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EXPERIMENTAL STUDY OF SOLAR ENERGY POTENTIAL IN THE GULF OF TUNIS, TUNISIA

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ABSTRACT

This work carries out the availability of the global solar radiation over the site of Borj-Cedria in the gulf of Tunis (36°43'04" N latitude and 10°25'41" E longitude), Tunisia. Global solar radiation variability was assessed on hourly, daily, monthly and seasonal scales. Solar potential in the gulf of Tunis was evaluated using the solar radiation data collected by the meteorological NRG weather station installed in the Centre of Research and Technologies of Energy (CRTEn) in the Borj-Cedria area. The collected measurements during the last three years (2008, 2009 and 2010) were based on 10 minute time step. These data have allowed us to evaluate the global solar flux, the sun duration, the yearly and the seasonal frequency distribution of the global solar radiation. Moreover, a conventional model has been used to estimate the hourly solar radiation on a horizontal plane and it has been validated by experimental measurements in specific days. The results show that the global solar radiation predicted by the conventional model has a good agreement with the experimental data during the clear sky conditions with a relative error percentage of 4.1%. However, the limitation of the conventional model appears under the cloudy sky weather which is proved by the highest value of relative error percentage reaching 14.26% occurred during the autumnal equinox day.

INTRODUCTION

Knowledge of the availability of the global solar flux at the earth's surface has a great importance in solving many scientific problems and harnessing the practical utilization of solar energy. This available quantity of energy changes within geographic place because it depends on climatic and atmospheric conditions.

It is known that global solar radiation is poorly sampled in weather station networks. For this reason, we find in the literature, recently, many authors who attempted to develop several models to estimate the global solar radiation and asses their corresponding solar potential. We can find also software packages allowing the solar flux density estimation of several sites.

Coskum et al. [1] have been modified the concept of the probability density frequency usually used to analyze the wind and the outdoor temperature distributions in order to estimate the solar radiation distribution and therefore to investigate and design better the solar energy systems. They have also conducted their study with global solar irradiation data of many years recorded by the Turkish State Meteorological Service.

Ryder et al. [2] have used the solar irradiance measurements from a new high density urban network in London. They have measured annual averages and demonstrated that central London receives 30 ± 10 W m^{-2} less solar irradiance than outer London at midday, equivalent to 9 ± 3% less than the London average. They have obtained these measurements basing on a new technique referred to the 'Langley flux gradients' that infer aerosol column concentrations over a clear periods of 3 h and this technique has been developed and applied to three case studies.

The survey of Ramachandra et al. [3] has focused on the assessment of the Indian potential resource with variability derived from high resolution satellite data. They have also presented a techno-economic analysis of the solar power technologies and a prospective for a minimal utilization of the available land.

Sorapipatana [4] has adopted a satellite technique to assess solar energy potential in Kampuchea. In his work, he has estimated the solar irradiation potential at an interval of half a degree grid. The seasonal variations of mean daily solar irradiation in Kampuchea were measured during two Asian winter and summer monsoon seasons.

Molero et al. [5] have developed a transient 3-D mathematical model for solar flat plate collectors. Their model is based on setting mass and energy balances on finite volumes and allows the comparison of different configurations. This model is a useful tool to improve the design of plate solar collectors and to compare different configurations.

Boudi et al. [6] treated a theoretical model to estimate the sun potential in Nouakchott and Dakar with an experimental validation. Paulain [7] studied the daily regime of the global sun brilliance in Quebec, Canada, by means of a numeric model feigning the transfer of solar energy through the atmosphere. Jannot [8] treated in his sun Thermal book a modeling of the deposit of the sun stream in some sites.

Kretzchmar et al. [9] has realized a research works within the framework of a thesis for the Characterization and the modeling of the sun stream EUV. The works has led to know the better extreme streams ultraviolet rays.

Abourra et al. [10] have focused on the development of a new methodology to evaluate radiotherapy solar energy reaching the ground basing on data satellites using a model of radioactive transfer.

Koussa et al. [11] have carried out the distribution of the global and diffuse radiotherapies according to some meteorological parameters. Yaiche et al. [12] have realized a conception and a validation of a program conceived to the incident solar flux evaluation in Algeria treating a totally clear sky case.

Liu Si-qing et al. [13] have made a study on the medium-term forecast of solar 10.7 cm radio flux (F10.7). By comparing their forecast results in the period from 21th September 2005 to 7th June 2007, they have been demonstrated that the accuracy of the autoregressive forecast method is equivalent to that of the forecast made by the American Air Force.

In this study, an overview of research works of all over the global solar radiation models is presented. The mentioned models can be considered as the representative of worldwide average. Its details can be found therein. Moreover, we present a classic theoretical model of the solar flux density of sun in the site of the gulf of Tunis in Tunisia. This model is used by many authors to estimate the direct and the diffuse radiation by clear sky or cloudy sky also.

We proceed to the validation of this model by experimental measurements which are conducted by means of a meteorological station during the period of 2008-2010 with a 10-min time step by the NRG weather station. The treatment of about 158 000 observations permit us to evaluate the global solar flux in the site of the gulf of Tunis.

SITE DESCRIPTION AND EXPERIMENTAL DESIGN

This present work is related to the solar energy assessment in the central coast of the gulf of the capital of Tunisia (Fig. 1) which is situated on the North African coast of the Mediterranean Sea between the approximate latitudes 30-37°N and longitudes 8-12°E. Tunisia is located between Algeria and Libya and just south of Italy. The southern regions of Tunisia have a saharan dry weather characterized by a high insulation and a low relative humidity values due to the high occurrence of hot southern winds while the northern states are endowed by a wet climatic conditions and a high relative humidity values especially near the coasts due to the hilly regions situated principally in the north-west regions.

Fig.1. Geographic description of the studied area

Radiometric data were registered at the NRG weather station in the gulf of Tunis, the capital of Tunisia which lies at the southern edge of the gulf. This station is installed in 36°43’04” N latitude and 10°25’41” E longitude. It is equipped by instrument allowing the measurement of ambient temperature, wind speed, wind direction, relative humidity and the global solar radiation solar of this region. This acquisition system of this station (Fig. 2) permits with a 10 min time-step the average, the max, the min and the standard deviation values for each sensor recorded at the technopole center of Borj-cedria. In this study, the treatment of 29 388 observations of 2008 permits us to assess the global solar radiation on horizontal plane.

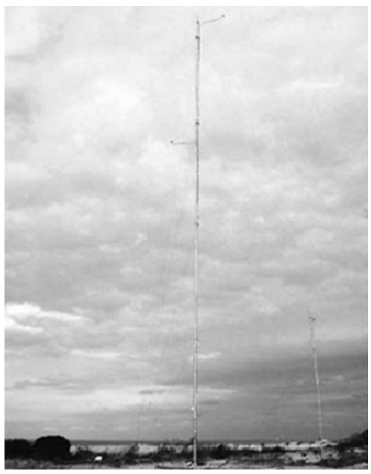

Fig.2. NRG weather station localization

GLOBAL SOLAR RADIATION PREDICTION

The knowledge of global solar radiation data can be considered as an important necessity for the architectural design, the exploitation of solar energy systems and many other industrial and agricultural projects. Tunisia is one of the countries that have solar energy in abundance. However, the solar radiation data is not readily available due to the cost and maintenance and calibration requirements of the measuring equipment which represents a handicap for most of the projects in the developing countries (Almorox and Hontoria, 2004). Thus, several empirical models have been used to predict solar radiation, using parameters such as sunshine hours (Angstrom, 1924), air temperature (Hargreaves and Samani, 1982), relative humidity (Elagib et al., 1998), precipitation (De Jong et al. 1993) and cloudiness (Black, 1956). The most usually used parameter for forecasting global solar radiation is sunshine duration. Sunshine duration data are widely available and can be easily and reliably measured.

The majority of the models for predicting global solar radiation in the literature use the sunshine ratio or the sun covering rate (Al-Lawati et al., 2003). The most commonly used correlation is that of Angstrom, who assumed a linear relationship between the ratio of average daily global radiation to the related value on a completely clear day and the sun covering rate.

The aim of this work was to validate several expression models for the estimation of monthly average daily global radiation on a horizontal plane from solar covering rate and to select the most satisfactory model.

The Angstrom correlation is:

$$\frac{H}{H_0} = a + b\,\sigma \qquad (1)$$

Where H, H_0 and σ are, respectively, the monthly mean daily global radiation, the daily extraterrestrial radiation on a horizontal plane and the sun covering rate. We note that a is a measure of the overall atmospheric transmission for total cloud conditions while b is the rate of increase of $\frac{H}{H_0}$ with σ.

We indicate that a and b are empirically determined regression constants. The sum $(a + b)$ is referred to the overall atmospheric transmission under clear sky conditions with a typical mean value of approximately 0.75 (Al-Lawati, 1992). The values of these regression constants depend on the considered location and can be inferred from correlations recognized at neighboring locations. This approach is very useful for accuracy predictions of global solar radiations on horizontal surfaces for a long period. For instance, Tadros (2000) proved that this method is the best for forecasting global solar radiation over eight meteorological stations across Egypt.

In the literature, a several forms of regression models have been proposed for predicting global solar radiation from sun covering rate.

Table 1
Regression models proposed in the literature

Models	Regression equations	Source
Linear	$\frac{H}{H_0} = a + b\,\sigma$	(Angstrom, 1924)
Quadratic	$\frac{H}{H_0} = a + b\,\sigma + c\,\sigma^2$	(Akinoglu and Ecevit, 1990)
Third degree	$\frac{H}{H_0} = a + b\,\sigma + c\,\sigma^2 + d\,\sigma^3$	(Ertekin and Yaldiz, 2000)
Logarithmic	$\frac{H}{H_0} = a + b\log(\sigma)$	(Ampratwum and Dorvlo, 1990)
Exponential	$\frac{H}{H_0} = a + b\exp(\sigma)$	(Almorox and Hontoria, 2004)

The require to rely an experimental determination of a and b is definitely the greatest short-incoming of the Angstrom correlation which is the simplest equation relating the monthly averaged daily global solar radiation and sun covering-rate. This formula is very useful and has an important interest because it needs only one regional-dependent parameter. Hence, the major aim of this study was to obtain sets of regression constants for six different regression models, as summarized in Table 1, for as many weather stations as possible with data available in Tunisia. In order to achieve this target, we employed the measured data of monthly average global solar radiation on horizontal planes and monthly sun covering-rate from the meteorological station NRG of Borj-cedria in the gulf of Tunis, to generate the formulas.

Five different regression models were applied, five proposed in the literature (linear, quadratic, polynomial third degree, logarithmic and exponential) and a polynomial forth degree model used in this work. Coefficient regression values were computed from regression examination between H/H_0 and σ for each month.

RADIOMETRIC AND SUN COVERING RATE ANALYSIS

Fig. 3 shows the statistical curves of the mean global solar radiation values over twelve months for the gulf of Tunis. Solar radiation achieves a maximum in July with a value of 223 kWh/m² and a minimum in December with a value of 60 kWh/m². One can observe that during the warmest months of

June and July, the pyranometer receives a high average monthly global solar radiation from 220 and 223 kWh/m² while the received global solar radiation during the coldest months of December and January is between 60 and 81 kWh/m². One can deduce that the differences in global solar radiation between each monthly average are larger in the cold months than in the warm months. The sum of all received global solar radiation for the twelve months was 1680 kWh/m².

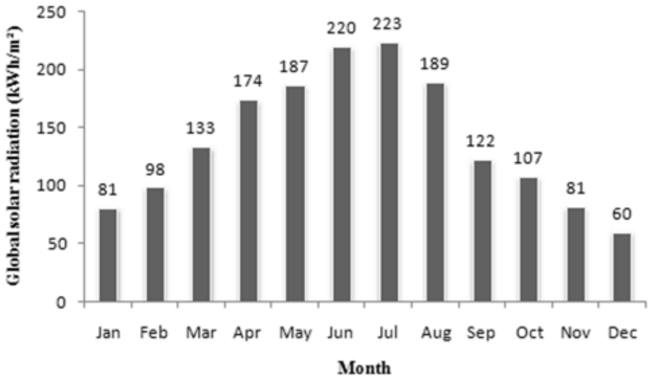

Fig.3. Monthly global solar radiation

The monthly sun covering-rates for the studied site are presented in Fig. 4. It is clear that the monthly sun covering-rates show a good similarity in tendency and magnitude with the monthly average global solar radiation (Fig. 3). The discrepancies are caused essentially to the cloudy sky conditions which affect the shape of the monthly sun covering rate. As shown in Fig. 4, sun covering-rate reaches a maximum in July and August with a value of 92% and a minimum in February and December with a value equal to 66%. During the clear sky months of June, July and August the monthly sun covering rate varies from 88 and 92% while it fluctuates from 66 to 72% during the cloudiest months of December, January and November. The average yearly sun covering-rate in the gulf of Tunis in 2008 reaches the value of 80% which proves that this region has a very important sunshine duration and a clear sky conditions.

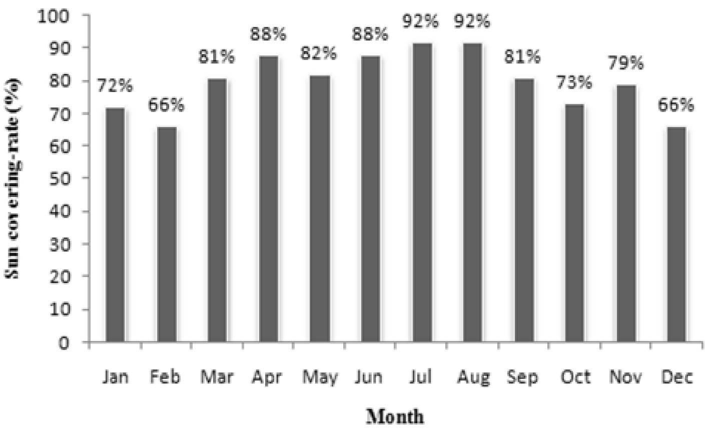

Fig.4. Monthly sun covering-rate

CUMULATED SOLAR FLUX ESTIMATION

Fig.5 shows the daily cumulated solar flux for the twelve months of 2008 in the gulf of Tunis. The experimental results shows that these cumulated radiations have a linear regression with the day of each month.

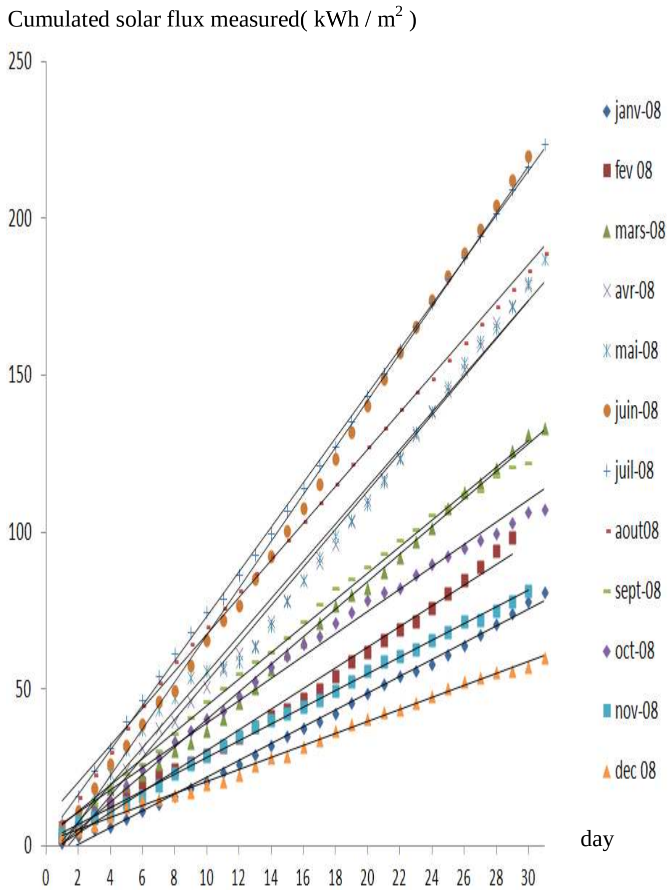

Fig.5. Daily cumulated solar flux for each month during 2008

This deduction lead us to develop a daily linear regression correlation for each month. This correlation has the following formula :

$$C_{SF,m} = c + d \times n \quad (2)$$

Where $C_{SF,m}$, n are respectively the daily cumulated solar fluxes for the m month and the ordinal day of the corresponding month. c and d are two linear regression coefficients.

The performance of the proposed model was evaluated by calculating the statistical R-squared errors. Table 2 recapitulates the developed daily linear regression coefficients and the R-squared error made between the values of measured cumulated solar flux values and the predicted ones obtained basing on the correlation (2).

Table 2
Regression coefficients and R-squared errors of proposed cumulated solar flux model

Month	c	d	R^2
January	-4.963	2.668	0.997
February	-2.475	3.286	0.992
March	-3.711	4.396	0.996
April	-8.260	6.066	0.995
May	-4.621	5.932	0.991
June	-7.641	7.471	0.997
July	2.188	7.099	0.999
August	8.377	5.892	0.998
September	2.376	4.222	0.995
October	3.720	3.454	0.999
November	1.530	2.667	0.998
December	1.266	1.266	0.997

According to the results summarized by Table 2, it is found that the measured daily cumulated solar flux values and the predicted are in good agreement. It is clear that the daily cumulated solar flux is well described by a linear fit with coefficients of determination R^2 between 0.991 and 0.999. Thus, such statistical results points toward the agreement between the $C_{SF,m}$, values measured and the predicted through the proposed model are good and the linear model is practical for the gulf of Tunis.

SKY CLEANESS INDEX EXAMINATION

The correlation proposed by Angstrom (eq. 1) and later modified by Prescot [31] was applied to predict the monthly average daily global radiation H. The formula is commonly expressed as [17]:

$$K_T = a + b\ \sigma \qquad (2)$$

where a, b and K_T are, respectively, two correlation coefficients, which can be determined from the measured sun covering rate σ, by using the least-squares fit technique, and clearness index $\left(K_{T\,sun} = \frac{H}{H_0}\right)$.

Table 3 determines the monthly local coefficients a and b for the gulf of Tunis.

Table 3
Regression coefficients of linear Angstrom model for the gulf of Tunis, Tunisia

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.030	0.656	0.035	0.032	0.025	0.062	1.015	0.372	0.044	0.182	0.005	0.011
2.619	2.757	3.846	4.925	5.336	6.043	4.539	4.424	3.642	3.201	2.472	2.131

A comparison of the sky clearness index obtained from equation 2 and its counterpart based on pyranometer measurements is showed in Fig.6 for the gulf of Tunis, Tunisia.

We can observe in Fig. 6 that the sun covering-rate derived prediction ($K_{T\,sun}$) are effectively confined to measured values. In fact, as shown from Fig. 6, the maximum error between the two clearness index estimates occurs in the month of February with a value of 6% which give credibility to the acceptance of the assumed regressions coefficients, basing on the Angstrom correlation, to calculate the desired long-term predictions in this solar research work under the climatic conditions of the gulf of Tunis.

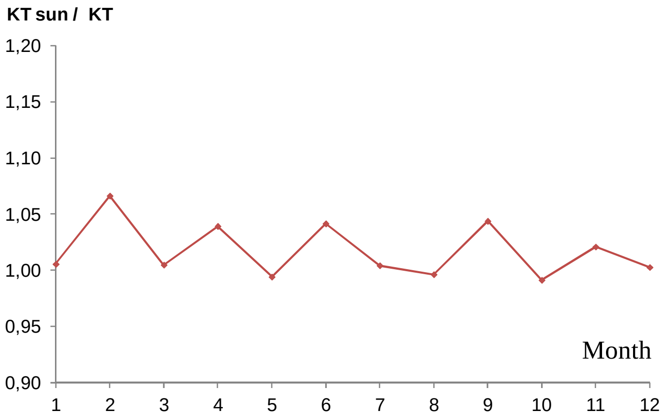

Fig. 6. Comparison of clearness indexes using the monthly ratio of (KT sun/KT)

COMPARAISON BETWEEN THE METHODS OF GLAOBAL SOLAR RADIATION ESTIMATION

ANNUAL REGRESSION

According to the annual results tabulated in Table 4, it is obvious that all the regression equations gave very good results and therefore all models fitted the data satisfactorily and can be employed to predict global solar radiation from sun covering-rate. It is clear that the polynomial third and forth degree models gave the best estimate and have the largest R^2 values of **0.819** and **0.845** respectively. Also, the logarithmic and the exponential equations performed poorer than the other models, corresponding to the smallest R-squared statistics with the value of **0.741** and **0.755** respectively. It is evident that the linear regression has the simplest equation and the widest applications but its accuracy is poorer that the quadratic, polynomial third and forth equations regression with a value of R^2 equal to **0.758**. The variance difference between the linear regression and the polynomial ones can be over than **8%** thus however the simplicity of the linear model and its accuracy for predicting the clearness indexes for the gulf of Tunis it cannot be a perfect tool of long-term global solar radiations estimates in this region. Finally, according to the above-mentioned results the polynomial forth degree correlation is the best model to predict the global solar radiation with accuracy in the gulf of Tunis is:

$$\frac{H}{H_0} = -2599 + 137.2\,\sigma - 2.701\,\sigma^2 + 0.023\,\sigma^3 + 8\,10^{-5}\,\sigma^4 \quad (3)$$

Table 4
Annual regression outcomes and R^2 values of models

	Equations	R^2
Linear	$\frac{H}{H_0} = -7.001 + 0.129\,\sigma$	0.758
Quadratic	$\frac{H}{H_0} = 12.63 - 0.373\,\sigma + 0.003\,\sigma^2$	0.787
Polynomial third degree	$\frac{H}{H_0} = 277.7 - 10.58\,\sigma + 0.133\,\sigma^2 - 0.000\,\sigma^3$	0.819
Polynomial forth degree	$\frac{H}{H_0} = -2599 + 137.2\,\sigma - 2.701\,\sigma^2 + 0.023\,\sigma^3 + 8\,10^{-5}\,\sigma^4$	0.845
logarithmic	$\frac{H}{H_0} = -40.5 + 10.02\log(\sigma)$	0.741
Exponential	$\frac{H}{H_0} = 0.112\exp(0.041\sigma)$	0.755

MONTHLY REGRESSION

In the above regression analysis, the accuracy of the different models have been tested basing on the average yearly measured data but it will be necessary to justify this accuracy by a monthly regression process. The model results and its corresponding R^2 for each month are listed in Table 5. The results show that the monthly estimation of global solar radiation by these equations is adequately reliable with the exception of the month of August because it corresponds to the poorest performance of the different models. In addition, the logarithmic regression equation has the worse R^2 values in comparison with the other models in the whole year. The cubic and the forth polynomial regression equations gave good and very similar accuracy. The exponential model is the most accurate model for estimating global solar radiation in the months of April, June, July and December. We note that during these four months, the difference between the R^2 results related to the forth polynomial and exponential correlations are negligible. According to the results given by table 5, we can say that the global solar radiation in the gulf of Tunis is well described by a forth polynomial regression.

The validity of this global radiation model requires be testing on other regions and improving by using long term data sets of global radiation on a horizontal surface.

Table 5
Statistical results of different models each month

	R^2					
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
January	0.966	0.966	0.969	0.969	0.945	0.921
Feb	0.952	0.952	0.962	0.963	0.917	0.912
Mar	0.907	0.910	0.925	0.948	0.810	0.888
Apr	0.814	0.816	0.816	0.818	0.799	0.901
May	0.935	0.954	0.979	0.981	0.863	0.961
Jun	0.924	0.934	0.934	0.936	0.877	0.956
Jul	0.821	0.824	0.831	0.831	0.798	0.876
Aug	0.473	0.529	0.655	0.723	0.477	0.522
Sep	0.914	0.914	0.960	0.968	0.864	0.869
Oct	0.948	0.953	0.987	0.990	0.867	0.908
Nov	0.919	0.924	0.944	0.969	0.835	0.924
Dec	0.957	0.972	0.973	0.974	0.871	0.976

CONCLUSION

The availability of global solar radiation data is fundamental to enhance the work of engineers and solar exploitation. Thus, the use of some models and correlations basing on sun covering-rate seems very interesting to predict global solar radiation on horizontal surfaces for the gulf of Tunis. The idea was to select, develop and test these models in order to decide which correlation is recommended in this site based on data at NRG meteorological station of Borj-cedria in the gulf of Tunis. As a first step in the process, the linear Angstrom correlation estimates of the sky clearness index were tested. The results showed that this model predicted with accuracy the sky clearness index basing on the climatic conditions of this region with a maximum error of 6%. After that, six different models basing on the sun covering-rate, for forecasting global solar radiation on horizontal planes, have been selected, developed and tested using the R-squared analysis basing on the average yearly solar radiation data.

The results showed that the forth polynomial regression equation is the most accurate model to predict global solar radiation on horizontal surfaces in the gulf of Tunis with a value of R^2 equal to 0.845. This model can be described with its yearly regression coefficients as follows:

$$\frac{H}{H_0} = -2599 + 137.2\,\sigma - 2.701\,\sigma^2 + 0.023\,\sigma^3 + 8\;10^{-5}\,\sigma^4$$

Furthermore, the monthly R^2 derived from the regression equations of different models have been used to justify the accuracy of the forth polynomial correlation. The results showed that this model remained the best one to predict the monthly global solar radiation in this area and several systems using solar energy can be designed.

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