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Original Article/Research

New model to estimate and evaluate the solar radiation

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Abstract

This research work proposed a new model used to predict the direct, diffuse and global solar flues for clear skies, by making the comparison between the numerical simulation of this model and the climatology measured data of Energetic Laboratory station the Faculty of science of Tetouan city (35.57361 latitude, −5.37528 longitude) in Northern Morocco.

The results indicate that the proposed model can be successfully used to estimate the solar radiation during all the seasons of year for studied position and for considered day, using as input the altitude (degrees), longitude (degrees) and latitude (m).

Keywords: Solar radiation; Solar irradiation; Meteorological parameters; Numerical simulation; Renewable energy

1. Introduction

The estimation of global solar radiation is essential for utilization the solar energy, design wherever appropriate observations missing (Iqbal, 1983). The values of solar radiation in clear skies are useful for determining the maximum performance heating and photovoltaic as well as for the design of air conditioning equipment in buildings or for the determination of thermal load their solar installations (Chiron de La Casinière, 2003).

Sizing and optimal management of energy systems can only be achieved by knowing the weather conditions that extensive studies are carried out in several parts of the world to assess and model the solar potential (Bekkouche, 2008).

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1.1. Measurements and used model

1.1.1. Instrument of measurements

The measurement of global and diffuse radiations at ground was performed by:

- a pyranometer (global solar radiation). This instrument measures the radiation incident on horizontal surface blackened from a solid angle of 2π steradians. The spectral range covers wavelengths from 0.3 to 3 μm. The received radiation is converted to heat by the blackened surface. The temperature difference between the surface and the body of the instrument is proportional to the irradiance of the global radiation; it is measured by a thermopile consisting of several thermocouples connected in series (La Météorologie, 2000).
- a similar pyranometer (diffuse solar radiation) having an added shades band obscure the direct radiation. Depending on circumstances, this screen maybe either a disk or a sphere (La Météorologie, 2000).

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Nomenclature

G_h	global flux received on a horizontal surface (W/m^2)	ψ	Azimuth of the sun (degrees)
I_h	direct flux received on a horizontal surface (W/m^2)	δ	solar declination (degrees)
D_h	diffuse flux received on a horizontal surface (W/m^2)	E_r	mean deference (dimensionless)
I_0	Solar constant (W/m^2)	ω	hour angle (degrees)
C_t	correction of the earth–sun distance	φ	latitude at local studied (degrees)
h	height of the sun (degrees)	λ	longitude at local studied (degrees)
T_{sv}	true solar time (hours)	z	altitude at local studied (m)
		τ_e	sunshine duration (hours)
		τ_j	duration day (hours)
		Γ	the turbidity factor (dimensionless)

1.1.2. Model of calculations

The Solar radiation who reaches the ground is formed by a direct radiation and a diffuse radiation which they are together form the global radiation (Bernard et al., 1980; Bertrand, 1980), we dedicate these respectful radiation respectively by the letters I (direct), D (diffuse) et G (global), all these are calculated with W m^{-2}.

1.1.2.1. Solar radiation on a horizontal surface full south.

1.1.2.1.1. Direct solar flux. It can be calculated by the formula:

$$I_h = I_0.C_t.\Gamma.\exp\left(-\frac{0.13}{\sin(h)}\right).\sin(h) \quad (1)$$

I_0 (W/m^2) is the solar constant, which is defined as the energy flux received by a unit area, in our case, the value that was selected 1367 W/m (Fekih and Saighi, 2010; Wong and Chow, 2001), Γ (dimensionless) is the turbidity atmospheric factor for clear skies (Capderou, 1987; Bouhadda et and Serrir, 2006), Can be calculated by the formula:

$$\Gamma = 0.796 - 0.01.\sin[0.986.(j+284)] \quad (2)$$

C_t (dimensionless) is the correction of the earth–sun distance can be calculated by the equation (Vienne; Ch, Perrin de Brichambrant et Ch, Vauge, 1982):

$$C_t = 1 + 0.034.\cos(j-2) \quad (3)$$

h (degrees) is the height of the sun, can be calculated by the following formula (Daniel and Gautret, 2008; Vienne; Hamdani, 2010):

$$h = \sin^{-1}(\sin(\varphi).\sin(\delta) + \cos(\varphi).\cos(\delta).\cos(\omega)) \quad (4)$$

δ (degrees) is the solar declination can be calculated by the approximate formula given by Cooper (1969) (Daniel and Gautret, 2008; Bird, 1984; La Gennusa and Rizzo, 2007):

$$\delta = 23.45.\sin(0.986.(j+284)) \quad (5)$$

where j is the day number of the year, ranging from 1 on 1 January to 365 on 31 December.

φ (degrees) is the latitude, in this case the Tetouan city in northern Morocco, is given in Table 1:

ω (degrees) is the hour angle of the sun, can be calculated by the following equation (Daniel and Gautret, 2008; Hamdani, 2010):

$$\omega = 15.(12 - T_{sv}) \quad (6)$$

T_{sv} (hours) is the true solar time of the study site, it is determined by the formula (Daniel et al., 2008; Nia et al., 2013):

$$T_{sv} = T_l - DT_l + (D_{hg} + E/60)/60 \quad (7)$$

- T_l: local time.
- DT_l: advance the local time through standard time.
- D_{hg}: the time difference (advance of 4 min per degree).
- E: equation of time, which is calculated by the equation (Raoui et al., 2011):

$$E = 450.8.\sin(2.\pi.j/365 - 0.026903) + 595.4.\sin(4.\pi.j/365 + 0.352835) \quad (8)$$

This formula gives time in seconds.

1.1.2.1.2. Diffuse solar flux. It can be calculated by the formula:

$$D_h = 120.\Gamma.\exp\left(-\frac{1}{(0.4511 + \sin(h))}\right) \quad (9)$$

1.1.2.1.3. Global solar flux. It is the sum of the direct and diffuse solar radiation (Yaïche and Bekkouche, 2008; Mesri-Merad et al., 2012):

$$G_h = I_h + D_h \quad (10)$$

Table 1
The geographical coordinates of the position study.

Position studied	Latitude	Longitude	Altitude
Tetouan City in northern Morocco	−5.37528	35.57361	1

1.1.2.2. Solar radiation on a inclined and oriented surface.
1.1.2.2.1. Direct solar flux. It can be calculated by the next formula (Yaïche and Bekkouche, 2010):

$$I_\theta = \mathcal{R}_I.I_h \tag{11}$$

θ (degrees) is the angle of incidence of solar radiation on a receiver inclined at an angle i with the horizontal and oriented at an angle γ with the south, it is defined by the formula (Bernard et al., 1980, page 76; Koussa et al., 2006):

$$\cos\theta = \sin i.\cos(\psi - \gamma).\cos h + \sin h.\cos i \tag{12}$$

$\mathcal{R}_I$ (dimensionless) is the ratio of the direct solar flux, there is calculated by the empirical equation (Bernard, 2011, page 82):

$$\mathcal{R}_I = \frac{\sin i.\cos(\psi - \gamma)}{\tan h} + \cos i \tag{13}$$

1.1.2.2.2. Diffuse solar flux. It is assumed that the diffuse radiation from the sky or the ground is isotope. Moreover it is considered that the ground is horizontal.

When the receiver is horizontal ($i = 0°$) it receives the diffuse radiation by the sky, and if it inclined at an angle i, it sees less air but against the ground receives a fraction of the quantite a^*. G_h which a^* is ground albedo (Bernard, 2011, pages 80–83; Hofierka and Suri, 2002).

Finally, the diffuse flux for inclined receiver is calculating by the formula (Bernard, 2011, page 82; Yaïche and Bekkouche, 2008, 2010):

$$D_i = \frac{1}{2}(1 + \cos i).D_h + \frac{1}{2}(1 - \cos i).a^*.G_h \tag{14}$$

a^* is the ground albedo of the study position.

1.1.2.2.3. Global solar flux. It is the sum of the direct and diffuse solar radiation (Yaïche and Bekkouche, 2008, 2010):

$$G_\theta = \mathcal{R}_G.G_h \tag{15}$$

$\mathcal{R}_G$ (dimensionless) is the ratio of the global solar flux, there can be calculated by the empirical equation (Bernard, 2011, page 82):

$$\mathcal{R}_G = \left(\mathcal{R}_I - \frac{1+\cos i}{2}\right).\frac{I_h}{G_h} + \frac{1+\cos i}{2} + \left(\frac{1-\cos i}{2}\right).a^* \tag{16}$$

2. Results and discussion

The data of the global and diffuse solar flux have been measured (w/m^2) by the meteorological station of the Laboratory of energy of the Science Faculty of Tetouan, Abdelmalek Essaadi University, Northern Morocco.

The data collected for the period of January–December 2011, 2012 and 2013. The time of recording is 10 min. A computer program has been installed to allow the import of measured data.

2.1. Comparison method

To validate the proposed model, we used the simulation in "Matlab", we have designed for each day considered a program. From each of these programs, we firstly prepared in the same diagram, curves representative of the measured values and the values estimated by the proposed model (Saheb-Koussa et al., 2006).

On the other hand, we have presented a model performance (Batlles et al., 2000; Gueymard, 1993a) using the means relative deference, Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE) and The Test Statistic (TS) between the measured values and those estimated by the proposed model.

The mean global solar flux G_{mean} (W/m^2) (Mechlouch et and Ben Brahim, 2001) is given by the following formula:

$$G_{\text{mean}} = \sum_i \frac{G_i}{i} \tag{17}$$

The daily global solar irradiation (kwh/m^2) is given by the following formula (Bernard, 2011, page 86):

$$G^* = \frac{2}{\pi}.\tau_j.G_{ms} \tag{18}$$

with G_{ms} (W/m^2) is the global solar flux for the solar noon and τ_j is the day length.

The monthly global solar irradiation (kwh/m^2) is given by the next following formula (Bernard, 2011, page 86):

$$G^*_m = N_j.G^*_{15} \tag{19}$$

with G^*_{15} (W/m^2) is the daily global solar irradiation for 15th day of the month and N_j is a number of the month's days.

We have calculated the relative difference between the global solar radiation of the measured data and those estimated by proposed model for each day considered. This mean relative difference can be calculated by the following equation (Yaïche and Bekkouche, 2008):

$$\varepsilon_r = abs\left(\frac{G_{\text{measured}} - G_{\text{estimated}}}{G_{\text{measured}}}\right).100 \tag{20}$$

The mean relative difference can be calculated by the formula (Christian, 2003):

$$\varepsilon_{\text{mean}} = \sum_i \frac{\varepsilon_{ri}}{i} \tag{21}$$

Other, the performance of the proposed model has been evaluated based on the following well established statistical error parameters (Sivamadhavi et al., 2012):

(i) Mean Bias Error (MBE) defined as:

$$MBE = \frac{1}{K}\Sigma\left(G^i_{\text{estimated}} - G^i_{\text{measured}}\right) \tag{22}$$

where K is the total number of observations, $G^i_{\text{estimated}}$ and G^i_{measured} are the ith observed value and ith calculated value of global radiation.

The test of MBE provides information on the long term performance of the models. A positive MBE gives the average amount of over estimation in the predicted values and a negative MBE value gives the average amount of under estimation in the predicted values. One drawback of this test is that over estimation in one observation will cancel the under estimation in another observation (Batlles et al., 2000).

(ii) Root Mean Square Error (RMSE) defined as:

$$\mathrm{RMSE} = \left(\frac{1}{K}\Sigma\left(G^{i}_{\text{estimated}} - G^{i}_{\text{measured}}\right)^{2}\right)^{1/2} \tag{23}$$

The RMSE is always positive, a zero value is ideal. This test provides information on the short-term performance of the models by allowing a term by term comparison of the actual deviation between the calculated value and the measured value.

(iii) Mean Absolute Percentage Error (MAPE) defined as:

$$\mathrm{MAPE} = \frac{100}{K}\Sigma\left|\frac{\left(G^{i}_{\text{estimated}} - G^{i}_{\text{measured}}\right)}{G^{i}_{\text{measured}}}\right| \tag{24}$$

The MAPE avoids this error cancelation problem. But, normally this test parameter is not preferred in the analytical point of view because the absolute value of error is not a differentiable quantity. It is always positive.

(iv) The Test Statistic (TS) defined as:

$$TS = \left[(K-1)MBE^{2}/(RMSE^{2} - MBE^{2})\right]^{1/2} \tag{25}$$

Apart from these statistical tests, the *t*-statistic test proposed by Stone (1993) was also employed to assess the proposed models. This method has the added advantage of telling whether the model's estimates are statistically significant or not at a particular confidence level (See Figs. 1–19) (Aissani and Mokhnache, 2008; Yettou et al., 2009).

Figure 1. The meteorological station energy systems laboratory of the Faculty of science of the Tetouan.

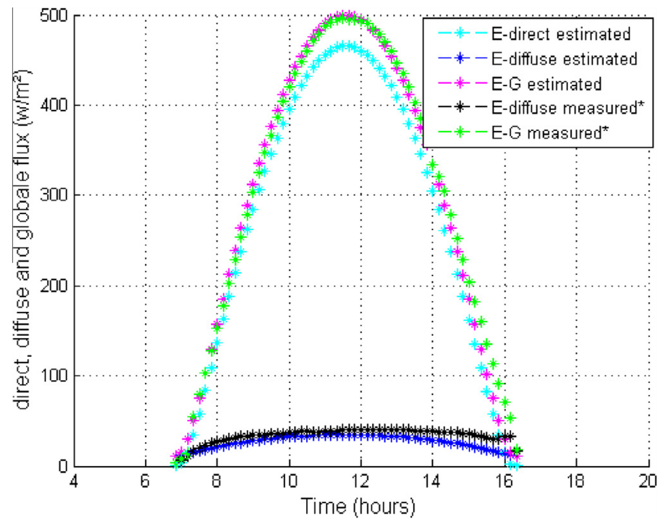

Figure 2. Direct, diffuse and global solar flues for 1 January 2013.

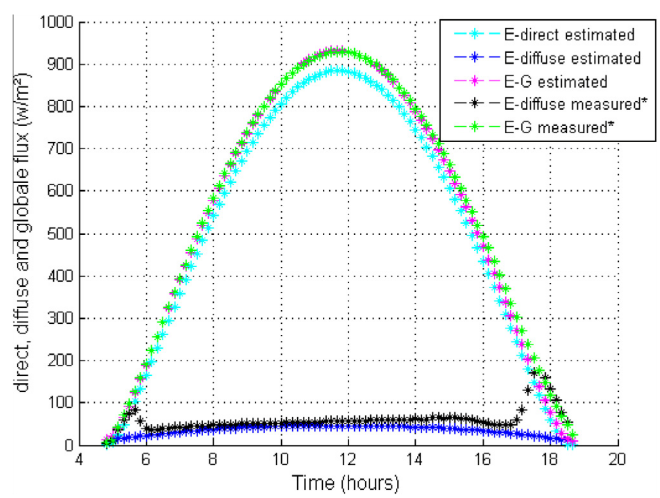

Figure 3. Direct, diffuse and global solar flues for 22 May 2013.

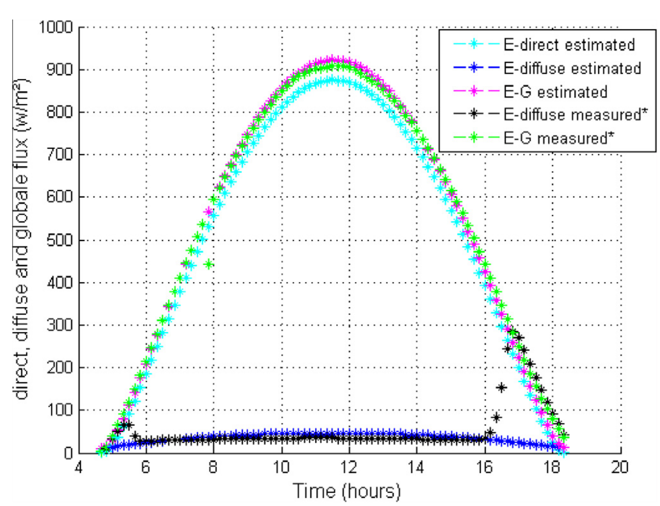

Figure 4. Direct, diffuse and global solar flues for 28 July 2013.

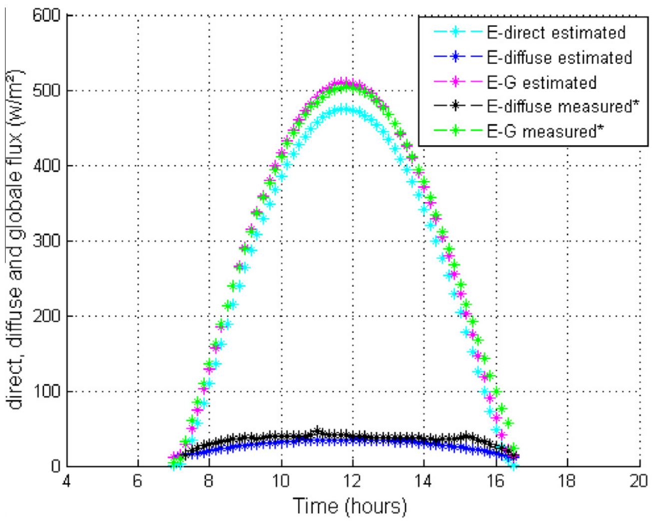

Figure 5. Direct, diffuse and global solar flues for 4 December 2013.

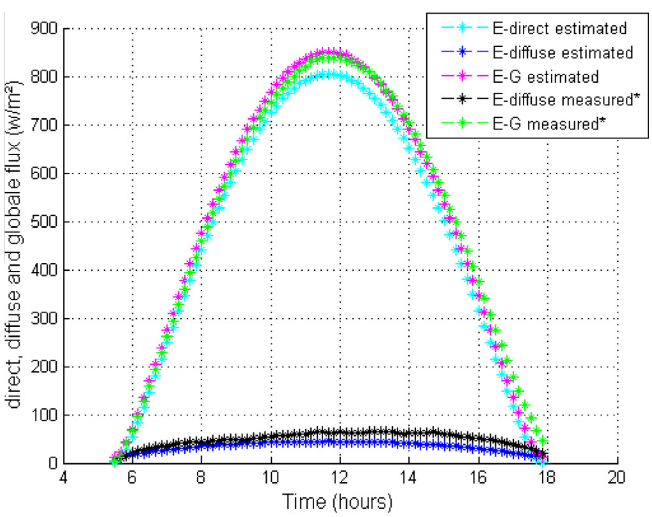

Figure 6. Direct, diffuse and global solar flues for 5 September 2012.

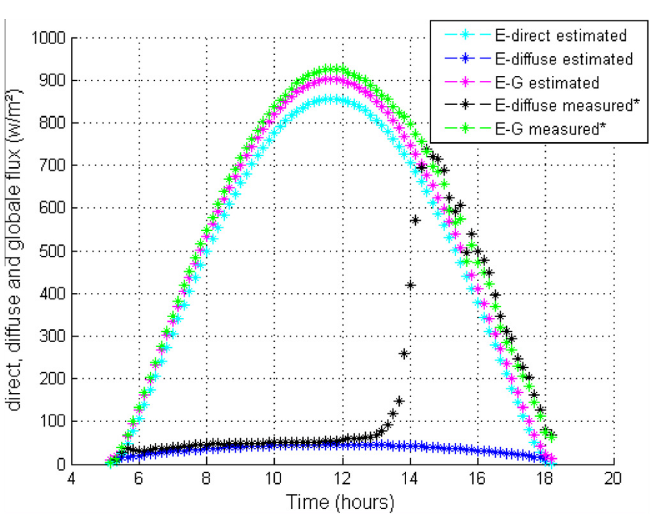

Figure 7. Direct, diffuse and global solar flues for 25 April 2012.

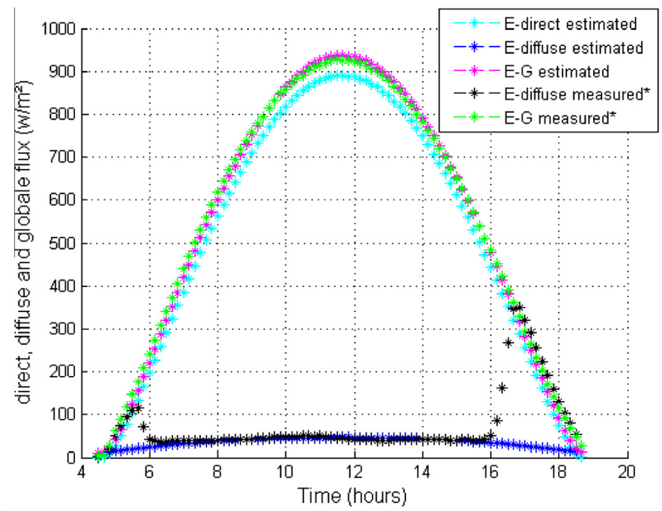

Figure 8. Direct, diffuse and global solar flues for 10 June 2012.

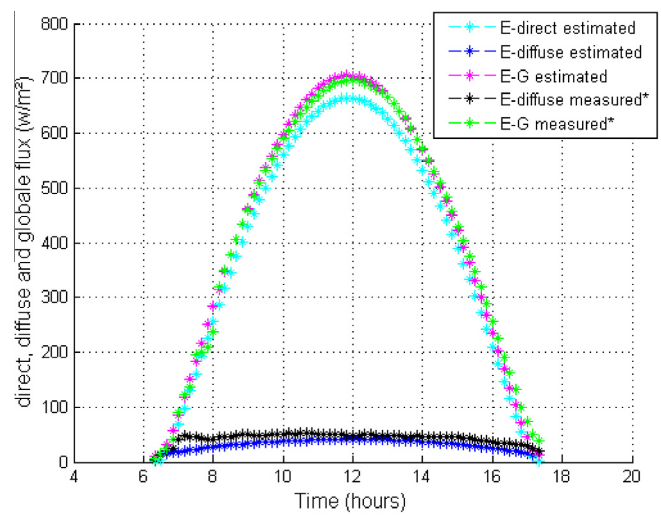

Figure 9. Direct, diffuse and global solar flues for 12 October 2012.

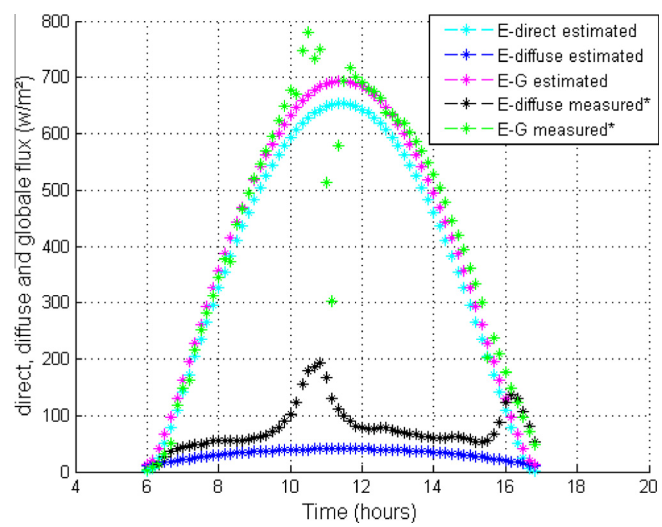

Figure 10. Direct, diffuse and global solar flues for 25 February 2011.

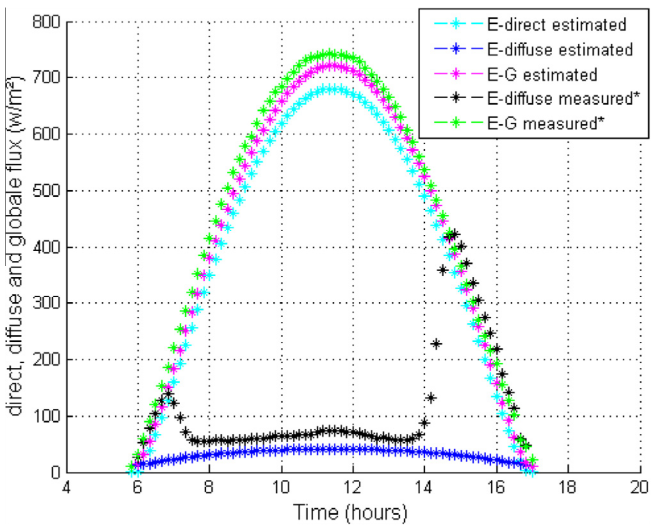

Figure 11. Direct, diffuse and global solar flues for 3 March 2011.

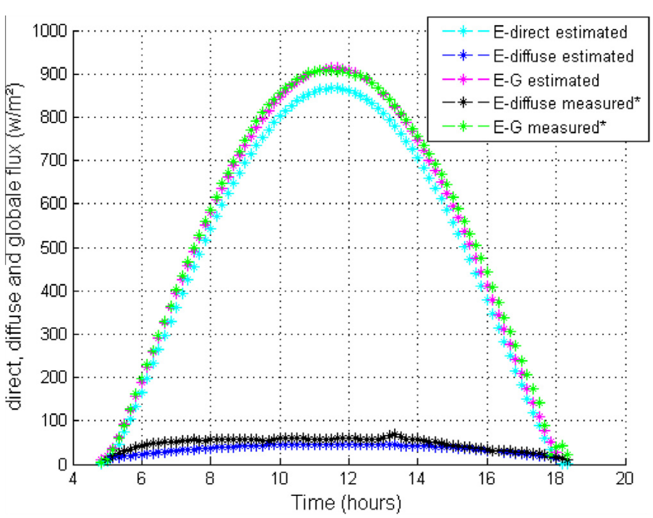

Figure 12. Direct, diffuse and global solar flues for 5 August 2011.

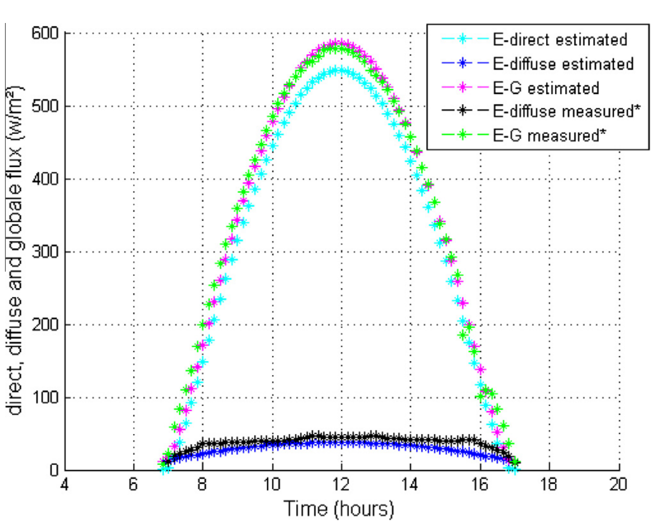

Figure 13. Direct, diffuse and global solar flues for 8 November 2011.

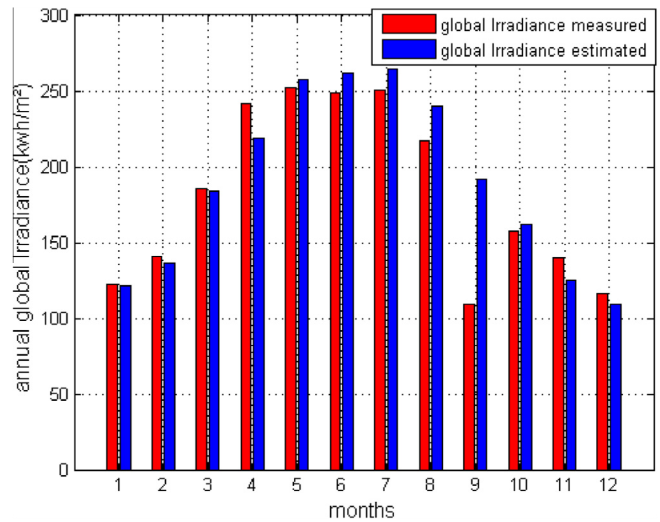

Figure 14. Annual global irradiation of 2011.

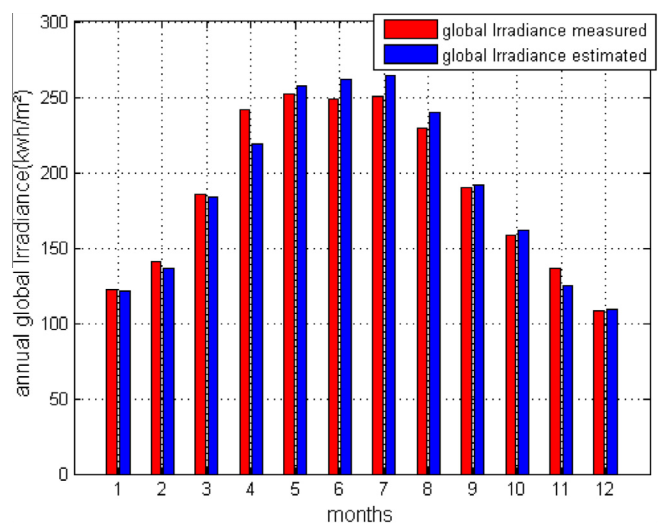

Figure 15. Annual global irradiation of 2012.

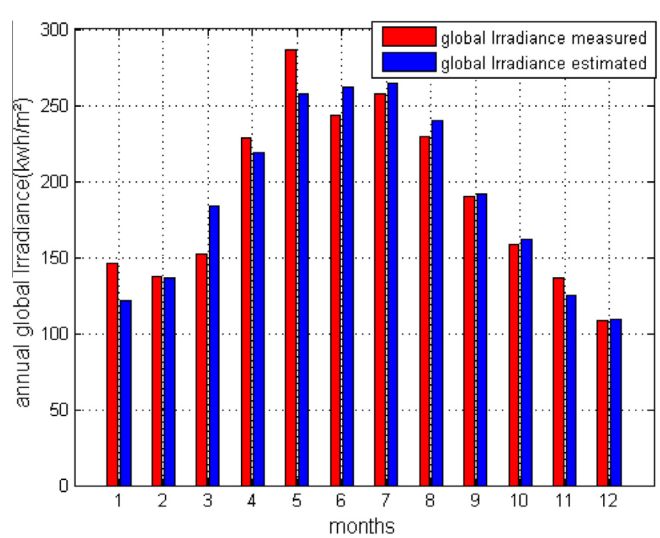

Figure 16. Annual global irradiation of 2013.

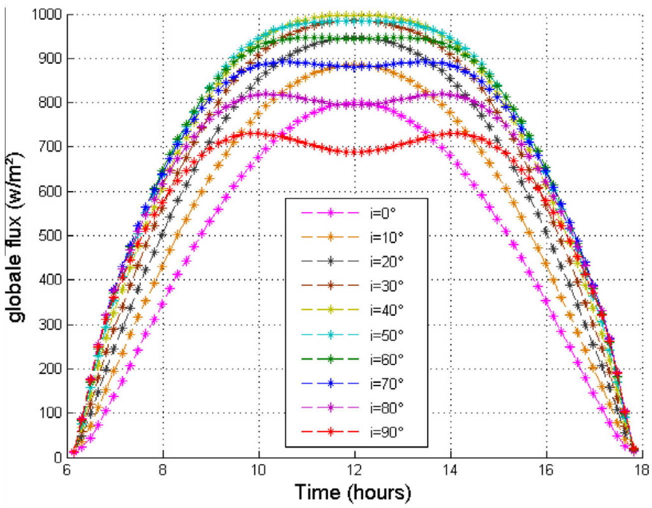

Figure 17. Global solar flux of the 21st day of March and September (the equinoxes) for different inclination angles.

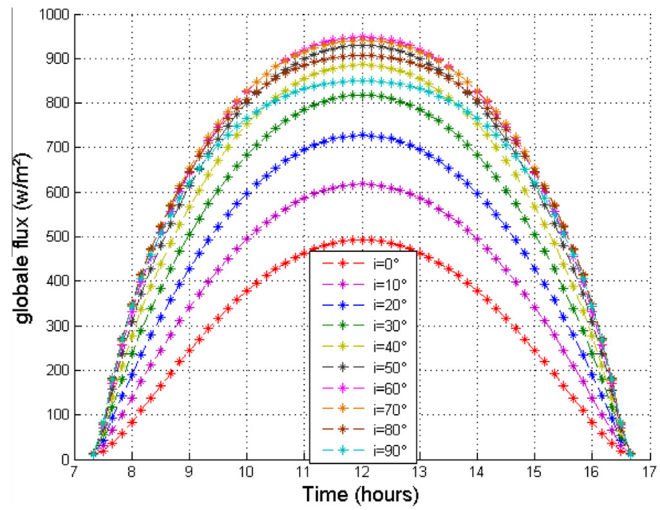

Figure 19. Global solar flux of the 21st day of June (Winter Solstice) for different inclination angles.

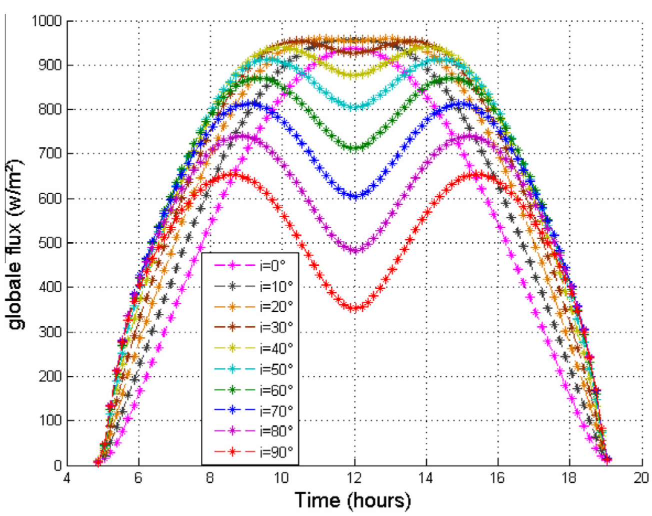

Figure 18. Global solar flux of the 21st day of June (Summer Solstice) for different inclination angles.

3. Numerical simulation

From the figures representing the global, diffuse and direct solar flues, from January 1 to December 31, 2013, for clear skies, we can say the model that we have proposed gives a good approximation for all the year, except in cases of very cloudy skies (Perez et al., 1990), the mean relative difference in 2013 does not exceed 5% except in the case of sunrise and sunset when the height of the sun is very low.

This explains the general expressions for calculating the solar radiation given by this model take into account the factor of atmospheric turbidity (Diabaté et al., 2003; Kasten, 1996), which is by definition a function of absorption and extinction coefficients to atmospheric constituents such as ozone O_3 the water vapor (H_2O to gaseous state) (Gueymard, 1993b), aerosols, air molecules and other gases (O_2, CO_2) (Tourta et al., 2012).

According to figures drawn above, we note that the estimated global solar flues with that measured by the station of Energetic Laboratory of the Faculty of Sciences, Abdelmalek Essaadi University, Tetouan, in northern Morocco. From January 1 to December 31, 2012 are superimposed.

The problem that we have is for the diffuse flux measured where the instrument used (pyranometer equipped cache) is configured manually according to the solar declination, which requires the presence permanent.

In this work, we tried to examine our proposed model for all months of the year, again, we note that the proposed model provides a good approximation of the solar flux received on a horizontal plane throughout the year, where the relative mean difference estimated with those measured value is reduced and does not exceed 5%, except in the case of sunrise and sunset.

In the following figures, we present an annual global solar irradiation estimated and measured for three years 2011, 2012 and 2013.

The monthly irradiation is calculated by the formula (19), where it takes into account the number of days in the month and daily irradiation of the 15th day of the month, in addition, if the sky is not clear to this day we won't have a good monthly approximation, for this it can be seen on Figure drawn well above the global irradiation that there are months where the monthly irradiation measured and estimated that there are a little close together.

The solar irradiation varies according to the inclination and orientation of the receiver, in addition, the numerical simulation shows that it's to receive the maximum solar energy, an inclination and orientation of the receiver should vary according to a declination of the sun.

Table 2
The performance evaluation of the proposed model for each day considered.

Day of the Year	Statistic study			
	RMSE	MBE	MAPE	TS
1 January 2013	11.9261	−6.0997	12.7121	407.7745
22 May 2013	13.4291	−9.6053	12.0686	7.5592e+03
28 July 2013	17.3766	−1.6224	13.3180	0.5328
4 December 2013	9.1294	−3.8295	10.8448	153.3777
25 April 2012	35.1028	−30.7410	38.9815	6.7572e+04
10 June 2012	18.1967	−5.5855	15.2004	78.1764
5 September 2012	14.9232	−2.2817	15.1328	3.2231
12 October 2012	11.0985	−2.3001	12.2900	9.0407
25 February 2011	62.7110	−7.2296	50.9330	0.7665
3 March 2011	28.9194	−26.3440	39.3920	1.0357e+05
5 August 2011	14.2039	−9.8890	14.5086	5.8058e+03
8 November 2011	19.4978	−6.4935	23.5181	57.9074

Estimation of the solar flux in plane the different inclination angles is shown in the following figures:

The global flux has a maximum value for the receiver facing south and inclined $i = 40°$ at the equinoxes when the declination of the sun is zero, for $i = 10°$ at the summer solstice where the declination of sun is a maximum value 23.45° and by $i = 60°$ in the winter when the declination of the sun has a maximum value −23.45° solstice.

In the next table we present the performance evaluation by certain error parameters (MBE, RMSE, MAPE and TS) of the proposed model for each day considered (See Table 2).

4. Discussion

The MBE, RMSE, MAPE and TS values obtained considering the study position individually and together are shown in next Figs. 20–22.

The RMSE and MAPE obtained for clear skies are uniform and also that obtained values less than 15%, except in case of the cloudy skies.

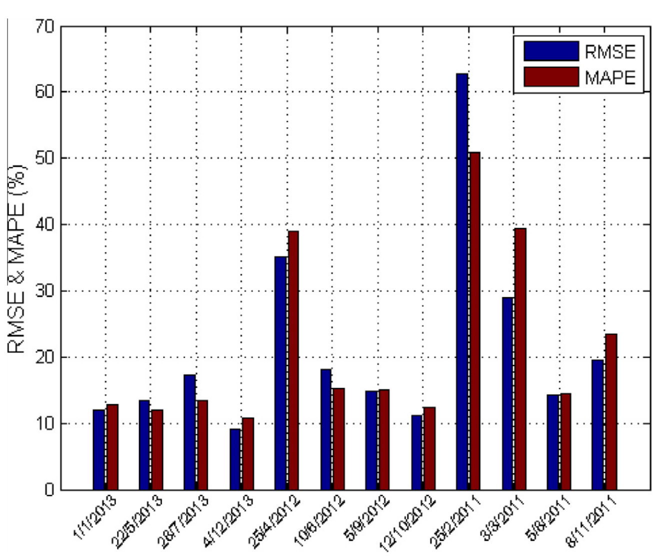

Figure 20. The RMSE and MAPE statistic study.

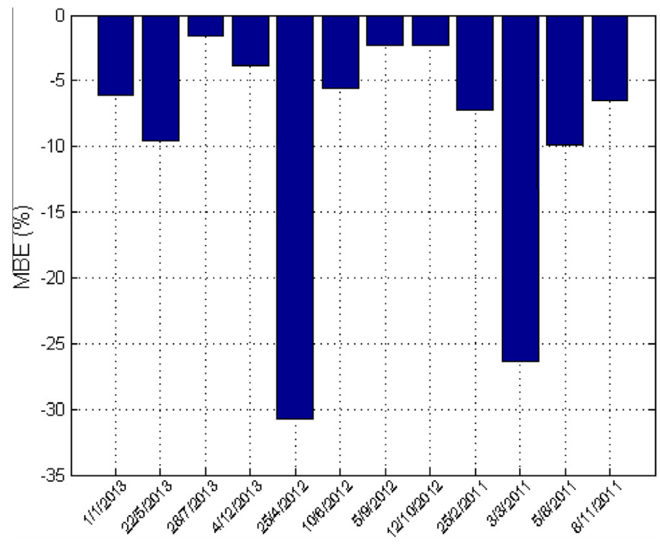

Figure 21. The MBE statistic study.

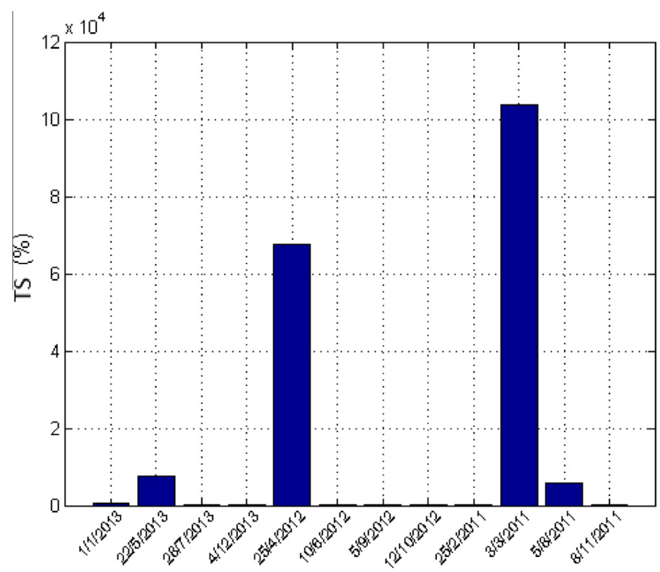

Figure 22. The TS statistic study.

Further discussions will be focused, the value of performance evaluation factor MBE obtained is slightly lower. Values of certain error parameters for cloudy skies are slightly higher than that of clear skies. This indicates that the model proposed in this study has generalized well for clear skies.

In addition, according to the figures drawn previously:

It can be seen that the diffuse and global solar flues estimated by the proposed model is almost superimposed with that measured by the energy station Laboratory for clear skies during all seasons of the year.

The means relative difference of the data processed, day by day, of diffuse and global solar flues incident on a surface horizontal is accepted, where this difference does not exceed 5%, except in the case of sunrise and sunset.

Finally, we can say that the use of this model gives a good estimation of solar radiation in Tetouan city in northern Morocco for all months of the year.

5. Conclusions

The study of the solar radiation is the starting point of any investigation for a new energy. The power energy incident on an inclined plane is more appropriate than that incident on a horizontal plane. The development of the confrontation was performed using a series of measurements of global and diffuse solar radiations on a horizontal surface. Data processing is performed on measures chosen by having clair skies couvrant the years 2011, 2012 and 2013 collected every ten minutes.

Finally, the proposed model is generally favorable to estimate the solar radiation incident on a horizontal or inclined plane.

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