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STUDY OF DIRECT SOLAR RADIATION in OUARZAZATE (MOROCCO)

H. Nfaoui* & A. Sayigh**
* Solar Energy & Environment Laboratory, Faculty of Sciences, B.P.1014 Rabat, Morocco.
**Chairman of WREC & Director General WREN, Editor-in-chief Renewable Energy
P O Box 362, Brighton BN2 1YH, UK. Email: nfaoui@fsr.ac.ma

Abstract

The first step in using photovoltaic and solar thermal plants is the study of the direct radiation on a normal surface, H_{bn}, and the choice of the right tilt angle, s, for its panels. Solutions depend on whether the panels are fixed (s remains constant) or are mobile (biaxially or uniaxially fellow the sun, change of tilt several times a year). However, whatever the chosen position, this requires to have availabl the measured data of H_{bn} in the considered site.

Ouarzazate region will accommodate the first large integrated solar project plants (500 MW) for electricity production on a large scale. As, H_{bn} is a very important component for concentrating systems and for the estimation of the radiation received by titled surfaces, we have been studying its characteristics. On the other hand, the sunshine duration is being measured in Ouarzazate station since 1957 and with the absence of H_{bn}, we determined a relationship between direct radiation and sunshine duration. This correlation allows us to compute the direct radiation from sunshine records with the same climatic conditions. Looking forward to have available the direct radiation records in order to compare them with the estimated ones to check if the statistical characteristics of H_{bn} are faithfully reproduced

So, the results obtained should be improved as far as the stochastic characteristics of H_{bn}, is concerned. Although, the considered correlation has been established for Ouarzazate, this relation could be extended to other areas in the country, with some corrections.

Key words: Direct radiation, estimation, stochastic, photovoltaic, concentrated Thermo-Solar, electricity.

1. INTRODUCTION

More than 85% of Morocco energy in use is imported. The Morocco government policy is to reduce their dependence on imported fossil fuels and to diversify energy sources by using significantly photovoltaic panels and Concentrated Thermo-Solar (CST) power station. As planned, Ouarzazate region will hold the first largest solar plant (500 MW) in Morocco for electricity production. The first phase would focus on 160MW and the first kilowatthours ought to have produced in 2015.

The CTS are devoted to high sunny regions, it means an important direct radiation on a normal surface, H_{bn}, within this framework comes our contribution to the statistical study of solar radiation particularly H_{bn}. For this reason, it is seemed important to study the characteristics of solar potential of Ouarzazate region because we have available the data of sunshine and the global radiation on a horizontal surface. On the other hand, the largest solar plant will be installed there [1-4].

2. EXTRATERRESTRIAL SOLAR RADITION

a. Global radiation on normal surface

The average intensity or power/unit area falling on a surface of unit area placed at the earth's outer atmosphere and at right angles to the incident radiation is called the solar constant, Io. In SI units the solar constant, I_0, is 1367 W/m^2. For a considered day, j, Io could be calculated with the aid of the following formula [5-13]:

$$I_0=1367(1+0{,}034\cos(0{,}986(j-3)) \quad (1)$$

j: day number

The daily solar radiation, H_{on}, is:

$$H_{on}= I_0.N \quad (2)$$

Where the maximum day length, N, is expressed in hours and H_{on} in Wh/m^2.

b. Global radiation on horizontal surface

In a given site, for a given date and hour, the energetic enlightenment on an extraterrestrial horizontal surface is linked to I_0 by [5-13]:

$$I_{oh} = I_0 \sin(h) \quad (3)$$

The daily radiation, H_{oh}, is obtained by integration of the previous equation. The integration variable is the True Solar Time (TST), t:

$$H_{oh} = \int_{t_1}^{t_2} I_o \sin(h) dt \quad (4)$$

Where t_1 and t_2 are the sunset and sunrise respectively, with $t_1 = t_2$

As, the hourly angle, ω, could be expressed in the form [5-13]:

$$\omega = 15(t_{heure}-12) \quad (5)$$

t: hourly day (TST)

And the solar height, h, could be given by [5-13]:

$$\sin(h) = \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(w) \quad (6)$$

φ : site latitude; δ : solar declination and ω : hourly angle.

According to the equation (5): dw =15dt (dw is expressed in degrees and t in hours) and using the formula (6). What they give:

$$H_{oh} = (\frac{24}{\pi}) I_o \int_o^{w_0} (\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(w))dw \quad (7)$$

After integration, we obtain:

$$H_{oh} = (\frac{24}{\pi}) I_o (w_o \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(w_o)) \quad (8)$$

ω_o is expressed in radians, I_{on} in W/m² and H_{oh} in Wh/m².

2.2. Representative days

For each month of the year, it is about the day for Ouarzazate site which N and H_{oh} are equal to monthly average values, noted down by $\overline{N}$ and $\overline{H_{oh}}$. The importance of these 12 representative days is that they permit to determinate the extraterrestrial monthly average of global radiation by realizing the calculation only for one day: the representative day of the considered month.

As, there is several formulas for calculating I_{on} and δ, with different precisions, the formulas used, are the ones accepted for selecting the representatives days for Rabat site [6]. Table 1 shows the list of representative days with day numbers, the values of δ, N and H_{oh} for Ouarzazate site.

Table 1: Représentative days of the daily average of the month, sun declination δ, maximum day length N, monthly average of the extraterrestrial solar radiation, H_{oh}, and H_{on}

Month	Selected days	Day N°	δ (°)	N(hours)	H_{oh}(kWh/m^2/day)	H_{on}(kWh/m^2/day)
January	17	17	-20.93	10.23	5.76	14.44
February	14	45	-13.65	10.88	7.02	15.27
March	16	75	-2.46	11.80	8.65	16.30
April	15	105	9.37	12.76	10.18	17.32
May	14	134	18.52	13.54	11.10	18.13
June	6	157	22.63	13.93	11.43	18.48
July	18	199	21.03	13.78	11.22	18.21
April	17	229	13.17	13.08	10.46	17.44
September	16	259	1.88	12.15	9.14	16.44
October	16	289	-9.90	11.20	7.47	15.41
November	15	319	-19.10	10.40	6.02	14.54
December	12	346	-23.17	10.02	5.36	14.13

2.3. Deduction of direct radiation on normal surface from global and diffuse radiations for Rabat site

Since July 1982 to December 1989, the Energy Solar and Environment Laboratory has available the hourly direct radiation on a normal surface and the hourly global radiation on a horizontal surface. The daily direct radiation on horizontal surface, H_b, is calculated from the measurements of the direct enlightenment on normal surface, $I_{bn:}$

$$I_b=I_{bn}\sin(h) \tag{9}$$

And the corresponding daily direct radiation H_b, by integration of I_b during the day:

$$H_b = \int_{t_l}^{t_c} H_{bn}\sin(h)dt \tag{10}$$

This integration has to be numerically done on account of random climatic behavior and rapid enlightenment variation due to the presence of clouds.

For the calculation of H_b, the trapezium method is used, by dividing the daily interval of the integration into successive hourly intervals, because the variation of I_{bn} as a function of h is practically negligible in an interval of 1 hour (mainly between 10 h and 14 h where the intensity is maximal).

Thus, appointing by $\overline{\sin(h_i)}$ the value of sin(h) for the middle of the considered hourly interval, i, and $(H_{bn})_i$ the corresponding value of the direct radiation on normal surface, the relation (10) can be written as:

$$H_b = \int_{t_l}^{t_c} H_{bn}\sin(h)dt = \sum_{i=1}^{k}(H_{bn})_i\overline{\sin(h_i)} \tag{11}$$

Where k is the number of day hours.

The study of concentrated solar systems, such CTS Plants, necessitate the knowledge of direct solar enlightenment. However, few are the methodological stations where this component is measured. For these reason, several informatics software have been proposed to estimate this component from the estimation of global and diffuse radiations, but, generally, they are limited to the monthly average.

Having available the monthly average of direct radiation on normal surface obtained from the measurement for Rabat site [6], the equation (11) has been modified and used to estimate the monthly average of the direct radiation on normal surface:

$$\overline{H_b} = \overline{H_{bn}} \sum_{i=1}^{k} \overline{\sin(\mathrm{h})_i} \qquad (12)$$

Where k is the hour number of the considered representative day.

We notice that this method under estimate the values of $\overline{H_{bn}}$ by 15% in average (Table 2). This could be due to the narrow dependence of H_{bn} to the atmosphere nature (clouds, humidity, etc…) and the traversed distance by the enlightenment through the atmosphere (TST at noon, sunset, etc…).

Table 2 : Comparison between monthly values of H_{bn} measured and estimated for Rabat

	J	F	M	A	M	J	July	A	S	O	N	D
$\dfrac{\left(\overline{H_{bn_{mesurée}}} - \overline{H_{bn_{estimée}}}\right)}{\overline{H_{bn_{mesurée}}}}$ (%)	-16	-6	-19	-9	-13	-12	-17	-21	-15	-23	-11	-19

3. CARACTERISTICS OF SOLAR POTENTIAL IN OURZAZATE SITE

3.1. Bright sunshine

The histogram (Fig.1) shows that the seasonal variation of monthly average of number of bright sunshine hours is regular, with an annual average of the order of 3405 hours. The maxima and minima correspond to June (338hours) and February (238hours) respectively.

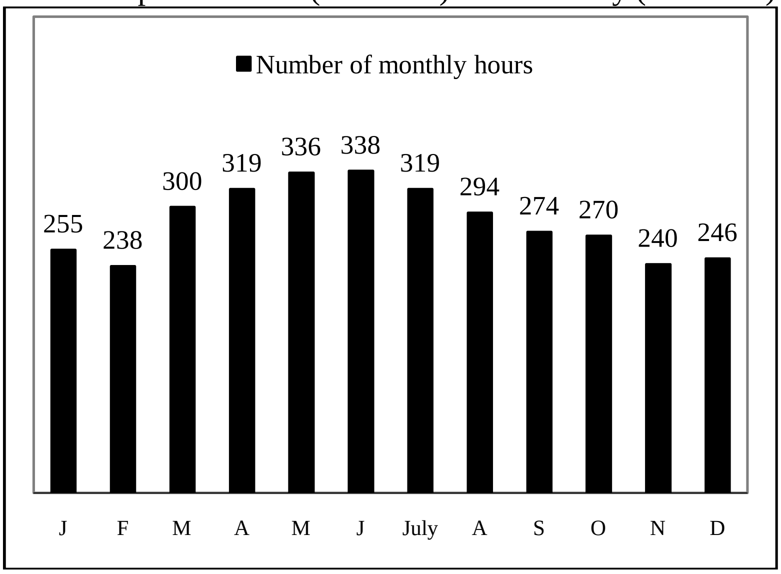

Figure 3: Bright sunshine Régime for Ouarzazate station [5]

3.2. Global radiation on horizontal surface

The variation of the monthly average of global radiation, H_h, on a horizontal surface is similar to this of the number of bright sunshine hours. It is regular (Fig.2). The maximal value is in winter (December) and the minimal value is in summer (June).

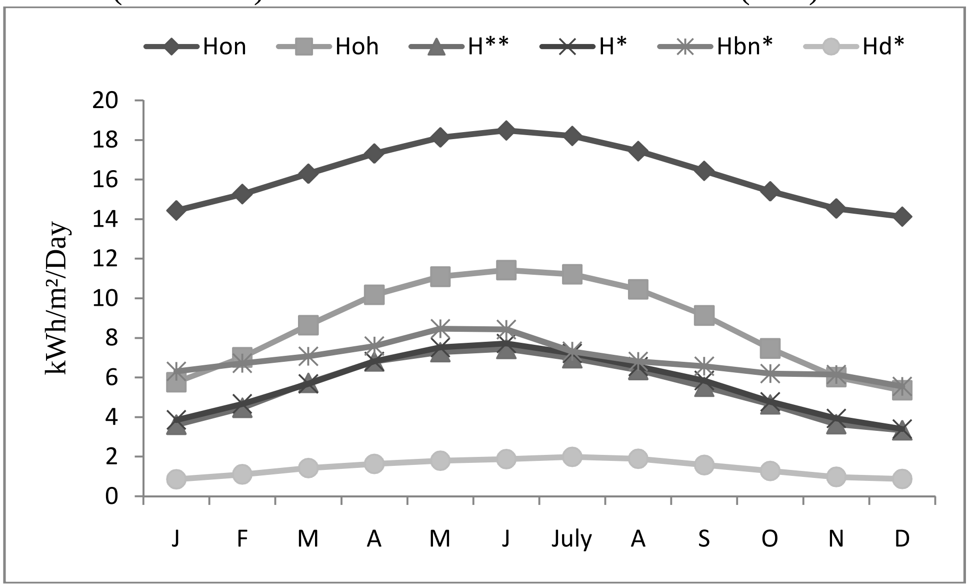

Figure 2: Seasonal variations of extraterrestrial solar radiations and terrestrial ones for Ouarzazate site [11-14]

3.3. Estimation of monthly averages of direct radiation on normal surface

Having used the monthly averages of H published by KHTIRA [11] and the monthly average if diffuse ration on a horizontal surface, H_d, published by NASA [14], we can deduce the direct radiation, H_b.

For Ouarzazate station, we have used the equation (12) and the correction coefficients calculated for Rabat station (Table 2) to estimate the monthly average of $\overline{H_{bn}}$ (Table 3). The values of $\overline{H_{bn}}$ are ranging within 5.56kWh/m^2/day (December) and 8.47kWh/m^2/day (May). This demonstrates that Ouarzazate area is profitable for the installation of concentrated solar systems for electricity production in large scale.

Table 3: Estimated of monthly average of H, H_{bn} and H_d

	J	F	M	A	M	J	July	A	S	0	N	D
$\overline{H}$	3.62	4.48	5.74	6.82	7.29	7.45	6.98	6.39	5.54	4.65	3.65	3.34
$\overline{H_{bn}}$	6.32	6.73	7.08	7.60	8.47	8.43	7.33	6.82	6.58	6.21	6.16	5.56
$\overline{H_d}$	0.86	1.11	1.43	1.64	1.80	1.88	1.99	1.89	1.58	1.28	0.98	0.87

We notice that the monthly averages of H_{bn} get closer to those of H_{oh} in winter and to those of H in summer (Fig.2). This could be explained by the localization of Ouarzazate site in a semiarid region, less clouds in Winter (clear sky) and dusty atmosphere in Summer (presence of sand).

3.4. Dimensionless Coefficients

The extraterrestrial global radiation on horizontal surface H_{oh} and the maximum day length N, vary with the declination δ and the latitude φ. On the other hand, the global radiation, H, and daily number of bright sunshine hours, n, depend not only of φ and δ, but also to the climatic conditions: nebulosity, atmospheric turbidity, etc., which are linked to the concentration of aerosols and atmospheric water vapor. To separate the astronomic aspect to the specifically climatic one and, on the other hand, to permit comparison in the same time spatial and seasonal, we generally uses dimensionless coefficients such as the sunshine fraction, $\sigma = n/N$, the clearness index, $K_t = H/H_{oh}$, etc.

a. Sunshine fraction, σ

The sunshine fraction, σ, is defined as the ratio n/N between the bright sunshine hours, n, and the maximum day length, N. The average is of the order of 78%. It translates mainly the nebulosity variation.

b. Clearness index, K_t

The clearness index, K_t characterizes the transparence of the atmosphere because it indicates the ratio of energy received at the limit of the atmosphere which reaches the ground. The maximum of the order of 68% corresponds to the sunny days without clouds and with minimum atmospheric turbidity (Fig.3). The complement (32%) corresponds to the attenuation of the atmosphere: absorption, reflection and diffusion. It reflects the effect of the atmospheric turbidity. The minimal value is obtained for November (60%), a part of the lost energy, being reflected by the cloud summit to the exterior atmosphere. It reflects mainly the effect of the nebulosity.

3.5. Comparison between σ, H_{bn}/H_{on} and K_t

Comparing the seasonal variation of K_t to this of σ, we notice that they are similar with, however, an amplitude variation higher for σ because the attenuation of the atmosphere due the effect of the atmospheric turbidity is involved in K_t, but not in σ (Fig.3).

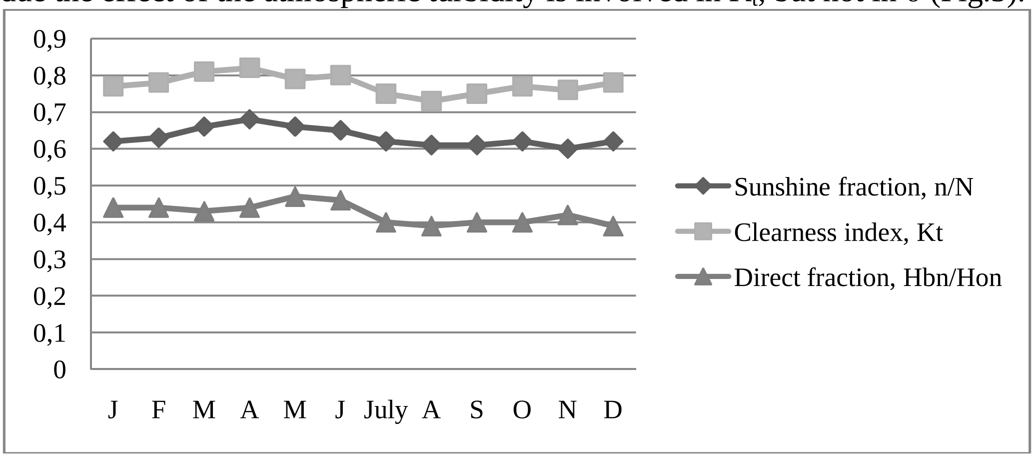

Figure 3: Seasonal variations of clearness index, K_t, and sunshine fraction, σ (Ouarzazate)

a. Correlation, H(σ)

The analysis of the seasonal variation allure of K_t and the σ one shows that there is a correlation between them and, consequently, there is a possibility to deduce the global radiation on horizontal surface by measuring only the sunshine, n. Such correlation would be in the following form, with a good correlation coefficient, R=0.99:

$$K_t = -0.012+0.830\sigma \tag{11}$$

b. Correlation $H_{bn}(\sigma)$

The observation of the seasonal variations of Hbn/Hon and the σ shows that they are similar. A linear relation has been obtained, with R=0.98:

$$H_{bn}/H_{on} = -0.108+0.685\sigma \tag{12}$$

4. CONCLUSION

The knowledge of the solar components, extraterrestrial and on the ground, is necessary to exploit the solar energy. For these reason, it is imperative to study deeply the characteristics of solar radiation.

In this work, we have carried out the calculation of the extraterrestrial solar radiation on a horizontal surface so that to select the representative day of every month for Ouarzazate site. In the absence of the measurement of direct radiation on a normal surface component, H_{bn}, we have been demonstrated that we could estimate the monthly average of H_{bn} from the simple measure of bright sunshine hours thanks to the correlation established. This correlation allows us to compute the direct radiation from sunshine records with the same climatic conditions.

It emerges from this work that the solar potential of Ouarzazate region (sunshine: 3400 hours/year, global radiation: 5,5 kWh/m²/day) is important. The seasonal variation of global radiation is regular. The attenuation of global radiation increases from 30% for June (maximal radiation) to 40% for November.

The monthly average of direct radiation on normal surface, $\overline{H_{bn}}$ are ranging within 5.56kWh/m^2/day (December) and 8.47kWh/m^2/day (May). This shows that Ouarzazate region is profitable for the installation of concentrated solar systems to produce electricity on a large scale.

Looking forward to have available the direct radiation records over a long period in order to compare the observed data with the estimated ones to check if the statistical characteristics of H_{bn} are faithfully reproduced

So, the results obtained should be improved as far as the stochastic characteristics of H_{bn}, is concerned. Although, the considered correlation has been established for Ouarzazate, this relation could be extended to other areas in the country, with some corrections.

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