

EVALUATION OF DIFFERENT SUNSHINE-BASED MODELS FOR PREDICTING GLOBAL SOLAR RADIATION – Case Study: New Borg El-Arab City, Egypt

by

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The unavailability of the solar radiation measurements for different locations around the world leads to develop various empirical models to estimate the global solar radiation. In this consider, this study aims to investigate the performance of different solar radiation models to predict the monthly average daily global solar radiation on a horizontal surface. To achieve this, the measured global solar radiation data for a case study location are used. The model predictions are compared with the measured data to introduce the most accurate model for estimating the global solar radiation. The performance of each model is evaluated based on the different statistical indicators. The results show that the Robaa model has the best performance among the other models. Consequently, it can be used for estimating global solar radiation on a horizontal surface in the location under consideration. The accurate estimations of the global solar radiation using this approach can be used in the design and evaluation of performance for different solar applications.

Key words: solar energy, solar radiation models, sunshine, empirical models, statistical indicators, Egypt

Introduction

There is a growing interest in different renewable energy resources, as well, developing new resources due to the instability of oil prices [1-6]. Some existing energy sources such as fossil fuel or nuclear power can be harmful to the human and environment. Therefore, the renewable energy especially the solar energy becomes one of the most important energy sources which can be considered to satisfy the increasing world's energy demand [7, 8]. In solar energy studies, estimating the solar radiation data for a certain location is the first step in the assessment of solar energy availability [9, 10]. It is the basic input for many natural processes [11], as well for the different type of solar energy applications [12, 13]. In the developing countries, there are a few solar radiation measurements due to high cost and poor operating technique

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[14, 15]. The unavailability of the measured solar radiation for the different places around the world leads to developing various empirical models which are used to estimate the global solar radiation [16, 17]. As well, various studies are also concerned about testing previous models at new sites with different weather conditions to evaluate their performance for these locations [18, 19]. The process of selecting the suitable model is depending on the data availability for the model inputs and the performance of the model at a certain location [20]. In fact, the sunshine duration is the major common parameter employed for estimating global solar radiation [19], since the sunshine based models provide the most accurate estimations [21, 22]. Although sunshine duration is unavailable at many locations, consequently several sunshine models also are developed to evaluate the sunshine duration [20, 23]. The performance of the developed model is considered one of the important issues in solar energy modeling. The performance of the models is assessed using the common statistical indicators such as root mean square error (RMSE) and R^2 [24, 25]. The issue of estimating the incident global solar radiation on a horizontal plane are studied by several researchers. The primary correlation for the global solar radiation is introduced by Angstrom. The correlation of Angstrom is modified by Prescott [26], it is widely used in predicting global solar radiation. The Angstrom- Prescott correlation and its numerous derivatives for estimating and predicting global solar radiation is tested in many location around the world [1, 9, 19, 27, 28]. Many studies are performed to investigate the applicability of different solar models for a specific location or various locations around the world [19]. For example, Ajayi *et al.* [7] develops a new model to estimate daily global solar radiation over Nigeria. A literature review for empirical models for estimating global solar radiation and a case study for Yazd city in Iran is proposed by Besharat *et al.* [19]. Similarly, this work aims to validate the performance of different proposed solar radiation models for Egypt in order to introduce the most accurate model. Generally, there are various studies which are concerned with developing models for estimating solar radiation in different locations around Egypt. Khalil and Shaffe [25, 29] introduces a comparative study of total, direct and diffuse solar radiation by using different models on a horizontal and inclined surfaces for Cairo, Egypt. A simple model is proposed by Taha and Hussaein [30] for evaluation the hourly solar radiation over three cities located in Egypt. Similarly, Robaa [31, 32] modified Barbaro *et al.* [33] model to estimate global solar radiation in Egypt. Moreover, different existing models are validated for predicting global solar radiation over Egypt [34]. Also, three empirical formulae are deduced to evaluate sunshine duration by using readily observed data of cloud amount, in Egypt [35]. On other side, a study of sunshine and global solar radiation estimation at different sites in Egypt is introduced by El-Metwally [20]. A non-linear model for predicting monthly mean daily global solar radiation on a horizontal surface is developed based on the estimated and the observed relative sunshine duration [20]. Moreover, El-Metwally [17] developed three simple new models in order to evaluate global solar radiation on a horizontal surfaces based on meteorological data in Egypt, the obtained results showed that the performance of proposed models significantly better than Kappel model [36] and small differences with the results of Angstrom- Prescott model are observed. Similarly, El-Sebaili and Trabea [37] studied the estimation of global solar radiation on a horizontal surfaces over Egypt. The issue of using sunshine duration to predict global solar radiation over eight meteorological station in Egypt are also proposed by Tadros [38]. On other side, Trabea [39] introduces the analysis of solar radiation measurements over Al-Arish area, North Sinai, Egypt. As well, the study of the global solar radiation correlation with meteorological parameters for five selected location over Egypt is presented by Trabea and Shaltout [40]. The results showed that the suggested model can be used with high accuracy for estimating the global solar radiation over all Egypt [40].

In order to assess the performance of the existing Egypt's solar models and introduce the best model for estimating the monthly average daily global solar radiation on a horizontal surface, the measured global solar radiation data at New Borg El-Arab city are used. The study is performed in two steps: the first one is to calculate the relative sunshine for New Borg El-Arab city using the available Egypt's sunshine models which are evaluated and published [20, 35], this is due to the unavailability of sunshine data in this location, which is an input data for global solar radiation sunshine-based models; the second step is to apply the global solar radiation models that are proposed to calculate the global solar radiation on a horizontal surface over the whole Egypt. The predicted values of global solar radiation are compared with the measured data. Moreover, the statistical indicators, namely, RMSE, MBE, MABE, MPE, MAPE, r , and R^2 are calculated to evaluate the performance of the models. Based on the results of the validation process with experimental data, the most accurate model for predicting global solar radiation on a horizontal surface is recognized. The main novelty of the current study is to examine the performance of different solar radiation models at study site which is as a new location for solar radiation predictions. This site is selected to be a location where different solar-energy-applications-based research projects are installed. One of these projects is *Solar-Greenhouse-Desalination System Self Productive of Energy and Irrigating Water Demand* which is supported by STDF, project ID: 10495. Another research project is *Multipurpose Applications by Thermodynamic Solar (MATS) - FP7* which is based on CSP technology and aims to generate 1 MW of electricity and 250 m³/day of desalinated water. For this type of solar energy application projects, prediction of solar radiation is considered as the first step to evaluate the feasibility and predict the performance of these projects. Another novelty is to identify the best model which has the ability to estimate solar radiation at any locations around Egypt.

Location description and data collection

In the present study, the global solar radiation data on a horizontal surface at New Borg El-Arab city, Egypt (latitude 30° 51' N and longitude 29° 34' E, elevation 76.2 m), during the period from January 2000 to December 2004 are used. The global solar radiation and temperature data are retrieved from NASA surface meteorology and solar energy web site [41, 42]. Also, the cloud cover data for the same period is obtained from the weather underground website [43]. The monthly average daily day length values, and the extraterrestrial solar radiation are calculated for each month of a year using in-house computer program which is developed using C# language [44]. The software engineering activities are used in the development of the software system. The software engineering is the field that used to develop the software system and it contains four activities. These activities are required to develop a software system [45, 46].

Generally, Egypt's climate can be categorized into three categories: the first one is the coastal regions either on the Mediterranean or the Red Sea coast, such as New Borg El-Arab city located 60 km far from Alexandria governorate and 7 km far from North Coast; the second category is the semi-arid warmer dry climate of a broad summer dry season, such as Egypt's capital (Cairo city); finally, the third category is the dry desert climate, such as upper Egypt's cities (like; Asyut, Kharga, and Aswan) [17]. Egypt's climate is distinguished by a clear sky during the summer season, from June to August, and partially cloudy skies during the autumn month (September to November) and spring month (March to May). Winter season at most of Egypt's sites is characterized by cloudy skies, particularly the northern part, where the cloud cover reduces from north to south. Egypt is located in the most favorable solar radiation belt, which enjoys abundant solar radiation (12-30 MJ/m²/day of solar energy, 3500-4500 h/year of sunshine) [20].

Mathematical model

Extraterrestrial solar radiation

Extraterrestrial solar radiation, G_o , is the solar radiation above the atmosphere and its as [19, 47]:

$$G_o = \frac{24 \times 3600 G_{sc}}{\pi} f \left[\left(\frac{\pi \omega}{180} \right) \sin(L) \sin(\delta) + \cos(L) \cos(\delta) \cos(\omega) \right] \quad (1)$$

where G_{sc} is called the solar constant which equals to 1367 W/m² [25, 48, 49], f – the eccentricity correlation factor of the Earth's orbit, ω – the hour angle at sunset with degrees, L – the latitude angle, and δ – the declination angle. The f , δ , ω can be calculated by the following equations [25, 34, 50]:

$$f = \left[1 + 0.033 \cos\left(\frac{360d}{365}\right) \right] \quad (2)$$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284+d)\right] \quad (3)$$

$$\omega = \cos^{-1}[-\tan(L) \tan(\delta)] \quad (4)$$

where d is the day number starting from 1st January.

The monthly average maximum possible daily sunshine/day length duration (hour), is given as:

$$s_0 = \frac{2\omega}{15} \quad (5)$$

Sunshine models

Robaa [35] evaluates the sunshine duration from cloud data in Egypt and introduces three empirical formulae to estimate relative sunshine duration using available data of cloud amount as shown in eq. (6). Three proposed formulae are verified for the whole Egypt and for any location in Egypt which lies above latitude 30° (Zone 1) and below latitude 30° (Zone 2). The first two formulae (all Egypt and latitude $\geq 30^\circ$) are used for calculating relative sunshine in the location of the study. Similarly, the issue of evaluating the sunshine and global solar at different locations in Egypt is carried out by El-Metwally [20]. Two simple non-linear methods are presented for estimating relative sunshine duration, S , and global solar radiation, G . The relative sunshine method depending on cloud cover and maximum and minimum air temperature, as displayed in eq. (7), and the global solar radiation method based on relative sunshine. The estimated values of relative sunshine from eq. (7) are used for assessing the performance of the proposed solar radiation method. The results provided trust to use eq. (7) for estimating relative sunshine in case of its unavailability. Table 1 introduces the empirical coefficients values (x , y , z , and k) in eqs. (6) and (7) which are calculated by their own authors and cited from their literature:

$$S = xC^3 + yC^2 + zC + k \quad (6)$$

$$S = x(T_{\max} - T_{\min})^y + z\left(\frac{C}{8}\right)^k \quad (7)$$

where $S = s/s_0$ is called the relative sunshine, s [hour] – the monthly average daily bright sunshine hour), s_0 [hour] – the day length, C [Octal] – the monthly average daily total cloud cover during daytime observation, T_{max} and T_{min} [°C] – the monthly average maximum and minimum daily temperature (°C), respectively, and $x, y, z,$ and k are empirical coefficients.

Table 1. Regression coefficients ($x, y, z,$ and k) for relative sunshine models, eqs. (6) and (7)

Model no.	Source	x	y	z	k
1	Robaa [35] (lat. $\geq 30^\circ$)	0.00334	-0.02827	-0.01414	0.87969
2	Robaa [35] (All Egypt)	0.00278	0.02282	0.02858	0.88831
3	El-Metwally [20]	0.934	-0.013	-0.897	2.124

Global solar radiation models

The collected global solar radiation models are introduced in different previously studies for predicting global solar radiation over Egypt. These models are considered by their own authors as the best model for estimating global solar radiation over the whole Egypt [20, 34, 37]. The first three Models 1-3 are introduced to evaluate G depending on the Angstrom-Prescott model [51], eq. (8), while the other models evaluate G based on different data such as relative sunshine, eq. (9), sunshine hour, and Sun elevation at solar noon, eq. (10). Model 1 and 4 are proposed by El-Metwally [20], Also El-Sebaai and Trabea [37] introduced Models 2 and 3 for all Egypt and Marsa-Matruh city, respectively, they founded Marsa-Matruh model can be used for all Egypt. Robaa [34] modified Barbora’s model [33] to be suitable for Egypt, and recommended Models 5 and 6 for calculating G over the northern Egypt and Mediterranean coast and for all locations around Egypt. Successively, empirical coefficients values (a and b) in eqs. (8)-(10) are obtained by their own authors and cited from their literature, as summarized in tab. 2.

Table 2. Regression coefficients (a and b) for global solar radiation models, eqs. (8)-(10)

Model no.	Source	a	b
1	El-Metwally [20]	0.228	0.527
2	El-Sebaai and Trabea [37] (All Egypt)	0.3647	0.3505
3	El-Sebaai and Trabea [37] (Marsa-Matruh)	0.508	0.186
4	El-Metwally [20]	0.713	
5	Robaa [34] (North Egypt lat. $\geq 30^\circ$)	13.7	
6	Robaa [34] (All Egypt)	14.4	

$$\frac{G}{G_0} = a + b \frac{s}{s_0} \tag{8}$$

$$\frac{G}{G_0} = a^{(1/s)} \tag{9}$$

$$G = a(s)^{1.24} (h)^{-0.19} + 10550[\sin(h)]^{2.1} + 300[\sin(h)]^3 \tag{10}$$

where G is the monthly average daily global solar radiation, h – the solar elevation at solar noon on the 15th day of the month, and a and b are empirical coefficients.

Models validation and verification

The most commonly statistical errors RMSE, MPE, MAPE, MBE, MABE, r , and R^2 are calculated to assess the performance of the models [19, 48, 34]. The RMSE value donates information about the short term performance of the model, its value always positive, and zero is representing the ideal case. The smaller RMSE value refers to the better model performance, and it is define by, eq. (11) [25]. The value of MPE between $\pm 10\%$ is considered acceptable value [25, 35], and it is clarify by, eq. (12) [19] and its absolute vales (MAPE) gives by, eq. (13) [24]. The MBE value donates information about the long-term performance of the model, the positive MBE value refers to overestimation in the calculated value and the negative MBE value refer to under-estimation in the calculated value. The smaller MBE value refers to the better model performance, and the small value is desired. The MBE and its absolute value are describe by, eq. (14) [48] and eq. (15) [52], respectively. The R^2 value gives information about the goodness of fit of the model, and it is between zero and one ($0 \leq R^2 \leq 1$). The largest value of R^2 is desired. The R^2 is express by, eq. (16) [19]. The highest value of r which approaches one is the desired value and it is define by, eq. (17) [19].

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (G_{i,c} - G_{i,m})^2} \quad (11)$$

$$MPE = \frac{1}{n} \sum_{i=1}^n \left(\frac{G_{i,c} - G_{i,m}}{G_{i,m}} \right) \cdot 100 \quad (12)$$

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \left(\frac{G_{i,c} - G_{i,m}}{G_{i,m}} \right) \cdot 100 \right| \quad (13)$$

$$MBE = \frac{1}{n} \sum_{i=1}^n (G_{i,c} - G_{i,m}) \quad (14)$$

$$MABE = \frac{1}{n} \sum_{i=1}^n |(G_{i,c} - G_{i,m})| \quad (15)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (G_{i,m} - G_{i,c})^2}{\sum_{i=1}^n (G_{i,m} - \bar{G}_m)^2} \quad (16)$$

$$r = \frac{\sum_{i=1}^n (G_{i,m} - \bar{G}_m)(G_{i,c} - \bar{G}_c)}{\sqrt{\sum_{i=1}^n (G_{i,m} - \bar{G}_m)^2 \sum_{i=1}^n (G_{i,c} - \bar{G}_c)^2}} \quad (17)$$

where $G_{i,m}$ and $G_{i,c}$ are the values of i^{th} measured and the calculated global solar radiation, respectively, \bar{G}_m – the average value of measured global solar radiation, \bar{G}_c – the average value of the calculated global solar radiation, and n – the number of observation that taken into account.

Results and discussion

The monthly average daily relative sunshine values are calculated for twelve months of the year using those three sunshine models as shown in fig. 1. It is found that the curves of the

sunshine Models 1 and 2 are approximately coincident with each other, and the obtained values from sunshine Model 3 are higher than Models 1 and 2. This difference can be explained by that the first two sunshine Models 1 and 2 use only the cloud cover as an input parameter, while sunshine Model 3 uses the cloud cover and temperature as an input parameter. The monthly average daily sunshine hour also calculated from the estimated relative sunshine. The day length and the calculated monthly average daily sunshine hour for three sunshine models are illustrated in fig. 2. Similarly, the curves of the first two sunshine hour are roughly conjunction to each other, this due to the dependency of sunshine hour calculation on the relative sunshine. To evaluate the performance of the six proposed Egypt's solar radiation models different statistical indicators are calculated and summarized in tabs. 3-5. The best model among all mentioned models is recognized and indicated in bold as shown in the tables.

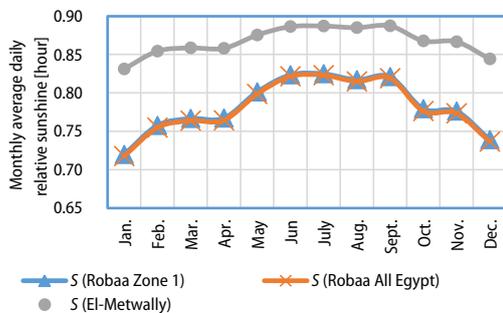


Figure 1. The monthly average daily relative sunshine (*S*) for New Borg El-Arab city in the periods 2000-2004 (for color image see journal web site)

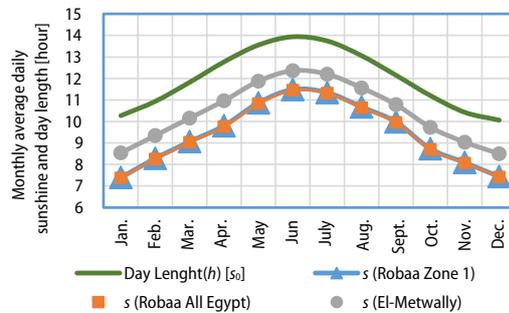


Figure 2. The monthly average daily sunshine hour (*s*) and day length (*d*) at New Borg El-Arab city in the periods 2000-2004 (for color image see journal web site)

Table 3. The statistical results for the estimated G_c by six global solar models using Robaa sunshine Model 1 (lat. $\geq 30^\circ$) values for New Borg El-Arab city

Model	MPE [%]	MBE [MJ/m ² day]	MAPE [%]	MABE [MJ/m ² day]	RMSE [MJ/m ² day]	<i>r</i>
	-10% ≤ acceptable value ≤ +10%					0 ≤ <i>r</i> ≤ 1
El- Metwally Model 1	7.812	0.556	12.8266	1.9610	2.113	0.996531
El-Sebaai Model All Egypt	7.696	0.473	13.3766	2.0683	2.250	0.996089
El-Sebaai Model Matruh	10.273	0.897	14.7362	2.1659	2.412	0.995245
El-Metwally Model 2	9.317	0.780	13.8116	2.0515	2.262	0.995966
Robaa Model North Egypt	-7.428	-1.600	7.4277	1.5998	1.977	0.995628
Robaa Model All Egypt	-7.357	-1.587	7.3574	1.5874	1.966	0.995632

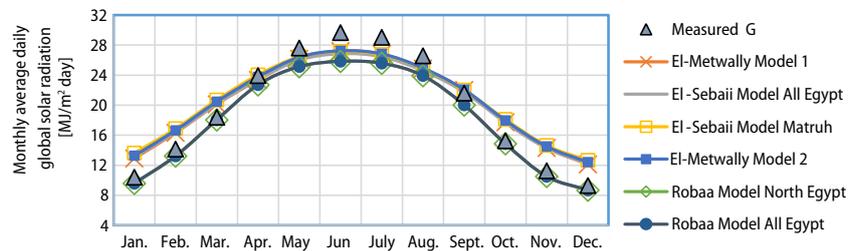
The prediction of six global solar models coupled with Robaa sunshine Model (1) (latitude $\geq 30^\circ$) is shown in fig. 3. The results of statistical comparison between models prediction and the measured values of global solar radiation are donated in tab. 3. According to the results, MPE values are in the acceptable rang with the exception of Model 3 (El-Sebaai Mod Matr) value is slightly larger than 10%, on the other hand, two Robaa Models (5, 6) have the best value among other models. The MBE values for all models are in the acceptable values. The values of MAPE for the Models (1-4) are exceeded the acceptable rang where its values exceed 10%. On the contrary, two Robaa Models (5, 6) give the superior MAPE values. The

Table 4. The statistical results for the estimated G_c by six global solar models using Robaa sunshine Model 2 (all Egypt) values for New Borg El-Arab city

Model	MPE	MBE	MAPE	MABE	RMSE	r
El- Metwally Model 1	7.581	0.514	12.7499	1.9604	2.108	0.996594
El-Sebaili Model All Egypt	7.543	0.445	13.3255	2.0679	2.248	0.996144
El-Sebaili Model Matruh	10.192	0.882	14.6950	2.1623	2.408	0.995280
El-Metwally Model 2	9.157	0.751	13.7530	2.0501	2.255	0.996028
Robaa Model North Egypt	-7.433	-1.601	7.4334	1.6008	1.978	0.995629
Robaa Model All Egypt	-7.363	-1.588	7.3634	1.5884	1.967	0.995634

Table 5. The statistical results for the estimated G_c by six global solar models using El-Metwally sunshine Model 3 values for New Borg El-Arab city

Model	MPE	MBE	MAPE	MABE	RMSE	r
El- Metwally Model 1	15.486	1.898	16.8566	2.2938	2.723	0.995466
El-Sebaili Model All Egypt	12.800	1.365	15.9017	2.2505	2.543	0.995063
El-Sebaili Model Matruh	12.982	1.371	16.2730	2.3097	2.602	0.994539
El-Metwally Model 2	14.215	1.622	16.6073	2.3073	2.658	0.994888
Robaa Model North Egypt	-7.230	-1.568	7.2298	1.5676	1.953	0.995606
Robaa Model All Egypt	-7.149	-1.553	7.1494	1.5534	1.941	0.995610

**Figure 3. Measured and estimated values of monthly average daily global solar radiation using Robaa sunshine Model 1 (lat. $\geq 30^\circ$) values for New Borg El-Arab city (for color image see journal web site)**

values of MABE and RMSE for all models are also in the acceptable range, and best values are donated by two Robaa Models (5, 6). Moreover, all models display an excellent r values which are large than 0.99. Based on these results (tab. 1), it can be conclude that two Robaa Models (5, 6) have the best estimation for G among other models when they join with Robaa sunshine Model (1). In contrast, Models (1-4) are excluded due to their MAPE values are exceeded the acceptable range when they coupled with Robaa sunshine Model (1).

Similarly, six global solar models estimation coupled with Robaa sunshine Model (2) (all Egypt) are displayed in fig. 4. The figure shows that two Robaa Models (model 5 and 6) also is approximately identical to each other, as well as the others four models (Model 1-4) are roughly consistent with each other. The prediction of the models are compared with the measured monthly average daily global solar radiation values, the statistical errors are calculated and introduced in tab. 2. The results show that MPE, MBE, MABE, and RMSE values are in the acceptable range with the exception of MPE value of Model 3 (El-Sebaili Model Matruh) is slightly larger than the acceptable value 10%. Moreover, two Robaa models (Model 5 and 6)

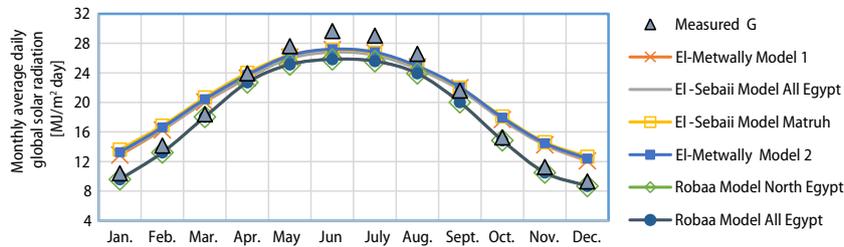


Figure 4. Measured and estimated values of monthly average daily global solar radiation using Robaa sunshine model 2 (all Egypt) values for New Borg El-Arab city (for color image see journal web site)

present the best value of MPE, MAPE, MABE, and RMSE among other models. Also, Model (1-4) MAPE values go too far for the acceptable value 10%. The r values for all models are excellent and its values are large than 0.995. Based on tab. 2 results, it is founded that the most accurate prediction for G is given by two Robaa models (Model 5 and 6) between other models when they coupled with Robaa sunshine Model (2). On the other side, Models 1-4 also are excluded because of the large values of MAPE which are surpassed the acceptable value when they combined with Robaa sunshine Model (2).

Furthermore, fig. 5 demonstrates six global solar models prediction paired with El-Metwally sunshine model. It illustrates that four models, Model 1-4, are approximately identical to each other, and also two Robaa models (Model 5 and 6) is roughly consistent with each other. Six models prediction is compared with the measured values of monthly average daily global solar radiation, the obtained statistical indicators are summarized in tab. 3. The obtained results show that MPE and MAPE values for Model 1-4 overstep the acceptable rang $\pm 10\%$, the best values are provided by two Robaa models (Model 5 and 6). Also, MBE, MABE, and RMSE values are in the acceptable range and two Robaa models (Model 5 and 6) displayed the best values for MABE, RMSE, and r . All models have an excellent r value where it is large than 0.994. According to what showed, two Robaa models (Model 5 and 6) have the best prediction for G among all models when they conjunction to El-Metwally sunshine model. On the contrary, Models 1-4 are rejected due to the higher MAPE values that are passed the acceptable range when they linked with El-Metwally sunshine model (Model 3).

Generally, two Robaa models have the best estimation among other models regardless of the sunshine models that used. The best performance is obtained when two Robaa Models (5, 6) are joined with El-Metwally sunshine Model (3). Besides, two Robaa Models (5, 6) are very close to each other when they integrate with any sunshine models, as shown in figs. 3-5

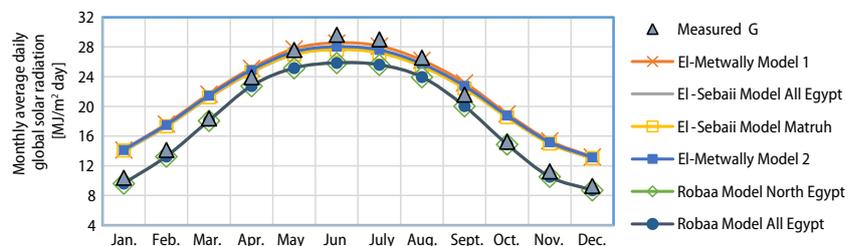


Figure 5. Measured and estimated values of monthly average daily global solar radiation using El-Metwally sunshine model 3 values for New Borg El-Arab city (for color image see journal web site)

and tabs. 3-5. According to results, the superior performance is presented by Robaa Model (6) when it combined with any sunshine model and the best value with El-Metwally sunshine model. Furthermore, the R^2 values are calculated and summarized in tab. 6. The results confirm that two Robaa Models (5, 6) have the best performance with the largest R^2 values among others models with any sunshine models. The best value when they coupled with El-Metwally sunshine Model (3), followed by Robaa sunshine Model (1) (latitude $\geq 30^\circ$). Also, the difference between the performance of two Robaa Models (5, 6) is very small. Robaa Model (6) has the best performance comparing with Robaa Model (5).

Table 6. The R^2 for six global solar models with three sunshine model values for New Borg El-Arab city

Model	$R^2 (0 \leq R^2 \leq 1)$		
	Robaa sunshine Model 1 (lat. $\geq 30^\circ$)	Robaa sunshine Model 2 (all Egypt)	El-Metwally sunshine Model 3
El- Metwally Model 1	0.9157	0.9161	0.8599
El-Sebaili Model All Egypt	0.9044	0.9046	0.8779
El-Sebaili Model Matruh	0.8902	0.8905	0.8722
El- Metwally Model 2	0.9034	0.9040	0.8666
Robaa Model North Egypt	0.9262	0.9261	0.9280
Robaa Model All Egypt	0.9270	0.9269	0.9289

Based on the obtained results it can be concluded that Robaa Model (6) have the best and the most accurate estimation for global solar radiation G with the acceptable range of statistical errors. Although, the percentage of error in sunshine models, global solar radiation model itself, and recorded cloud cover data which record by observations [20]. All these error sources effect on the accuracy of the predicted global solar radiation values and they should be taken into account. Consequently, the Robaa Model (6) (all Egypt) can be used for New Borg El-Arab city, Egypt. On the contrary, the low performance of the other models can be explained by different weather conditions especially at coastal sites [17, 24]. Moreover, the obtained results from this study are consistent with the results of previous study by Robaa [34] which demonstrates that the modified Robaa models provide the best estimation of the global solar radiation on a horizontal surface. From the previous discussion, it can be concluded that some models are not suitable for the studied location while other models show good performance. In fact, sunshine data is the most common meteorological parameter utilized for predicting global solar radiation, since the sunshine based models provide the best estimations with high accuracy [21, 22]. In general, sunshine based models are difficult to be applied at many sites because sunshine data are not available [20, 23]. Sunshine data are not as widely available compared with the temperature data at standard meteorological stations [53], and the ambient temperature is simply measured for most standard meteorological tasks [54]. Hence, some effective parameters such as relative humidity or temperature can be employed for developing new models in the future as alternatives to the widely used sunshine-based models due to the unavailability of sunshine data at all sites around the world.

Conclusions

In this study, the performances of different general global solar radiation models for Egypt are assessed to estimate the monthly average daily global solar radiation on a horizontal

surface using the measured data for global solar radiation and other meteorological parameters. As well, the most accurate global solar radiation model is recognized. Due to the unavailability of sunshine hour data at the location of the study, the available sunshine models for Egypt are used to calculate these values to be used as inputs to the previously validated solar radiation models which are based on sunshine data. The model predictions are compared with the measured global solar radiation data, and the performance of these models are evaluated using the most commonly statistical indicators. According to the results, Robaa Model (all Egypt formula) which based on solar elevation provides the best and the most accurate predictions of the global solar radiation among all other investigated Egypt's global solar models. However, the sunshine-based models have the most accurate estimation, they are difficult to be applied in many sites where sunshine data is unavailable. Therefore, other meteorological parameters such as temperature can be used for presenting new models in the future as alternatives to the widely used sunshine-based models due to the unavailability of sunshine data. According to the results, the best models are significant and applicable for predicting global solar radiation on a horizontal surface. The models and the computer code can be considered to be the backbone of any computer program for designing different solar energy systems.

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Nomenclature

a, b, c	– empirical coefficients	R^2	– coefficient of determination
C	– monthly average daily total cloud cover during daytime observation [Octal]	r	– correlation coefficient
d	– day number starting from 1 st January	S	– relative sunshine, ($=s/s_0$)
f	– eccentricity correlation factor of the earth's orbit	s	– monthly average daily bright sunshine hour [hour]
G	– monthly average daily global solar radiation on a horizontal surface [$\text{MJm}^{-2}\text{d}^{-1}$]	s_0	– monthly average maximum possible daily sunshine or day length duration, ($=2\omega/15$), [hour]
G_o	– monthly average daily extraterrestrial global solar radiation on a horizontal surface [$\text{MJm}^{-2}\text{d}^{-1}$]	T_{\max}	– monthly average maximum daily temperature, [$^{\circ}\text{C}$]
G_{sc}	– solar constant, equal to 1367 W/m^2	T_{\min}	– monthly average minimum daily temperature, [$^{\circ}\text{C}$]
$G_{i,m}$	– values of i^{th} measured global solar radiation	x, y, z, k	– empirical coefficients
$G_{i,c}$	– values of i^{th} calculated global solar radiation	<i>Greek symbols</i>	
\bar{G}_m	– average value of measured global solar radiation	δ	– declination angle
\bar{G}_c	– average value of calculated global solar radiation	ω	– hour angle at sunset with degrees
h	– solar elevation at solar noon on the 15 th day of the month	<i>Acronyms</i>	
L	– latitude angle	CSP	– concentrated solar power
n	– number of observation that taken into account	MABE	– mean absolute bias error
		MAPE	– mean absolute percentage error
		MBE	– mean bias error
		MPE	– mean percentage error
		RMSE	– root mean square error
		STDF	– Egyptian Science and Technology Development Fund

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