Research Article

Prediction of Global Solar Radiation in Abu Dhabi

Ali Assi, Mohammed Jama, and Maitha Al-Shamisi

Electrical Engineering Department, United Arab Emirates University, P.O. Box 71555, Al Ain, UAE

Correspondence should be addressed to Ali Assi, ali.assi@uaeu.ac.ae

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Mathematical expressions have been employed to estimate global solar radiation on horizontal from relative sunshine duration for two weather stations in the United Arab Emirates (UAE), which are Abu Dhabi and Al Ain. These expressions include the original Angstrom-Prescott regression function (linear), quadratic function, third-order function, single-term exponential function, power function, logarithmic, and linear-logarithmic function. The predicted values were compared to the measured values using number of statistical methods to validate the goodness of the fits, such as residual analysis and goodness of fit statistics. All the used mathematical models performed generally well in both cities of Abu Dhabi and Al Ain, with all values of the coefficient of determination (R^2) higher than 75%. Specifically, the linear Angstrom-Prescott model estimated the average monthly global radiation on horizontal best for the city of Abu Dhabi, providing the second lowest mean absolute percentage error (MAPE) of 1.89% and the highest value of R^2 , which is approximately 94%, while the third-order model proved to be the best estimator for the city of Al Ain, providing the lowest MAPE value (3.06%) and a corresponding R^2 of 83%.

1. Introduction

Solar radiation is a primary factor in many applications, such as solar energy systems, architecture, agriculture, and irrigation. Despite the significance of solar radiation measurements, they are not yet available everywhere in the world. Due to the cost and maintenance and calibration requirements, this information is not readily available in many developing countries [1]. Therefore, it is of great importance to propose an efficient alternative to be used as a solar radiation estimator based on other more readily available meteorological data. Several empirical models for calculating solar radiation have been suggested in the literature. Some of these models use variables like sun hours, air temperature, relative humidity, and cloudiness. The most widely used parameter to estimate solar radiation is sunshine duration, which can be easily and reliably measured [2]. Angstrom regression model is the most commonly used method, which is a linear correlation between the average daily global radiation to the corresponding value on a completely clear day and the ratio of average daily sunshine duration to the maximum possible sunshine duration. Prescott suggested replacing the clear sky global radiation with the extraterrestrial radiation,

producing a more convenient form of Angstrom equation called Angstrom-Prescott regression model [3, 4].

In [5], the daily diffuse solar radiation was estimated using Liu and Jordan method, while number of correlations for different periods of the day proved to give better fit to estimate hourly diffuse solar radiation on horizontal. In [6], several empirical correlations were utilized to estimate the global monthly solar radiation on horizontal for number of provinces in Turkey, while in [7] a generic correlation was developed to calculate the daily diffuse solar radiation based on Liu and Jordan methodology. Similar study was conducted by [8], where the Angstrom-Prescott linear regression model and its quadratic and cubic derivatives were used to estimate the global monthly solar radiation for five different Egyptian provinces.

The potential of solar radiation in UAE is significant, with an average annual solar hours of 3568 h (i.e., 9.7 h/day), which corresponds to an average annual solar radiation of approximately 2285 kWh/m² (i.e., 6.3 kWh/m² per day) [9]. In this work, a number of regression models were investigated and validated to estimate monthly average daily global radiation on horizontal using only sunshine duration measurements for both cities of Abu Dhabi and Al-Ain

FIGURE 1: UAE map showing the location of Abu Dhabi and Al Ain.

geographically situated as shown in Figure 1. To choose the most adequate model, all models have been tested using statistical methods. The meteorological data used in this work were provided by the National Center of Meteorology and Seismology (Abu Dhabi) for the periods between 1995 and 2007. MATLAB tool was used to obtain and validate the regression models.

2. Theory

Several types of regression models have been proposed in the literature for predicting global solar irradiance on horizontal from the daily sunshine hours and extraterrestrial solar radiation. Table 1 shows the regression models used in this study. The regression models in Table 1 are given in terms of the clearness index; $K_T = G/G_o$ is the ratio of the monthly average daily global radiation on horizontal and its corresponding extraterrestrial radiation, and the other variable is the sunshine duration ratio (R_s), which is the ratio between measured daily sun hours (S) and theoretical maximum daily sun hours (S_o). The daily extraterrestrial solar radiation on horizontal can be calculated as shown in

$$G_o = \frac{24}{\pi} G_{sc} \left(1 + 0.033 \cos \left(\frac{2\pi d_n}{365} \right) \right) \times (\cos \phi \cos \delta \sin \omega_s + \omega_s \sin \phi \sin \delta), \quad (1)$$

where G_{sc} is the solar constant and is approximately 1.367 kW/m^2 [10], d_n is number of the day in the year, ϕ is the site latitude, δ is the solar declination angle computed using (2) [10], and ω_s is the daily sun rise hour computed using (3). While S_o can be computed using (4) [7]

$$\delta = 23.45 \sin \left(\frac{360(284 + d_n)}{365} \right), \quad (2)$$

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

$$S_o = \frac{2}{15} \omega_s. \quad (4)$$

As shown in Table 1, the objective of this study is to determine the regression coefficients of the seven regression models, which are “ a ”, “ b ”, “ c ”, and “ d ”. Each of these coefficients gives an indication about the solar radiation characteristics for the location under investigation. For

TABLE 1: Regression models used in this paper.

Model (source)	Regression model
Linear (Angstrom-Prescott [3, 4])	$K_T = a + bR_s$
Quadratic (Akinoglu and Ecevit [11])	$K_T = a + bR_s + cR_s^2$
Third order (Samuel [12])	$K_T = a + bR_s + cR_s^2 + dR_s^3$
Logarithmic (Ampratwum and Dorvlo [13])	$K_T = a + b \log(R_s)$
Linear-logarithmic (Newland [14])	$K_T = a + bR_s + c \log(R_s)$
Exponential (Elagib and Monsell [15])	$K_T = ae^{(bR)}_s$
Power (Coppolino [16])	$K_T = e^a R_s^b$

example, in the modified linear Angstrom-Prescott model, the regression parameter “ a ” is a measure of the overall atmospheric transmission for total cloud conditions, while the parameter “ b ” represents the rate of change of G/G_o with respect to S/S_o [6].

3. Methodology

The main objective of this research work is to obtain the correlation coefficients for seven different regression models for Abu Dhabi and Al Ain. To produce the regression equations, daily weather data for Abu Dhabi (Latitude: 23.5°N , Longitude: 54.5°E , and Elevation: 6 m) and Al Ain (Latitude: $24^\circ 16' \text{N}$, Longitude: $55^\circ 36' \text{E}$, and Elevation: 250 m) were obtained from the National Center of Meteorology and Seismology (Abu Dhabi, UAE). The obtained weather data includes measured daily global solar radiation on horizontal and daily sun hours for an observation period of 13 years.

The proposed regression models (Table 1) are the linear Angstrom-Prescott model, which is considered the most commonly used model [3, 4]. The second model is the Akinoglu and Ecevit regression model, which is a correlation between K_T and R_s in a second-order (quadratic) polynomial [11]. Samuel suggested the third regression model, which represents a third-order correlation [12]. Ampratwum and Dorvlo proposed the fourth used regression model, which is a logarithmic correlation between K_T and R_s [13]. The fifth model was suggested by Newland, which represents a linear-logarithmic correlation equation [14]. The sixth (exponential) and seventh (power) regression models were proposed by Elagib & Monsell and Coppolino, respectively [15, 16]. Correlation coefficient values were calculated from the regression analysis between K_T and R_s in a daily and monthly basis as proposed by Tadros in Egypt [17].

MATLAB was used to compute the coefficients and to compare between the seven regression models statistically in order to find the best predictive model. Number of statistical methods was used to validate the accuracy and goodness of the fits. These methods included the residual analysis and goodness of fits statistics, such as the coefficient of determination (R^2), mean absolute percentage error

TABLE 2: Correlation coefficients.

Station	Model	a	b	c	d
Abu Dhabi	Linear	0.1833	0.5301		
	Quadratic	0.1890	0.8450	-0.3900	
	Cubic	0.4201	0.5292	-0.7771	0.5211
	Exponential	0.5399	0.1630		
	Logarithmic	0.6290	0.1053		
	Linear-logarithmic	0.7621	-0.16268	0.08576	
	Power	-0.4698	0.034		
Al Ain	Linear	0.1833	0.6478		
	Quadratic	0.6351	0.0966	-0.0255	
	Cubic	0.4411	0.8292	-0.9771	0.4211
	Exponential	0.6416	0.099		
	Logarithmic	0.6858	0.0153		
	Linear-logarithmic	0.7081	-0.01268	0.01276	
	Power	-0.4058	0.00014		

TABLE 3: Goodness of fit statistics for the used regression models.

Station	Model	R^2	MAPE	MBE	MABE	RMSE	SSR	SST
Abu Dhabi	Linear	94%	1.89	-0.0035	0.1080	0.1330	17.751	18.862
	Quadratic	90%	1.94	0.0094	0.1162	0.1529	16.979	18.863
	Cubic	91%	1.75	0.0006	0.1038	0.1324	17.209	18.861
	Exponential	88%	2.23	0.0370	0.1338	0.1742	16.628	18.878
	Logarithmic	88%	2.39	0.0148	0.1410	0.1777	16.687	18.864
	Linear-logarithmic	87%	3.11	0.0151	0.1799	0.2141	16.449	18.864
	Power	88%	2.52	0.0077	0.1474	0.1825	16.682	18.862
Al Ain	Linear	81%	3.39	-0.1341	0.1751	0.2173	16.328	20.766
	Quadratic	83%	3.15	-0.0068	0.1935	0.2134	16.610	19.919
	Cubic	83%	3.06	0.0016	0.1881	0.2078	16.497	19.918
	Exponential	81%	3.32	0.0053	0.2142	0.2592	16.166	19.919
	Logarithmic	84%	3.45	0.1040	0.2131	0.2332	16.794	20.048
	Linear-logarithmic	83%	3.07	-0.0059	0.1896	0.2104	16.505	19.918
	Power	74%	4.10	0.2658	0.2781	0.3685	15.351	20.766

FIGURE 2: Residual analysis for Abu Dhabi.

FIGURE 3: Residual analysis for Al-Ain.

FIGURE 4: Continued.

(d)

(e)

(f)

FIGURE 4: Continued.

FIGURE 4: (a–g) Comparison between the measured and the calculated values of the monthly average daily global solar radiation using seven different regression models for Abu Dhabi, UAE.

(MAPE), root mean square error (RMSE), mean bias error (MBE), and mean absolute bias error (MABE). The residuals from a fitted model are defined as the differences between the response data and the fit to the response data at each predictor value. Assuming the model fitted to the data is correct, the residuals approximate the random errors. Therefore, if the residuals appear to behave randomly, it suggests that the model fits the data well. However, if the residuals display a systematic pattern, it will be a clear sign that the model poorly fits the data [18].

Equation (5) shows how to calculate MAPE of the fit, which is a measure of the forecast accuracy. MBE gives information on the long-term performance. A positive MBE shows an overestimation while a negative MBE represents an underestimation (6) [7]. The MABE is a measure of the goodness of the fit used to produce the models (7). RMSE gives information on the short-term performance of the correlations (8) [18]. Low values of MAPE, MBE, MABE, and RMSE are always required;

$$\text{MAPE} = \frac{1}{n} \sum_{i=1}^n \left(\left| \frac{G_m^i - G_c^i}{G_m^i} \right| \times 100 \right), \quad (5)$$

$$\text{MBE} = \frac{\sum_{i=1}^n (G_m^i - G_c^i)}{n}, \quad (6)$$

$$\text{MABE} = \frac{\sum_{i=1}^n (|G_m^i - G_c^i|)}{n}, \quad (7)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (G_m^i - G_c^i)^2}{n}}, \quad (8)$$

where G_m and G_c represent the measured and calculated monthly global solar radiation on horizontal. The coefficient

of determination (R^2) measures how successful the fit is in explaining the variation of the data, which can be calculated using (9). SST and SSR are the total sum of squares and the sum of squares of the regression, respectively,

$$\begin{aligned} R^2 &= \frac{\text{SSR}}{\text{SST}}, \\ \text{SSR} &= \sum_{i=1}^n (\bar{G}_m - G_c^i)^2, \\ \text{SST} &= \sum_{i=1}^n (\bar{G}_m - G_m^i)^2, \\ \bar{G}_m &= \frac{1}{n} \sum_{i=1}^n G_m^i. \end{aligned} \quad (9)$$

4. Results and Discussion

The coefficients of the seven regression models used in this work are reported in Table 2. The statistical results of the corresponding models are given in Table 3. As mentioned earlier, it is preferred to have the statistics like MAPE, MABE, and RMSE as small as possible (i.e., close to zero).

The residual analysis showed that the fitting error for the developed models are scattered randomly around zero, which indicates a good fit as illustrated in Figures 2 and 3. However, as it can be observed from Figure 3, the regression models for Al Ain produced a slightly greater fitting errors compared to those for Abu Dhabi. The lowest coefficient of determination was 74%. Abu Dhabi data produced a generally better fits than that of Al Ain, with a minimum R^2 of 87%. The logarithmic (Ampratwum and Dorvlo) regression model offered the best estimate with the highest coefficient of determination value ($R^2 = 84\%$) for Al Ain. While the linear Angstrom-Prescott model performed best ($R^2 = 94\%$)

(a)

(b)

(c)

FIGURE 5: Continued.

(d)

(e)

(f)

FIGURE 5: Continued.

FIGURE 5: (a–g) Comparison between the measured and the calculated values of the monthly average daily global solar radiation using seven different regression models for Al-Ain, UAE.

for Abu Dhabi. The power (Coppolino) model performed worse overall in Al Ain, giving the lowest coefficient of determination (R^2) value of 74% and the highest values of MAPE, MABE, and RMSE. The quadratic, third-order, and exponential regression equations offered good and almost similar statistic results for Al Ain.

Regarding RMSE values, all models resulted in very small values of RMSE for both cities of Abu Dhabi and Al Ain. The cubic model (Samuel) gave the smallest MAPE for Abu Dhabi and Al Ain, 1.75 and 3.06, respectively.

The regression coefficients obtained for Abu Dhabi are different than those of Al Ain. The variations between the measured data of monthly average daily global radiation for Abu Dhabi and Al Ain and its calculated counterparts for the seven different regression models are shown in Figures 4 and 5.

It is obvious that all regression models except the power (Coppolino) model performed almost with the same degree of accuracy in Al Ain. In order to come up with a more accurate regression models, several estimators (models) can be used to predict the monthly average daily global radiation on horizontal across the year. For example, the power model performed very well in the winter months (Dec, Jan, Feb, and Mar) in Al Ain as shown in Figure 5, which are the months in which the third-order regression model performed poorly.

Regarding the MBE, underestimation of the solar radiation on horizontal for the linear Angstrom-Prescott model was noted in both cities of Abu Dhabi and Al Ain. A negative value gives the average amount of underestimation in the predicted values and vice versa. The third-order model offered the lowest values of MBE compared to the other used models in both Abu Dhabi and Al-Ain stations, 0.0006 and 0.0016, respectively. Also the third-order model performed best regarding RMSE for both stations, with approximately 0.1324 in Abu Dhabi and 0.2078 in Al-Ain.

It can be noted that all regression models in Al-Ain failed to provide a value of R^2 better than 84%, which was obtained using the logarithmic model. Since almost all regression models in Al-Ain station performed closely in terms of the value of R^2 except the power (Coppolino) model, the third-order model was chosen to be the best estimator model in terms of the other statistical tests such as MBE, MAPE, RMSE, and MABE.

5. Conclusion

Many regression models that estimate global solar radiation using more readily meteorological data were proposed in literature. A number of sunshine duration regression models have been studied and analyzed to estimate monthly average daily global solar radiation on horizontal in both cities of Abu Dhabi and Al Ain, UAE. In general, all models performed well with minimum R^2 of 74% given by the power (Coppolino) model in Al Ain. It was found that the linear Angstrom-Prescott model performed the best overall by the means of R^2 (94%) in Abu Dhabi. While the logarithmic model offered the best estimate in Al Ain, other models also offered almost similar accuracy except for the power model. In order to improve the accuracy of the estimation, multiple estimators can be used to predict the average monthly global solar radiation on horizontal across the year.

Abbreviations

- G_{sc} : Solar constant (W/m^2)
- Φ : Site latitude (deg)
- Δ : Solar declination angle (deg)
- ω_s : Sun rise hour (deg)
- G : Global solar radiation on horizontal (kWh/m^2)

G_o :	Extraterrestrial radiation (Wh/m^2)
d_n :	Number of the day in the year
K_T :	Clearness index
S :	Monthly average daily sun hours (h)
S_o :	Monthly average maximum possible daily sun hours (h)
R_S :	The sunshine hours ratio
R^2 :	Coefficient of determination (kWh/m^2)
G_m :	Measured monthly global solar radiation on horizontal (kWh/m^2)
G_c :	Calculated monthly global solar radiation on horizontal (kWh/m^2)
n :	Number of samples
MAPE:	Mean absolute percentage error (kWh/m^2)
RMSE:	Root mean square error (kWh/m^2)
MABE:	Mean absolute bias error (kWh/m^2)
MBE:	Mean bias error (kWh/m^2)
SSR:	Sum of squares of the regression (kWh/m^2)
SST:	Total sum of squares (kWh/m^2).

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