**	43 (10%)	**92** (21%)	**0.954**
Erbs [7]	24	63	0.971	25	78	0.883	82	136	0.921
Louche [8]	-92	116	**0.979**	-109	132	**0.964**	-38	**92**	**0.949**
Orgill [9]	-29	60	**0.978**	-31	77	**0.963**	37	102	0.939
Reindl [10]	184	237	0.839	156	198	0.886	223	268	0.844
Ruiz-Arias1 [2]	8	57	0.973	11	**74**	0.960	81	131	0.933
Ruiz-Arias2 [2]	-92	118	0.967	-100	128	0.956	**-23**	100	0.933
Skartveit [11]	**-4**	**45**	**0.983**	**1**	**70**	**0.967**	60	114	0.945

Table 2. Comparison of BHI estimated by global-to-direct methods to the measurements.

The methods Erbs, Louche, Orgill, Reindl, Ruiz-Arias1, Ruiz-Aris2 and Skartveit are described respectively in [7], [8], [9], [10], [2], [2] and [11]. They are polynomials and exponential functions, using as inputs the Kt, the measured GHI and the SZA. The Skartveit method also uses an hour-to-hour variability of Kt.

Best performances are marked in bold. The correlation coefficients are higher with the Louche and New method (between 0.98 and 0.96), showing that they reproduce the temporal variation of direct irradiance better than other methods. The root mean square deviation is similar to that obtained with the most accurate models at each station. At Carpentras, the lowest RMSD are 45 W/m^2 (Skartveit) and 52 W/m^2 (New method). At Sede Boqer, the lowest RMS is 70 W/m^2 (16%) obtained with Skartveit, and 19% RMSD is obtained with the new method. At Tamanrasset, the lowest RMSD are 92 W/m^2 (New method) and 92 W/m^2 (Louche). The comparisons also depict that the Reindl method, which depicted very good performances in its "mother-location", gives very high deviations in these stations.

6. Conclusion

Global-to-direct conversion schemes are often needed to derive BHI from GHI ground measurements. They are also necessary as extension of many satellite-based irradiance models, such as Heliosat-2 and NASA SSE, which compute only the GHI. In this paper, we present preliminary results of the development of a flexible and adaptive method. The proposed method assumes that the diffuse fraction in cloudy sky is a sigmoid function of clearsky index. The figure 1 shows that for some values of Kc, the sigmoid is above the moving average and it is below the Kc for others. This leads to an overestimation of BHI for low GHI and underestimation for high GHI and vice-versa. The figure 1 also depicts a significant dispersion around the sigmoid. The Table 1 confirms it with the RMSD which reaches 21% on BHI, higher deviations could be obtained on BNI. These show that other parameters such as cloud properties and the variability of clear sky index should be taken into account for high-accuracy direct irradiance estimation. The estimated BHI is coherent with the BHI under clear sky condition, and its performances are closed to that obtained with the best models. Results need to be confirmed with other ground stations. Improvements on the method, considering the air mass, the variability of clear-sky index and cloud optical properties are ongoing.

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