Numerical methods applied to global solar radiation modeling – comparison with measured data

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Abstract

Purpose – The purpose of this paper is to predict the global solar radiation intensity in areas where meteorological stations do not exist and information on solar radiation cannot be obtained experimentally.

Design/methodology/approach – The approach to achieve the objective of the paper is developing multiple regression relations between the global solar radiation intensity (the dependent variable) and geographical, geometrical, astronomical and meteorological parameters (the independent variables). The independent variables used for this purpose were selected based on their ease of measurability outside the meteorological station and without expensive equipment. The number of independent variables is arbitrarily chosen and directly affects the accuracy of predictions.

Findings – Linear regression relations using one, two, three, four, five, six, and seven independent variables were developed to predict the global solar radiation intensity on horizontal surfaces. An advanced computer program based on least square analysis was used to obtain the regression coefficients. The relations having the highest correlation coefficients were selected. The study shows even when only one independent variable (declination angle) is used, the one variable regression relation predicts the global solar radiation with an accuracy that is satisfactory in most engineering applications.

Originality/value – The diversity of regression relations introduced in this paper gives the engineer such a broad freedom of choice, that knowing only an astronomical parameter of the site makes him capable of estimating the global solar radiation intensity within acceptable margins. The predicted values of global solar radiation intensity by this approach can be used for the design and performance estimation in solar applications. The statistical model developed in this research was validated when compared with the measured data in Yazd airport. The measured data used to analyze the model equations were collected in a 13-year period. No investigation of this type exists having such degree of accuracy in geographical, geometrical, astronomical and meteorological parameters in Iran.

Keywords Solar radiation, Modelling, Iran

Paper type Research paper

Nomenclature

H_o	Mean daily extraterrestrial radiation flux
H	Mean daily global radiation flux
$\overline{H}$	Mean monthly global radiation flux
P	Mean daily atmospheric pressure
N	Potential astronomical sunshine hours
n	Number of data pairs, Equations (8), (10) and (11)

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$n-1$	Degrees of freedom, Equation (12)	R	Coefficient of correlation
n	Hours of measured sunshine	MBD	Mean Bias Differences
T_{max}	Mean daily maximum air temperature	$RMSD$	Root mean square differences
$T_{dp,\,max}$	Mean daily maximum dew point temperature	G_{sc}	Extraterrestrial solar constant
G_0	Extraterrestrial irradiance on horizontal plane	φ	Latitude of the place
E_0	Eccentricity correction factor of the earth's orbit	α	Level of significance
e	Relative percentage error	n^*	Day of year
		δ	Solar declination angle
		ω_s	Mean sunrise hour angle
		t	Test statistic
		R_h	Mean daily relative humidity

Introduction

Rating and sizing of solar energy systems and performance analysis of such systems requires information on solar radiation at Earth's surface is available. Such information is also essential in many other applications such as crop growth models, evaporation–transpiration estimates and building comfort conditions. There is no doubt that measured data are the best source of obtaining information on solar radiation. But, the measurement of solar parameters is made only in meteorological stations. Therefore, it has been necessary to estimate solar radiation by theoretical models. Another approach, which has been used for estimation purposes, involves the empirical relationships between global solar radiation and more readily available meteorological, climatological and geographical parameters such as sunshine duration, relative humidity, air temperature, latitude, etc. These models, however, are semi-empirical in nature and depend on spatial data of interest, that is, applying these models to conditions different from the conditions of observation is questionable at least and/or inadmissible. The parameters affecting solar radiation can be categorized in astronomical, geographical, geometrical, physical and meteorological factors (Ertekin and Yaldiz, 1999). The astronomical factors include solar constant, world-sun distance, solar declination angle and hour angle. The geographical factors include latitude, longitude and elevation of the site. The geometrical factors include surface azimuth, surface tilt angle, solar altitude and solar azimuth. The physical factors include scattering of air molecules, water vapor content, scattering of dust and other atmospheric constituents such as O_2, N_2, CO_2, O_3, etc. The meteorological factors include effect of cloudiness and reflection of the environs.

Many investigations have been carried out to estimate the global solar radiation on a horizontal surface. The first empirical investigation was proposed by Angstrom (1924), who correlated the global solar radiation and the ratio of sunshine duration. The Angstrom correlation was modified by Prescott (1940) and Page (1964), and the modified correlations are being used most correctly and widely to estimate the global irradiance in many countries throughout the world. Furthermore, a global study of the world distribution of solar radiation has been conducted by Lof *et al.* (1966), while there have been many attempts to find common models applicable anywhere in the world (Rietveld, 1978) or in large regions such as Europe (Soler, 1990) and humid tropical countries (Turon, 1987).

Singh *et al.* (1996) used solar declination angle and latitude to develop their empirical correlation. Reddy (1971) combined sunshine duration, air temperature and relative humidity to estimate the global solar radiation. Sabbagh *et al.* (1977) related the daily global solar radiation to sunshine duration, relative humidity, maximum air temperature, altitude and location of the place relative to water surfaces. Togrul and Onat (1999) derived their equations using sunshine duration, relative humidity, air temperature, soil temperature and the sine of the solar declination angle. Trabea and Shaltout (2000) related the daily global solar radiation to sunshine duration, relative humidity, maximum air temperature, mean daily vapor pressure and mean daily sea level pressure. Ertekin and Yaldiz (1999) derived their equations using sunshine duration, relative humidity, mean air temperature, mean soil temperature, solar declination angle, mean cloudiness, mean precipitation and mean evaporation.

The purpose of this paper is to develop a relationship between global solar radiation and some astronomical, geographical, geometrical and meteorological factors in the Yazd province. Different combinations of the mean daily extraterrestrial solar radiation intensity, average daily ratio of sunshine duration, mean daily relative humidity, mean daily maximum air temperature, mean daily maximum dew point temperature, mean daily atmospheric pressure and the sine of the solar declination angle are used to develop the empirical equations. The coefficients in these equations were deduced, and the predicted global solar radiation values, as calculated from the model equations were compared with measured data. It is worth mentioning that solar energy in Iran is abundant, the annular solar energy incident on the Yazd land has a magnitude of about 7,787 MJ/m^2, the sunshine duration is roughly 3,270 h/year and the cloudy duration is nearly 1,110 h/year. It is expected that the applications of solar energy engineering, especially solar water heaters, becomes widespread in this province in the near future. Having only one meteorological station in the province (Yazd airport), makes it legitimate to develop correlations to estimate the desired data of global solar radiation on horizontal surfaces at sites other than the airport station.

Measured data

Solar radiation parameters, most importantly, the hourly global solar radiation intensity on a horizontal plane are measured by the IMO at the meteorological station based in the Yazd international airport. The station is located at 31°54′ North latitude, 54°17′ East longitude and has an elevation of 1,237.2 m above sea level. The data obtained from the IMO, especially the maximum air temperature, sunshine duration and global solar radiation intensity, are used as reference quantities in order to be compared with the model predictions. The information regarding these parameters were available in the following periods:

- Maximum air temperature, dew point temperature and relative humidity in a 45-year period, from 1961 until 2005.
- Sunshine duration measured by Campbell–Stoke sunshine recorder in a 24-year period, from 1982 until 2005.
- Global solar radiation intensity using pyranometer model cc-1-681 (Clipp & Zonen, Hollands) in a 13-year period, from 1992 until 2004.

The measured data in a 13-year period (common to the above periods) are used to analyze the model equations. No investigation of this type exists having such degree of accuracy in GGAM parameters in Iran.

Selection of variables

Selecting the independent variables to predict the global solar radiation intensity is an important task that requires lots of experience and vast knowledge on how the independent variables affect the global solar radiation intensity. The independent variables used for this purpose were selected based on their ease of measurability outside the meteorological station and without expensive equipment. A brief introduction of the independent variables used in this study is presented here.

The extraterrestrial solar radiation intensity H_0(W/m^2) on a horizontal surface is calculated from the following equation (Duffie, 1991):

$$H_0 = \frac{24G_0}{\pi}\left(\cos\varphi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\varphi\sin\delta\right) \quad (1)$$

G_0 is the extraterrestrial irradiance on horizontal plane, defined as

$$G_0 = G_{sc}E_0 = G_{sc}\left(1 + 0.033\cos\frac{360n^*}{365}\right) \quad (2)$$

G_{sc} is the solar constant, equal to 1,367 W/m^2 (ASHRAE Handbook, 1985), E_0 the eccentricity correction factor of the earth's orbit and n^* the number of the day of the year starting from January first. ω_s is the mean sunrise hour angle for the month, is defined as

$$\omega_s = \cos^{-1}(-\tan\varphi\tan\delta) \quad (3)$$

δ being the solar declination angle, can be computed using the following equation:

$$\delta = 23.45\sin\left(360\frac{284 + n^*}{365}\right) \quad (4)$$

N is the maximum possible sunshine hours from sunrise to sunset is related to the mean sunrise hour angle as follows:

$$N = \frac{2\omega_s}{15} \quad (5)$$

Statistical estimation method

The purpose of this investigation is to develop statistical models to estimate the monthly mean daily global solar radiation, H, using multiple linear regression to various parameters, such as H_0, n/N, R_h, T_{max}, $T_{dp,max}$, P and sin δ. To achieve this goal, the data described in the previous section were used. In linear regression starting with one parameter, the relations take the form

$$y = a + bx \quad (6)$$

As the number of parameters is increased, the correlation becomes a multiple linear regression of the following form:

$$y = a + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6 + b_7x_7 \quad (7)$$

where b_i and x_i are the regression coefficients and correlated parameters, respectively. The calculated values are compared to the measured values in each regression relation through correlation coefficient R, defined as (Freund, 2000)

$$R = \frac{n\sum_{i=1}^{n} H_{i,m}H_{i,c} - \sum_{i=1}^{n} H_{i,m}\sum_{i=1}^{n} H_{i,c}}{\sqrt{\left[n\sum_{i=1}^{n} H_{i,m}^2 - \left(\sum_{i=1}^{n} H_{i,m}\right)^2\right]\left[n\sum_{i=1}^{n} H_{i,c}^2 - \left(\sum_{i=1}^{n} H_{i,c}\right)^2\right]}} \quad (8)$$

$H_{i,m}$ is the ith measured value, $H_{i,c}$ the ith calculated value and n is the number of data pairs. The correlation coefficient is a statistical parameter determining how close a calculated data is to its counterpart measured data. In this practice, the correlation coefficient varies between zero and one. The higher (closer to unity) the correlation coefficient, the better.

In addition, the variations between the two values are shown by the relative percentage error (e), root mean square differences (RMSD), mean bias differences (MBD) and t-statistics which are fundamental measures of accuracy in solar energy calculations.

The relative percentage error is the measured–calculated variation of an individual month, defined as

$$e = \frac{H_{i,m} - H_{i,c}}{H_{i,c}} \times 100 \quad (9)$$

Relative percentage errors between -10 and $+10$ percent are considered acceptable.

The root mean differences are defined as

$$RMSD = \left[\frac{1}{n}\sum_{i=1}^{n}\left(H_{i,m} - H_{i,c}\right)^2\right]^{1/2} \quad (10)$$

This test provides information on the short-term performance of the correlations by allowing a term-by-term comparison of the actual deviation between the calculated value and the measured value. The smaller are the deviations, the better is the model performance. However, a few large differences in the sum can produce a significant increase in the RMSD.

The mean bias differences are defined as

$$MBD = \frac{1}{n}\sum_{i=1}^{n}(H_{i,m} - H_{i,c}) \quad (11)$$

This test provides information on the long-term performance. A low MBD is an indication of good model performance. A positive value gives the average amount of under estimation in the calculated value and vice versa. A drawback of this test is that over-estimation of an individual observation will cancel under-estimation in a separate observation.

It is obvious that each test by itself may not be an adequate indicator of a model's performance. It is possible to have a large RMSD value and, at the same time, a small

MBD (a large scatter about the line of perfect estimation). On the other hand, it is also possible to have a relatively small RMSD and a relatively large MBD (consistently small over estimations or under estimations). However, although these statistical indicators generally provide a reasonable procedure to compare models, they do not objectively indicate whether a model's estimates are statistically significant, i.e. not significantly different from their measured counterparts. Therefore, an additional statistical indicator, the *t*-statistic, is used. The *t*-statistic depends on both the RMSD and MBD, so that it is more effective for determining the statistical properties. This statistical indicator allows the mean value of model predictions to be compared with the mean value of real data and at the same time indicates whether or not a model's estimates are statistically significant at a particular confidence level. The *t*-statistic for paired data is defined as (Almorox *et al.*, 2005)

$$t = \left[\frac{(n-1)MBD^2}{RMSD^2 - MBD^2}\right]^{1/2} \tag{12}$$

The smaller is the value of *t*, the better is the model performance. To determine whether a model's estimates are statistically significant, one simply has to determine a critical *t*-value from standard statistical tables, i.e. $t_{\alpha/2}$ at α level of significance and $(n-1)$ degrees of freedom. For the model's estimate to be judged statistically significant at the $1-\alpha$ confidence level, the calculated *t*-value must be less than the critical *t*-value.

Results

Multiple linear regression of seven parameters $(H_0, \sin\delta, n/N, R_h, T_{\max}, T_{dp,\max}, P)$ used in different combinations, gave hundreds of different relations to estimate global solar radiation. They have been processed and analyzed using an advanced computer program to obtain the correlations and the regression coefficients a and b_i in Equation (7). A least square regression analysis was used to obtain these constants. The relations having the highest correlation coefficients were selected.

In the case of using one variable, the highest correlation coefficients were obtained from relations containing $\sin\delta$ and H_0:

$$H = 5{,}926.6 + 5{,}830.6\sin\delta \quad (R = 0.93828) \tag{13}$$

$$H = -330.84 + 0.728H_0 \quad (R = 0.93857) \tag{14}$$

For relations with two variables, the highest correlation coefficients were obtained when the relations used contained $\sin\delta, n/N$ and $n/N, H_0$:

$$H = 3{,}000 + 5{,}202.47\sin\delta + 3{,}949.3n/N \quad (R = 0.96026) \tag{15}$$

$$H = -2{,}682.7 + 4{,}095.9n/N + 0.65H_0 \quad (R = 0.96243) \tag{16}$$

In the case of three variables, the highest correlation coefficients were obtained from the relations containing $n/N, H_0, T_{\max}$ and $n/N, H_0, R_h$:

$$H = -2{,}380.63 + 3{,}669.24n/N + 0.62H_0 + 10.96T_{\max} \quad (R = 0.96258) \tag{17}$$

$$H = -2{,}084.2 + 3{,}759.2n/N + 0.63H_0 - 5.7R_h \quad (R = 0.96254) \tag{18}$$

For the relations with four variables, the highest values of R were obtained using the variables $n/N, H_o, R_h, P$ and $n/N, H_0, T_{\max}, T_{dp,\max}$:

$$H = 14{,}171.18 + 3{,}634.4n/N + 0.60H_0 - 7.42R_h - 18.06P \quad (R = 0.96268) \tag{19}$$

$$H = -2{,}693.98 + 3{,}393.9n/N + 0.63H_0 + 21.28T_{\max} - 48.75T_{dp,\max} \quad (R = 0.96288) \tag{20}$$

To estimate the global solar radiation using five variables, the highest values of R were obtained from the variables of $n/N, H_0, T_{\max}, R_h, T_{dp,\max}$ and $\sin\delta, n/N, H_0, T_{\max}, T_{dp,\max}$. The corresponding relations are:

$$H = -4{,}184.08 + 3{,}336.32n/N + 0.64H_0 + 52.98T_{\max} + 18.36R_h - 84.32T_{dp,\max} \quad (R = 0.96309) \tag{21}$$

$$H = -1{,}434.13 + 1{,}305.56\sin\delta + 3{,}347.87n/N - 0.49H_0 + 22.21T_{\max} - 64.24T_{dp,\max} \quad (R = 0.96301) \tag{22}$$

To reach the highest values of R in the six variable relations, the following variables were used: $n/N, H_0, T_{\max}, R_h, T_{dp,\max}, P$ and $\sin\delta, n/N, H_0, T_{\max}, R_h, T_{dp,\max}$. The corresponding relations are:

$$H = -17{,}624.54 + 3{,}288.51n/N + 0.67H_0 + 70.35T_{\max} + 27.84R_h - 103.65T_{dp,\max} + 14.26P \quad (R = 0.96313) \tag{23}$$

$$H = -3{,}326.6 + 589.140\sin\delta + 3{,}326.74n/N + 0.57H_0 + 47.25T_{\max} + 14.79R_h - 84.4T_{dp,\max} \quad (R = 0.96311) \tag{24}$$

To estimate the global solar radiation in Yazd province, the following relationship containing seven variables ($\sin\delta, H_0, n/N, R_h, T_{\max}, T_{dp,\max}, P$) is constructed, having fairly high correlation coefficient:

$$H = -17{,}082.9 + 619.68\sin\delta + 0.59H_0 + 3{,}277.15n/N + 24.34R_h + 64.78T_{\max} - 104.25T_{dp,\max} + 14.64P \quad (R = 0.96315) \tag{25}$$

The seven variable relation has the maximum R among hundreds of regression relations. The values of monthly mean daily global solar radiation intensity estimated using the above derived correlations were compared with the corresponding measured values. The results are illustrated in Figures 1-7. Comparisons of relations with the same number of variables are depicted in the same figure. The figures show that the agreement between the measured and estimated values is remarkable.

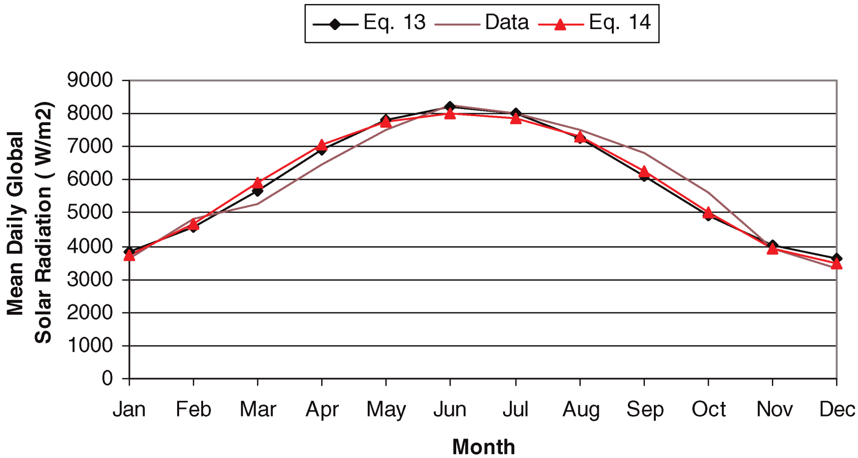

Figure 1.
Comparison of measured and estimated values using sample relations with one variable (H_0 and $\sin \delta$)

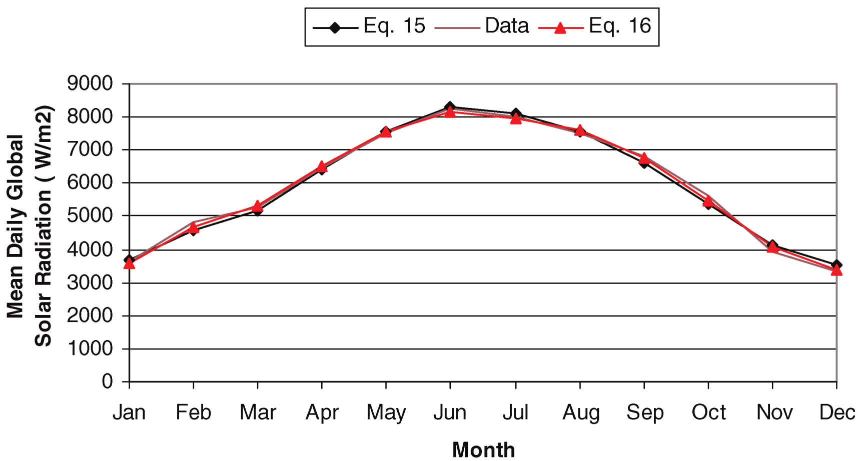

Figure 2.
Comparison of measured and estimated values using sample relations with two variables ($\sin \delta, n/N$ and $n/N, H_0$)

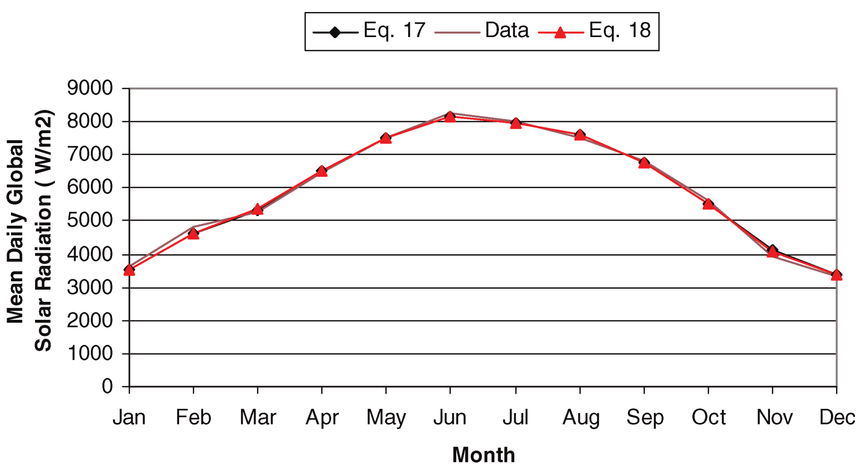

Figure 3.
Comparison of measured and estimated values using sample relations with three variables (n/N, H_0, T_{max} and n/N, H_0, R_h)

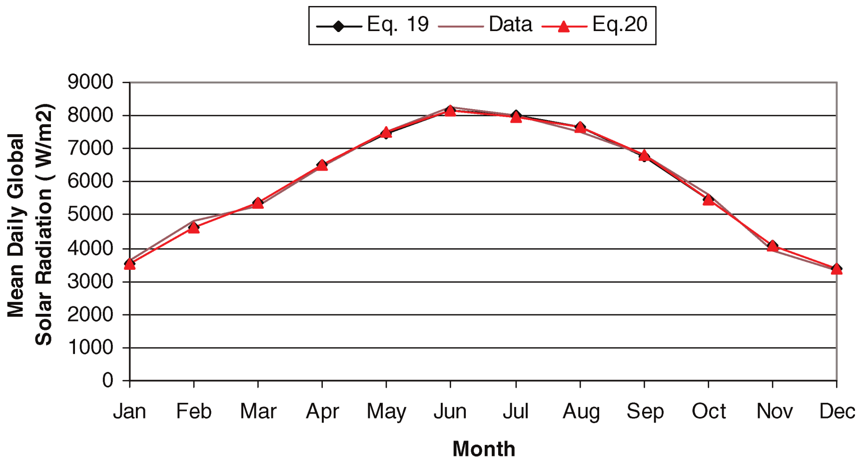

Figure 4. Comparison of measured and estimated values using sample relations with four variables ($n/N, H_0, R_h, P$ and $n/N, H_0, T_{\max}, T_{dp\,\max}$)

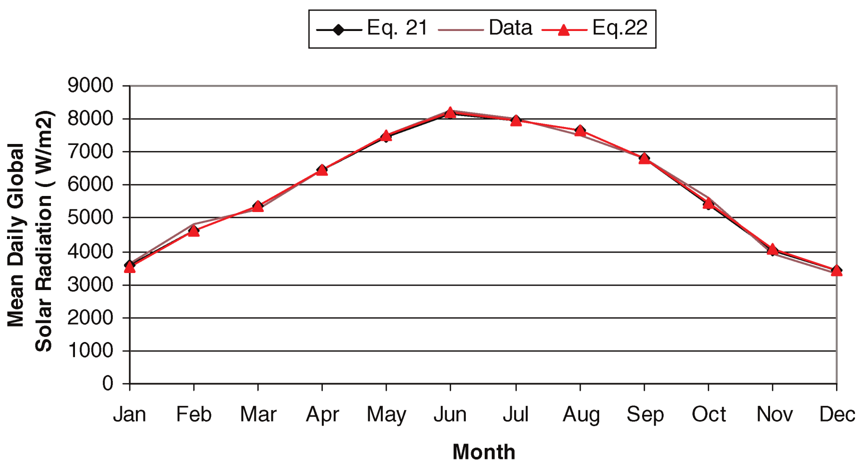

Figure 5. Comparison of measured and estimated values using sample relations with five variables ($n/N, H_0, T_{\max}, R_h, T_{dp,\max}$ and $\sin\delta, n/N, H_0, T_{\max}, T_{dp,\max}$)

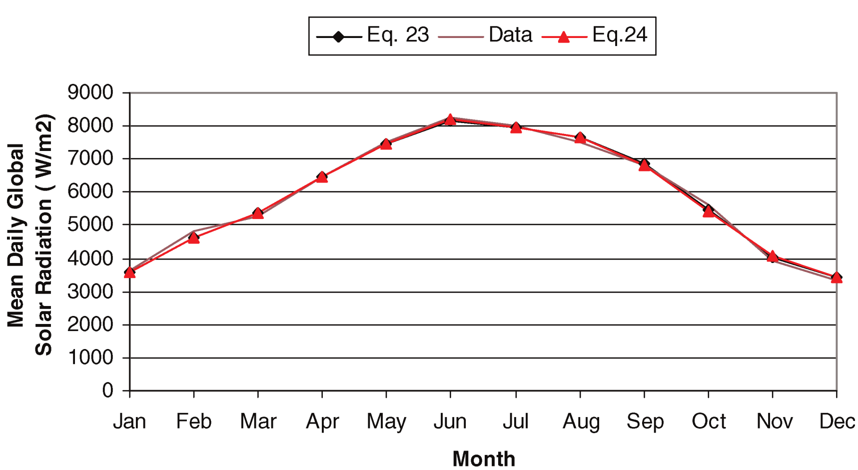

Figure 6. Comparison of measured and estimated values using sample relations with six variables ($\sin\delta, n/N, H_0, T_{\max}, R_h, T_{dp,\max}$ and $n/N, H_0, T_{\max}, R_h, T_{dp,\max}, P$)

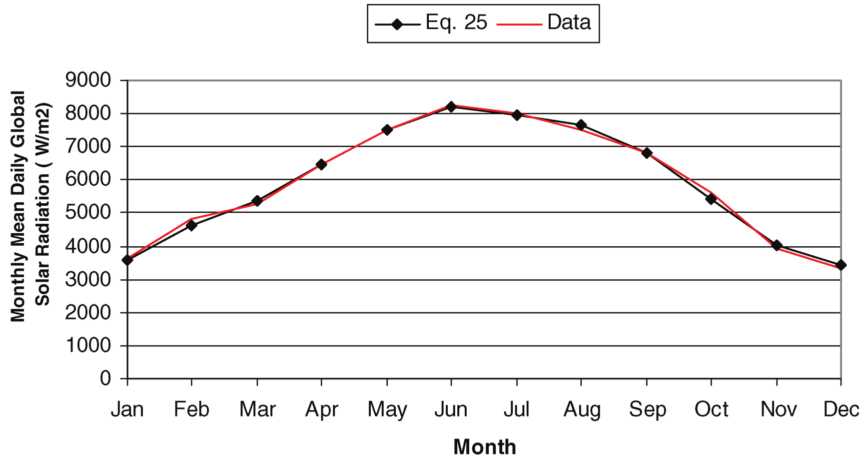

Figure 7.
Comparison of measured and estimated values using sample relation with seven variables ($\sin\delta, H_0, n/N, R_h, T_{\max}, T_{dp,\max}, P$)

Discussion

The relative percentage errors between the estimated and measured values of the monthly mean daily global solar radiation intensity were determined for the 12 months of the year. The results are given in Tables I-IV. Moreover, it is obvious that the performances of the developed relations are different. Therefore, the MBD and RMSD used separately can lead to a wrong decision in selecting the best suited relation from the candidate relations, and the use of MBD and RMSD in isolation is not an adequate indicator of the relation's performance. Therefore, the *t*-statistic was used in conjunction with these two indicators to better evaluate the accuracy of the estimated data. This is because the *t*-test depends on both the MBD and RMSD, so that it is more effective for determining the statistical properties. The MBD, RMSD and *t*-statistic tests are also given in Tables I-IV. The critical *t*-values are also shown in the same tables. Higher *t*-values than the critical *t*-values show that the relation has no statistical significance. According to

Table I.
The *e*, MBD, RMSD, *t*-statistics and critical *t*-values of Equations (13)-(16) developed for Yazd

		Equation (13)		Equation (14)		Equation (15)		Equation (16)	
Month	$\bar{H}_{i,m}$	$\bar{H}_{i,c}$	e (%)	$\bar{H}_{i,c}$	e (%)	$\bar{H}_{i,c}$	e (%)	$\bar{H}_{i,c}$	e (%)
January	3,630	3,852	−6.14	3,752	−3.36	3,664	−0.96	3,563	1.85
February	4,813	4,584	4.75	4,677	2.83	4,573	4.99	4,651	3.35
March	5,267	5,684	−7.91	5,908	−12.15	5,164	1.97	5,343	−1.44
April	6,457	6,887	−6.66	7,048	−9.15	6,410	0.72	6,538	−1.26
May	7,485	7,805	−4.27	7,764	−3.73	7,576	−1.21	7,535	−0.67
June	8,257	8,212	0.55	8,025	2.81	8,313	−0.68	8,156	1.22
July	7,999	8,025	−0.33	7,873	1.57	8,085	−1.08	7,956	0.53
August	7,511	7,266	3.26	7,287	2.97	7,581	−0.94	7,615	−1.39
September	6,823	6,129	10.17	6,279	7.97	6,599	3.29	6,750	1.07
October	5,611	4,931	12.12	5,028	10.38	5,388	3.98	5,489	2.17
November	3,907	4,025	−3.00	3,950	−1.08	4,141	−5.99	4,074	−4.27
December	3,308	3,639	−10.02	3,459	−4.58	3,552	−7.37	3,382	−2.25
MBD		2.3613		1.4822		1.8869		1.1025	
RMSD		376		371		161		101	
t		0.0209		0.0133		0.039		0.0363	
t-critical		2.2010		2.2010		2.2010		2.2010	

Month	$\bar{H}_{i,m}$	Equation (17) $\bar{H}_{i,c}$	e (%)	Equation (18) $\bar{H}_{i,c}$	e (%)	Equation (19) $\bar{H}_{i,c}$	e (%)	Equation (20) $\bar{H}_{i,c}$	e (%)
January	3,630	3,547	2.28	3,527	2.82	3542	2.42	3519	3.06
February	4,813	4,601	4.40	4,622	3.97	4,633	3.74	4,623	3.94
March	5,267	5,334	−1.26	5,356	−1.68	5,361	−1.78	5,393	−2.39
April	6,457	6,527	−1.08	6,535	−1.21	6,505	−0.75	6,506	−0.76
May	7,485	7,518	−0.44	7,523	−0.51	7,476	0.12	7,486	−0.01
June	8,257	8,147	1.34	8,145	1.36	8,153	1.26	8,153	1.26
July	7,999	7,980	0.23	7,957	0.52	8,002	−0.04	7,947	0.64
August	7,511	7,630	−1.59	7,619	−1.44	7,646	−1.81	7,641	−1.74
September	6,823	6,766	0.84	6,772	0.75	6,770	0.79	6,822	0.02
October	5,611	5,502	1.93	5,512	1.76	5,479	2.35	5,492	2.11
November	3,907	4,102	−4.99	4,102	−4.98	4,091	−4.69	4,085	−4.54
December	3,308	3,397	−2.68	3,383	−2.26	3,396	−2.65	3,386	−2.36
MBD		1.446		1.2465		1.2543		1.2049	
RMSD		112		110		109		111	
t		0.043		0.0377		0.0382		0.0359	
t-critical		2.2010		2.2010		2.2010		2.2010	

Table II.
The *e*, MBD, RMSD, *t*-statistics and critical *t*-values of Equations (17)-(20) developed for Yazd

Month	$\bar{H}_{i,m}$	Equation (21) $\bar{H}_{i,c}$	e (%)	Equation (22) $\bar{H}_{i,c}$	e (%)	Equation (23) $\bar{H}_{i,c}$	e (%)	Equation (24) $\bar{H}_{i,c}$	e (%)
January	3,630	3,577	1.44	3,536	2.58	3,586	1.20	3,574	1.54
February	4,813	4,623	3.94	4,619	4.02	4,605	4.33	4,621	3.98
March	5,267	5,375	−2.05	5,371	−1.97	5,365	−1.86	5,369	−1.92
April	6,457	6,476	−0.29	6,473	−0.25	6,482	−0.39	6,467	−0.15
May	7,485	7,462	0.31	7,493	−0.10	7,482	0.04	7,470	0.20
June	8,257	8,174	1.01	8,199	0.70	8,174	1.01	8,190	0.81
July	7,999	7,973	0.31	7,967	0.40	7,953	0.57	7,977	0.27
August	7,511	7,670	−2.13	7,634	−1.64	7,666	−2.07	7,661	−2.01
September	6,823	6,828	−0.06	6,798	0.38	6,840	−0.24	6,816	0.11
October	5,611	5,440	3.04	5,458	2.72	5,446	2.94	5,435	3.13
November	3,907	4,044	−3.51	4,087	−4.59	4,041	−3.41	4,053	−3.73
December	3,308	3,408	−3.03	3,418	−3.34	3,410	−3.10	3,418	−3.34
MBD		1.323		1.2615		1.4321		1.3256	
RMSD		109		110		109.6323		108.9214	
t		0.0403		0.038		0.0433		0.0404	
t-critical		2.2010		2.2010		2.2010		2.2010	

Table III.
The e, MBD, RMSD, *t*-statistics and critical *t*-values of Equations (21)-(24) developed for Yazd

Tables I-IV, Equation (25) shows the best results among the relations developed. The *e* is in the range of acceptable values, −3.64 and 4.38 percent. This error is acceptable from the engineering calculation point of view. The reason for this error may be mainly due to the low accuracy of the used measuring apparatus. The MBD, RMSD and *t*-test values are 1.4378 W/m^2, 110 W/m^2 and 0.0435. Since this relation gives the smallest values of the statistical indicators, it is considered as the best relation for estimating the global solar radiation intensity for the Yazd province with acceptable error.

It is of great concern to realize that selecting seven independent variables among the GGAM parameters in order to predict the global solar radiation intensity is very

Table IV.
The *e*, MBD, RMSD, *t*-statistics and critical *t*-values of Equation (25) developed for Yazd

Month	$\bar{H}_{i,m}$	$\bar{H}_{i,c}$	Equation (25) $e(\%)$
January	3,630	3,583	1.30
February	4,813	4,602	4.38
March	5,267	5,358	−1.72
April	6,457	6,473	−0.24
May	7,485	7,491	−0.08
June	8,257	8,192	0.79
July	7,999	7,956	0.53
August	7,511	7,656	−1.94
September	6,823	6,827	−0.06
October	5,611	5,440	3.03
November	3,907	4,050	−3.64
December	3,308	3,421	−3.43
MBD		1.4378	
RMSD		110	
t		0.0435	
t-critical		2.2010	

idealistic. Equation (13) shows even when only one independent variable ($\sin\delta$) is selected, the coefficient of correlation is 0.9383 and the *t*-statistic is 0.0209. That means the one-variable regression relation (Equation (13)) predicts the global solar radiation with an accuracy that is satisfactory in most engineering applications. This diversity of regression relations gives the engineer such a broad freedom of choices that knowing only an astronomical parameter of the site ($\sin\delta$) makes him capable of estimating the global solar radiation intensity. Of course, the more independent variables available, the better.

Conclusions

Data on several meteorological parameters for the Yazd province have been obtained, investigated and analyzed. Many types of correlations are tested against experimental results and relations having the highest correlation coefficients were selected. The correlation and regression coefficients for each selected relation have been calculated. The values of the correlation coefficient vary between 93.83 percent for the relations with two variables and 96.31 percent for the relation with seven variables, and the error did not exceed 4.38 percent. New multiple regression relations that give accurate estimates of monthly mean daily global solar radiation on a horizontal surface are suggested. The multiple regression relation with seven variables of $(H_0, \sin\delta, n/N, R_h, T_{\max}, T_{dp,\max}, P)$ has the highest $R = 0.96315$. The accuracy of the estimation is higher than that of all the other relations. The values of MBD (1.4378 W/m^2) and also RMSD (70 W/m^2) are within acceptable ranges. This indicates that the model presents valid estimates of the monthly mean global solar radiation intensity in Yazd airport. Furthermore, until solar radiation can be measured in more stations, the model can be applied to any site in Yazd province. The global solar radiation intensity values predicted by this approach can be used in the design and performance estimation of solar energy systems which are gaining increasing attention in Yazd.

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