Estimating Global Solar Radiation on Horizontal from Sunshine Hours in Abu Dhabi – UAE

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Abstract: - Number of mathematical correlations have been used to predict the monthly average global solar radiation on horizontal using the sun hours as an input parameter. The study was carried out on two weather stations in the UAE, which are Abu Dhabi and Al Ain, using a daily weather data recorded for 13 years. The used correlations included the linear Angstrom-Prescott model and its derivations, namely, the second and third order correlations. Moreover, the single term exponential model, logarithmic model, linear logarithmic model and power model were all examined in this work. The performance of the aforementioned correlations as global solar radiation estimators was evaluated by comparing the predicted values with the measured values. Different statistical error tests were employed to examine the accuracy of the mathematical models. In general all fits performed well in both Abu Dhabi and Al Ain, with all giving values of R^2 greater than 81% except for the power model in Al Ain, which produced R^2 of 74%. The linear Angstrom-Prescott model and the third order model performed the best for Abu Dhabi and Al Ain, respectively.

Key-Words: - Solar energy, global solar radiation, mathematical correlations, regression models, sunshine duration.

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 has been 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 literature. Some of these models use variables like sun hours, air temperature, relative humidity, and cloudiness [2]. 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].

Photovoltaic systems offer a clean, renewable, and free of charge energy source towards establishing a real sustainable society. The UAE has taken serious steps to emerge into solar energy market by launching its outstanding MASDAR initiative in Abu Dhabi. Besides, UAE has been awarded to be the permanent host of the International Renewable Energy Agency (IRENA) headquarters in 2009. The potential of solar radiation in UAE is significant, with average annual solar hours of 3568 h (average of 9.7 h/day), corresponding to an average annual solar radiation of approximately 2285 kWh/m^2 (average of 6.3 kWh/m^2 per day) [5].

In this work, 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 in UAE. All models have been tested using statistical methods, to choose the most adequate model. The meteorological data used in this study were taken from the National Center of Meteorology and Seismology (Abu Dhabi) in the periods between 1995 and 2007. MATLAB was used to obtain the regression models and validate them.

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, the other variable is the sunshine duration ratio (R_s), which is the ratio between measured daily sun hours (S) and theoretical maximum daily solar hours (S_o).

The daily extraterrestrial solar radiation on horizontal can be calculated as shown in Eq.1.

$$G_o = \frac{24}{\pi} G_{SC} \left(1 + 0.33 \cos\left(2\pi\, d_n / 365\right)\right) \times \left(\cos\phi \cos\delta \sin\omega_S + \omega_S \sin\phi \sin\delta\right) \quad (1)$$

Where G_{sc} is the solar constant and it is approximately 1367 W/m^2 [6], d_n is number of the day in the year, Φ is the sun azimuth angle, δ is the solar declination angle and is calculated using Eq.2 [6], ω_s is the daily sun rise hour and is calculated using Eq.3. While So can be calculated using Eq.4 [7].

$$\delta = \pi \frac{23.45}{180} \sin\left(2\pi \frac{284 + n}{365}\right) \quad (2)$$

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

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

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 one of these coefficients gives an indication about the solar radiation characteristics for the location under investigation.

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 develop the regression equations, daily weather data for Abu Dhabi (Latitude: 23.5°N, Longitude: 54.5°E) and Al Ain (Latitude: 24° 16’ N, Longitude: 55° 36’ E) were obtained from the National Center of Meteorology and Seismology (Abu Dhabi, UAE).

Table 1: Regression models used in this paper

Model (Source)	**Regression Model**
Linear (Angstrom – Prescott)	$K_T = a + bR_S$
Quadratic (Akinoglu & Ecevit)	$K_T = a + bR_S + cR_S^2$
Third order (Samuel)	$K_T = a + bR_S + cR_S^2 + dR_S^3$
Logarithmic (Ampratwum & Dorvlo)	$K_T = a + b\log(R_S)$
Linear – Logarithmic (Newland)	$K_T = a + bR_S + c\log(R_S)$
Exponential (Elagib & Monsell)	$K_T = ae^{(bRS)}$
Power (Coppolino)	$K_T = e^a R_S^b$

The obtained weather data included 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 [9]. Samuel suggested the third regression model, which represents a third order correlation [10]. Ampratwum and Dorvlo proposed the fourth used regression model, which is a logarithmic correlation between K_T and R_S [11]. The fifth model was suggested by Newland, which represents a linear – logarithmic correlation equation [12]. The sixth (exponential) and seventh (power) regression models were proposed by Elagib & Monsell and Coppolin, respectively [13, 14]. 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 [15].

MATLAB was used to calculate 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 (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 [7].

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 (Eq.7) [7]. The MABE is a measure of the goodness of the fit used to produce the models (Eq.6). RMSE gives information on the short term performance of the correlations (Eq.8) [16]. Low values of MAPE, MBE, MABE, and RMSE are always required.

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

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

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

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

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 Eq.9-12. Where SST and SSR are the total sum of squares and the sum of squares of the regression, respectively.

$$\overline{G_m} = \frac{1}{n}\sum_{i=1}^{n} G_m^i \quad (9)$$

$$SST = \sum_{i=1}^{n}\left(\overline{G_m} - G_m^i\right)^2 \quad (10)$$

$$SSR = \sum_{i=1}^{n}\left(\overline{G_m} - G_c^i\right)^2 \quad (11)$$

$$R^2 = \frac{SSR}{SST} \qquad (12)$$

4 Results & 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 (close to zero).

All used regression models showed a good degree of accuracy as global solar radiation estimators. The residual analysis showed that the residuals for the developed models are scattered randomly around zero, which indicates a good fit. However, the regression models associated with Abu Dhabi provided slightly better residual analysis than their Al Ain counterparts.

All developed regression models produced permissible values of coefficient of determination (R^2) for both of Abu Dhabi and Al Ain.

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 & 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%) 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 gave 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.

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	82%	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

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 Fig.1 and Fig.2.

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 gave 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.

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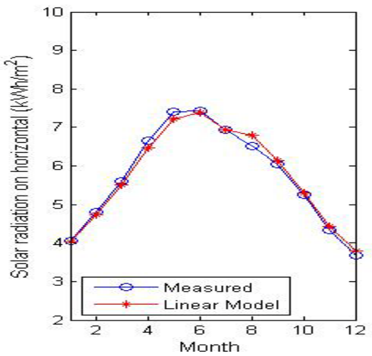

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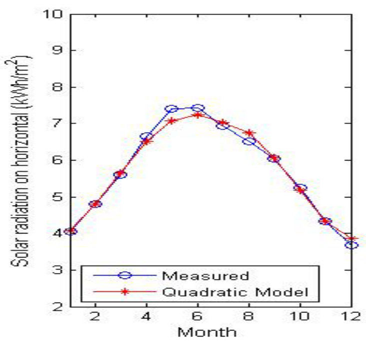

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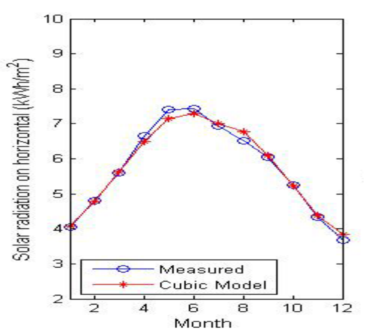

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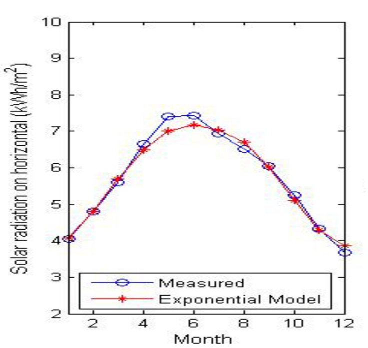

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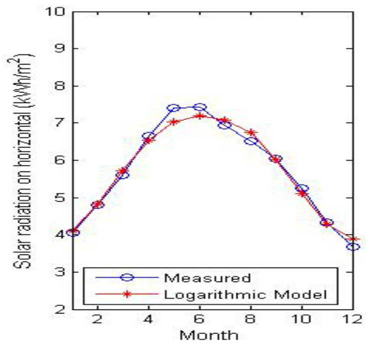

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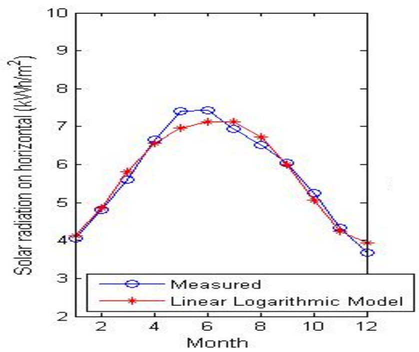

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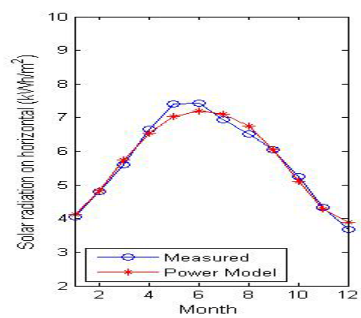
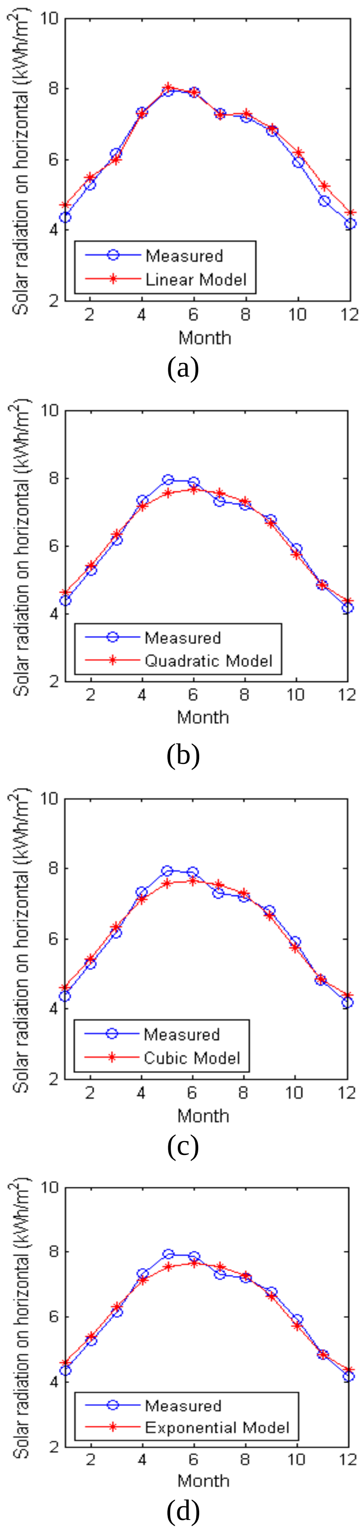


(g)

Fig.1 (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.



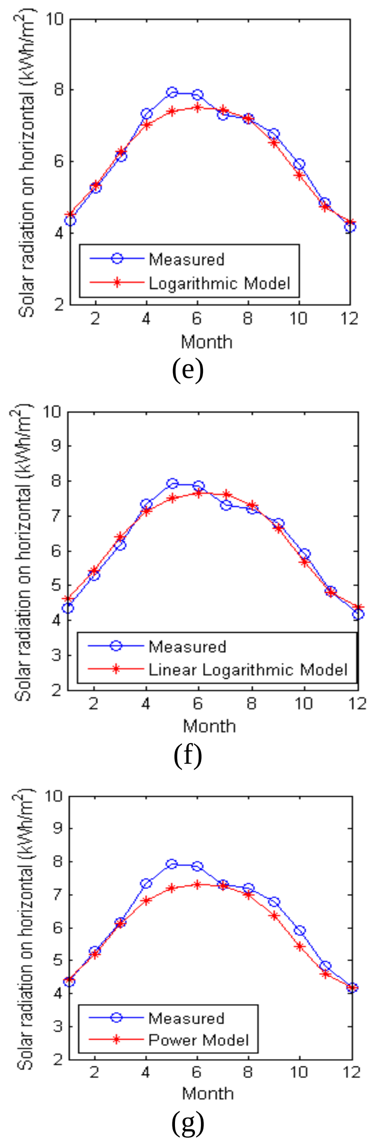


Fig.2 (a-g): Comparison between the measured and the calculated values of the monthly average daily global solar radiation using seven different regression models for Al-Ain, UAE.

5 Conclusion

Number of sunshine duration regression models have been studied and analyzed to predict 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 model in Al Ain, while the linear Angstrom-Prescott model proved to be the best estimator in Abu Dhabi. More than one regression model can be used to predict the global solar radiation across the year.

Nomenclature

G_{sc}	Solar constant
Φ	Azimuth angle
Δ	Solar declination angle
Ω_s	Sun rise hour
G	Global solar radiation on horizontal
G_o	Extraterrestrial radiation
d_n	Number of the day in the year
n	Number of the day in the year
K_T	Clearness index
S_o	Monthly average maximum possible daily sun hours
R_S	The sunshine hours ratio
R^2	Coefficient of determination
MAPE	Mean absolute percentage error
RMSE	Root mean square error
MABE	Mean absolute bias error
SSR	Sum of squares of the regression

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