An Empirical Method for Estimating Global Solar Radiation over Egypt

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Global solar radiation has been estimated on the basis of measurements of sunshine duration for different selected sites in Egypt; (Marsa-Matruh, Cairo, Aswan, Al-Kharga, Abu-Simble and Halaib-Shalatin). The regression coefficients (a) and (b) of Angstrom type correlation are calculated for the selected sites. The values of the regression coefficients are found to vary from 0.219–0.611 and 0.107–0.576, respectively. These values have been calculated by three different approaches. The estimated values of the global solar radiation are compared with the measured values. Although the (a) and (b) values differ from one site to another; the summation (a+b) is almost the same for the selected sites. The difference between the estimated and measured values of the global solar radiation at the various sites varies from 4 % to 12 %.

Keywords: Regression coefficient, sunshine duration, global solar radiation.

1 Introduction

The availability of solar radiation data and the relevant meteorological parameters are important to solar engineers and architects in order to give an accurate estimate of the available solar energy resource. Solar radiation data is always a necessary basis for the design of any solar energy conversion device and for a feasibility study of the possible use of solar energy [1]. The sunshine duration at a given site depends on the topography of the site and the prevailing meteorological conditions, such as the clearness of the sky and the height above sea level, water vapor content, air temperature, pressure, humidity, wind direction and force, etc. [2].

The first attempt at estimating global solar radiation was the well-known empirical relation between global solar radiation under clear sky conditions and bright sunshine duration, given by Angstrom, see [3]. Theoretical and empirical models have been postulated to compute the components of the insolation [4–13]. Some of these models are theoretical, dealing with the solution of the radiative transfer equation, while others are simply regression models.

In this paper o give an accurate estimate of the available solar energy resource.sitesvaries an empirical sunshine-based model is applied to match observed values of the global solar radiation of selected geographical sites in Egypt. This paper is simply a continuation of several previous studies conducted at different sites in Egypt to define the degree of empirical insolation models in the examined area [14–16].

2 Methodology

The original form, proposed by Angstrom, expressed the correlation between clear sky global solar radiation and sunshine duration as follows:

$$G = G_c \{a + b(S/N)\}. \tag{1}$$

The linear relation correlating G/G_0 and S/N is given in [4] as:

$$G/G_0 = \{a + b(S/N)\}. \tag{2}$$

Where G_0 is the extraterrestrial solar radiation on a horizontal surface in kW/m^2, given by:

$$G_0 = \frac{24}{\pi} * I_{SC} * E_0 * \left[\cos \varphi \cos \delta \sin \omega + \frac{\pi \omega}{180} \sin \varphi \sin \delta \right]. \tag{3}$$

Where E_0 is the correction factor of the Earth's orbit and ω is the sunrise/sunset hour angle given by:

$$E_0 = 1 + 0.033 \cos \left(\frac{2\pi dn}{365} \right), \tag{4}$$

$$\omega = \cos - 1(\tan \varphi \tan \delta). \tag{5}$$

The declination angle of the sun δ is given in degrees according to [17] as:

$$\delta = (0.006918 - 0.399912 \cos \Gamma + 0.070257 \sin \Gamma$$
$$- 0.006758 \cos 2\Gamma + 0.000907 \sin 2\Gamma \tag{6}$$
$$- 0.002697 \cos 3\Gamma + 0.00148 \sin 3\Gamma) \frac{180}{\pi},$$

where Γ is the day angle in radiance, it is represented by:

$$\Gamma = \frac{2\pi(dn - 1)}{365}. \tag{7}$$

t-statistics [18] is applied as an indicator to select a coefficient of the empirical best method that gives the smallest percentage error, in the estimated G-values,

$$t = \left[\frac{(n - 1)(\text{MBE})^2}{(\text{RMSE})^2 - (\text{MBE})^2} \right]^{\frac{1}{2}}, \tag{8}$$

where (RMSE) is the root mean square error and (MBE) is the mean bias error to assess the performance of the relativity model, and n is the number of data pairs.

The absolute percentage error of the estimated values of the global solar radiation at each site may be calculated from the following equation:

$$\left| \propto \% \right| = \left| \frac{G_m - G_{es}}{G_m} \right| * 100. \tag{9}$$

3 Observational data

Observations of the total solar radiation were carried out using a Pyronometer with sensitivity 9 μV/Wm^2. The Pyronometer was originally introduced by Kimball and Hobbs in 1923. The detector is a differential thermopile with the hot-junction receiver blackened and the cold-junction receiver whitened.

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The calibration of the Pyronometer readings was carried out by the Egyptian Meteorological Authority, and the defined errors of the observations range from 5 % to 8 %. The data in this paper was obtained from the Meteorological Authority of Egypt.

The data was gathered at six selected sites in Egypt: Marsa-Matruh (lat. 310°33´N & long. lat. 270°35´E), Abu-Simble (lat. 220°34´N & long. lat. 310°63´E), Cairo (lat. 300°05´N & long. lat. 320°17´E), Aswan (lat. 230°58´N & long. lat. 320°47´E), Al-Kharga (lat. 250°27´N & long. lat. 300°34´E) and Halaib-Shalatin (lat. 230°30´N & long. lat. 340°30´E).

The data was gathered at the Marsa-Matruh, Cairo and Aswan sites during the period (1991–1993) and at the Abu-Simble, Al-Kharga and Halaib-Shalatin sites during the period (1992–1995).

4 Computations

Substituting the global solar radiation data in equation (2), we obtained the values of the regression coefficients constant a and b for the examined sites by least square method.

The a and b values were determined for different methods. In the first method, we substituted by the daily data values, while in the second method, the constants were calculated using the monthly data values of G/G_0 and S/N for each month according to the available data.

Table 1: Values of Angstrom coefficients given by different methods at the selected sites

Methods		Marsa-Matruh	Cairo	Aswan	Abu-Simble	Al-Kharga	Halaib-Shalatin
(1)	a	0.351	0.449	0.219	0.241	0.311	0.191
	b	0.406	0.281	0.553	0.502	0.429	0.582
	$a+b$	0.757	0.730	0.772	0.743	0.740	0.773
(2)	a	0.249	0.461	0.446	0.472	0.291	0.490
	b	0.576	0.259	0.297	0.281	0.439	0.223
	$a+b$	0.825	0.720	0.743	0.753	0.730	0.713
(3)	a	0.338	0.568	0.596	0.611	0.609	0.593
	b	0.425	0.215	0.174	0.107	0.137	0.098
	$a+b$	0.763	0.783	0.770	0.718	0.746	0.691

Table 2: Comparison between measured G_m and estimated G_{es} global solar radiation values (kW/m^2) at Abu-Simble given by different methods

Month	G_0	S/N	G_m	Method 1		Method 2		Method 3	
				G_{es}	$\propto \%$	G_{es}	$\propto \%$	G_{es}	$\propto \%$
Jan.	6.63	0.911	4.64	4.95	6.6	4.70	1.3	4.76	2.6
Feb.	7.75	0.939	5.61	6.15	9.5	5.93	5.7	6.10	8.7
Mar.	9.19	0.825	6.51	6.09	6.5	6.36	2.3	5.91	9.3
Apr.	10.61	0.841	7.54	7.91	4.9	7.47	0.9	7.64	1.4
May	11.34	0.826	7.84	7.64	2.5	7.72	1.5	7.45	5.0
Jun.	11.04	0.853	8.20	8.42	2.7	8.23	0.4	7.82	4.6
Jul.	10.54	0.947	7.76	8.12	4.8	7.92	2.1	7.76	0.1
Aug.	10.32	0.924	7.53	7.33	2.7	7.62	1.3	7.44	1.3
Sep.	10.07	0.886	6.99	6.80	2.6	7.17	2.6	6.99	0.04
Oct.	8.58	0.850	6.19	6.45	4.2	6.59	6.6	6.50	5.1
Nov.	7.56	0.892	5.32	5.63	5.8	5.51	3.7	5.21	2.1
Dec.	6.42	0.814	4.55	4.36	3.2	4.64	2.0	4.47	1.8
MBE				0.193		0.136		0.072	
RMSE				0.783		0.491		0.463	
T				0.625		0.511		0.439	

In the third case, the constants were calculated using the monthly mean daily values of the global solar radiation.

The different values of the constants determined using the three methods for the given locations are listed in Table 1. These constants were in turn used to recalculate the estimated values of the global solar radiation at the selected sites. A comparison of the measured and estimated global solar radiation values is shown in Tables 2–7.

The physical significance of regression coefficients a and b is that a represents the case of overall atmospheric transmission for overcast sky conditions, i.e. $S/N = 0$, while b is the rate of increase of G/G_0 with S/N. The summation $(a + b)$ denotes the overall atmospheric transmission under clear sky conditions or the clearness index.

5 Results and discussion

For Cairo, the a-values given by the three methods are generally higher than the b-values (see Table 1). In the coastal site at Marsa-Matruh an opposite behavior is noted, i.e. the b-values are higher than the a-values. Aswan and Abu-Simble have the same behaviors, i.e. the b-values are higher than the a-values for method one, while the reverse results are provided by the second and the third methods. At the Al-Kharga and Halaib-Shalatin sites, the results reveal fluctuating behavior of these parameters. However, the summations $(a + b)$ are almost the same at the examined sites, except for the results of the third method at Halaib-Shalatin, where the summation is slightly lower.

In fact, under full clear sky conditions, i.e. $S = N$, according to Eq. (2), we find that, the values of G/G_0 are equal to the value of a at the examined location.

The applied empirical methods give estimated values of global solar radiation nearly coinciding with the measured values at the various selected sites, where the errors range from 4 % to 12 % (see Tables 2–7).

According to Eq. (9), we obtained the values of ($\approx$ %) for the different methods at all the selected locations, where we compare the values of ($\approx$ %) for the different methods at all the sites. The smallest values are considered the best method, but we have to compare their MBE, RMSE and t-test values. Thus the method which gives the smallest values for the t-test is considered as the best method for estimating the global solar radiation for different selected sites with an acceptable error.

In fact, it is difficult to select one empirical method that explains the time fluctuations of the observed global solar radiation values at various sites. For example, methods 1 and 2 are more applicable at Aswan, Al-Kharga and Halaib-Shalatin, but method 2 is best for estimating the global solar radiation at these sites. At Cairo and Abu-Simble, methods 2 and 3 are more applicable throughout the various seasons, but method 3 is best for estimating at Abu-Simble, whereas method 2 is best at Cairo. At Marsa-Matruh, method 1 and 3 seem to the best for representing the trend of the measured global solar radiation values throughout the seasons. Method 1 is generally best at Marsa-Matruh.

6 Conclusion

The results of this paper clearly indicate the primary importance of developing empirical approaches for formulating the global solar radiation field reaching the Earth at various geographical sites in Egypt. Method two provides

Table 3: Comparison between measured (G_m) and estimated (G_{es}) global solar radiation values (kW/m^2) at Cairo given by different methods.

Month	G_0	S/N	G_m	Method 1		Method 2		Method 3	
				G_{es}	$\approx$ %	G_{es}	$\approx$ %	G_{es}	$\approx$ %
Jan.	6.16	0.598	3.40	3.29	3.1	3.13	7.9	3.26	4.2
Feb.	6.64	0.647	3.92	3.67	6.2	3.75	4.3	3.83	2.3
Mar.	8.24	0.689	5.26	5.07	3.5	4.99	5.1	5.07	3.6
Apr.	10.04	0.771	6.20	5.96	3.8	6.37	2.7	6.08	1.8
May	11.06	0.815	7.33	7.59	3.5	7.47	2.0	7.45	1.7
Jun.	11.51	0.859	7.99	8.11	1.5	7.77	2.7	8.17	2.3
Jul.	11.28	0.883	7.76	7.84	1.1	7.81	0.6	7.95	2.5
Aug.	10.60	0.809	7.26	7.17	1.1	7.45	2.6	7.36	1.8
Sep.	9.99	0.731	6.18	6.57	6.3	6.05	2.1	6.37	3.1
Oct.	8.09	0.702	5.26	4.97	5.3	5.07	3.5	5.37	2.1
Nov.	6.15	0.693	3.94	4.34	10.2	4.11	4.5	4.07	3.6
Dec.	5.16	0.645	3.30	3.44	4.0	3.49	5.6	3.54	7.1
MBE				0.185		0.122		0.489	
RMSE				0.649		0.571		0.631	
T				0.797		0.460		1.227	

Table 4: Comparison between measured (G_m) and estimated (G_{es}) global solar radiation values (kW/m^2) at Aswan given by different methods

Month	G_0	S/N	G_m	Method 1		Method 2		Method 3	
				G_{es}	$\approx$ %	G_{es}	$\approx$ %	G_{es}	$\approx$ %
Jan.	6.52	0.875	4.70	4.51	4.1	4.79	1.9	4.75	1.1
Feb.	7.77	0.911	5.78	5.68	1.8	5.92	2.4	5.87	1.6
Mar.	9.39	0.825	6.58	6.36	3.4	6.28	4.6	6.49	1.4
Apr.	10.81	0.859	7.87	7.75	1.6	7.61	3.4	7.44	5.6
May	11.31	0.813	8.03	7.82	2.6	7.90	1.6	7.82	2.6
Jun.	11.63	0.881	8.25	8.01	3.0	7.84	5.0	8.10	1.9
Jul.	11.43	0.925	7.90	7.76	1.8	7.54	4.6	7.63	3.4
Aug.	10.66	0.961	7.70	7.62	0.9	7.59	1.4	7.73	0.4
Sep.	10.21	0.905	7.20	7.06	1.9	7.30	1.4	7.26	0.8
Oct.	9.00	0.863	6.50	6.38	2.0	6.62	1.8	6.59	1.3
Nov.	7.81	0.815	5.59	5.79	3.5	5.76	2.9	5.86	4.8
Dec.	6.44	0.85	4.77	4.86	1.8	4.70	1.5	4.96	3.9
MBE				0.171		0.69		0.059	
RMSE				0.711		0.532		0.496	
T				0.692		0.486		0.436	

Table 5: Comparison between measured (G_m) and estimated (Ges) global solar radiation values (kW/m^2) at Al-Kharga given by different methods

Month	G_0	S/N	G_m	Method1		Method2		Method3	
				G_{es}	$\approx$ %	G_{es}	$\approx$ %	G_{es}	$\approx$ %
Jan.	6.64	0.863	4.79	4.75	0.8	4.99	4.1	4.90	2.3
Feb.	7.93	0.905	5.86	5.79	1.2	5.97	1.9	5.71	2.7
Mar.	9.47	0.846	6.62	6.66	0.6	6.71	1.3	6.79	2.5
Apr.	10.91	0.849	7.98	8.12	1.8	8.19	2.6	7.95	0.4
May	11.34	0.872	8.16	8.07	1.1	8.02	1.7	8.29	1.5
Jun.	11.66	0.909	8.29	8.16	1.6	8.04	2.9	7.92	4.5
Jul.	11.60	0.913	7.92	7.81	1.4	7.80	1.5	7.76	2.1
Aug.	10.79	0.932	7.76	7.87	1.5	7.98	2.8	7.37	4.9
Sep.	10.32	0.895	7.19	7.29	1.3	7.38	2.6	6.98	2.9
Oct.	9.33	0.879	6.49	6.42	1.1	6.35	2.2	6.30	2.9
Nov.	7.88	0.845	5.87	5.80	1.2	5.97	1.7	5.77	1.6
Dec.	6.59	0.870	4.96	4.76	4.2	5.09	2.7	5.04	1.6
MBE				0.283		0.149		0.262	
RMSE				0.641		0.627		0.539	
T				0.539		0.391		0.473	

Table 6: Comparison between measured (G_m) and estimated (G_{es}) global solar radiation values (kW/m^2) at Marsa-Matruh given by different methods

Month	G_0	S/N	G_m	Method1		Method2		Method3	
				G_{es}	≈ %	G_{es}	≈ %	G_{es}	≈ %
Jan.	5.45	0.672	2.81	2.85	1.4	3.02	7.4	3.18	13.3
Feb.	6.66	0.692	3.86	3.97	3.0	3.68	4.6	4.02	4.1
Mar.	8.47	0.715	4.97	4.80	3.5	4.89	1.6	4.67	6.1
Apr.	9.78	0.759	6.42	6.61	3.0	6.74	4.9	6.65	3.6
May	10.51	0.771	7.20	7.45	3.1	7.03	2.3	7.26	0.8
Jun.	10.91	0.815	7.87	8.21	4.3	7.75	1.5	8.04	2.2
Jul.	10.60	0.849	7.94	8.28	4.3	7.82	1.5	7.99	0.6
Aug.	10.39	0.807	7.26	7.54	3.7	7.35	1.1	7.45	2.6
Sep.	9.76	0.782	6.34	6.48	2.2	6.37	0.5	6.56	2.5
Oct.	8.11	0.731	5.14	5.32	3.6	5.38	4.8	5.49	6.8
Nov.	6.66	0.671	3.92	4.18	6.7	4.14	5.6	4.07	3.9
Dec.	5.24	0.619	3.13	3.31	5.6	3.40	8.4	3.42	9.2
MBE				0.086		0.137		0.479	
RMSE				0.763		0.849		1.063	
T				0.211		0.473		1.395	

Table 7: Comparison between measured (G_m) and estimated (G_{es}) global solar radiation values (kW/m2) at Halaib-Shalatin given by different methods

Month	G_0	S/N	G_m	Method1		Method2		Method3	
				G_{es}	≈ %	G_{es}	≈ %	G_{es}	≈ %
Jan.	6.82	0.882	4.83	4.95	2.6	4.69	2.8	4.60	4.8
Feb.	7.97	0.895	5.99	6.22	3.9	5.81	2.9	5.78	3.4
Mar.	9.67	0.932	6.66	6.47	2.9	6.74	1.1	6.37	4.4
Apr.	10.91	0.865	8.18	7.97	2.5	8.09	1.1	7.99	2.8
May	11.36	0.876	8.26	8.20	0.6	8.14	1.3	7.94	3.8
Jun.	11.80	0.942	8.43	8.68	2.9	8.24	2.3	8.04	4.7
Jul.	11.56	0.963	8.20	8.09	1.4	7.85	4.2	7.92	3.9
Aug.	10.99	0.951	7.90	7.74	2.0	7.66	2.9	7.54	4.5
Sep.	10.38	0.918	7.40	7.26	1.8	7.54	1.9	7.49	1.3
Oct.	9.51	0.885	6.89	6.66	3.3	6.61	4.2	6.75	2.1
Nov.	8.09	0.839	5.99	5.79	3.9	6.09	1.5	6.22	3.8
Dec.	6.74	0.874	5.14	5.27	2.5	5.34	4.0	5.24	1.9
MBE				0.231		0.181		0.211	
RMSE				0.682		0.575		0.425	
T				0.573		0.431		0.511	

good agreement at the Cairo, Halaib-Shalatin and Al-Kharga sites, while at Abu-Simble and Aswan sites the third method is considered best. For Marsa-Matruh, the first method is considered best. Other topographic, climatological and environmental parameters should be inserted into the adopted empirical formula to increase the accuracy of the estimated values of the observed quantities. The dependence of coefficients a and b in the Angstrom formula should be tested as a function of the prevailing environmental conditions at the tested sites.

List of symbols

G_c clear sky global solar radiation in kW/m^2,

S sunshine duration in hours,

N length of the daylight in hours,

G_0 extraterrestrial solar radiation on a horizontal surface in kW/m^2,

E_0 correction factor of the Earth's orbit,

ω sunrise/sunset hour angle,

dn day number in the year ($1 \leq dn \leq 365$),

δ declination of the sun,

φ latitude of the station,

Γ day angle in radiance,

RMSE root mean square error,

MBE mean bias error,

n number of data pairs,

$|\propto \%|$ absolute percentage error,

G_m measured values of global solar radiation,

G_{es} estimated values of global solar radiation.

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