International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Impact Factor (2012): 3.358

Estimate of the Direct, Diffuse and Global Solar Radiations

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Abstract: ***The purpose of this work is to develop the models, which will be used to predict the daily direct, diffuse and global solar radiation data for clear skies by combining simulations through these models, and climatology measured of the station of Energetic Laboratory of the Faculty of Sciences, Abdelmalek Essaadi University, Tetouan, in northern Morocco. We used two empirical models: Capderou [4,19,23,26] and Perrin & Brichambaut ([1 pages 74-90,3,36])models; the latter uses meteorological data: of sunshine duration, The Linke Turbidity Factor [19, 21], albedo. The results obtained indicate that the proposed models can successfully be used for the estimation of the daily solar radiation data for the days considered. In addition, these model scan be generalized for an application of PV systems in Solar Buildings.***

Keywords: Solar radiation, Meteorological parameters, Numerical simulation, Renewable energy.

Nomenclature

- G : Global flux on horizontal surface (W/m²).
- I : Direct flux on horizontal surface (W/m²).
- D : Diffuse flux on horizontal surface (W/m²).
- I_0 : Solar constant(W/m²).
- C_t : Correction factor of the Earth-Sun mean distance (dimensionless).
- h : Height of the Sun (degrees).
- T_{sv} : True solar time (hours).
- ψ : Azimuth of the Sun (degrees).
- δ : Solar declination (degrees).
- E_r : Relative difference (dimensionless).
- ω : Hour angle (degrees).
- φ : Latitude at local studied (degrees).
- λ : Longitude at local studied (degrees).
- z : Altitude at local studied (m).
- S_e : Sunshine duration (hours).
- S_j : Day length (hours).
- T_L : The Linke turbidity factor (dimensionless).

1. Introduction

The Earth receives daily a large flux of solar energy. The power of this radiation based on several criteria, weather, atmospheric diffusion (dispersion phenomena, reflection and absorption). Knowledge of solar radiation is essential for the calculation of various performance-related solar systems, such as solar water heaters, photovoltaic systems, solar concentration, but also for the construction of buildings with a view to a better thermal insulation adapted to local climate and also for heating houses and rooms by solar energy. The usage examples are only increase over time. However, the development of these sectors cannot be achieved without a thorough knowledge of solar radiation. In this work, we intend to show how the solar radiation at ground level by latitude, season, time of day and weather conditions. It also outlines the measures taken by the weather station of the Laboratory for Energy and the Faculty of Sciences to compare the results obtained by the models estimates with those of the station.

1.1 Solar Gisement

1. Earth-Sun distance:

The trajectory of the Earth around the Sun is an ellipse with the Sun at one of the foci. The mean Earth-Sun distance varies from 144 (21 December) to 154 million Km (21 June) [6,7]. The correction coefficient of the Earth-Sun distance (dimensionless) can be calculated by the equation [1, 6, 7]:

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

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

2. Solar declination

The solar declination δ (degrees) is the angle between the direction of the Sun with the equatorial plane of the Earth [4]. The declination varies from-23°27’ at the winter solstice to +23°27’ at the summer solstice, while at the equinoxes is zero [6].

The solar declination can be calculated by the equation given by Copeer (1967) [1-page 22]:

$$\delta = 23.45.\sin(0.986.(j + 284)) \quad (2)$$

3. Hour Angle:

The hour angle ω (degrees) is the angle between the meridian plane passing through the center of the Sun and the vertical plane of the place (meridian) and defines the true solar time T_{sv} (hours) [20]. The hour angle can be calculated by the next equation [5,32] :

$$\omega = 15.(12 - T_{sv}) \quad (3)$$

with T_{sv}(hours) is the true solar time of the local studied and it is determined by the relationship:

$$T_{sv} = T_l - DT_l + (D_{hg} + E/60)/60 \quad (4)$$

- T_l : local time (hours).
- DT_l : Difference of local and standard time (hours).

- D_{hg} : the time difference (advance of 4 minutes per degree).
- E : equation of time, which is calculated by the equation (second):

$$E = 450.8.sin(2.\pi.j/365 - 0.026903) + 595.4.sin(4.\pi.j/365 + 0.352835) \quad (5)$$

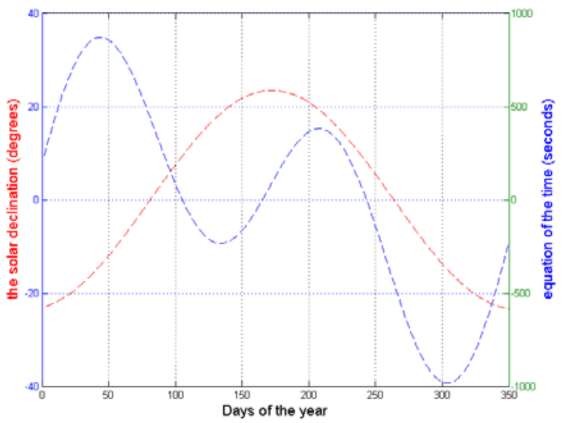

Figure 1: The evolution of the solar declination and equation of the time during the year

4. Geographical coordinates

The geographical coordinates of the studied location are represented by the latitude φ (degrees), longitude λ (degrees) and altitude h or z (m), where the latitude is the angle between the position study with the equator and longitude is the angle between the meridian of the study with the meridian position [1,6].

Table 1: The geographical coordinates of the position study

Position studied	latitude	longitude	altitude
Tetouan in northern Morocco	-5.37528	35.57361	1

5. Height of the Sun

The height of the Sun h (degrees) is the angle between the horizontal planes with the direction of the Sun. The value $h = 0$ is at sunrise and sunset, The Height of the Sun varies between 90 ° (zenith) and -90 ° (nadir) [20] and it is calculated by the following formula:

$$h = \sin^{-1}(sin(\varphi).sin(\delta) + cos(\varphi).cos(\delta).cos(\omega)) \quad (6)$$

6. Azimuth of the Sun

The azimuth of the sun ψ (degrees) is the angle on the horizontal plane, being the projection of the direction of the Sun with the direction to the south. The azimuth is between -180 $\leq \psi \leq$ 180 ° [4], and it is a function of the solar declination δ, Height of the Sun h and hour angle ω ;can be calculated by the next formula:

$$\psi = \sin^{-1}(cos(\delta).sin(\omega)/cos(h)) \quad (7)$$

7. Day length

It is calculated by the following formula [20]:

$$S_j = 24(1 - cos^{-1}(tan(\delta).tan(\lambda))/\pi) \quad (8)$$

It is expressed in hours.

8. Sunshine duration

It is calculated by the following formula [20]:

$$S_g = \frac{2}{15}.cos^{-1}(-tan(\varphi).tan(\delta)) \quad (9)$$

It is expressed in hours.

2. Materials and Methods

1. Instrumentations

The measurement of global and diffuse radiations at ground was perfomed 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 wave lengths 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 [9].

a similar pyranometer (diffuse solar radiation) having an added shades band obscure the direct radiation. Depending on circumstances, this screen may be either a disc or a sphere [9].

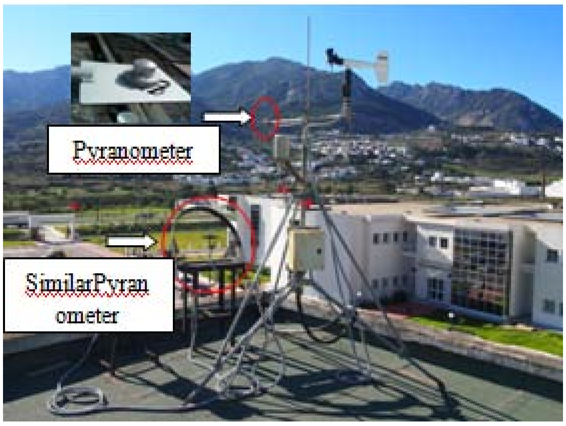

Figure 1: The meteorological station laboratory energy systems of the Faculty of science of Tetouan

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 [1], 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. The Cooper and Perrin of Brichambaut Models

The Cooper model [1] calculates the solar flues (Cooper 1992) [1-Page 74] as :

- The direct flux can be calculated by :

$$I = I_0.\sin(h) \quad (10)$$

- The diffuse flux can be calculated by:

$$D = 125(\sin(h))^{0.4} \quad (11)$$

- The global flux can be calculated by:

$$G = I + D \quad (12)$$

More specifically, in Perrin brichambaut model [1-3,36], the above relationships are transformed into the following ones according to the atmospheric conditions and climatic conditions ([1] pages 74-90) and ([3] Table III.6 page 91):

- Areas with air pollution
  - Direct flux :

$$I_{min} = 1260\ \exp\left(-\frac{2{,}23}{4\sin(h+1)}\right) \quad (13)$$

- Diffuse flux :

$$D_{min} = 166{,}67(\sin(h))^{0,4} \quad (14)$$

- Global flux :

$$G_{min} = 995(\sin(h))^{1,25} \quad (15)$$

- Normal conditions
- Direct flux :

$$I_{mean} = 1230 \exp\left(-\frac{1}{3{,}8\sin(h+1{,}6)}\right) \quad (16)$$

- Diffuse flux :

$$D_{mean} = 125(\sin(h))^{0,4} \quad (17)$$

- Global flux :

$$G_{mean} = 1080(\sin(h))^{1,22} \quad (18)$$

- Clear Skies
- Direct flux :

$$I_{max} = 1210 \exp\left(-\frac{1}{6\sin(h+1)}\right) \quad (19)$$

- Diffuse flux :

$$D_{max} = 93{,}75(\sin(h))^{0,4} \quad (20)$$

- Global flux :

$$G_{max} = 1130(\sin(h))^{1,15} \quad (21)$$

2. The Capderou Model

The Capderou model [4,19,23,26] uses the atmospheric turbidity to calculate the direct and diffuse components of solar radiation received on horizontal plane. The absorption and diffusion caused by the atmospheric constituents can be expressed by turbidity factors [19], the knowledge the atmospheric turbidity factor refers to determine the solar radiation for clear skies.

The most commonly used is the Link turbidity factor T_L, which for clear skies is given by [28]:

$$T_L = T_0 + T_1 + T_2 \quad (22)$$

With T_0 (dimensionless) is the turbidity factor the gaseous absorption [23]. The modeling of this factor based only on geo-astronomical parameters, is given by the following expression :

$$T_0 = 2{,}4 - 0{,}9\sin(\varphi) + 0{,}1(2+\sin(\varphi))A_{he} - 0{,}2Z - (1{,}22 + 0{,}14A_{he})(1-\sin(h)) \quad (23)$$

T_1 (dimensionless) is the turbidity factor of absorption by atmospheric gases [23] (CO_2, O_2, O_3), can be calculated by the formula :

$$T_1 = 0{,}89^Z \quad (24)$$

T_2(dimensionless) is the turbidity factor caused by aerosols [23], and can be calculated by the formula:

$$T_2 = (0{,}9 + 0{,}4A_{he})0{,}63^Z \quad (25)$$

With Z (m) is the altitude of the location [4] :

We set :

$$A_{he} = \sin((360/365)(j-121)) \quad (26)$$

✓ **Direct solar radiation :**

It can be calculated by the formula [19]:

$$I = I_0 . C_t . \exp\left(-T_L . \left(0{,}9 + \frac{9{,}4 . \sin(h)}{T_1}\right)^{-1}\right) . \sin(h) \quad (27)$$

✓ **Diffuse solar radiation :**

It can be calculated by the formula [19]:

$$D = I_0 . C_t . \exp(-1 + \log(\sin(h)) + a - \sqrt{a^2 + b^2} \quad (28)$$

With :

$$a = 1.1 ;\ b = \log(T_L - T_0) - 2.8 + 1.02.(1 - \sin(h))^2 \quad (29)$$

✓ **Globale solar radiation :**

It is the sum of the direct and diffuse solar radiation [19]:

$$G = I + D \quad (30)$$

3. Results and Discussion

The diffuse and global solar flues were measured ($W.m^{-2}$) by the meteorological station of the Energy Laboratory of the Sciences Faculty of Tetouan, Abdelmalek Essaadi University, Northern Morocco. The collected data cover the period January-December 2013 and consist of 10-min averages, there are 52416 measurements. A computer program was installed to import the measured data.

1. Comparison Method:

For a validation of the solar radiation, we'll confront some values for clear skies, the solar radiation provided by the meteorological station of Tetouan, with values on the horizontal plane calculated by Matlab. The following figures present the comparative graphs of the direct, diffuse and global solar radiations, for the Cooper [1,3], Perrin Brichambaut [1,3], and Capderou [4,19,23,26] models, with the experimental data of the site.

The mean global solar flux is given by the following formula:

$$G_{mean} = \sum_i \frac{G_i}{i} \quad (31)$$

The daily global solar irradiation ($KWh.m^{-2}$) is given by the followingformula [3] (page 86) :

$$G^* = \frac{2}{\pi} . S_j . G_{ms} \quad (32)$$

With G_{ms} is the global solar flux of the solar noon and S_j the day length.

The monthly global solar irradiation ($KWh.m^{-2}$) is given by the following formula [3] (page 86) :

$$G_m^* = N_j . G_{15}^* \quad (33)$$

With G_{15}^* the daily global solar irradiation of the day 15 of the month and N_j is a number of days in the month.

Other, we have drawn on the same diagram the relative difference for the global solar radiation between the measured values and those estimated by each model for each day considered. This relative difference is calculated by the following equation [19] :

$$E_r = abs\left(\frac{G_{mesured} - G_{estimated}}{G_{mesured}}\right) . 100 \quad (34)$$

The mean relative difference can be calculated by the formula [37]:

$$E_{mean} = \sum_i \frac{E_{ri}}{i} \quad (35)$$

2. Numerical Simulation:

a. The Cooper and the Perrin Brichambaut Models :

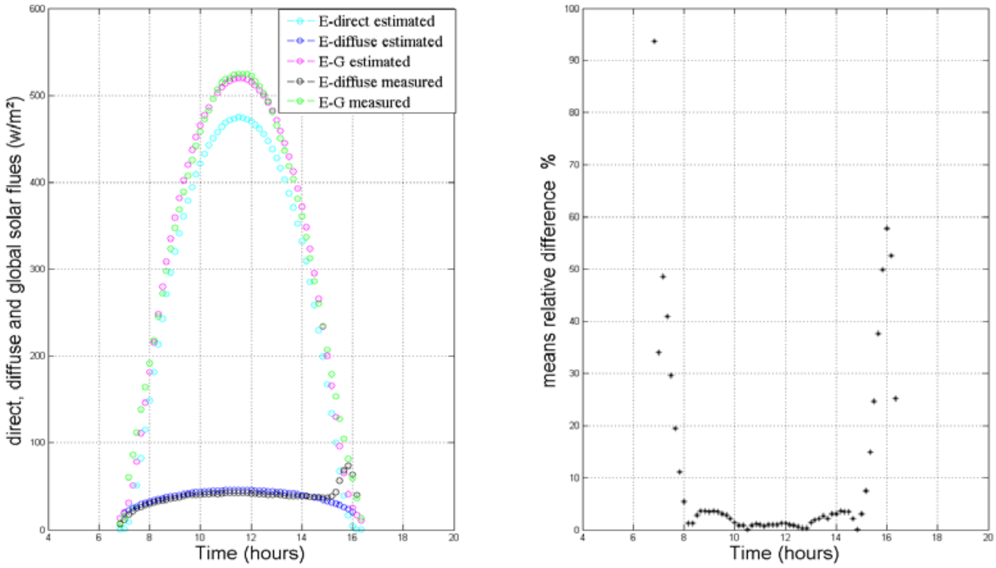

Figure 3 : direct, diffuse and global solar flues & means relative deference for 6 January 2013

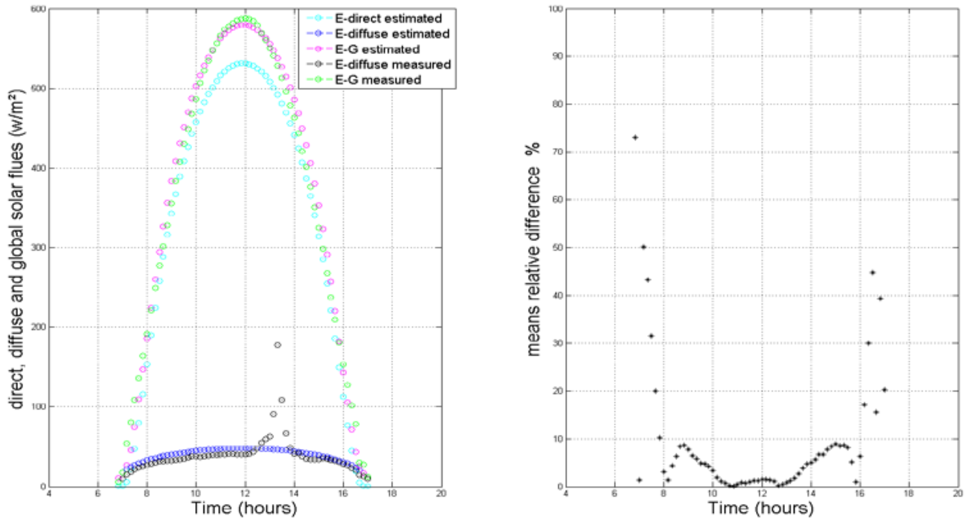

Figure 4 : direct, diffuse and global solar flues & means relative difference for 8 November 2013

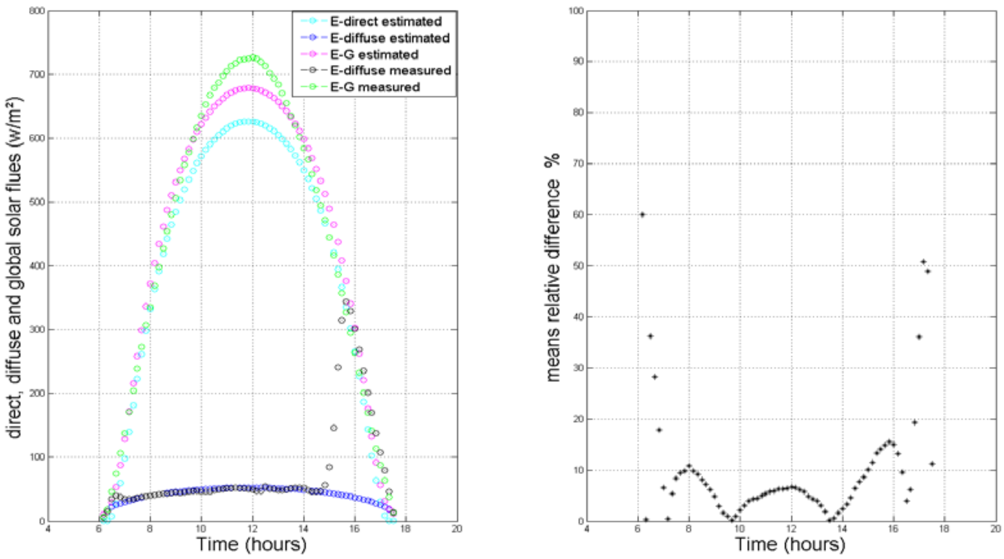

Figure 5 : direct, diffuse and global solar flues & means relative deference for 4 October 2013

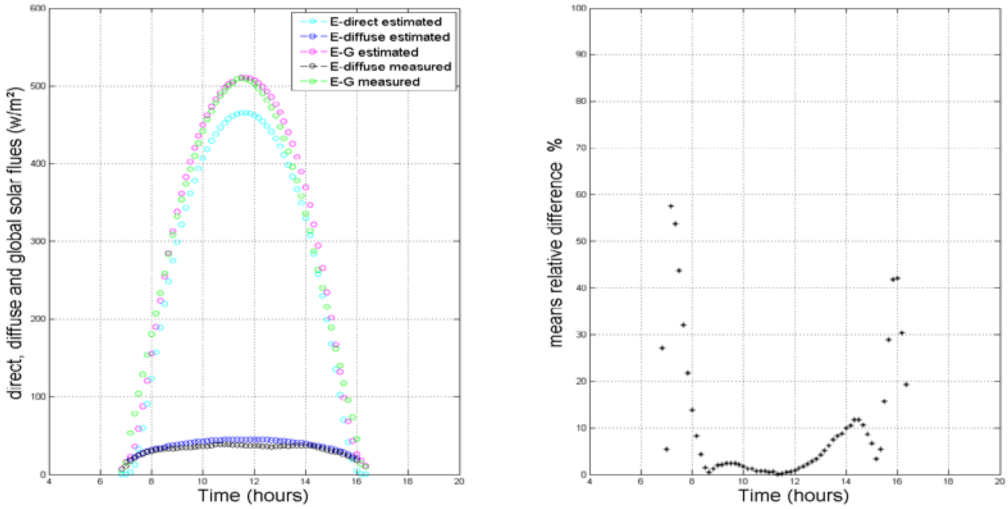

Figure 6 : direct, diffuse and global solar flues & means relative deference for 28 December 2013

a. The Capderou Model :

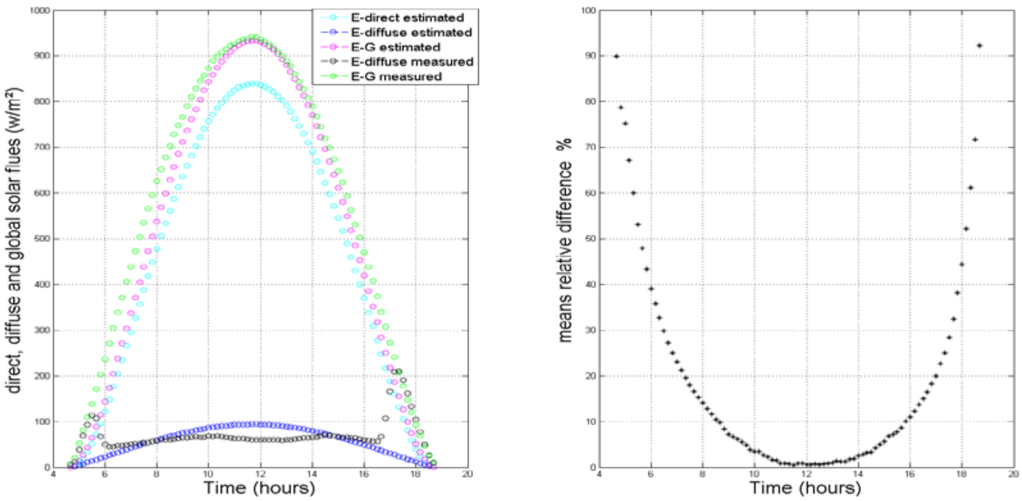

Figure 7 : direct, diffuse and global solar flues & means relative deference for 24 May 2013

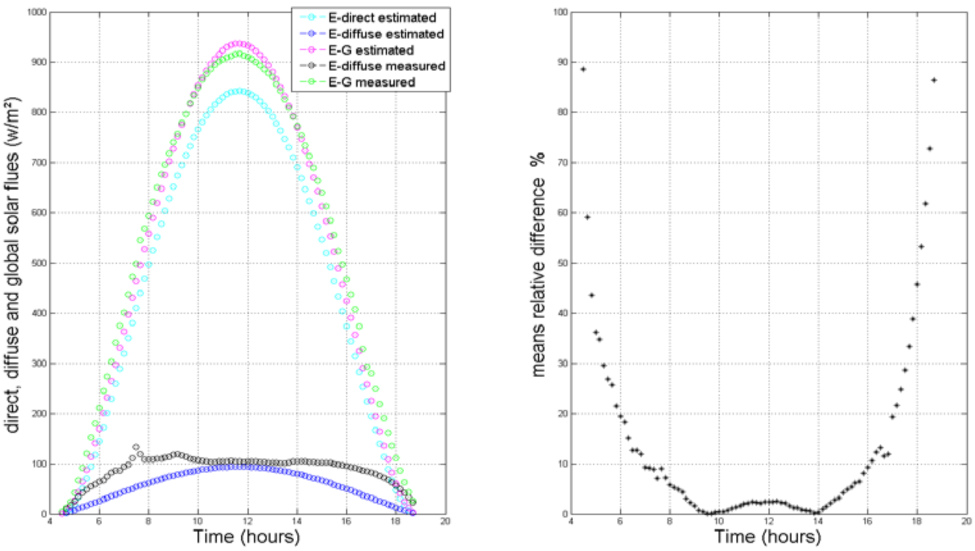

Figure 8 : direct, diffuse and global solar flues & means relative deference for 12 June 2013

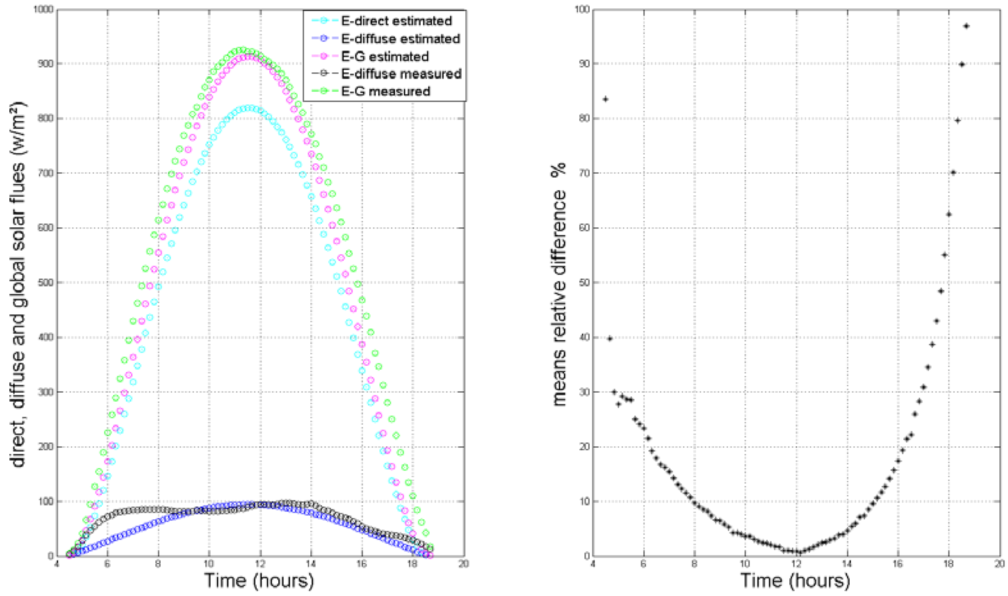

Figure 9 : direct, diffuse and global solar flues & means relative deference for 10 July 2013

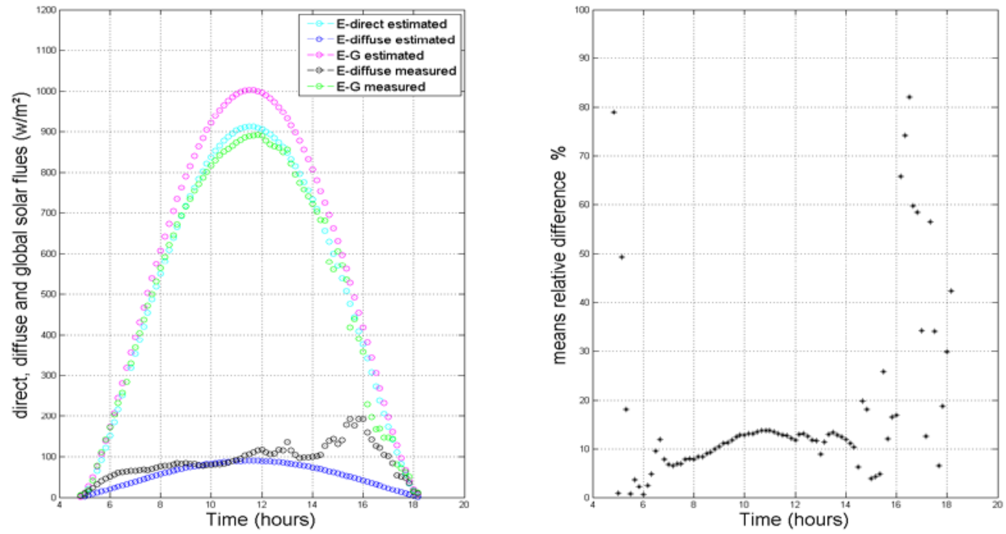

Figure 10 : direct, diffuse and global solarflues & means relative deference for 10 August 2013

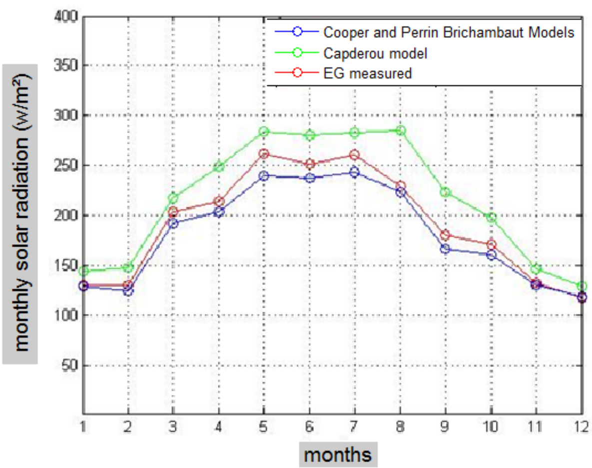

Figure11:monthly global radiation $kwh.m^{-2}$

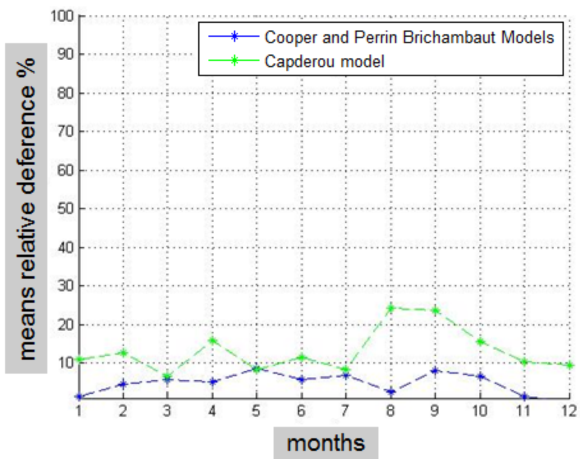

Figure12: monthly means relative deference %

The sunshine duration, during of day, the declination, the global flux measured and those estimated by the two models and the means relative deference are given in the following table 2 (Annex1), and the daily, monthly and annual global solar irradiance measured by the two models are given in the following table 3 (Annex 1).

4. Discussion

According to the figures drawn previously :
It can be seen that the diffuse and global solar flues estimated by the Cooper and Perrin Brichambaut [1-3,36] models are almost super imposed with those measured by the energy laboratory station for winter months (December, January, February) where the sun can reach lower heights. The diffuse and the global solar flues estimated by the Capderou [4,19,23,26] model are almost super imposed with those measured by the energy laboratory station for the summer months (May, June, July, August), where the sun can reach great heights.

On the figures of the relative difference and the results of the Table 3.1, we can say, in general, that the relative difference of the data processed, day by day, diffuse and global flues incident on a horizontal surface are accepted to the winter months for Cooper and Perrin Brichambaut [1-3] models and to summer months for Capderou model [4,19,23,26], where this relative difference does not exceed 10% except in the case of sunrise and sunset solar.
Finally, we can say that the use of Cooper and Perrin Brichambaut [1-3,36] model gives a good estimate of the solarr irradiance for the winter months compared to summer months, and the use of Capderou [4,19,21,23,27] model gives a good estimate for the summer months compared to winter months, and this is due to the use of empirical formulas for calculating the link turbidity factor (formulas 22-26 previous).

5. Conclusion

In this work, it was developed and presented the models of calculations of solar radiation for the site of Tetouan in northern Morocco, and this matter will be considered for any day and for any month of the year, this work can be used as a tool for calculating the monthly and annual solar radiation for solar concentration systems or solar water heating systems.

To validate our work, we compared the measured data by energy laboratory station of sciences faculty of Tetouan, for clear skies, and the solar energy estimated by the empirical models : the Cooper and the Perrin Brichambaut [1-3] models, the Capderou model [4,19,21,23,27]. The results are very satisfactory and we can say that the work is an interesting and necessary tool to estimate the solar power at a given position, in our case to the Tetouan city in northern Morocco.

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Annexure 1

Table 2: Resultsof calculationof the means relative deference for solar radiation on horizontal plane by two models

Months	Number Days of the Month	Day length (hours)	sunshine duration (hours)	Declination of the Sun (degrees)	The Mean $EG_{measured} W.m^{-2}$	The Means $EG_{estimated} W.m^{-2}$		The means relative deference (%)	
						The Cooper and the Perrin Brichambaut Models	The Capderou Model	The Cooper and the Perrin Brichambaut Models	The Capderou Model
January	23	11,743	10,03	-19,733	344,01	347,67	339,05	11,772	9,6338
February	6	11,793	10,417	-16,14	383,9037	378,683645	384,35	15,8707069	13,374
March	25	12,11	11,919	-0,85193	507,44	472,1	479,79	14,772	16,233
April	12	12,789	12,104	8,2492	528,66	496,74	541,66	15,155	10,075
May	24	14,078	12,271	20,707	566,16	598,94	533,91	17,679	16,316
June	12	14,358	12,306	23,145	544,15	605,62	531,76	26,781	11,014
July	10	14,255	12,293	22,258	552,61	600,74	519,51	28,019	15,549
August	15	13,344	12,176	13,835	523,83	512,42	579,47	14,508	13,992
September	17	12,14	12,018	1,479	476,98	480,99	528,22	10,8	11,908
October	4	11,933	11,493	-5,3333	444,06	444,18	447,07	9,823	11,023
November	8	11,777	10,291	-17,332	360,3	364,95	345,71	9,4106	12,017
December	28	11,692	9,6259	-23,277	310,37	313,21	308,11	10,385	11,283

Table 3: Results the calculation of the relative difference for global solar irradiance

Months	Number Days of the Month	Number Days of Month	Daily $EG^{*}_{mesured}$ $KWh.m^{-2}$	Daily $EG^{*}_{estimated} KWh.m^{-2}$		Monthly $EG^{*}_{mesured}$ $KWh.m^{-2}$	Monthly $EG^{*}_{estimated} KWh.m^{-2}$	
				The Cooper and the Perrin Brichambaut Models	The Capderou Model		The Cooper and the Perrin Brichambaut Models	The Capderou Model
January	23	31	4,1977	4,1404	4,6563	130,13	128,35	144,35
February	6	28	4,6547	4,4428	5,2495	130,33	124,40	146,99
March	25	31	6,5764	6,1892	7,0175	203,87	191,86	217,54
April	12	30	7,1401	6,7645	8,2779	214,2	202,93	248,34
May	24	31	8,4426	7,7198	9,1418	261,72	239,31	283,40
June	12	30	8,3913	7,9060	9,3550	251,74	237,18	280,65
July	10	31	8,4125	7,8381	9,1248	260,79	242,98	282,87
August	15	31	7,3908	7,1973	9,1917	229,11	223,12	284,94
September	17	30	6,0207	5,5417	7,4406	180,62	166,25	223,22
October	4	31	5,5229	5,1552	6,3811	171,21	159,81	197,82
November	8	30	4,4091	4,3467	4,8626	132,27	130,40	145,88
December	28	31	3,7931	3,8020	4,1574	117,59	117,86	128,88
Annual global solar radiation $KWh.m^{-2}$						2283,6	2164,5	2584,9