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DAILY GLOBAL SOLAR RADIATION ESTIMATE BASED ON SUNSHINE HOURS

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ABSTRACT

Monthly average daily global solar radiation data are essential in the design and study of solar energy conversion devices. In this regard, different empirical models based on Angstrom-Prescott model were selected to estimate the monthly average daily global solar radiation, *H*, on a horizontal surface for Terengganu state using only the sunshine duration. The hourly solar radiation data measured at Kuala Terengganu station during the period (2004–2007) were used to calculate the monthly mean values of *H* using selected models. The selected models were compared on the basis of the statistical error tests as the mean bias error, the mean percentage error, the root mean square error, Nash–Sutcliffe equation, correlation coefficient and the *t*-test. Based on the statistical results a new linear model H/H_o= 0.2207 + 0.5249 *(n/N)* based on modified Angstrom model is extremely recommended to estimate monthly average daily global solar radiation for Terengganu state areas and in elsewhere with similar climatic conditions areas where the radiation data is missing or unavailable. The present work will help to advance the state of knowledge of global solar radiation to the point where it has applications in the estimation of monthly average daily global solar radiation.

Keywords: Daily global solar radiation, Sunshine hours, Empirical models, Validation, Terengganu State-Malaysia

NOMENCLATURE AND SYMBOLS

H- Monthly average daily global radiation (Wh m^{-2} /day)
H_c- Monthly average clear sky daily global radiation (Wh m^{-2} /day)
H_o- Monthly average daily extraterrestrial radiation (Wh m^{-2} /day)
I_{sc}- Solar constant (=1367 W m^{-2})
MBE- Mean Bias Error
MMD- Malaysian Meteorology Department
MPE- Mean Percentage Error
N- Monthly average maximum daily sunshine duration (hours)
NSE- Nash–Sutcliffe Equation
RMSE- Root Mean Square Error
a, b- Empirical constants
n- Monthly average daily bright sunshine duration (hours)
r- Coefficient of correlation
w_s- Mean sunrise hour angle
Φ- Latitude of the site
δ- The sun declination angle

1 INTRODUCTION

The accurate information of the solar radiation intensity at a given location is of essential to the development of solar energy-based projects and in the long-term evaluation of the solar energy conversion systems performances. This information is used in the design of a project, in cost analysis, and in the efficiency calculations of a project. Furthermore, monthly mean daily data are needed for the estimation of long-term solar systems performances. The Malaysia has the opportunity to utilize the solar energy effectively, promoting a clean environment, and developing renewable energy technologies in the country. The use of photovoltaic devices, on the other hand, is suitable for rural electrification, pumping water from wells, cathodic protection, telecommunications, solar thermal devices, etc. Given these many possible uses of solar energy, it is important to know the global solar radiation distribution throughout the year for the interested region.

In addition, the values of the average daily global radiation in the solar energy applications are the most important parameter, measurements of which are not available at every location due to cost, maintenance, and calibration requirements of the measuring equipment. In places where no measured values are available, a common application has been to determine this parameter by appropriate correlations which are empirically established using the measured data. Several empirical models have been used to calculate solar radiation, utilizing available meteorological, geographical and climatological parameters such as sunshine hours (Kadir Bakirci, 2009; Koussa et al., 2009; Bulut and Buyukalaca, 2007; Akinoglu and Ecevit, 1990), air temperature (Fletcher, 2007), latitude (Raja, 1994), precipitation (Rietveld, 1978), relative humidity (Trabea and Shaltout, 2000; Alnaser, 1993), and cloudiness (Kumar and Umanand, 2005). The most commonly used parameter for estimating global solar radiation is sunshine duration. Among various correlations, the modified version of Angstrom equation who proposed a linear relationship between the ratio of 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 and its derivations have been widely used. Furthermore, these correlations can be used to estimate the values of the monthly average daily global radiation for other locations on the basis of their similarities. Consequently, the bright sunshine data at these places can be used to estimate the values of the global radiation with the help of models detailed in literatures. Global solar radiation has been measured at the various parts in the Malaysia (Chuah and Lee, 1981; 1982; Saidur et al. 2008). Angstron model have been performed to estimate solar energy on clear day. Monthly average daily global solar radiation on the horizontal surface in Kuala Lampur, Penang and Kota Baru was studied by Chuah and Lee (1981; 1982). Further, monthly average daily global solar radiation in Malaysia was investigated in eight cities such as Kuching, Kota Kinabalu, Kota Baru, Senai, Bayan Lepas, Kuala Lumpur, Petaling Jaya and Bandar Baru Bangi by Kamaruzzaman Sopian and Othman (1992).

As this literature review shows, although solar radiation data have been reported for few cities of Malaysia, global solar radiation data is still needed for other cities of Malaysia as Kuala Terengganu. The objective of this study was to evaluate various models for the estimation of the monthly average daily global radiation on a horizontal surface from bright sunshine hours and to select the most appropriate model for Terengganu state. Furthermore in our paper, we first performed a literature review of all the existing models and we made a description of each retained model. This was followed by a statistical comparison of the monthly mean daily retained models to the measured data obtained from Kula Terengganu site.

2 MONTHLY MEAN DAILY GLOBAL RADIATION MODELS

The first correlation proposed for estimating the monthly average daily global radiation is based on the method of Angstrom (1924). The original Angstrom-type regression equation-related monthly average daily radiation to clear day radiation in a given location and average fraction of possible sunshine hours:

$$\frac{H}{H_c} = a + b\left(\frac{n}{N}\right) \quad (1)$$

where H is the monthly average daily global radiation (Wh m^{-2} /day), H_c is the monthly average clear sky daily global radiation for the location (Wh m^{-2} /day), n is the monthly average daily bright sunshine duration (hours), N is the monthly average maximum possible daily bright sunshine duration (hours), and a and b are empirical constants. A basic difficulty with Equation (1) lies in the definition of the terms n/N and H_c. Prescott (1940) and the others have modified the method to base it on extraterrestrial radiation on a horizontal surface rather than on clear day radiation. Various attempts have been undertaken to model these constants and improve the equation. However, few authors have introduced new elements that would generalize Angstrom's concept and replace the present parameters for choosing the right coefficients with a true model incorporating enough physical underpinning input so that such a modified equation could acquire worldwide validity. Although the Angstrom –Prescott equation can be improved and more accurate results are possible, it is used for many applications. Only Linear Angstrom and Prescott global radiation model related to Malaysia has been found by reviewing all available literatures. Further, ten models have been selected from different previous studies for estimating daily global solar radiation. The first nine models (Models 1 to 9) have been proposed for estimating H based on the above Angstrom–Prescott model, while the other remaining one model (Model 10) (Glover and McCulloch, 1958) have been proposed for estimating H based on the latitude of the location, monthly average daily bright sunshine duration and the monthly average maximum possible daily bright sunshine duration. The Angstrom–Prescott model (Prescott, 1940) is the most commonly used model as given by

$$\frac{H}{H_o} = a + b\left(\frac{n}{N}\right) \quad (2)$$

where H is the monthly average daily global radiation, H_o is the monthly average daily extraterrestrial radiation, n is the day length, N is the maximum possible sunshine duration, and a and b are empirical coefficients. The values of the monthly average daily extraterrestrial radiation (H_o) are calculated for days giving average of each month (Iqbal, 1983; Zekai, 2008; Saidur et al. 2009). H_o was calculated from the following equation (Iqbal, 1983; Zekai, 2008):

$$H_o = \frac{24 * I_{sc}}{\pi}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right]x \quad (3)$$
$$\left[\cos\varphi\cos\delta\sin w_s + \left(\frac{2\pi.w_s}{360}\right)\sin\varphi\sin\delta\right]$$

where I_{sc} is the solar constant (=1367 W m^{-2}), φ is the latitude of the site, δ is the sun declination and w_s is the mean sunrise hour angle for the given month. δ, w_s and N can be computed by the following equations (Iqbal, 1983; Zekai, 2008):

$$\delta = 23.45\sin[360(n + 284)/365] \quad (4)$$

where n is the day number of the year starting 1st of January.

$$w_s = \cos^{-1}(-\tan(\varphi)\tan(\delta)) \quad (5)$$

$$N = \frac{2.w_s}{15} \quad (6)$$

The regression models proposed in the literature based on Angstron and Prescott and other parameters are listed in Table 1.

Table 1 Regression models proposed in the literature

Model No.	Regression equation	Model type	Source
1	$H/H_o=a+b(n/N)$	Linear	Angstrom, (1924) and Prescott (1940)
2	$H/H_o=a+b(S/S_o)+c(n/N)^2$	Quadratic	Akinoglu and Ecevit (1990)
3	$H/H_o=a+b(S/S_o)+c(n/N)^2+d(n/N)^3$	Cubic	Samuel (1991)
4	$H/H_o=a+b(n/N)+c\ log(n/N)$	Linear logarithmic	Newland (1988)]
5	$H/H_o=a+b\ log(n/N)$	Logarithmic	Ampratwum and Dorvlo (1999)
6	$H/H_o=a+b(n/N)+c\ exp(n/N)$	Linear exponential	Kadir Bakirci (2009)
7	$H/H_o=a+b\ exp(n/N)$	Exponential	Almorox et. al. (2005)
8	$H/H_o=a(n/N)^b$	Exponent	Kadir Bakirci (2009)
9	$H/H_o=0.18+0.62(n/N)$	Linear, known constants	Rietveld (1978)
10	$H/H_o= 0.29 \cos(\varphi)+0.52(n/N)$	Linear, latitude related	Glover and McCulloch (1958)

3 COMPARISON TECHNIQUES

There are numerous works in literature which deal with the assessment and comparison of monthly mean daily solar radiation estimation models. The most popular statistical parameters are the mean bias error (*MBE*) and the root mean square error (*RMSE*). In this study, to evaluate the accuracy of the estimated data, from the models described above, the following statistical tests were used, *MBE*, *RMSE*, mean percentage error (*MPE*) and coefficient of correlation (*r*), to test the linear relationship between predicted and measured values. For better data modeling, these statistics should be closer to zero, but coefficient of correlation, *r*, should approach to 1 as closely as possible. The Nash–Sutcliffe equation (*NSE*) is also selected as an evaluation criterion. A model is more efficient when *NSE* is closer to 1. However, these estimated errors provide reasonable criteria to compare models but do not objectively indicate whether a model's estimates are statistically significant. The *t*-statistic allows models to be compared and at the same time it indicates whether or not a model's estimate is statistically significant at a particular confidence level, so, *t*-test of the models was carried out to determine statistical significance of the predicted values by the models.

3.1. The Mean Bias Error

$$MBE=\frac{1}{n}\sum_{1}^{n}\left(H_{i,calc}-H_{i,meas}\right) \qquad (7)$$

This test provides information on long-term performance. A low *MBE* value is desired. A negative value gives the average amount of underestimation in the calculated value. So, one drawback of these two mentioned tests is that overestimation of an individual observation will cancel underestimation in a separate observation.

3.2. The Mean Percentage Error

$$MPE(\%)=\frac{1}{n}\sum_{1}^{n}\left(\frac{H_{i,calc}-H_{i,meas}}{H_{i,meas}}\right)*100 \qquad (8)$$

where $H_{i,meas}$, $H_{i,calc}$ and n are, respectively, the i^{th} measured values and i^{th} calculated values of daily solar radiation and the number of values. A percentage error between −10% and +10% is considered acceptable.

3.3. The Root Mean Square Error

$$RMSE=\left[\frac{1}{n}\sum_{1}^{n}\left(H_{i,calc}-H_{i,meas}\right)^2\right]^{\frac{1}{2}} \qquad (9)$$

The value of *RMSE* is always positive, representing zero in the ideal case. The normalized root mean square error gives information on the short term performance of the correlations by allowing a term by term comparison of the actual deviation between the predicted and measured values. The smaller the value, the better is the model's performance.

3.4. The Nash–Sutcliffe Equation

$$NSE=1-\frac{\sum_{1}^{n}\left(H_{i,meas}-H_{i,calc}\right)^2}{\sum_{1}^{n}\left(H_{i,meas}-\overline{H}._{meas}\right)^2} \qquad (10)$$

where $\overline{H}_{meas}$ is the mean measured global radiation. A model is more efficient when *NSE* is closer to 1 (Chen et al., 2004).

3.5. The Coefficient of Correlation

The coefficient of correlation, *r* can be used to determine the linear relationship between the measured and estimated values.

3.6. t-Statistic Test

As defined by Student (Bevington, 1969) in one of the tests for mean values, the random variable *t* with *n*−1 degrees of freedom may be written here as follows:

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2 - (MBE)^2} \right]^{1/2} \qquad (11)$$

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

4 USED DATA, DATA VALIDATION AND METHODOLOGY

The models were tested for Kuala Terengganu site of Malaysia. The geographical co-ordinates of the site are 5^0 $10'$ N latitude 103^0 06' E longitude and 5.2 m altitude. The values of the monthly average daily global radiation on a horizontal surface used in the present study were taken from January 1, 2004 to December 31, 2006 from the recording data station installed at site by Malaysian Meteorology Department (MMD). In addition to this, solar radiation and surface air temperature data from University Malaysia Terengganu Renewable Energy Station from January 1, 2004 to April 30, 2007, which is nearly 2 km northwest to the Kuala Terengganu MMD station. The meteorological data were collected every minute. From this raw data, the mean, maximum and minimum hourly values were calculated. From the hourly data set, daily and monthly statistics were made for the solar radiation and temperature data.

The measured global solar radiation data are checked for errors and inconsistencies. The purpose of data quality control is to eliminate spurious data and inaccurate measurements. In the database, there are missing and invalid measurements in the data and they are identified in the data. The missing and invalid measurements account for approximately 0.5% of the whole database. To complete the data, missing and atypical data are replaced by estimated values.

The monthly mean values of extraterrestrial solar radiation, H_o, and the day length, *N*, were calculated for each month of a year using Equations (3) and (6) and were then employed to estimate *H* for each month of a year. The estimation of monthly mean daily global solar radiation was tried for a large number of data for the above site applying the ten models as outlined above. The values of monthly mean daily global solar radiation intensity estimated at each month. The corresponding measured values were compared with estimated values using the above ten models. The estimated and measured values of the monthly mean daily global solar radiation intensity were analyzed using the statistical tests of *MBE*, *MPE*, *RMSE*, *NSE*, *r* and *t*-test for the months of the year. The results are summarized in Section 5.0. A program was developed using MATLAB to analysis the monthly mean daily global solar estimations. The models were checked with repeated runs and different sequences, as required for the prediction of monthly mean daily global solar radiation.

5 RESULTS AND DISCUSSIONS

In this study, the accuracy among the ten models was determined using the data measured at Kuala Terengganu in the periods between 2004 and 2007. By using the data, the regression constants *a*, *b*, *c* and *d* are given for the eight models 1 to 8 in Table 2. The regression constants *a*, *b*, *c* and *d* were obtained using curve fitting tool of MATLAB. It is evident from Table 2 that the Angstrom-Prescott coefficients *a, b, c* and *d* are subjected to a large variability according to type of model. The values of monthly mean daily global solar radiation intensity estimated using the above 10 models 1 to 10 were compared with the corresponding measured values. The statistical tests of *MBE*, *MPE*, *RMSE*, *NES*, *r* and *t*-test were determined for the entire period; the results are summarizes in Table 3.

Table 2 The regression coefficients for Kuala Terengganu, Malaysia, in the period of 2004–2007

Model type	Models No.	*A*	*B*	*c*	*d*
Linear	1	0.2207	0.5249	-	-
Quadratic	2	0.2299	0.5137	0.01104	-
Cubic	3	0.6410	0.4970	-	-
Linear logarithmic	4	0.2239	0.5098	0.01644	-
Logarithmic	5	0.06013	0.3271	-	-
Linear exponential	6	0.1949	0.4771	0.02994	-
Exponential	7	0.6909	0.5033	-	-

Exponent	8	0.1484	1.091	-1.342	0.9887

Table 3 Validation of the models under different statistical tests

Statistical parameters	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10
MBE	0.0000	0.0000	-0.0001	0.0001	0.0000	0.0000	0.0001	-0.0001	0.0065	0.0661
MPE (%)	-0.0052	-0.0026	-0.0270	0.0141	0.0058	0.0020	0.0132	-0.0180	1.3535	13.7190
RMSE	0.0398	0.0398	0.0397	0.0398	0.0416	0.0398	0.0401	0.0402	0.0420	0.0771
NSE	0.7312	0.7313	0.7326	0.7312	0.7059	0.7313	0.7277	0.7251	0.7000	-0.0096
r	0.8551	0.8551	0.8559	0.8551	0.8402	0.8551	0.8530	0.8516	0.8551	0.8551
t-value	0.0040	0.0020	0.0205	0.0107	0.0042	0.0015	0.0099	0.0134	0.9800	10.3660

According to the statistical test results, it can be seen that the estimated values of monthly mean daily global solar radiation are in favorable agreement with the measured values of monthly mean daily global solar radiation for all the models except model 10 (Table 3), whereas the mean percentage error for the model 10 exceeds ±10% for the location. However, it was found that models 1 to 9 shows the good results. This is due to models 1 to 9 have the lowest values of *MBE*, *MPE*, *RMSE* and *t*-test and highest values of *NES* and *r* compared to the model 10. It was found that, the mean percentage errors , *MPE*, of models 1 to 9 is in the range of acceptable values between −0.027% and +1.3535% with lowest *RMSE* values that range from 0.0397 to 0.0420. Also, the *MBE* values of model 1 to 9 are equal to zero or very close to zero (± 0.0065) while the values of *t*-test range from 0.0015 to 0.9800 ($t_{critical}$ = 2.0227 at 5% confidence level) . The comparison between the different models according to the *t* value shows that the calculated *t* values were less than the critical *t* value other than model 10, this results show that the models 1 to 9 have statistical significance. Also, as seen in Table 3, according to the statistical test of the correlation coefficient (*r*), all the models achieve the good results (above 0.84) for the studied site. This means that the models obtained are reasonably compatible with the measured data. Furthermore, models 1 to 9 has the highest values of *NSE* and closest to 0.7 whereas they range from 0.7000 to 0.7326. These are considered excellent indicators in that the models 1 to 9 gives precise estimation for monthly mean daily global solar radiation at Kuala Terengganu station. Therefore, it has been concluded that models 1 to 9 was recommended for use to estimate monthly mean daily global solar radiation at Kuala Terengganu station. On the other hand, based on statistical test results of *MPE*, *t*-test and *NSE* (Table 3), model 10 is not recommended to be used to estimate monthly mean daily global solar radiation of Kuala Terengganu.

The measured and calculated values of the monthly average daily global radiation using models 1 to 10 for the Kuala Terengganu is illustrated in Figure 1. As can be seen from Figure 1, agreement between the values obtained from models (1 to 9) and the measured data are good for all the months of the year. It is clear that the deviation between the measured and calculated values using model 10 in Figure 1 is very larger than that of others. Therefore, it has been concluded that models 1 to 9 was recommended for use to estimate monthly mean daily global solar radiation at Kuala Terengganu station.

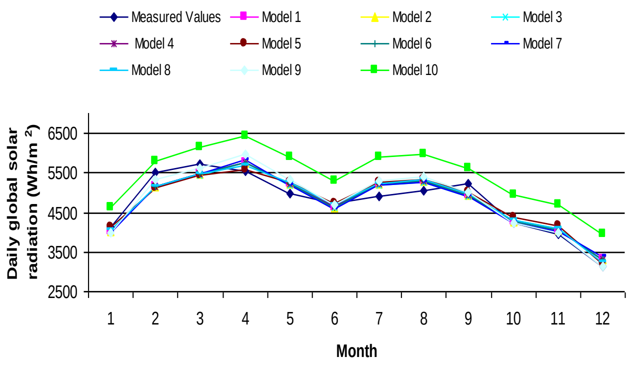

Figure 1 Measured monthly average daily global radiation versus simulated radiation.

It has been shown that the global solar radiation can be related with the relative sunshine duration. The linear model with regression constants *a and b* are 0.2207 and 0.5249 respectively is extremely recommended to estimate monthly average daily global solar radiation for Terengganu state areas based on the statistical results and simplicity. With this new model based on modified Angstrom model, one could accurately (more than 99%) estimate the monthly average daily global solar radiation for Terengganu state.

6 CONCLUSIONS

The objective of this study was to evaluate various models for the estimation of the monthly average daily global radiation on a horizontal surface from bright sunshine hours and to select the most appropriate model for Terengganu state. All available empirical models that can be used to estimate monthly average daily global solar radiation over Terengganu state in Malaysia have been collected from literatures to evaluate the applicability of these models. The collected models were compared on the basis of the statistical error tests such as mean bias error (*MBE*), the mean percentage error (*MPE*), root mean square error (*RMSE*), Nash–Sutcliffe equation (*NSE*), correlation coefficient (*r*) and the *t*-test. According to the results, models 1 to 9, which are based on Angstron and Prescott model showed the good estimation of the monthly average daily global solar radiation on a horizontal surface for Kuala Terengganu. Therefore, based on the statistical results a new simple linear model $H/H_o = 0.2207 + 0.5249\ (n/N)$ based on modified Angstrom model is extremely recommended to estimate monthly average daily global solar radiation for Terengganu state areas and in elsewhere with similar climatic conditions areas where the radiation data is missing or unavailable. The present work will help to advance the state of knowledge of global solar radiation to the point where it has applications in the estimation of daily global solar radiation.

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