4ème Conférence Internationale des Energies Renouvelables (CIER-2016)
Proceedings of Engineering and Technology – PET
Vol.16, pp.13 - 19

New Models to Estimate and Evaluate Monthly Mean Global Solar Radiation

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***Abstract*—For many years, predicting future values of solar radiation at isolated sites is a challenge by researchers and scientists. In the present work, five new models have been proposed to assess monthly mean global solar radiation on a horizontal surface at Algiers and Tamanrasset cities, in function of three parameters: extraterrestrial solar radiation (Go), duration sunshine (S) and daylight hours (So). Then, to ensure the accuracy level of the new proposed models, its performance was compared against six empirical models used in the literature using seven statistical error tests, comparison between measured and calculated values of global solar radiation has been performed.**

This study finds that the proposed models which based on duration sunshine performed the best accuracy. Moreover, these new developed models can be used for predicting the monthly mean global solar radiation over Algeria.

***Keywords*— GSR, duration sunshine, Regression coefficient, Statistical analysis.**

I. Introduction

According to renewable energy program that is announced in 2011, the Government of Algeria is aimed to develop solar energy to produce about 37% of domestic electricity from both photovoltaics (CPV) and Concentrating Solar Power (CSP) [1]. This is due to the huge potential of solar energy and the longer sunshine duration in Algeria. Unfortunately, solar radiation data is not available due to the high costs involved in buying and maintaining solar measuring equipment. Therefore, the accurate prediction of solar radiation intensity and knowledge of the available solar resource in the country is an important issue for the design, optimization and performance evaluation of solar energy systems for any particular area, it is necessary to develop models to estimate the intensity of solar radiation based on other available climate data. A number of techniques of the prediction have been developed so far are widely used by researchers to get accurate information.

Indeed, solar radiation data play very important role in designing, sizing and performance of energy and renewable energy systems. Nevertheless, these data are not always available, especially in isolated areas. Accordingly, predicting solar radiation values is often the only practical way to acquire these data. This is because measured sequences of radiation values are available only for a few locations or regions in each country [2].

The use of empirical correlation for predicting monthly mean daily global solar radiation (GSR) on horizontal surface is date as far back as 1924, it was carried out by Angstrom [3]. This equation is the simplest and most widely used and it related to the monthly average daily radiation to clear day radiation in a given location and average fraction of possible sunshine hours. And later in 1940, Prescott [4] has modified a formula of Angstrom equation and has focused on the extraterrestrial radiation on a horizontal surface, rather than on clear day radiation. After that, many models have been developed through these two models Angstrom-Prescott to estimate monthly mean daily radiation utilizing available meteorological, geographical and climatological parameters such as sunshine hours, air temperature, latitude, precipitation, relative humidity, and cloudiness. However, the most commonly used parameter for estimating global solar radiation is sunshine duration; it provides the best results compared with other parameters.

This work presents the use of five proposed models and six models used in the literature for predicting monthly mean global solar radiation on a horizontal surface, where these models are compared using seven criteria to validate the suitability and capability the new models for estimating global solar radiation in Algiers and Tamanrasset cities in Algeria. This contribution's goal is to evaluate the accuracy of the monthly mean of GSR in order to choose the best data for CSP and CPV application in Algeria.

The rest of the paper is organized as follows. In section 2, the descriptions of the two selected locations and databases used are presented. Also the structure of eleven models and the formulas of seven main statistical indicators are provided in section 2. Section 3, illustrates the experimental results and discussions of the results. Finally, the conclusions are presented in the last section.

II. Data and Methodology

ISSN 2356-5608

A. Data and Study Area

The two sites considered in this study are Algiers and Tamanrasset (Algeria), where the two locations are located in the north and southern of Algeria, respectively (fig. 1);

These two sites are ideal locations to benefit the advantages of solar energy utilization and adoption of its related technologies. Detailed geographic and climatic characteristics of these sites are given in Table I. In this work, the measured monthly mean daily data of global solar radiation on a horizontal surface (MJ/m^2.day), as well as the monthly mean daily sunshine duration (hr) for the selected sites, were obtained from the Algerian National Office of Meteorology (NOM).

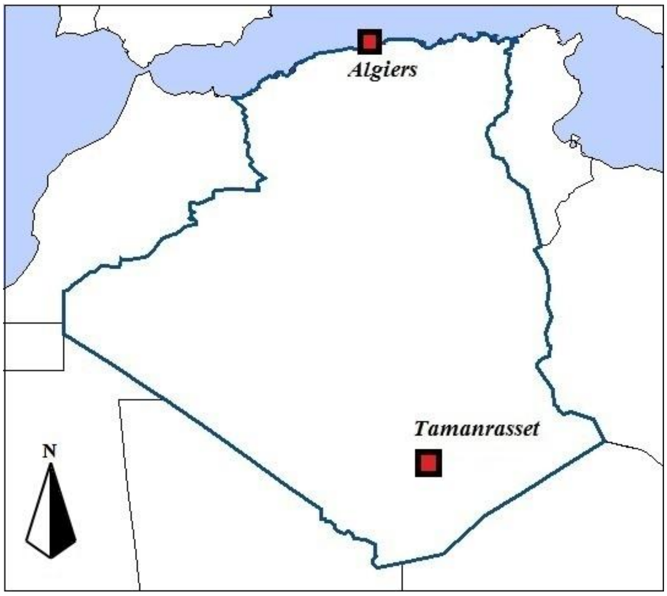

Fig. 1 Location of the stations considered on the map of Algeria.

TABLE I

GEOGRAPHICAL AND CLIMATIC CHARACTERISTICS OF THE TWO STUDIED STATIONS

Location	Latitude (N)	Longitude (E)	Elevation (m)	Climate
Algiers	36.43	3.15	25	Mediterr-anean
Tamanrasset	22.783	5.516	1377	Desert arid

B. Models and Comparison Technique

In the present subsection, to estimate the monthly mean daily global solar radiation G (MJ/m^2.day) and to compare the models below, we take the data of monthly mean sunshine duration from Algerian National Office of Meteorology (NOM). The monthly mean daily extraterrestrial radiation G_o, maximum possible sunshine hours S_o, and declination angle δ_s, for using the average days of the month, were calculated from the standard following relations [5]:

$$G_o = \frac{24 \cdot 3600 \cdot G_{sc}}{\pi} \cdot G_t \cdot [\cos\varphi \cdot \cos\delta_s \cdot \sin\omega_s + \frac{\pi \cdot \omega_s}{180} \cdot \sin\varphi \cdot \sin\delta_s] \quad (1)$$

$$G_t = 1 + 0.034 \cdot \cos(360 \cdot nj / 365) \quad (2)$$

$$\delta_s = 23.45^o \sin(360(284 + nj)/365) \quad (3)$$

$$\omega_s = \cos^{-1}(-\tan\varphi \cdot \tan\delta_s) \quad (4)$$

$$S_o = 2/15 \cdot \omega_s \quad (5)$$

Where φ is the latitude of the site (rad), δ_s is the declination solar (rad), ω_s is the sunset hour angle (rad), G_{sc} is the corrected solar constant (= 0.082 MJ /m^2), G_{sc} is the relative correction of the earth–sun distance and nj is the number of day in the year starting 1[st] of January.

A description of the mathematical expressions of the used regression models to predict monthly mean daily GSR on a horizontal surface can be divided into two categories:

1) *Category One*: contain six empirical models: linear, quadratic and cubic, logarithmic, exponential and exponent. These empirical models are the most used to estimate monthly mean global solar radiation on horizontal surface in the literature and have the form of the Angstrom equation (see Table II).

TABLE II

REGRESSION MODELS BASED ON SUNSHINE DURATION USED IN THE STUDY

Model N^o	Model type	Regression equation
Eq. (1)	Linear [3], [4]	$G_d/G_o = a + b \cdot (S/S_o)$
Eq. (2)	Quadratic [7]	$G_d/G_0 = a + b \cdot (S/S_0) + c \cdot (S/S_0)^2$
Eq. (3)	Cubic [8]	$G_d/G_0 = a + b \cdot (S/S_0) + c \cdot (S/S_0)^2 + d \cdot (S/S_0)^3$
Eq. (4)	Logarithmic [9]	$G_d/G_o = a + b \cdot \log(S/S_o)$
Eq. (5)	Exponential [10]	$G_d/G_0 = a \cdot e^{b \cdot (S/S_0)}$

ISSN 2356-5608

Eq. (6)	Exponent [6]	$G_d/G_0 = a\cdot(S/S_0)^b$

2) *Category Two*: include five proposed models which are based on: Fourier series (#7), Sin equations (#8), Rational model (#9), Gaussian model (#10) and Power series (#11). The regression models proposed in this work are given in Table III below:

TABLE III
PROPOSED REGRESSION MODELS

Model type	Regression equation	Number of terms
Eq.7 (Fourier series)	$G_d/G_0 = a_0 + \sum_{i=1}^{j} a_i\cdot\cos(i\cdot(S/S_0)\cdot w) + b_i\cdot\sin(i\cdot(S/S_0)\cdot w)$, $1\le j\le 8$	$j=5$
Eq.8 (Sin equations)	$G_d/G_0 = \sum_{i=1}^{j} a_i\cdot\sin(b_i\cdot(S/S_0)\cdot c_i)$, $1\le j\le 8$	$j=4$
Eq.9 (Rational model)	$G_d/G_0 = \dfrac{\sum_{i=1}^{j+1} a_i\cdot(S/S_0)^{j+1-i}}{(S/S_0)^k\cdot\sum_{i=1}^{k} b_i\cdot(S/S_0)^{k-i}}$, $0\le j\le 5,\ 1\le k\le 5$	$j=5$ $k=5$
Eq. 10 (Gaussian model)	$G_g/G_0 = \sum_{i=1}^{j} a_i\cdot\exp\left[-\left(\dfrac{(S/S_0)-b_i}{c_i}\right)^2\right]$, $1\le j\le 8$	$j=4$
Eq. 11 (Power series)	$G_g/G_0 = \sum_{i=0}^{j} a_i\cdot(S/S_0)^i$, $0\le j\le 7$	$j=5$

In order to compare the accuracy of the predicted monthly global solar radiation against the measured data, using the eleven models described above, we use the seven statistical indicators, namely: mean percent error MPE (%) and Mean Absolute Percent Error MAPE (%), Mean Bias Error MBE (MJ/m^2), mean absolute bias error MABE (MJ/m2) and Root Mean Square Error RMSE (MJ/m^2), Coefficient of determination R^2 (%) and T-statistic test (TT). These parameters are the most widely used by researchers that mentioned in the literature to control the performance of these regression models [11]-[15], and defined as below:

$$MPE = \frac{1}{k}\sum_{i=1}^{k}\left(\frac{H_c^i - H_m^i}{H_m^i}\right)\times 100 \tag{6}$$

$$MAPE = \frac{1}{k}\sum_{i=1}^{k}\left|\frac{H_c^i - H_m^i}{H_m^i}\right|\times 100 \tag{7}$$

$$MBE = \frac{1}{k}\sum_{i=1}^{k}\left(H_c^i - H_m^i\right) \tag{8}$$

$$MABE = \frac{1}{k}\sum_{i=1}^{k}\left|H_c^i - H_m^i\right| \tag{9}$$

$$RMSE = \left[\frac{1}{k}\sum_{i=1}^{k}\left(H_c^i - H_m^i\right)^2\right]^{1/2} \tag{10}$$

$$R^2 = \frac{\sum_{i=1}^{k}\left(H_c^i - \bar{H}_c\right)\cdot\left(H_m^i - \bar{H}_m\right)}{\sqrt{\sum_{i=1}^{k}\left(H_c^i - \bar{H}_c\right)^2\cdot\sum_{i=1}^{k}\left(H_m^i - \bar{H}_m\right)^2}} \tag{11}$$

$$TT = \left[\frac{(N-1)MBE^2}{RMSE^2 - MBE^2}\right]^{1/2} \tag{12}$$

H_m^i, $\bar{H}_m$, H_c^i and $\bar{H}_c$ are the ith measured clearness index (G_m/G_0), the average of measured clearness index, the predicted of clearness index (G_d/G_0) and the average of predicted of clearness index values of solar radiation, respectively, k is the total number of data points. For better data modeling, the ideal values of statistical tests such as MPE, MAPE, MBE, MABE, RMSE and TT should be closer to zero, but R^2 should approach to 1 as closely as closely as possible [12].

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

In this work, the monthly mean daily of GSR are analyzed using eleven regression models, for the two locations; Algiers and Tamanrasset (Algeria), where the predicted values with the measured values are compared using the only main parameter input and is the sunshine duration. It's the most commonly used in the literature and provides the best results compared with other parameters.

For this purpose, regression analysis was conducted in order to establish eleven models for the Algiers and Tamanrasset cities in Algeria. For validation, seven statistical indicators have been used in this study, i.e., MPE, MAPE, MBE, MABE, RMSE, R^2 and TT. The regression coefficients ($\{a_0,..,a_6\}$, $\{b_1,..,b_5\}$, $\{c_1,..,c_4\}$ and w) generated by the five proposed models in the second category are shown in Table IV. The accurate indicators of the selected models of first and second category are illustrated in Table V. The simulated results from each category of models during the selected months are visualized in Figs. 2, 3, 4 and 5.

From comparing the results obtained in Table V, it has been observed that the new proposed models are more accurate than those models used in the literature.

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TABLE IV
REGRESSION CONSTANTS OF THE NEW MODELS FOR ALGIESR AND TAMANRASSET STATIONS

Reg coeff	Algiers					Tamanrasset				
	Mod 7	*Mod 8*	*Mod 9*	*Mod 10*	*Mod 11*	*Mod 7*	*Mod 8*	*Mod 9*	*Mod 10*	*Mod 11*
a_0	1.236	-	-	-	-13.11	49.77	-	-	-	-21.2
a_1	1.592	0.7414	5.481	0.6247	60.67	13.84	1.001	2.719	0.238	146.1
a_2	2.075	0.2719	-1.283	0.4935	-42.44	-57.61	0.3751	-1.336	0.7252	-400.1
a_3	-2.474	0.04271	-1.398	0.1513	-163.7	-13.77	0.05633	-2.257	0.2654	545.6
a_4	-1.107	0.01207	2.101	3.961	301.7	9.457	0.05241	-0.2722	0.6182	-370.4
a_5	-1.212	-	-2.217	-	-144.6	1.349	-	0.6025	-	100.1
a_6	-	-	0.6682	-	-	-	-	0.6121	-	-
b_1	-1.342	7.724	2.155	0.7849	-	-86.18	9.147	0.4931	0.7758	-
b_2	-1.213	17.47	4.343	0.5146	-	-18.57	19.52	-0.2011	0.884	-
b_3	-4.203	35.94	0.2262	0.6062	-	28.35	42.2	-1.626	0.6986	-
b_4	-3.869	62.02	-5.083	0.6643	-	6.105	65.98	-1.933	0.6188	-
b_5	4669	-	1.779	-	-	-1.736	-	2.314	-	-
c_1	-	2.782	-	0.1523	-	-	0.8957	-	0.03027	-
c_2	-	-0.2903	-	0.09899	-	-	2.495	-	0.1577	-
c_3	-	3.782	-	0.01323	-	-	1.1	-	0.0293	-
c_4	-	-5.082	-	0.02152	-	-	-0.2093	-	0.09045	-
w	3.86	-	-	-	-	10.76	-	-	-	-

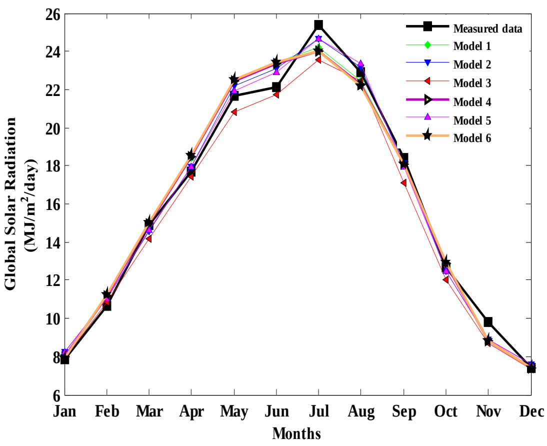

Fig. 2. Measurements and estimates of the literature models for Algiers station.

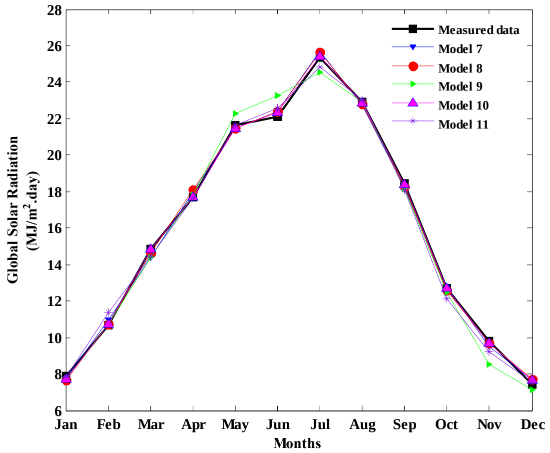

Fig. 3. Measurements and estimates of the five proposed models for Algiers station.

ISSN 2356-5608

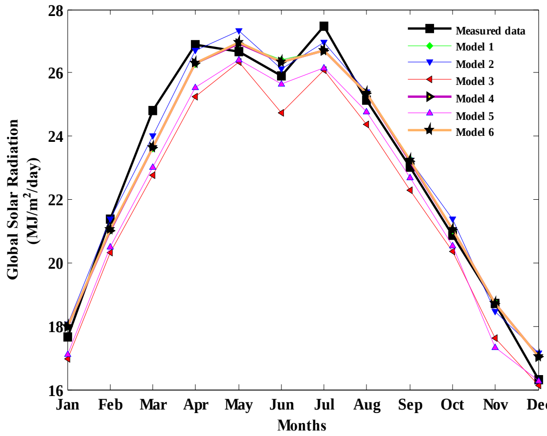

Fig. 4. Measurements and estimates of the literature models for Tamanrasset station.

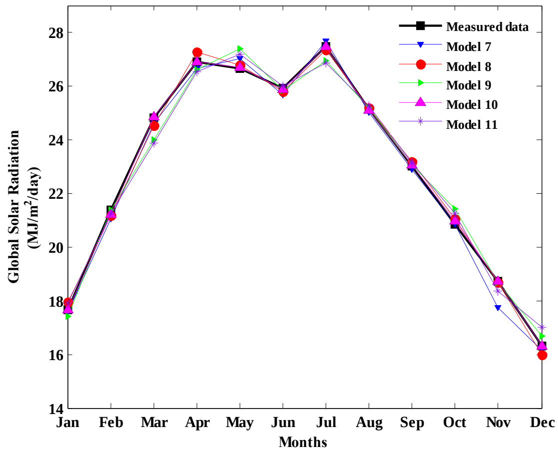

Fig. 5. Measurements and estimates of the five proposed models for Tamanrasset station.

TABLE V
STATISTICAL ANALYSES OF THE ELEVEN MODELS FOR THE TWO STATIONS

Site	Models #	MPE	MAPE	MBE	MABE	RMSE	R^2	TT
Algiers	1	-0.1817	3.2415	-0.0001	0.0173	0.0226	0.9097	0.0086
	2	-0.2794	3.1329	-0.0007	0.0162	0.0195	0.9334	0.1204
	3	3.5705	3.9029	0.0199	0.0214	0.0276	0.9411	3.4314
	4	-0.1199	3.4793	0.0004	0.0187	0.0234	0.9025	0.0622
	5	-0.1308	3.0582	0.0000	0.0160	0.0189	0.9373	0.0061
	6	-0.1999	3.6872	-0.0000	0.0198	0.0244	0.8936	0.0027
	7	-0.0070	1.6801	0.0001	0.0086	0.0097	0.9840	0.0513
	8	0.0116	1.4831	0.0001	0.0075	0.0086	0.9874	0.0487
	9	1.6116	3.1650	0.0084	0.0166	0.0242	0.9240	1.2221
	10	**-0.0198**	**0.7259**	**-0.0000**	**0.0036**	**0.0054**	**0.9951**	**0.0304**
	11	0.5721	2.3534	0.0035	0.0122	0.0161	0.9572	0.7342
Tamanrasset	1	-0.0536	1.9901	0.0000	0.0138	0.0169	0.7236	0.0081
	2	-0.6866	1.8623	-0.0044	0.0128	0.0158	0.7868	0.9668
	3	4.1265	4.1265	0.0287	0.0287	0.0323	0.8059	6.4327
	4	-0.0335	1.9271	0.0002	0.0133	0.0166	0.7365	0.0318
	5	3.1918	3.1918	0.0225	0.0225	0.0285	0.7370	4.2368
	6	-0.0548	1.9297	0.0000	0.0134	0.0165	0.7399	0.0025
	7	0.8048	1.1505	0.0057	0.0080	0.0124	0.8933	1.7111
	8	0.0025	0.8489	0.0000	0.0059	0.0070	0.9609	0.0128
	9	0.0190	1.3589	0.0003	0.0094	0.0122	0.8661	0.0922
	10	**0.0017**	**0.1681**	**0.0000**	**0.0012**	**0.0017**	**0.9967**	**0.0293**
	11	-4.5348	4.5348	-0.0309	0.0309	-4.5348	0.8467	7.7959

A. Algiers

From comparing the results obtained in Table V, it has been observed that the proposed models are more accurate than those models used in the literature. On this ground, for each station of the two selected sites the best model among all of the nominated models has been recognized and introduced in Table V in bold.

According to the obtained statistical performances of the eleven aforementioned models, the Gaussian model (#10) represents the best model for assessment the monthly mean global solar radiation for Algiers station data, as it yields the lowest error parameter values (MPE= -0.0198%, MAPE=0.7259%, MBE=-0.0000 MJ/m^2, MABE=0.0036 MJ/m^2, RMSE= 0.0054 MJ/m^2, TT=0.0304%) and a coefficient of determination R^2 = 0.9951%.

Moreover, the Cubic model (#3) is assessed as the worst model for forecasting the monthly mean GSR because it has highest values of MPE, MAPE, MBE, MABE and RMSE such as: 3.5705, 3.9029, 0.0199, 0.0214 and 0.0276, respectively. The Gaussian model based on sunshine hours data (model #10) in which:

$$\begin{cases} G_g/G_0 = \sum_{i=1}^{4} a_i \cdot \exp\left[-\left(\frac{(S/S_0)-b_i}{c_i} \right)^2 \right] \textit{ where}: \\ a_1 = 0.6247,\ a_2 = 0.4935,\ a_3 = 0.1513,\ a_4 = 3.961; \\ b_1 = 0.7849,\ b_2 = 0.5146,\ b_3 = 0.6062,\ b_4 = 0.6643; \\ c_1 = 0.1523,\ c_2 = 0.09899,\ c_3 = 0.01323,\ c_4 = 0.02152 \end{cases}$$

is assessed as the best model for estimation the monthly mean global solar radiation for Algiers station.

B. Tamanrasset

In the case of Tamanrasset station data, the Gaussian model (#10) also shows the best performance for evaluating monthly mean of GSR, where presents the lowest values of MPE, MAPE, MBE, MABE, RMSE and TT such as: 0.0017, 0.1681, 0.0000, 0.0012, 0.0017 and 0.0293, respectively. With maximum value of R^2 is 0.9967%. Whereas the worst prediction model was (#3) with the highest values of MPE and TT such as: 4.1265, 6.4327, respectively.

Also the Gaussian model based on sunshine hours data (model #10) in which:

$$\begin{cases} G_g/G_0 = \sum_{i=1}^{4} a_i \cdot \exp\left[-\left(\frac{(S/S_0)-b_i}{c_i} \right)^2 \right] \textit{ where}: \\ a_1 = 0.238,\ a_2 = 0.7252,\ a_3 = 0.2654,\ a_4 = 0.6182; \\ b_1 = 0.7758,\ b_2 = 0.884,\ b_3 = 0.6986,\ b_4 = 0.6188; \\ c_1 = 0.03027,\ c_2 = 0.1577,\ c_3 = 0.0293,\ c_4 = 0.09045 \end{cases}$$

is assessed as the best model for estimation the monthly mean global solar radiation for Tamanrasset station.

IV. CONCLUSION

In this study, six empirical models based on sunshine duration are compared with five proposed models to estimate the monthly mean daily global solar radiation on a horizontal surface for two ground sites in Algeria (Algiers and Tamanrasset). The presented models were compared on the basis of seven statistical error indicators (MPE, MAPE, MBE, MABE, RMSE, R^2 and TT). The results confirm that the five proposed models provide a very good estimation for monthly and daily average GSR.

This study found that the new proposed models are potentially capable to estimate the monthly mean global solar radiation and may then be used for all ground sites with similar meteorological and geographical characteristics at which solar data are not available.

ACKNOWLEDGMENT

The authors would like to thank Mr. Taqiy Eddine Boukelia for providing the data of the Algerian National Office of Meteorology (NOM). In addition to Mr. Kamel Boudaoud for his academic help.

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ISSN 2356-5608