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# A simple New Developed Model for Forecasting the Solar Radiation in Egypt

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***Abstract:*** *Solar radiation data is very important for many applications. Several mathematical models were built-up to predict the solar radiation in different countries. During this study, five different mathematical models of solar radiation intensity on a horizontal surface were discussed. Based on the measured data throughout the year and the different between the five models, a new suggested model has been built-up for forecasting the global solar radiation. The models were validated and compared based on the statistical error tests such as the relative percentage error, the coefficient of determination, mean bias error, root mean square error and the t- statistic method. According to the results, the new suggested model is more accurate and recommended to foretell the global solar radiation at different cities in Egypt. According to the available published measured data, the new suggested model was also validated for different countries such as Saudi Arabia, Turkey, Iran and India. The results showed that, the new suggested model gives good agreement prediction of the global solar radiation over these countries.*

***Keywords:*** *Mathematical models; global; solar radiation; solar energy.*

## I. INTRODUCTION

The sun fusion furnace produces energy and transmitted as an electromagnetic wave and called solar radiation (energy). The universal solar radiation across through the atmosphere to reach the earth is divided to scattered, absorbed and reflected solar radiation. The scattered and reflected part returns back to the Earth as diffuse solar radiation. The incident solar energy that reaches the Egyptian ground has a value of 12–30 MJ per $m^2$/ day, and has a sunshine period magnitude between 3500 and 4500 h / year [1-2]. Solar radiation data is very important for different applications, such as the thermal collecting systems, the atmospheric studies and the analysis of thermal loads. Egypt has abundant solar energy along the year approximately [2]. Many terminals are used to measure and record the different solar radiation components in Egypt. Therefore, different empirical models have been established and developed to estimate the components of solar radiation, over different cities in Egypt and different countries along the world.

Ramadan and El-Sebaii [3] measured the universal solar radiation component on a horizontal flat face in Tanta city and compared the results with several independent predictions methods. The results illustrate that the best technique is based on Angstrom formula. This method correlates the relative global solar radiation to the bright sunshine of relative duration. Abdel-Salam et al. [4] developed a model to estimate the beam and diffuse solar radiation components in Egypt. Their model was used to forecast the monthly moderate daily solar radiation for seven terminals in Egypt. They compared the results with previous publications of Egyptian Meteorological Authority and showed that the calculations are more accurate and their model can be used to

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appraisal the solar radiation components. Kamel et al. [5] studied the solar irradiance measurement on a horizontal surface at five different terminals in Egypt. They compared the results of the three years with the computed values by two independent methods. The first one is based on the Angstrom formula meanwhile the second technique is based on an empirical relation including inputs parameters. The results showed that the first method gives the better results for forecasting the solar radiation values. El-Metwally [6] developed new methods to estimate the global solar radiation in Egypt. The models were tested at different weather conditions at different seven locations in Egypt. The obtained results showed that the determination coefficient is higher for the new developed methods for all the tested locations. The new developed methods showed also better results when applied to different seasons along the year. El-Metwally [7] represented a non-linear equation to forecast the monthly average daily global solar radiation at different six sites in Egypt. The proposed equation is based on the duration of sunshine. This method was tested at different sky conditions include partially cloudy, clear and overcast skies. Also he tested the equation in 32 terminals at different sites. The results showed that the proposed method performed better than the other models. Hafez et al. [8] presented an empirical approach to forecast the average global solar radiation for various locations in Egypt using the bright sunshine hours. Also, they used MATLAB/GUI interface to generate a solar radiation simulation model. Their model was developed using the solar radiation basic equations including the effects of time change and locations in Egypt. The obtained results showed that their model is useful for the different solar energy applications in Egypt for horizontal and tilted surface. Yaniktepe and Genc [9] investigated a new model for horizontal surface by utilizing the meteorological measurement data constructed for university of Osmaniye Korkut Ata. They used different statistical methods to evaluate this model. The results showed that the new model is acceptable for estimating the solar radiation in Osmaniye. Hassan et al. [10] predicted the global solar radiation by using the ambient-temperature-based models. They established and validated seventeen new temperature-based models with three different models. They suggested a general formula and examined it for different ten locations in Egypt. They used different statistical errors methods to evaluate the models performance and identify the most accurate model. The results showed that the suggested formula provides good forecasting for solar radiation at different locations.

Khalil and Shaffie [11] studied and evaluated different models of solar radiation over Egypt. Their study included a comparison between the monthly hourly and the daily beam, diffuse and global solar radiation. Their study was performed on inclined and horizontal surfaces for Cairo city in Egypt. They used variable statistical errors methods to compare between the measured values with the calculated. The results showed that Perez's and Klucher models are more accurate than the other models. Also the results give good agreement with different models. Hassan et al. [12] developed seven different models to appraisal the solar radiation for ten cities in Egypt. Based on the statistical evaluation methods the results showed that there are two models have the best performance compared with the other models. The first model is the hybrid sine and cosine wave model and the second one is the $4^{th}$ order polynomial model. Zang et al. [13] established 14 day of the year-based (DYB) model to estimate daily global solar radiation based on measured data from 1994 to 2015 at 35 meteorological terminals in six climate zones of China. They found that it is useful for the forecasting and estimation of long-term daily global solar radiation, and is suitable for terminals with few climatic data recorded. In their study, seven EMs and seven ML methods (i.e. ANFIS-GP, ANFIS-SC, ANFIS-FCM, ANFIS-CFA, ANFIS-WOASAR, SVR and GPR) for DYB models are verified and compared in six climate zones in China. Marzouq et al. [14] build-up an automatic selection of ANN inputs from obtainable parameters set for the estimation of horizontal daily global solar irradiation in the Fez city, Morocco. Their model gives an achievement of 97.50% for $R^2$ and 17.85% for RRMSE with rainfall, wind direction, daily temperature gradient and global solar radiation at the top of the atmosphere as the best set of input parameters. Bailek et al. [15] introduce a systematic path for DSR estimation over the Algerian Sahara. They check the available meteorological and radiometric data during six years from 2010 to 2015 measured in the Adrar region. They flinched that the correlation is applied to estimate the monthly average daily spread radiation on a horizontal surface for any site over the Algerian Sahara region, which can serve as a resource for the design of photovoltaic systems. Benkaciali et al. [16] investigated eighteen clear sky broadband models for predicting the direct irradiance at normal incidence (DNI). They recorded data from two sites of different weather conditions; Bouzareah site (Algiers). Their results affirm that the ESRA, Dogniaux, MAC and Yang models performed superior to the remaining models, with the RMSE of 0.443, 1.066, 1.237 and 1.283 for Algiers, and 0.390, 1.100, 1.223 and 1.443 for Ghardaïa. Chen et.al [17] developed twenty satellite-based models for estimating radiation components using MOD08-M3 atmospheric product and evaluated utilizing measured radiation data at 15 sites across China. The preferable site-specific models for diffuse and direct beam radiation were proposed, with the average RMSE of 0.642 MJ $m^2$ (9.299%), and 0.736 MJ $m^2$(10.69%), respectively.

The main objective of the present study is to compare between the common five different mathematical models used for forecasting the solar radiation intensity on a horizontal surface in Egypt. Based on the measured data throughout the year and the basis of statistical error, a new suggested model has been developed. These models were compared and validated by comparing the forcasting values with the measured data by using different statistical evaluation methods.

## II. SOLAR RADIATION MODELS

The knowledge of solar radiation data is very important for many engineering applications and researchers. In order to fulfil this, different several mathematical models have been developed to appraisal the solar radiation intensity in several countries. This study presents different five mathematical models of solar radiation estimation on a horizontal surface. Based on the basis of statistical error, a new suggested model was developed for Egypt and other cities in different countries.

### 2.1 Morcos Correlations (Model -1)

Morcos, [18] developed a mathematical model to calculate the global solar radiation on a tilted surface in Assiut city, Egypt. This model depends on Liu and Jordan study [19]. They considered the radiation on the surface depends on the beam solar radiation, diffuse radiation and reflected solar radiation from the ground, buildings and trees. The total solar radiation on a tilted surface *I*, for the standard clear day's solar radiation is given from the following relation,

$$I = I_o[\tau_b \cos\theta + \tau_d \cos\theta_z \ (1+\cos\beta)/2 + \rho_g \ (\tau_b + \tau_d)\cos\theta_z \ (1-\cos\beta)/2] \qquad (1)$$

Where, $I_o$ and $\tau_b$ are calculated from Liu and Jordan study [19]. The value of $\tau_d$ can be calculated from Morcos empirical correlations for beam and diffuse solar radiation for a clear sky weather, $\theta$ and $\theta_z$ are the incidence angle and the zenith angle respectively which depends on the latitude angle of the location [20], $\beta$ is the tilt angle and $\rho_g$ is the diffuse ground reflectance. For clear sky and no snow cover the value of diffuse ground reflectance is 0.2 [18] and a correction factors are used due to the climate types.

### 2.2 Moghadam et al. Correlations, (Model -2)

Moghadam et al. [21] evaluated the global solar radiation on a tilted surface. They neglected the ground reflected solar radiation due to its minor value compared with the direct and diffuse solar radiation component. The total solar radiation is calculated as follows,

$$I = S_c \cos\theta \ (\tau_b + \tau_d) \qquad (2)$$

Where, $S_c$ is the solar constant (1373 W/m$^2$). The value of $\tau_{d,}$ can be determined as a function of $\tau_b$. The value of $\tau_{b,}$ can be easily determined as,

$$\tau_b = a_0 + a_1 e^{-k/\cos\theta} \qquad (3)$$

The constants $a_0$, $a_1$ and *k* are determined according to Morcos, [18] study.

### 2.3 Sakonidou et al. Correlations, (Model -3)

Sakonidou et al. [22] used Duffie and Beckman relations [20] to estimate the components of total solar radiation on a tilted surface of $\beta$, from the following relation,

$$I = I_b R_b + I_d \left(\frac{1+\cos\beta}{2}\right) + I_t \ r_g \ \left(\frac{1-\cos\beta}{2}\right) \qquad (4)$$

Where, $I_b$ and $I_d$ are the beam and diffuse solar radiation intensities on horizontal surface. $R_b$ is the geometric factor and it can be calculated from Duffie and Beckman relations and $r_q$ is the surroundings diffuse reflectance and equals to 0.25. The total hourly solar irradiation $I_{t,}$ can be calculated based on the total daily irradiation *H*.

### 2.4 The ASHRAE Clear-Sky model, (Model -4)

The ASHRAE clear sky model is an important commonly model and used for different solar engineering applications. This model is considered as a semi-empirical method and described in detail in ASHRAE (2001), [23]. The hourly global, beam and diffuse solar radiation on a horizontal surface for clear days are estimated from the following equations as [24],

$$I = I_b \cos\theta_z + I_d \qquad (5)$$

$$I_b = A\exp[-B/\cos\theta_z] \qquad (6)$$

$$I_d = C \, I_b \qquad (7)$$

Where, *A*, *B* and *C* are constants and their values are obtained from the solar radiation data analysis. The input data to the ASHRAE model are the day number, latitude and the constants.

**2.5 Radiation on Collector Program, (Model -5)**

The radiation on collector program is an open source code, which is used to calculate the components of solar radiation. The full source code for this program before any editing is available and can be downloaded from this web site [25]. The origin algorithms used in the program are given from Peter J. Lunde, [26]. The source code for this program is edited in its shape, input data and the output. The results were recorded in the SI system units. The program estimates the radiation for sunny day only and the effects of clouds, fog and pollution are not included.

**2.6 The New Suggested Model**

A lot of measured data along year seasons have been recorded for many cities in Egypt (Shebin-El-Kom, Mansoura, Kafr El-Sheikh, Suez, Cairo, Alexandria and Al Arish). The measured data includes the hourly average global, beam and diffused solar radiation for horizontal surface. Based on these experimental data permutations and combinations were done using a computer program along the year. A combination between the previous models was done, and a new mathematical model was suggested based on these data and statistical evaluation methods. This model is a semi-empirical model based on Morcos and ASHRAE correlations. By neglecting the ground reflected radiation, the new model is defined as follows,

$$I = \underbrace{I_b R_b}_{Beam\ from\ model\ (1)} + \underbrace{I_d}_{Diffuse\ from\ model\ (4)} \quad (8)$$

Substituting the values from the model, the above equation can be written as,

$$I = I_o\ \tau_b\ \cos\theta\ + C\,A\,\exp[-B/\cos\theta_z\,] \quad (9)$$

and

$$\tau_b = a_o + a_1 \exp[-k/\cos\theta_z\,] \quad (10)$$

Where, $A$, $B$ and $C$ are the same constants as ASHRAE model, while $I_o$ is calculated according to Morcous model.

During this study a computer program was built for the first four models and the new suggested model to investigate the solar radiation for a horizontal surface. These models were checked with different repeated runs as required for hourly solar radiation forcasting. The results of these models were compared and validated with the published measured solar radiation over different selected cities in Egypt and different countries.

## III. STATISTICAL MODELS EVALUATION METHODS

The models described previously were evaluated and tested according to the different statistical error tests as follows**:**

**3.1 The Relative Percentage Error (*e*)**

The relative percentage error *e*, provides the deviation percentage between the predicted and measured data. The perfect value for the relative percentage error equals to zero. A relative percentage error ±10% is acceptable [2]. The *e* value is given by,

$$e=[(I_{T,m} - I_{T,c})/I_{T,m}]\times 100 \quad (11)$$

Where, $I_{T,m}$ and $I_{T,c}$ are the solar radiation for measured and calculated values, respectively.

**3.2 The Determination Coefficient ($R^2$)**

The determination coefficient $R^2$, can be used to test the linear relationship between the measured and the estimated values; the value of $R^2$ should be closer to unity as possible and is given by the following equation [27],

$$R^2 = 1 - \frac{Error\ between\ Experimental\ and\ predicted\ results}{Experimental\ results\ deviation} \quad (12)$$

$$R^2 = 1 - \frac{\sum (I_{T,m} - I_{T,c})^2}{\sum (I_{T,m} - \bar{I}_{T,m})^2} \quad (13)$$

The term $\bar{I}_{T,m}$ in equation (13) is defined as [27],

$$\bar{I}_{T,m} = \frac{\sum_{i=1}^{n_p} I_{T,m}}{n_p} \tag{14}$$

Where, $n_p$ is the number of experimental points.

### 3.3 The Mean Bias Error (*MBE*)

The values of mean bias error *MBE*, give information about the correlations performance. The perfect value for *MBE* is equal to 'zero' and the mean bias error can be given from the following [2]

$$MBE = \frac{1}{n_p}\sum_{i=1}^{N}(I_{T,m} - I_{T,c}) \tag{15}$$

### 3.4 The Root Mean Square Error (*RMSE*)

The *RMSE,* gives information for the short term performance of the different correlations. The minimum *RMSE* value means the best performance of the model. The *RMSE* is given as [2],

$$RMSE = \left(\frac{1}{n_p}\sum_{i=1}^{N}(I_{T,m} - I_{T,c})^2\right)^{0.5} \tag{16}$$

The *RMSE* has a positive value, and the 'zero' value is the ideal case.

### 3.5 The *t*- Statistic Method

The *t*-statistic method depends on the values of *MBE* and *RMSE*, and it is very important to determine any statistical properties. The smallest *t*-statistic value means the best performance of the model [2]. The *t*-statistic, *t* is given by,

$$t = \left(\frac{(n_p - 1)\,MBE^2}{RMSE^2 - MBE^2}\right)^{0.5} \tag{17}$$

## IV. RESULTS AND DISCUSSION

The measured and predicted values from the different models of the average hourly global solar radiations for the months of a year are presented. The statistical summary of the different models using statistical data and evaluation methods are discussed. The different statistical errors such as *e*, between the forecasted and measured values of the average monthly solar radiation are determined for the twelve months around the year. The different statistical tests of *RMSE*, *MBE*, *t-test* and the coefficient of determination $R^2$ are also determined. Results of these coefficients were also discussed in the following figures and tables. Figure (1) shows a comparison between the present models and the published measured data by Amer [28] along different selected months of the year for Shebin-El-Kom city, Egypt. From these figures it can be noticed that, there is a large deviation between the forecasted and measured values especially in the winter season such as January. This deviation occurs due to the unstable weather conditions during these months in Egypt. The solar radiation reaching the Earth's surface reduces due to the aerosol particles, rains and wind velocity that scattering and absorbing the sunlight. Also it can concluded that, the new suggested model gives the more acceptable prediction of solar radiation compare to the others models. Figure (2) presents the variations of hourly average global measured data along different selected months of the year for Mansoura city, Egypt as reported by Taha [29] with predicted values from the different models. From these figures, it can be concluded that, all models give precise prediction for the global solar radiation rather than that of Shebin-El-Kom city.

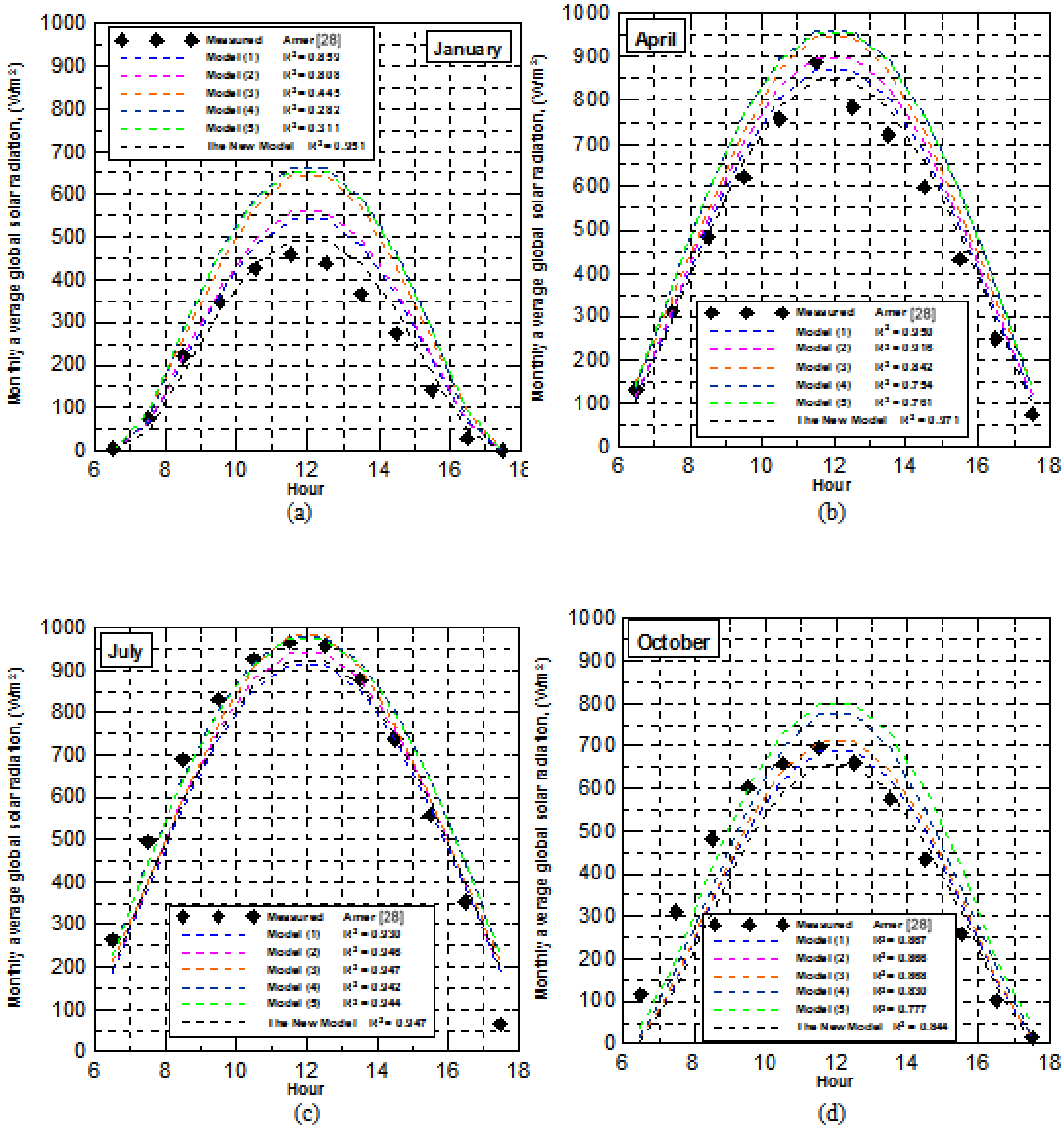



***Fig. (1):*** *Variation of measured and predicted monthly average global solar radiation during different selected months in Shebin-El-Kom city.*

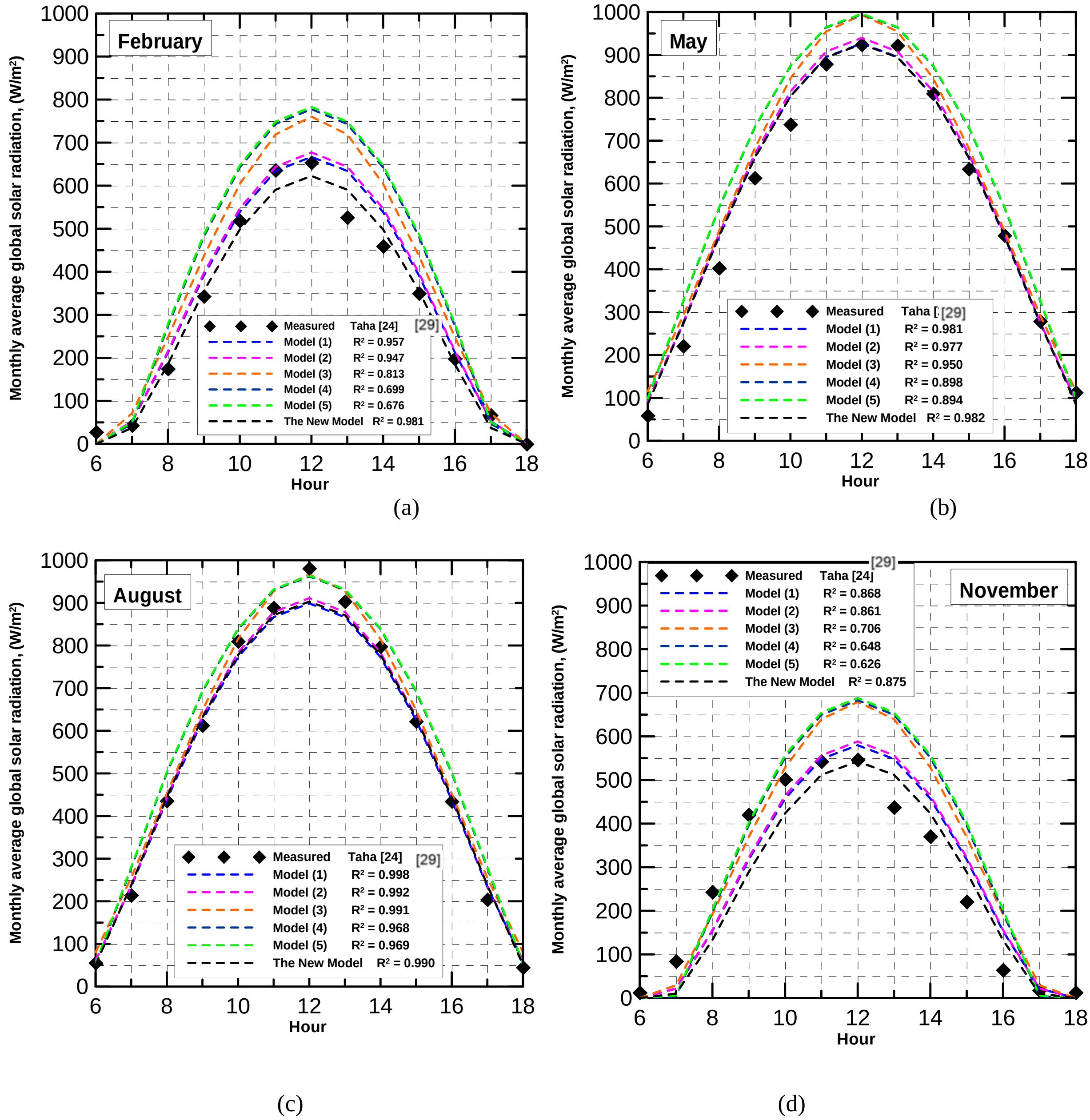


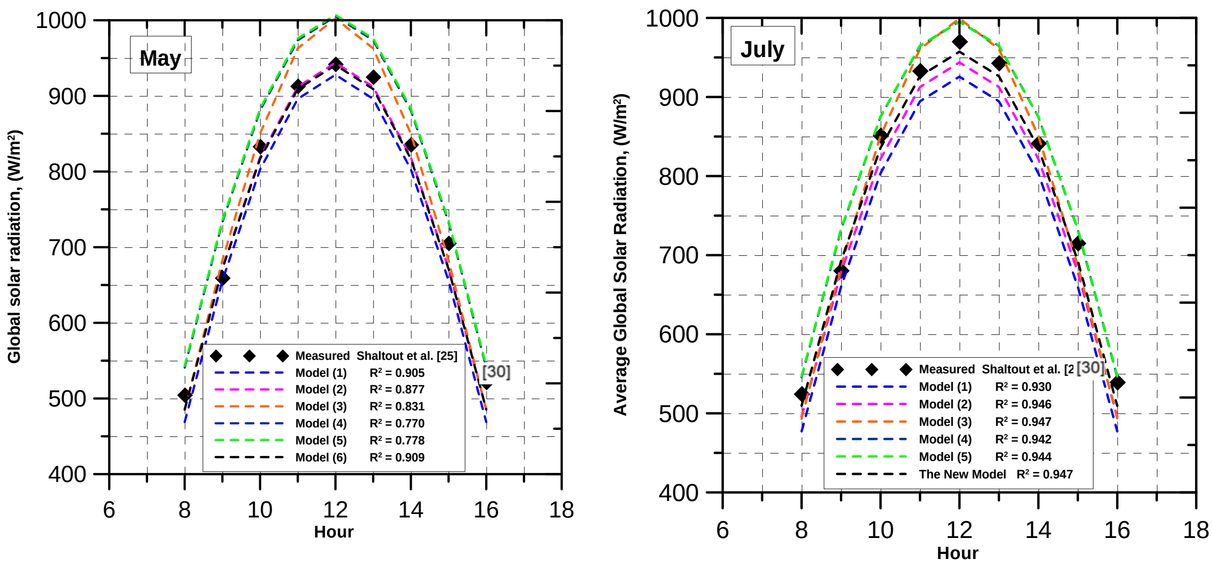

***Fig. (2):*** *Variation of measured and predicted monthly average global solar radiation during different selected months in Mansoura city.*

Table (1) summarizes the statistical test results for all models during the year for Shebin-El-Kom and Mansoura cities. From the table it can be observed that, the new suggested model depicts the best results and gives good prediction of solar radiation overall the year. It has the lowest statistical values of *RMSE*, *MBE* and *t-test* with highest values of $R^2$ compared to the other different models. For Shebin-El-Kom city, it can be noticed that, the overall statistical percentage errors, *e* of the new suggested model has an acceptable value of -7.019. Furthermore, the *MBE* value is the lowest value of 1.834, while the *t*-test value is 1.724. Finally, the new suggested model has the highest value of the determination coefficient $R^2$ ranging between 0.844 and 0.971. Also the average value for $R^2$ around the year based on the new model, model (1) and model (2) are about 0.913, 0.875 and 0.843 respectively. For Mansoura city, it can be observed that, the overall percentage errors, *e* and *RMSE* are lower than Shebin-El-Kom city. Finally the average value for $R^2$ around the year based on the new model, model (1) and model (2) are about 0.943, 0.921 and 0.912 respectively.

The measured data of Shaltout et al. [30] for Al-Menia city (28.12°N and 30.55°E), Egypt are also validated with the previous models as shown in Fig. (3). The measured data of solar radiation were recorded from January to December 1997 from 8:00 to 16:00. Figure (3) represents a sample of results for May and July months. From this figure and Table (2) it can be concluded that, the new model gives the best value of $R^2$ which is equal to 0.909 for May followed by model (1) with $R^2$ of 0.905. All models give a good prediction for global solar radiation in July. The new model and model (3) have the best value of $R^2$ is 0.947, model (2) also has a good value of $R^2$ is 0.946. From this figure it can be concluded that the new model gives a good prediction values for global solar radiation in Al-Menia city.

***Table (1):*** *Summary of the statistics errors average values of the tested models for Shebin-El-Kom and Mansoura cities*

| City | *Statistics Errors* | Model (1) | Model (2) | Model (3) | Model (4) | Model (5) | The New Model |
|---|---|---|---|---|---|---|---|
| Shebin-El-Kom city | *e, (%)* | -14.923 | -18.442 | -32.081 | -32.10 | -43.22 | -7.019 |
| | *MBE* | -12.909 | -27.458 | -57.437 | -77.24 | -83.45 | 1.834 |
| | *RMSE* | 76.622 | 81.035 | 102.993 | 115.78 | 118.18 | 66.494 |
| | *t- test* | 2.359 | 2.262 | 2.7192 | 3.233 | 3.603 | 1.724 |
| | $R^2$ | 0.875 | 0.843 | 0.726 | 0.650 | 0.634 | 0.913 |
| Mansoura city | *e, (%)* | -8.887 | -10.418 | -24.032 | -20.214 | -22.278 | -1.199 |
| | *MBE* | -15.905 | -22.077 | -55.626 | -73.079 | -75.953 | -4.165 |
| | *RMSE* | 54.870 | 56.5859 | 82.045 | 100.669 | 103.129 | 46.365 |
| | *t- test* | 2.013 | 2.073 | 3.598 | 4.188 | 4.3105 | 1.032 |
| | $R^2$ | 0.921 | 0.912 | 0.798 | 0.734 | 0.72117 | 0.943 |




(a) (b)

***Fig. (3):*** *Variation of measured and predicted global solar radiation in Al-Menia city.*

Other comparisons are investigated between the suggested new model and the other different models with the measured published data during one day in different cities in Egypt. Figure (4) represent the comparison between the published measured hourly global solar radiation and the predicted values for Kafr El-Sheikh city, Egypt. Kafr El-Sheikh city which has latitude of 30.61 North and longitude of 31.62 East and it is located at an elevation of 14 meters above the sea level. The published measured data were recorded in August, 2010 by Kabeel et al. [31]. The same previous statistical tests are done and summarized in Table (2). From the analysis of this figure and the table, it is can be noticed that there is a mismatch between the results of all models. The new suggested model and model (1) give the highest values of $R^2$ with a value of 0.935 and 0.930 respectively. Figure (5) presents the predicted values with the published measured global solar radiation of Nafey et al. [32] in Suez city, Egypt. The measured data were recorded in May, 1998. Suez city has latitude of 29.58 North, longitude of 32.33 East and it is located at an elevation of 5 meters above sea level. From this figure and Table (2), it can be noticed that the coefficient of determination $R^2$ does not change significantly with the results of all models and models (1), (2) and the suggested new model can be used for predicting the global solar radiation for Suez city. The suggested new model gives the highest value of $R^2$ which is equal to 0.952 followed by model (1) and model (2) with $R^2$ of 0.949 and 0.944 respectively and model (5) gives the lowest value of 0.901.

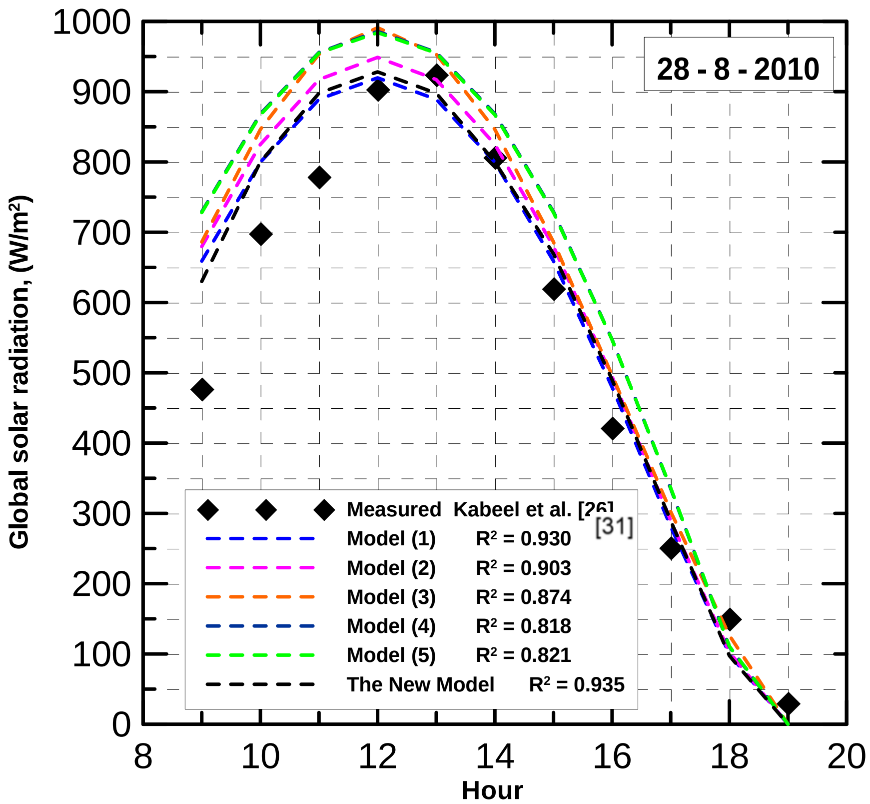



***Fig. (4):*** *Variation of measured and predicted monthly average global solar radiation in Kafr El-Sheikh city.*

The measured data of Abdel-Rehim and Lasheen [33] for Cairo city, Egypt are also validated with the previous models as shown in Fig. (6). The measured data were recorded in June 2005. From this figure and Table (2) it is clear that, the new model gives the best value of $R^2$ which is equal to 0.902 followed by model (1) and (2) with $R^2$ of 0.883 and 0.829 respectively. The minimum value of $R^2$ is 0.644 and is given from model (4). The hourly measured solar radiation is also plotted versus the estimated models for Alexandria and Al Arish cities, Egypt as shown in Figs. (7) and (8). The measured data for Alexandria, Egypt were done by Kassem et al. [34], while the measured data for Al Arish, Egypt were done by Trabea [35]. The same previous statistical tests are summarized in Table (2). From the evaluation of these figures and the table, it can be noticed that high correlation coefficient between the estimated and measured values is observed for Al Arish city, while low values are observed for Alexandria city. The new suggested model gives the highest value of $R^2$ which is equal to 0.825 for Alexandria, while model (3), (2), (1) and the new suggested model can be used to predict and estimate the global solar radiation in Al Arish city.

All the previous considered cities over Egypt in this study are shown in the map of Egypt in Fig. (9). This figure contains the different tested locations with latitude extended from 30$^o$ to 31.5$^o$ North and longitude extended from 28$^o$ to 33.8$^o$ east. The altitude is also shown in the map.

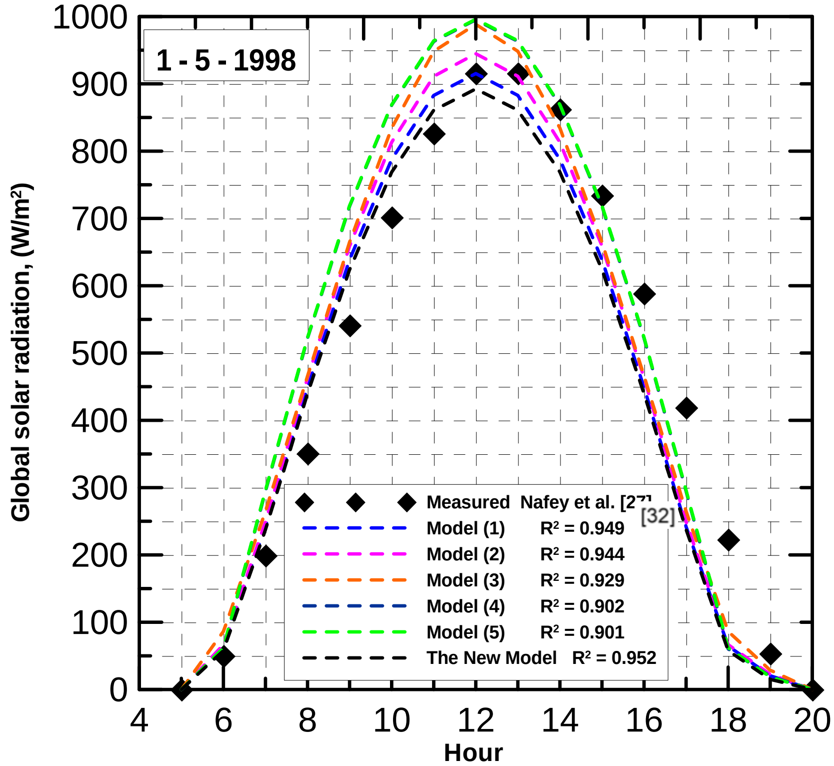



***Fig. (5):*** *Variation of measured and predicted monthly average global solar radiation in* Suez *city.*

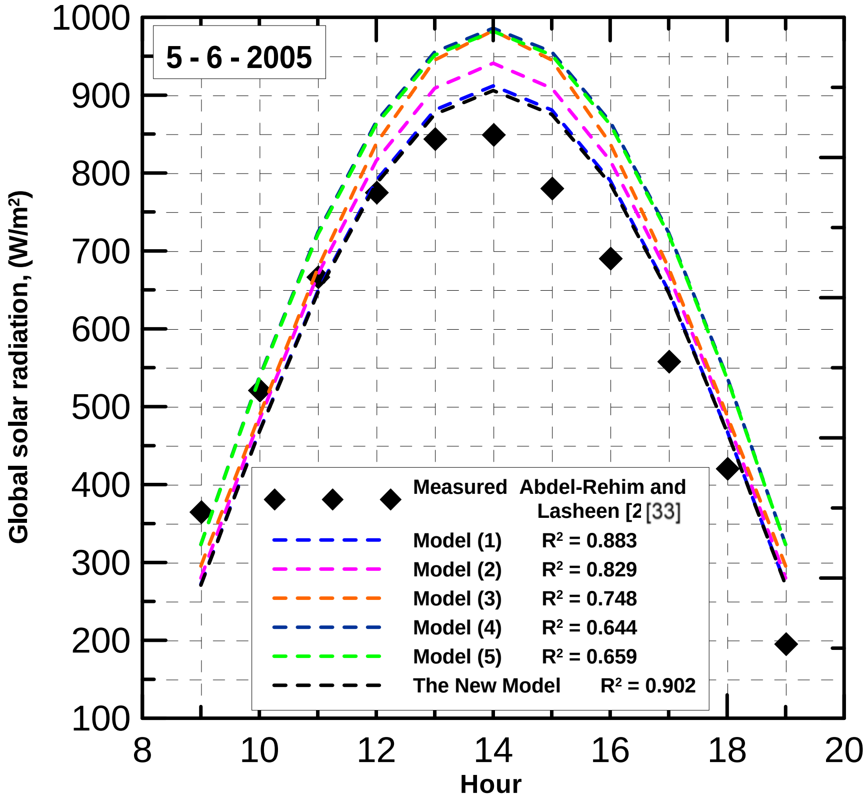



***Fig. (6):*** *Variation of measured and predicted monthly average global solar radiation in* Cairo *city.*

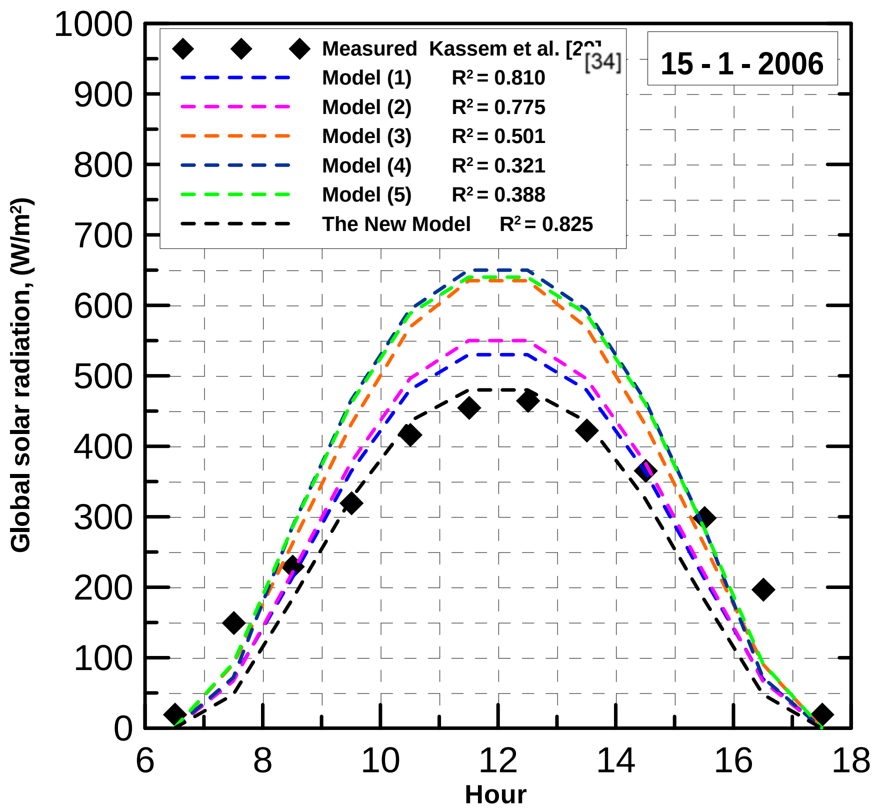



***Fig. (7):*** *Variation of measured and predicted monthly average global solar radiation in Alexandria city.*

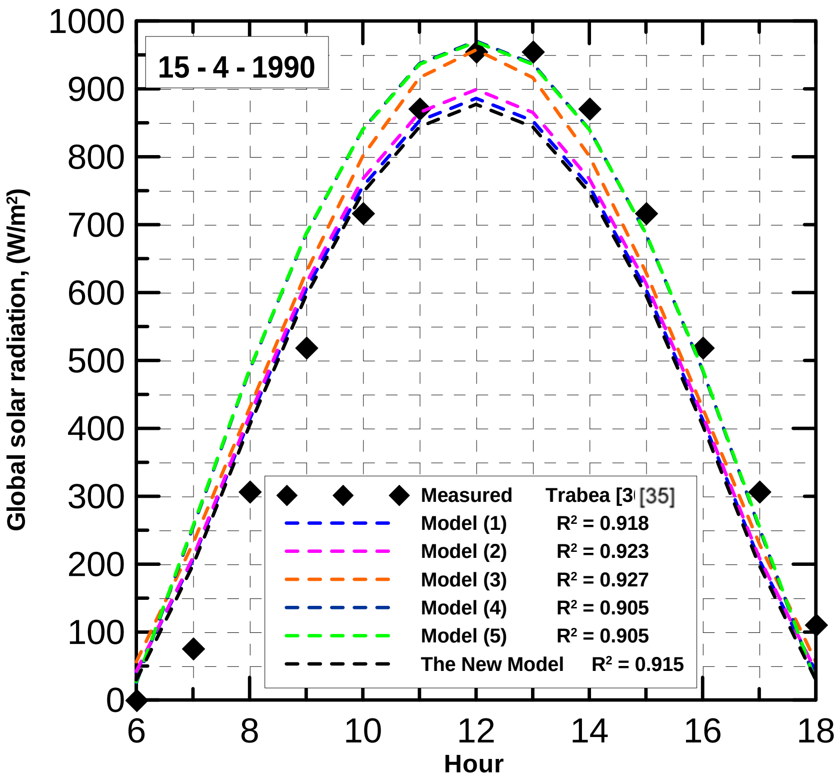



***Fig. (8):*** *Variation of measured and predicted monthly average global solar radiation in Al Arish city.*

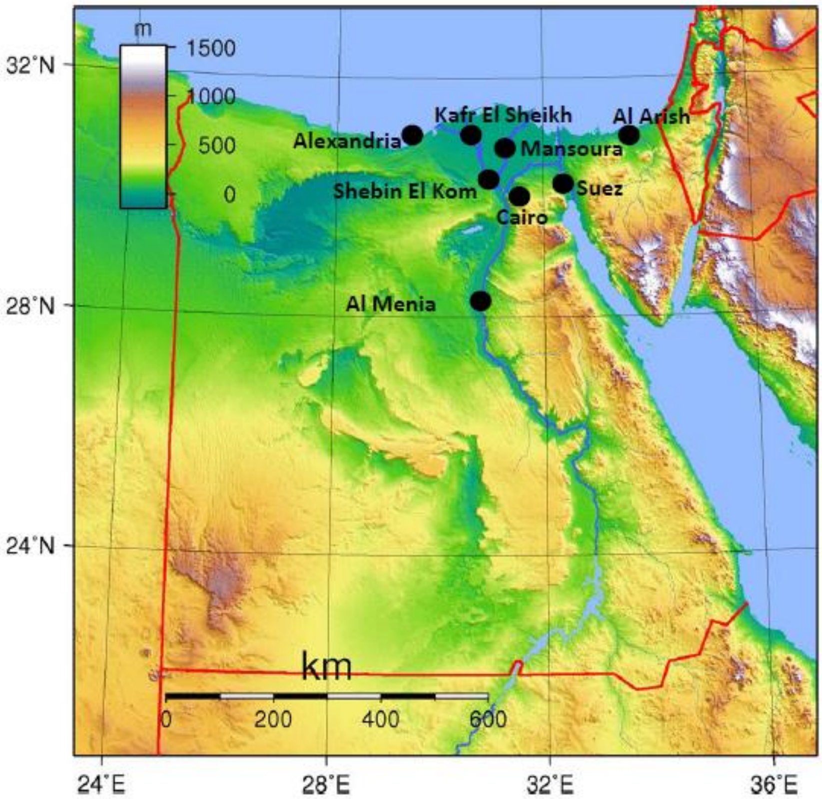
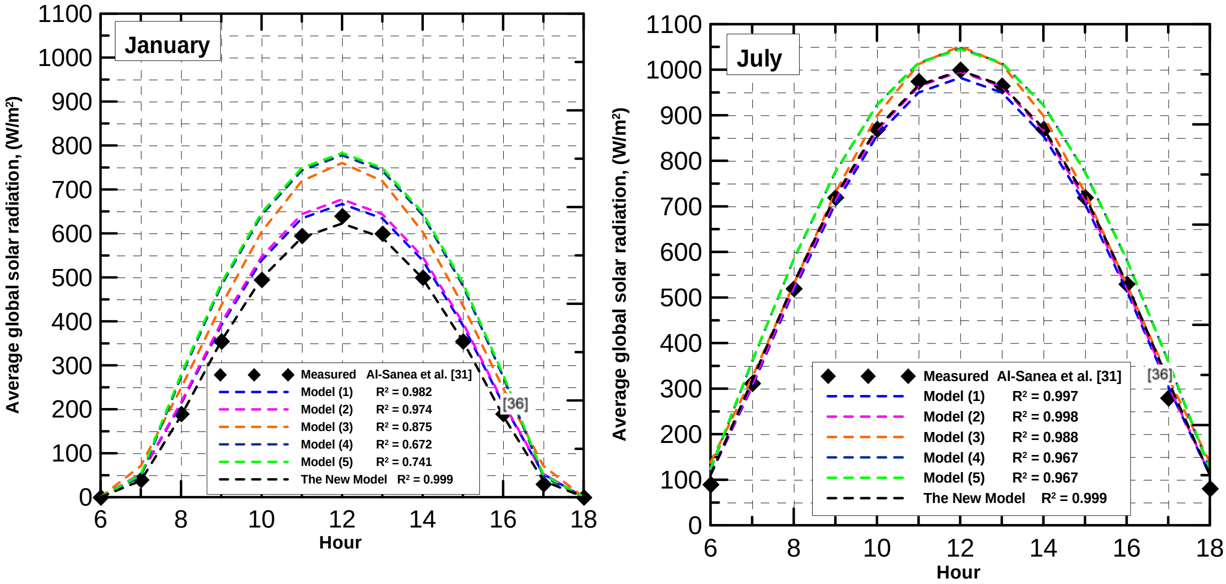



***Fig. (9):*** *The considered cites location and altitude.*

According to the available published measured data, the new suggested model was also validated for different countries such as Saudi Arabia, Turkey, Iran and India. Figure (10) represent the measured and estimated global solar radiation for Riyadh, Saudi Arabia. The measured data of Al-Sanea et al [36] were the averaged values over four years from 1996 to 2000. From this figure evaluation, it can be concluded that, the new suggested model gives the highest value of $R^2$ which is equal to 0.999 for January and July. Models (1) and (2) give a good prediction of global solar radiation in January while in July all models give a good prediction of global solar radiation. The measured data of Arslan [37] for Reno, Turkey was validated with the previous models as shown in Fig. (11). From this figure it is clear that, the new model gives the best value of $R^2$ which is equal to 0.950 followed by model (1) and (2) with $R^2$ of 0.945 and 0.910 respectively. The minimum value of $R^2$ is 0.767 and is given from model (4). Figure (12) represents the measured and estimated global solar radiation for Zahedan city, Iran. Moghadam et al [21] measured the global solar radiation for this city in May 2008 and compared their results with model (2). From the analysis of this figure, it can be noticed that, model (5) gives the highest value of $R^2$ which is equal to 0. 972 followed by the new suggested model with value of $R^2$ which is equal to 0.965 and model (2) with value of $R^2$ which is equal to 0.961. The measured data of Srivastava and Agrawal [38] for Rewa city, India are also validated with the previous models as shown in Fig. (13). The measured data were recorded for the weather of a clear day of the month of November. From this figure it is clear that, all models give a good prediction values for global solar radiation in this city. Model (2) gives the best value of $R^2$ which is equal to 0.982, the new model and model (1) gives also good value of $R^2$ which is equal to 0.981.




(a) (b)

***Fig. (10):*** *Variation of measured and predicted global solar radiation for Riyadh, Saudi Arabia.*

***Table (2):*** *Summary of the statistics errors average values of the tested models for different cities in Egypt.*

| City | *Statistics Errors* | Model (1) | Model (2) | Model (3) | Model (4) | Model (5) | The New Model |
|---|---|---|---|---|---|---|---|
| Al-Menia city | ***e, (%)*** | 4.33 | -16.14 | -6.14 | -17.142 | -17.442 | -8.897 |
| | ***MBE*** | 6.10 | -35.3 | -31.9 | -26.158 | -26.458 | -15.915 |
| | ***RMSE*** | 92.51 | 95.17 | 65.68 | 80.025 | 80.035 | 54.880 |
| | ***t- test*** | 0.208 | 1.347 | 1.597 | 2.062 | 2.162 | 0.833 |
| | $R^2$ | 0.941 | 0.905 | 0.885 | 0.855 | 0.856 | 0.925 |
| Kafr El-Sheikh city | ***e, (%)*** | -2.69 | -5.72 | -9.60 | -12.88 | -12.84 | -2.58 |
| | ***MBE*** | -39.6 | -58.1 | -77.1 | -95 | -94.4 | -39.2 |
| | ***RMSE*** | 78.16 | 91.2 | 104.3 | 125 | 124.3 | 77.37 |
| | ***t- test*** | 1.988 | 2.616 | 3.471 | 3.695 | 3.688 | 1.856 |
| | $R^2$ | 0.930 | 0.903 | 0.874 | 0.818 | 0.821 | 0.935 |
| Suez city | ***e, (%)*** | 7.74 | 4.63 | -2.02 | -1.84 | -2.13 | 6.41 |
| | ***MBE*** | 22.56 | 6.299 | -11.8 | -34.9 | -35.7 | 20.42 |
| | ***RMSE*** | 94.3 | 95.51 | 98.81 | 111.1 | 111.3 | 93.42 |
| | ***t- test*** | 0.888 | 0.238 | 0.434 | 1.192 | 1.222 | 0.899 |
| | $R^2$ | 0.949 | 0.944 | 0.929 | 0.902 | 0.901 | 0.952 |
| Cairo city | ***e, (%)*** | -6.24 | -9.58 | -13.0 | -19.17 | -18.82 | -5.76 |
| | ***MBE*** | -32.9 | -53.2 | -72.9 | -102 | -100 | -29.8 |
| | ***RMSE*** | 69.68 | 84.33 | 102.3 | 121.6 | 119.1 | 67.45 |
| | ***t- test*** | 1.697 | 2.572 | 3.213 | 4.956 | 4.899 | 1.56 |
| | $R^2$ | 0.883 | 0.829 | 0.748 | 0.644 | 0.659 | 0.902 |
| Alexandria city | ***e, (%)*** | 7.448 | 5.103 | -9.717 | -12.853 | -14.079 | 7.17 |
| | ***MBE*** | 0.748 | -8.09 | -54.3 | -67.4 | -67.3 | 0.635 |
| | ***RMSE*** | 64.04 | 71.47 | 107.7 | 125.3 | 118.2 | 62.52 |
| | ***t- test*** | 0.037 | 0.36 | 1.844 | 2.019 | 2.191 | 0.704 |
| | $R^2$ | 0.810 | 0.775 | 0.501 | 0.321 | 0.388 | 0.825 |
| Al Arish city | ***e, (%)*** | -6.425 | -7.97 | -17.43 | -16.38 | -17.14 | -0.863 |
| | ***MBE*** | 24.8 | 17.35 | -9.68 | -36.1 | -36.5 | 34.09 |
| | ***RMSE*** | 89.7 | 87.17 | 83.95 | 98.21 | 98.27 | 92.8 |
| | ***t- test*** | 0.996 | 0.704 | 0.402 | 1.387 | 1.387 | 1.368 |
| | $R^2$ | 0.918 | 0.923 | 0.927 | 0.905 | 0.905 | 0.915 |

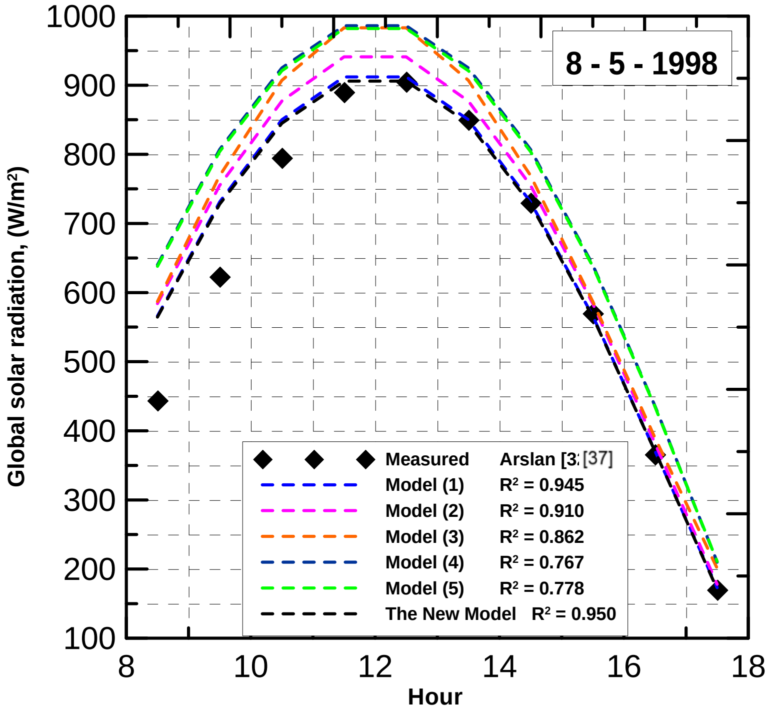



***Fig. (11):*** *Variation of measured and predicted global solar radiation for Reno, Turkey.*

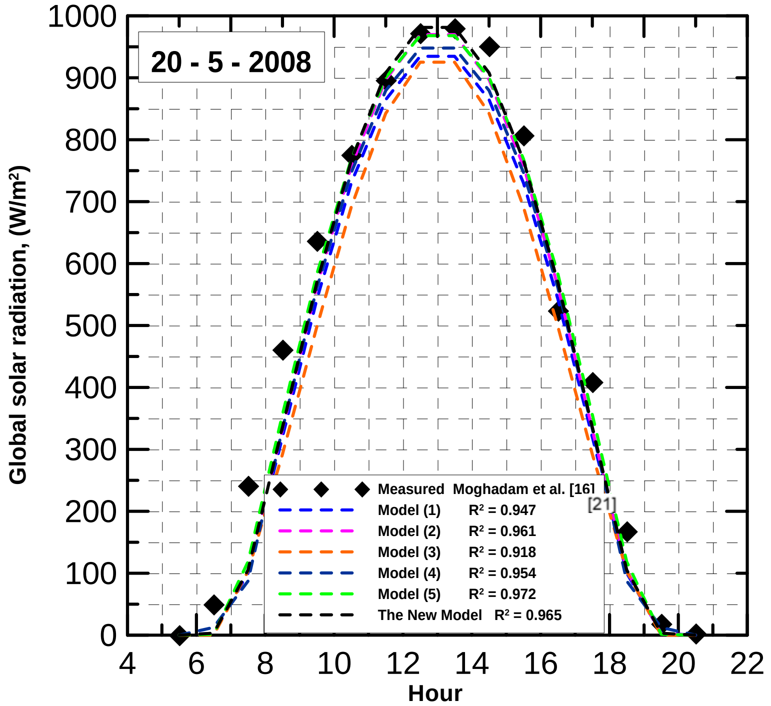



***Fig. (12):*** *Variation of measured and predicted global solar radiation for Zahedan city, Iran.*

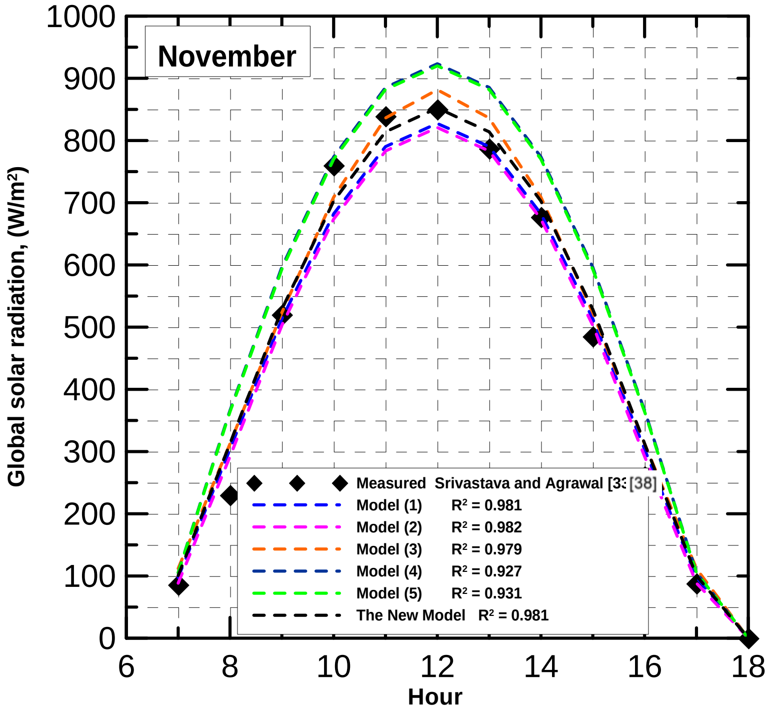



***Fig. (13):*** *Variation of measured and predicted global solar radiation for at Rewa city, India.*

## V. CONCLUSIONS

Several different mathematical models were developed to predict the solar radiation intensity in many different countries. The choice of model strongly depends on the climate characteristic conditions of the country site. According to the measured data, a suggested new model has been developed to estimate and predict the global solar radiation over many cities in Egypt. Based on the basis of different statistical error tests, five different models were compared and validated. According to the different published results, the suggested new model is more accurate and recommended for estimating the global solar radiation in Egypt especially for the coastal sites. The new suggested model has the best values for the coefficient of correlation $R^2$ for the results. Based on the published measured data, the new model was also validated for different countries such as Saudi Arabia, Turkey, Iran and India. From the results it can be concluded that the new suggested model gives a good prediction for global solar radiation estimation over these countries.

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## Nomenclature

| Symbol | Definition | Units |
|---|---|---|
| $H$ | Daily irradiation on horizontal surface | $MJ/m^2$ |
| $I$ | Global solar radiation intensity on a surface | $W/m^2$ |
| $R_b$ | The ratio of beam radiation for inclined surface to that on a horizontal one | - |
| $S_c$ | Solar constant | - |

***Subscript***

| | | |
|---|---|---|
| $b$ | Beam | |
| $d$ | Diffuse | |

***Greek symbols***

| | | |
|---|---|---|
| $\beta$ | The tilt angle | degrees |
| $\theta$ | The incidence angle | degrees |
| $\theta_z$ | The zenith angle | degrees |
| $\rho_g$ | The diffuse ground reflectance | - |
| $\tau$ | The atmospheric transmittance | - |

***Abbreviations***

| | |
|---|---|
| *ASHRAE* | American Society of Heating, Refrigerating and Air-Conditioning |
| *MBE* | Mean Bias Error |
| *MPE* | Mean Percentage Error |
| *RMSE* | Root Mean Square Error |

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