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A Global Solar Radiation Model for the Design of Solar Energy Systems

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Abstract: In order to obtain the global solar radiation for practical applications, a mathematical model was developed in this study. The experimental data for five years were correlated in order to calculate the model parameters. Knowing the values of cloudiness degree k, Julian date N, the global solar radiation can be estimated at any hour t by the developed model. We have testing this model at different periods of two years and at different cloudiness degree classes, in the second a monthly global solar radiation was estimated and compared with the results of Sivkov model. To evaluate the accuracy of the model, three methods are used, RMSE, MPE and MBE. The mean monthly and yearly global radiation was estimated with an accuracy of 4.5 and 0.34%, respectively. The prediction results were found to be in good agreement with the experimental data can be employed for estimating global solar radiation for the south of Tunisia.

Key words: Solar model, global radiation, solar systems

INTRODUCTION

Modelization of global and diffus solar irradiation has many practical applications in the calculation of the design and performance of solar energy systems. However, while the number of stations recording the different meteorological parameters has increased rapidly in recent years, experimental data on global and diffuse radiation are very rare. In the solar energy literature there have been numerous papers dealing with the evaluation and comparison of solar radiation estimation models.

There are some universal models, that are, designed to be independent of location and time of the year; other models have been constructed for specific regions, for example, for Spain; Palomo (1989), for Italy; Mustacchi *et al*. (1979), for Athens; Balouktsis and Tsalides (1986), for Singapore; Goh and Tan (1977), for Canada; Graham *et al*. (1987) and for the USA; Knight (1988).

Some regression models incorporating trigonometric functions have been proposed by Dorvlo and Ampratwum (1999) and Coppolino (1994).

Radiation data being time dependent have also been modeled using harmonic analysis methods by Philips (1984), Herroro (1993) and Dorvlo and Ampratwum (1999).

Hokoi *et al*. (1990) used a stationary autoregressive moving average model (ARMA) of order three to model hourly solar radiation while Mora-Lopez and Sidrach-de-Cardona (1998) used an ARMA model of order unity to model monthly solar radiation data.

Mohandes *et al*. (2000) have compared radial basis function methods with regression models for Saudi stations and found the radial basis method models to be better than the regression models.

Soares *et al*. (2004) used Artificial Neural Network to estimate solar radiation and the list is not exaustive.

The objective of this study is to develop a global solar radiation model using a simple meteorological data for the design of solar energy systems in the south of Tunisia.

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MODEL DEVELOPMENT AND DESCRIPTION

The present global solar radiation model was formulated in the laboratory of applied thermodynamics. The experimental data was collected hour by hour at the climate station of Gabes in the south of Tunisia (lat. = 33°53', long. = 10°06').

The model is based on five years of data (1997 to 2002). We performed during different periods of the year that has been subdivided into two classes and each of them defined by its cloudiness degree.

- Class I from 0 to 0.5 cloudiness
- Class II from 0.5 to 1 cloudiness

The parameters introduced in this model are cloudiness degree K, julian day N and the hour of the day t. The hourly global solar radiation on horizontal surface can be expressed as the product of three functions:

$$G_H = A_k A_N A_t \quad (1)$$

Where, A_k, A_N and A_t are a functions defined, respectively by Eq. 2-5.

$$A_k = 1.1296k - 23.04 \text{ for } k<0.5 \quad (2)$$

$$A_K = 297672 \text{ k-}37.853 \text{ for } 0.5<k\leq 1 \quad (3)$$

$$A_N = 0.01407\sin[\tfrac{360}{365}(284+N)]\text{-}0.0357 \quad (4)$$

$$A_t = t^4\text{-}47.958t^3 + 795.68t^2\text{-}5291t + 12158 \quad (5)$$

Where,
G_H = The hourly global solar irradiation on a horizontal surface (W m^{-2}).
N = The Julian day of the year.
t = The hour of the day.
K = The cloudiness degree.

Figure 1 and 2 show estimated and measured hourly global solar radiation in two weather conditions. They indicate that the global solar radiation is more estimated for clear sky (K<0.5) than that for cloudy sky (0.5<K<1). To estimate daily global solar radiation we used:

$$G_D = \sum_{t_1}^{t_2} G_H \quad (6)$$

Where,
G_D = The daily global solar radiation.
t_1 and t_2 = The sunset and the sunrise hours, respectively.
G_H = The hourly global radiation in horizontal surface.

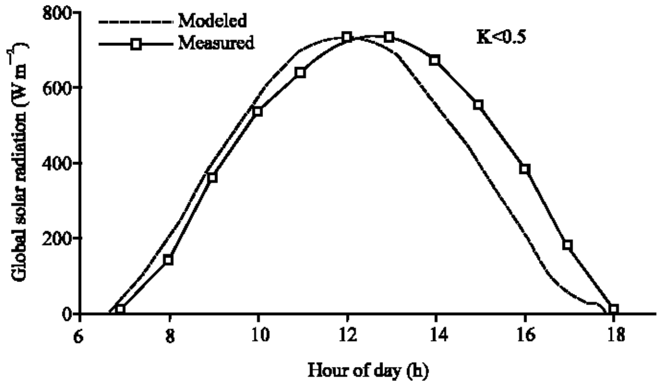

Fig. 1: Hourly global radiation for julian day N = 52, 1997 and K<0.5

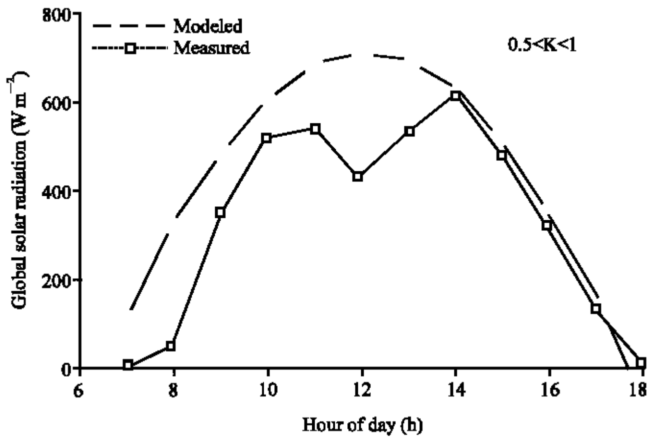

Fig. 2: Hourly global radiation for N = 47, 1997 and 0.5< K< 1

The monthly global solar radiation can be estimated by:

$$G_M = \sum_{d_1}^{d_e} G_D \tag{7}$$

Where, d_1 and d_e are, respectively the first and the latest day of the month.

RESULTS AND DISCUSSION

Daily Global Solar Radiation

Knowing cloudiness degree K, julian day N and the hour t, the model was computed for two years, the daily global solar radiation was estimated using Eq. 1-6. To evaluate the accuracy of the model three methods are used. The root mean square error is defined as:

$$RMSE = \left\{\left[\sum (G_{ical} - G_{imes})^2\right]/n\right\}^{1/2} \tag{8}$$

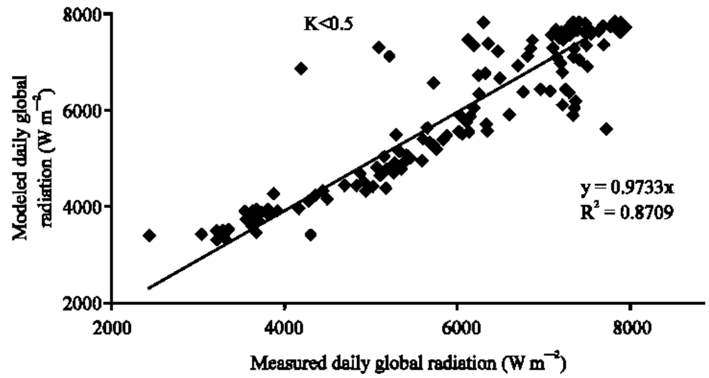

Fig. 3: Daily global radiation (W m^{-2}) modeled versus measured for K<0.5

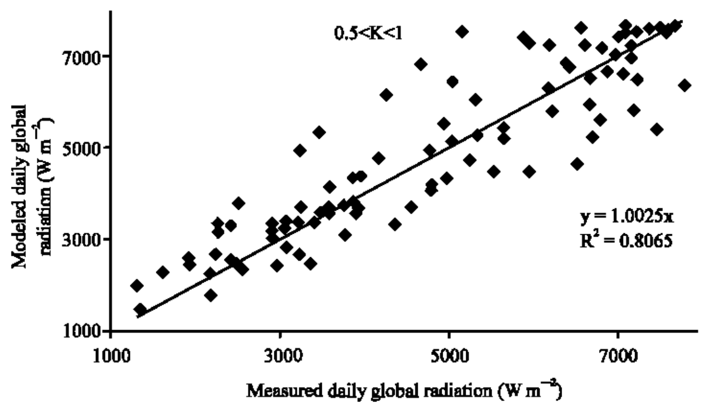

Fig. 4: Daily global radiation (W m^{-2}), modeled versus measured for 0.5<K<1

Where,

$G_{i.cal}$ = The ith calculated value.

$G_{i.mes}$ = The ith measured value and n is the total number of observation.

The mean bias error is defined as:

$$MBE = \left[\sum\left(G_{i.cal.} - G_{i.meas.}\right)\right]/n \quad (9)$$

The mean relative percentage error is defined as:

$$MPE = \left[\sum\left(\frac{G_{i.meas} - G_{i.cal}}{G_{i.meas}} \times 100\right)\right]/n \quad (10)$$

The sign of the errors is neglected in the Eq. 10.

The daily linear regression coefficients a and the coefficients of determination R^2 confirmed that the model is more accurate for K<0.5 than for 0.5<K<1 (Fig. 3 and 4).

Table 1: RMSE, MBE (MJ m^{-2}) and MPE vs cloudiness degree class for daily global radiation

Cloudiness degree class	RMSE	MBE	MPE
K<0.5	2.0	-0.5	7.22
0.5<K<1	2.7	0.3	12.61

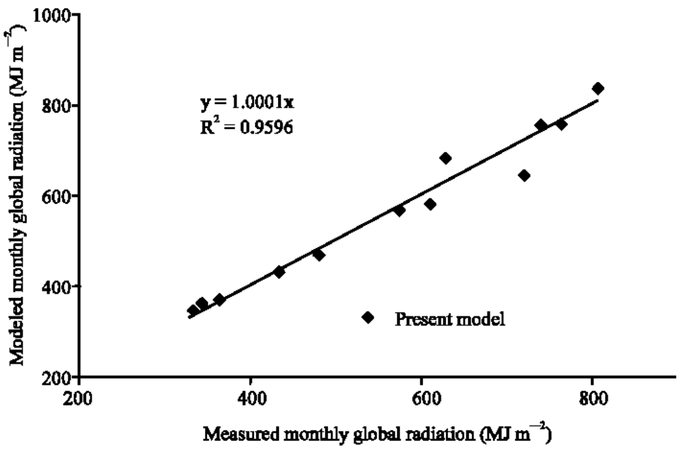

Fig. 5: Monthly global radiation (MJ m^{-2}), modeled versus measured using the present mode

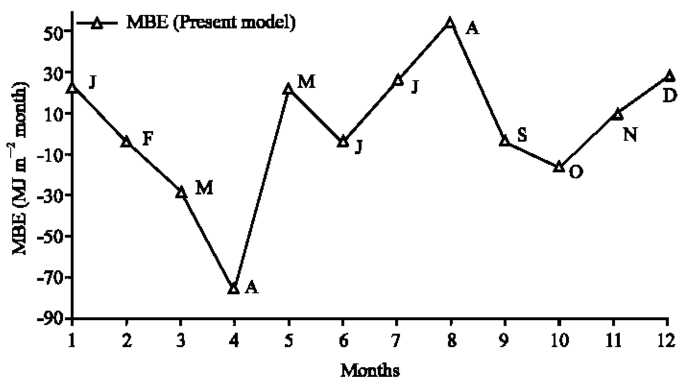

Fig. 6: Mean bias errors for monthly global radiation

Table 1 shows RMSE, MBE, MPE versus cloudiness degree class. The analysis of results confirmed that good results can be obtained using this model. For K< 0.5 a negative value of the MBE gives under-estimation in calculated values and vice versa for 0.5<K<1. Finally the model can be employed for estimating daily global solar radiation for the southern region of Tunisian.

Monthly Global Solar Radiation

The monthly global solar radiation at the south of Tunisia (Gabès) was estimated by using Eq. 1-7 for two years.

The high level of agreement between the predicted and measured values of global radiation can be appreciated from the monthly linear regression coefficient a and coefficient of determination R^2 shown in Fig. 5.

Table 2: Modeled and measured mean monthly global radiation (MJ m^{-2})

Months	Measured (MJ m^{-2})	Modeled (MJ m^{-2})
January	329.969	352.923
February	431.806	427.994
March	610.063	581.073
April	720.034	592.265
May	739.008	760.342
Jun	762.951	757.044
July	808.261	834.466
August	630.763	735.307
September	572.289	566.460
October	481.637	464.839
November	364.777	373.892
December	343.224	371.250

Table 3: Annual and seasonal means of measured and estimated global solar radiation (MJ m^{-2})

Seasons	Measured (MJ m^{-2})	Estimated (MJ m^{-2})	MPE
Winter	1105	1152	4.30
Spring	2069	1984	4.10
Summer	2202	2277	3.40
Autumn	1419	1405	1.00
Annual	6795	6818	0.34

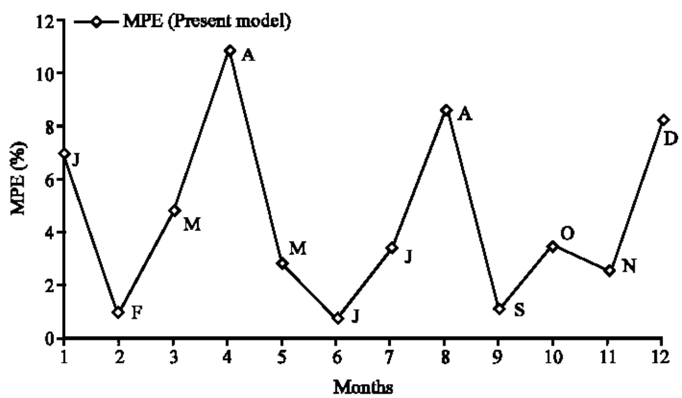

Fig. 7: Mean relative percentage error for monthly global radiation

The MBE and MPE plots in Fig. 6 and 7 show that the performance of the model was excellent during the year but is relatively poor for April and August where the MBE was respectively 78 and 55 and the MPE was 11 and 9%. The model is under-estimated for six months and over estimated for the others.

Seasonal Variation of Global Solar Radiation

Table 2 shows the variation in the average monthly global radiation on horizontal surface. Measurements and computation, both show similar evolutions. The minimum is 353 MJ m^{-2} month for January and the maximum is 835 MJ m^{-2} month for July. The monthly global radiation was estimated with an accuracy of 4.5%.

Table 3 shows annual and seasonal means in which lower value is 1152 MJ m^{-2} in winter and the higher value is 2277 MJ m^{-2} in summer. If the mean percent errors are compared, the best results are for Autumn and Summer where the MPE are, respectively 1 and 3.4% while spring and winter were estimated with an accuracy about 4%. Results show that the annual mean of estimated global radiation is 6818 MJ m^{-2} with 0.34 of mean percent error.

Table 4: Monthly linear regression coefficients a, (calculated/measured), coefficients of determination R^2, RMSE, MBE ($MJ\ m^{-2}$) and MPE for the tow models

Models	a	R^2	RMSE	MBE	MPE
Present	0.9991	0.9047	33	1.9	4.5
Sivkov	1.0645	0.8852	69	3.4	9.9

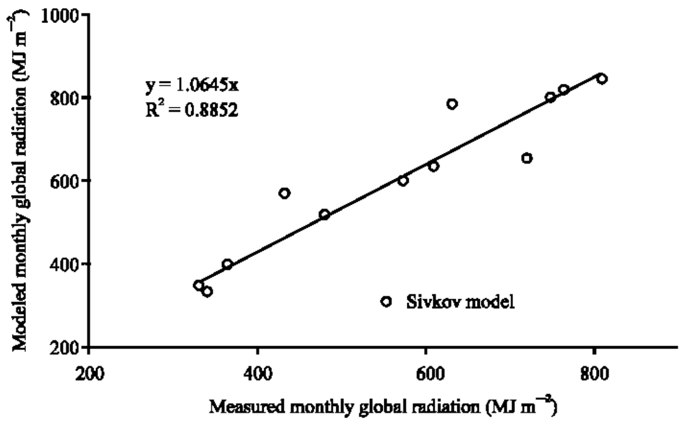

Fig. 8: Mean monthly global insolation ($MJ\ m^{-2}$), modeled versus measured using Sivkov model

COMPARISON WITH SIVKOV MODEL

In this part the objective is to compare the results of the newly-developed model with results from other existing model using data obtained in the south of Tunisia. The second model is an empirical formula (11) which was originally proposed by Sivkov (1964a and b) in the form:

$$H_m = 4.9(n_m)^{1.31} + 10.500(\sin\alpha)^{2.1} \tag{11}$$

Where, H_m and n_m are the monthly global irradiance (in cal. cm^{-2}) and the monthly sunshine hours, respectively (Fig. 8), while α is the noon altitude of the sun on the 15th of the month. The Root Mean Square Error (RMSE), Mean Bias Error (MBE) and Mean Percent Error (MPE) are used for this comparison. RMSE, MBE and MPE are shown in Table 4.

Table 4 shows that the low values of RMSE, MBE and MPE are remarkable for the two models but the first one yield the best results. The MBE indicates that the tow models are generally over-estimated. We mention that the Sivkov model was developed on using data from other stations.

CONCLUSIONS

The development of a mathmatical model for prediction of global solar radiation in horizontal surface is presented. The test of this model confirmed that the low values of RMSE, MBE and MPE are remarkable with estimating the daily global solar radiation and that the best results are for $k< 0.5$, the model produces a low values of RMSE, MBE and MPE with estimating the mean monthly and yearly global solar radiation that have an accuracy of 4.5 and 0.34%, respectively. The model predictions are in good agreement with the experimental data, consequently the developed model will be a useful tool for the design of various solar energy systems.

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