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Estimation of global solar irradiation on horizontal and inclined surfaces based on the horizontal measurements

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ABSTRACT

Solar radiation data are essential in the design of solar energy conversion devices. In this regard, empirical models were selected to estimate the global solar radiation on horizontal and inclined surfaces. The hourly solar radiation data measured at the study area during the period of 2004–2007, were used to calculate solar radiations using selected models. The selected models were compared on the basis of statistical methods. Based on the results, a new model, $H/H_o = 0.19490 + 0.4771(n/N) + 0.02994\exp(n/N)$ has been developed, based on Kadir Bakirci linear exponential model. This is highly recommended to estimate monthly mean daily global solar irradiation, on a horizontal surface. Further, a model to convert horizontal solar global radiation to that of radiation on a tilted surface is also presented. It is based upon a relatively simple model proposed by Olmo et al. which requires only measurements of horizontal solar radiation. The developed model appears to give excellent results and has the advantage of being relatively simple for applications. The present work will help to improve the state of knowledge of global solar radiation to the point where it has applications in the estimation of global solar radiation, both on horizontal and inclined surfaces.

1. Introduction

The global solar irradiation on a horizontal surface is the minimum information generally needed as an input parameter for building a solar energy project. The accurate knowledge of the solar radiation intensity at a given location is of importance to the development of solar energy system design. This information is used in the design, cost and effectiveness estimation of a project. Further, monthly mean daily data are needed for the estimation of long-term solar systems performances.

The values of the daily global irradiation measurements are not available at every location due to the cost of measuring equipment, maintenance, and calibration. 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.

Many empirical models have been used to calculate solar radiation, utilizing the available data on meteorological [1,2], geographical and climatological parameters. Among these parameters, sunshine hours [3–6], air temperature [7], latitude [8], longitude [8], altitude [8], precipitation [9], relative humidity [7,10,11], and cloudiness [12] were used. Of these, the most commonly used parameter for estimating global solar irradiation is sunshine hours. In this respect, the modified version of Ångströom equation, among various correlations, has been widely used to estimate the global solar irradiation on horizontal surfaces.

The solar collector orientation is extremely important in solar energy systems. Collectors that track the sun by remaining perpendicular to the sun's rays, intercept more solar radiation than the stationary collectors. But, the tracking system is costly. Stationary solar conversion systems are tilted toward the sun in order to maximize the amount of solar radiation incident on the collector or cell surface. Thus, knowledge of the solar global radiation incident on such a tilted surface is a prerequisite for the design of cost effective systems.

The amount of elevation from the horizontal, the tilt angle, should be equal to the latitude angle of the location of the collector. This orientation is often selected for flat-plate collector installations, since it averages the installation peaks over the year. The surface axis tilted from the horizon by the latitude angle toward the south, is called an

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Nomenclature

MBE	mean bias error
MPE	mean percentage error
NSE	Nash–Sutcliffe equation
RMSE	root mean square error
F_c	a multiplying factor
H	monthly average daily global irradiation (Wh m^{-2}/day)
H_c	monthly average clear sky daily global irradiation for the location (Wh m^{-2}/day)
H_o	monthly average daily extraterrestrial irradiation
I	hourly global radiation on a horizontal surface
I_{sc}	solar constant (=1367 W m^{-2})
I_β	hourly global irradiance on an inclined surface
N	monthly average maximum possible daily sunshine duration (hours)
a, b, c, d	empirical constants
k_t	hourly clearness
n	monthly average daily bright sunshine duration (hours)
n_o	day number of the year starting 1st of January
r	coefficient of correlation
w	hour angle calculated at mid-hour
w_s	mean sunrise hour angle for the given month
α	level of significance
β	surface incline angle
θ	incidence angle (in radians)
θ_z	solar zenith angle (in radians)
δ	sun declination
ρ	albedo of the underlying surface
φ	latitude of the site
Ψ_o	function that converts the horizontal solar global radiation to that incident on a tilted surface

equatorial mounting. This is the ideal way of setting up the collectors. It is also the easiest and cheapest. In this study, the solar radiation was measured on the inclined surface at inclinations equal to the latitude angle.

In most of the solar energy applications, inclined surfaces at different angles are widely employed. The global irradiation on a horizontal surface has been measured in many meteorological stations around the world, but there are only a few stations that measure the solar component on inclined surfaces. There are a number of models available to estimate global irradiation on an inclined surface from the radiation on a horizontal surface, but these models require knowledge of the global irradiation, direct or diffused irradiation or reflected irradiation on a horizontal surface. An inclined surface global irradiation model developed by Olmo et al. [13] requires only the horizontal surface global irradiation, with incidence and solar zenith angles as input parameters.

This paper has two objectives. The first consists in carrying out statistical comparison of specific models for estimating the horizontal monthly mean daily global irradiations and retaining the most accurate model(s). The second objective is to determine the global solar irradiation on tilted surfaces using Olmo et al. model from the global solar irradiations on a horizontal plane.

2. Monthly mean daily global irradiation models

The first correlation proposed for estimating the monthly average daily global irradiation is based on the method of Ångström [14]. The original Ångström-type regression equation-related monthly average daily irradiation to clear day irradiation at a given location and average fraction of possible sunshine hours and is given by:

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

where H is the monthly average daily global irradiation (Wh m^{-2}/day), H_c is the monthly average clear sky daily global irradiation 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 sunshine duration (hours), and a and b are empirical constants. A basic difficulty with Eq. (1) lies in the definition of the terms n/N and H_c. Prescott [15] 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 Ångström'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 Ångström–Prescott equation can be improved for more accurate results, it is used as such for many applications.

2.1. Global radiation on a horizontal surface

By reviewing all available literature related to Malaysia, it has been found that Ångström and Prescott linear model on global radiation can calculate the global radiation on a horizontal surface. Ten models from previous studies have been selected and projected below. The Rietveld [9] model has been proposed for estimating monthly average daily global irradiation (H), based on the latitude of the location, while the other models have been proposed for estimating H based on the monthly average daily sunshine and the monthly average maximum possible daily sunshine durations.

The regression models proposed in literature are given below.

2.1.1. The Ångström–Prescott model [14,15]

The most commonly used model is given by

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

where H is the monthly average daily global irradiation, H_o is the monthly average daily extraterrestrial irradiation, 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 irradiation (H_o) are calculated for days giving average of each month [16,17].

H_o was calculated from the following equation [16,17]:

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

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 [16,17]:

$$\delta = 23.45\sin[360(n_o + 284)/365] \tag{4}$$

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

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

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

2.1.2. Akinoglu and Ecevit model

Akinoglu and Ecevit [6] has given the quadratic type model as follows

$$H/H_o = a + b(n/N) + c(n/N)^2 \quad (7)$$

2.1.3. Samuel model

Samuel [18] examined cubic type model as:

$$H/H_o = a + b(n/N) + c(n/N)^2 + d(n/N)^3 \quad (8)$$

2.1.4. Newland model

Newland [19] has given the linear logarithmic type model as:

$$H/H_o = a + b(n/N) + c\log(n/N) \quad (9)$$

2.1.5. Ampratwum and Dorvlo model

Ampratwum and Dorvlo [20] has reported that the logarithmic type model as:

$$H/H_o = a + b\log(n/N) \quad (10)$$

2.1.6. Kadir Bakirci linear exponential model

Kadir Bakirci [3] obtained the following linear exponential regression equation to estimate the daily global values.

$$H/H_o = a + b(n/N) + c\exp(n/N) \quad (11)$$

2.1.7. Almorox et al. model

Almorox et al. [21] obtained the following exponential regression type model:

$$H/H_o = a + b\exp(n/N) \quad (12)$$

2.1.8. Kadir Bakirci exponent model

Kadir Bakirci [3] has also proposed following exponent equation:

$$H/H_o = a(n/N)^b \quad (13)$$

2.1.9. Rietveld model

Rietveld [9] has used a linear, known constants equation as:

$$H/H_o = 0.18 + 0.62(n/N) \quad (14)$$

2.1.10. Glover and McCulloch model

Glover and McCulloch [22] have used a linear, latitude related equation as:

$$H/H_o = 0.29\cos(\varphi) + 0.52(n/N) \quad (15)$$

2.2. Global irradiation on an inclined surface

The models for determining the solar global irradiation on inclined surfaces can be classified based upon the radiation data input required. They can be classified as non-partitioned (models requiring only solar global irradiation) or partitioned models (solar global irradiation and at least one of its components).

This study has only considered a non-partitioned model to estimate the global solar irradiation on inclined surfaces. Olmo et al. [13] found a good match between the predicted and experimental values obtained from their experimental site and various inclinations. Ruiz et al. [23] tested this model for vertical surfaces and concluded that this model performed poorly for the vertical surfaces.

2.2.1. Olmo et al. model

The Olmo et al. [13] model was developed to estimate the global radiation on inclined surfaces using the data collected on horizontal surfaces. This model depends on the clearness index and avoids the direct and diffused solar radiation components. In the case of no ground reflections, the Olmo et al. model estimates the global irradiance I_β on an inclined surface from the corresponding global radiation I on a horizontal surface by the following equation

$$I_\beta = I\,\psi_o \quad (16)$$

where Ψ_o is a function that converts the horizontal solar global radiation to that incident on a tilted surface and is given as

$$\psi_o = \exp\left[-k_t\left(\theta^2 - \theta_z^2\right)\right] \quad (17)$$

and θ and θ_z (in radians) are the incidence and solar zenith angles, respectively, and k_t is the hourly clearness index.

Solar zenith angle can be calculated by the well-known formula [16]

$$\cos\theta_z = \sin\delta\sin\varphi + \cos\delta\cos\varphi\cos w \quad (18)$$

where, δ is the declination, φ the latitude and w is the hour angle calculated at mid-hour.

The angle of incidence for an arbitrarily inclined surface oriented toward the equator can be calculated by

$$\cos\theta = \sin\delta\sin(\varphi-\beta) + \cos\delta\cos(\varphi-\beta)\cos w \quad (19)$$

where, β is surface inclination angle.

Further, Olmo et al. [13] proposed a multiplying factor F_c, to take into account anisotropic reflections and it is given as

$$F_c = 1 + \rho\sin^2(\theta/2) \quad (20)$$

where ρ is the albedo of the underlying surface. This is the most commonly used expression for the radiation reflected from the ground. In this work, a constant value for the albedo is used equal to 0.25.

The Olmo et al. model for determining the solar global radiation on an inclined surface from that on a horizontal surface is then

$$I_\beta = I\,\psi_o\,F_c \quad (21)$$

3. Comparison techniques

The relative ability of the different models to predict the global radiation on horizontal and tilted surfaces was tested. The performance of the individual models was determined by utilizing statistical methods. There are numerous works in literature which deal with the assessment and comparison of daily solar radiation estimation models. The most popular are the *MBE* (mean bias error) and the *RMSE* (root mean square error). In this study, to evaluate the accuracy of the estimated data, from the models described above, the following statistical estimators were used, *MBE*, *RMSE*, *MPE* (mean percentage error) and the correlation coefficient (r), to test the linear relationship between predicted and measured values. For higher modeling accuracy, these estimators should be closer to zero, and the correlation coefficient, r, should approach to 1. The NSE (Nash–Sutcliffe equation) was 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 the estimates from a model 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, the t-test was carried out on the models to determine the statistical significance of the predicted values.

3.1. The MBE [24]

$$MBE = \frac{1}{n}\sum_{1}^{n}(H_{i,calc} - H_{i,meas}) \tag{22}$$

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

3.2. The MPE [24]

$$MPE(\%) = \frac{1}{n}\sum_{1}^{n}\left(\frac{H_{i,\mathrm{calc}} - H_{i,\mathrm{meas}}}{H_{i,\mathrm{meas}}}\right)*100 \tag{23}$$

The subscript i refer to the ith value of the daily solar irradiation; n is the number of the daily solar irradiation data. The subscripts "calc" and "meas" refer to the calculated and measured daily solar irradiation values, respectively. A percentage error between -10% and $+10\%$ is considered acceptable [24].

3.3. The RMSE [22]

$$RMSE = \left[\frac{1}{n}\sum_{1}^{n}(H_{i,\mathrm{calc}} - H_{i,\mathrm{meas}})^2\right]^{\frac{1}{2}} \tag{24}$$

The value of $RMSE$ is always positive, representing zero in the ideal case. The normalized $RMSE$ 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 the model's performance is.

3.4. The NSE [25]

$$NSE = 1 - \frac{\sum_1^n (H_{i,\mathrm{meas}} - H_{i,\mathrm{calc}})^2}{\sum_1^n (H_{i,\mathrm{meas}} - \overline{H}\cdot_{\mathrm{meas}})^2} \tag{25}$$

where $\overline{H}\cdot_{\mathrm{meas}}$ is the mean measured global radiation. The NSE represents a measure of the precision of the model results. A model is more efficient when NSE is closer to 1 [25].

3.5. The correlation coefficient [1]

The correlation coefficient, r can be used to determine the linearity relationship between the measured and estimated values, which can be calculated from the following equation:

$$r = \left[\frac{SS_{\mathrm{cm}}}{\sqrt{S_{\mathrm{c}}}\sqrt{S_{\mathrm{m}}}}\right]^{\frac{1}{2}} \tag{26}$$

where SS_{cm}, S_{c} and S_{m} are defined as follows:

$$SS_{\mathrm{cm}} = \sum(H_{\mathrm{meas}} - H_{a,\mathrm{meas}})(H_{\mathrm{calc}} - H_{a,\mathrm{calc}}) \tag{27}$$

$$S_{\mathrm{c}} = \sum_{1}^{n}(H_{a,\mathrm{calc}} - H_{\mathrm{calc}})^2 \tag{28}$$

$$S_{\mathrm{m}} = \sum_{1}^{n}(H_{a,\mathrm{meas}} - H_{\mathrm{meas}})^2 \tag{29}$$

where $H_{a,\mathrm{meas}}$ is the average of the whole measured values, $H_{a,\mathrm{calc}}$ is the average of the whole calculated values and are given by

$$H_{a,\mathrm{meas}} = \frac{1}{n}\sum_{1}^{n}H_{\mathrm{meas}} \tag{30}$$

$$H_{a,\mathrm{calc}} = \frac{1}{n}\sum_{1}^{n}H_{\mathrm{calc}} \tag{31}$$

3.6. t-Test statistic [16]

The tests for mean values, the random variable t with $n-1$ degrees of freedom may be written here as follows:

$$t = \frac{\frac{1}{n}\sum_1^n d_{\mathrm{i}}}{S/n^{\frac{1}{2}}} \tag{32}$$

where S is the standard deviation of the differences d_{i}, between calculated and measured values, while S is given by:

$$S^2 = \frac{1}{n-1}\left[\sum_{1}^{n}d_{\mathrm{i}}^2 - \left(\frac{\sum_1^n d_{\mathrm{i}}}{n}\right)^2\right] \tag{33}$$

Using Eqs. (22) and (24) in Eq. (33), we have:

$$S^2 = \frac{n\left[(RMSE)^2 - (MBE)^2\right]}{n-1} \tag{34}$$

Substituting for S in Eq. (32) gives:

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2 - (MBE)^2}\right]^{1/2} \tag{35}$$

The smaller the value of t the better the performance is. To determine whether the estimates from a model 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 $(1-\alpha)$ confidence level, the calculated t value must be less than the critical value ($t_{\mathrm{critical}} = 2.0227$ at 95% confidence level).

4. Used data, data validation and methodology

The global radiation on a horizontal surface and a south facing surface, tilted at latitude angle were measured. The geographical co-ordinates of the site are 5° 10' N, 103° 06' E and 5.2 m altitude. The values of the monthly average daily global irradiation on a horizontal surface used in the present study were taken in the period January 1, 2004 to December 31, 2006 from the recording data station installed at the site by the MMD (Malaysian Meteorology Department). In addition to this, solar radiation and surface air temperature data were used from Renewable Energy Station, University Malaysia Terengganu from January 1, 2004 to April 30, 2007. This location is nearly 2 km northwest to the Terengganu MMD station. The meteorological data were collected every minute. From this raw data, the hourly values were calculated.

The measured global solar radiation data were checked for errors and inconsistencies. The purpose of data quality control was to eliminate faulty data and inaccurate measurements. In the database, there are missing and invalid measurements (missing dates, time and values) and they are identified. The missing and invalid measurements account for approximately 0.5% of the whole database. To complete the data, these missing and invalid measurements were replaced with those estimated by interpolation between preceding and subsequent hours of the day.

The monthly mean values of the extraterrestrial solar irradiation and the day length were calculated for each month of a year and were then employed to estimate monthly average daily global irradiation for each month of a year. The estimation of monthly mean daily global solar irradiation on a horizontal surface was tried for a large number of data, for the above site applying all models outlined above. The values of monthly mean daily global solar irradiation intensity were estimated for each month. The corresponding measured values were compared with estimated values using all models. The estimated and measured values of the monthly mean daily global solar irradiation intensity were analyzed using the statistical tests for all months of the year.

The estimation of hourly global solar irradiation on an inclined surface was tried for the Terengganu site applying the Olmo et al. model as outlined above. The value of hourly global solar irradiation intensity was estimated for each hour. The corresponding measured values were compared with estimated values using the Olmo et al. model. The ability of the Olmo et al. model to predict the solar global irradiation on an inclined surface was determined by comparing the calculated values to the measured values. The results were compared using the statistical indicators presented in Section 3.

Table 1
The regression coefficients for Kuala Terengganu, Malaysia, in the period of 2004–2007.

Models	*a*	*b*	*c*	*d*
Ångström and Prescott [14,15]	0.2207	0.5249	–	–
Akinoglu and Ecevit [6]	0.2299	0.5137	0.01104	–
Samuel [18]	0.6410	0.4970	–	–
Newland [19]	0.2239	0.5098	0.01644	–
Ampratwum and Dorvlo [20]	0.06013	0.3271	–	–
Kadir Bakirci linear exponential [3]	0.19490	0.4771	0.02994	–
Almorox et al. [21]	0.69090	0.5033	–	–
Kadir Bakirci exponent [3]	0.14840	1.0910	−1.34200	0.9887

Computer programs have been developed to examine data in the database and to calculate solar radiation on horizontal and inclined surfaces. The programs are prepared using the MATLAB software because of its mathematical capabilities. Eqs. (2)–(15) and (16)–(21) are used to calculate the monthly mean daily global solar irradiation on a horizontal surface and hourly global solar irradiation on an inclined surface, respectively. The models were checked with repeated runs with different sequences, as required for the prediction of global solar radiation on horizontal and inclined surfaces.

5. Results and discussions

5.1. Global radiation on a horizontal surface

By using the data measured at Terengganu during the study period, the regression coefficients *a*, *b*, *c* and *d* are given for the first eight models in Table 1. It is evident from Table 1 that the Ångström–Prescott coefficients *a* and *b* are subjected to a very large variability. In the developed models, the values of the coefficient *a* varies from 0.060 to 0.691, while the coefficient *b* varies from 0.327 to 1.091.

As can be seen from Table 2, agreement between the values obtained from models other than Glover and McCulloch model and the measured values are good. It is clear that the deviation between the measured and calculated values using Glover and McCulloch model in Table 2 is quite large than that of others.

The values of the monthly mean daily global solar irradiation estimated using all ten models were compared with the corresponding

Table 2
The comparison between Measured values and Estimated values Monthly average daily global irradiation (Wh/m^2) for 10 Models.

Month	Measured	Models									
		Ångström and Prescott [14,15]	Akinoglu and Ecevit [6]	Samuel [18]	Newland [19]	Ampratwum and Dorvlo [20]	Kadir Bakirci linear exponential [3]	Almorox et al. [21]	Kadir Bakirci exponent [3]	Rietveld [9]	Glover and McCulloch [22]
January	4144.2	4008.7	4008.6	4000.3	4009.5	4021.1	4008.7	4008.0	4007.9	3996.7	4617.1
February	5515.4	5170.0	5171.5	5171.2	5170.0	5105.7	5172.2	5188.3	5146.5	5328.5	5802.5
March	5721.4	5474.8	5474.7	5450.7	5475.7	5452.3	5474.6	5466.4	5473.4	5627.3	6158.0
April	5536.9	5760.1	5764.6	5785.1	5758.0	5589.0	5766.9	5826.5	5687.0	5986.4	6421.2
May	4980.3	5229.8	5228.8	5215.4	5231.5	5254.7	5228.4	5209.8	5247.3	5340.4	5913.1
June	4736.8	4642.5	4640.1	4637.1	4645.3	4730.7	4639.2	4604.6	4686.1	4696.2	5287.9
July	4900.9	5214.2	5213.0	5200.9	5216.1	5248.6	5212.5	5191.8	5235.4	5316.2	5902.6
August	5053.1	5295.2	5293.5	5271.9	5297.2	5334.4	5292.8	5264.6	5321.1	5407.5	5986.6
September	5239.3	4938.1	4936.3	4927.0	4940.4	4997.8	4935.6	4907.8	4969.9	5017.1	5605.4
October	4226.1	4266.0	4264.4	4299.0	4269.1	4386.5	4264.2	4246.3	4309.8	4219.7	4942.7
November	3962.7	4055.0	4053.6	4087.0	4057.7	4163.3	4053.6	4040.5	4092.4	4004.1	4704.2
December	3141.8	3314.4	3319.0	3309.2	3311.2	3181.1	3321.3	3393.4	3223.9	3155.2	3947.9

Table 3
Statistics for the validation of the selected models.

Statistical estimator	Models									
	Ångström and Prescott [14,15]	Akinoglu and Ecevit [6]	Samuel [18]	Newland [19]	Ampratwum and Dorvlo [20]	Kadir Bakirci linear exponential [3]	Almorox et al. [21]	Kadir Bakirci exponent [3]	Rietveld [9]	Glover and McCulloch [22]
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

measured values. The statistical tests of *MBE*, *MPE*, *RMSE*, *NSE*, *r* and *t*-test were determined for the entire period; the results are summarized in Table 3. From the statistical results, it can be seen that the estimated values of monthly mean daily global solar irradiation are in good agreement with the measured values for all models except Glover and McCulloch model, whereas the *MPE* for the Glover and McCulloch model exceeds ±10% for the location. It was found that the mean percentage errors of all the models other than Glover and McCulloch model is in the range of acceptable values between −0.03% and +1.36%, with lowest *RMSE* values ranging from 0.034 to 0.042. Also, the *MBE* values of all the models other than Glover and McCulloch model are equal to zero or very close to zero while the values of *t*-test range from 0.002 to 0.980. The comparison between the different models according to the *t* value shows that the calculated *t* values were less than the critical *t* value (2.023 at 5% confidence level) except the Glover and McCulloch model. The results show that all models other than Glover and McCulloch model have statistical significance. According to the correlation coefficient, Ångström and Prescott, Akinoglu and Ecevit, Samuel, Newland and Kadir Bakirci models give values more than 0.85. Furthermore, the same models have the *NSE* values more than 0.73 (Table 3). These are considered excellent indicators since these five models give precise estimation for monthly mean daily global solar irradiation at the study area. According to *t*-test, the Kadir Bakirci model has the lowest value at 0.0015. Therefore, it has been concluded that the Kadir Bakirci linear exponential model is recommended for use to estimate the monthly mean daily global solar irradiation at Terengganu.

5.2. Global irradiation on an inclined surface

The Olmo et al. model was applied to the database corresponding to the horizontal solar global irradiation to determine values for a south facing surface, tilted at latitude angle for all sky conditions. In this analysis, all measured data with a solar altitude lower than 10° were not considered in accordance with Olmo et al. study [13]. The hourly solar irradiation data have been used in this study and the statistical coefficients have been computed on the basis of the experimental data. The results of the statistical analysis of the relative ability of the Olmo et al. model to determine the solar global irradiation on the inclined surface are presented in Table 4.

Table 4
Statistical results for Olmo et al. [13] model.

Month	*r*	*MPE* (%)	*RMSE* (%)
January	0.931	6.9	32.2
February	0.985	1.2	23.7
March	0.988	−1.1	18.5
April	0.986	1.3	20.6
May	0.988	−2.4	24.1
June	0.973	4.2	12.6
July	0.976	5.2	13.4
August	0.982	3.9	16.7
September	0.968	2.3	10.5
October	0.983	1.4	12.8
November	0.976	−5.7	20.2
December	0.925	−6.5	36.4
Whole data	0.973	0.90	20.14

It is evident from Table 4 that a correlation coefficient is subjected to a very small variation, from 0.925 to 0.988. The model has the correlation coefficient value of 0.973 for the whole data. It was found that, the *MPE* is in the range of between −6.5% and +6.90% with lowest *RMSE* values, less than 25.00% except January and December. Normally, these two months are subject to heavy rainfall and less solar radiation. The high values of *MPE* and *RMSE* and low value of correlation coefficient for these months can be justified. The model provides a good estimation tool for the other months. In general, considering the statistics as a whole, the global solar radiation data estimated by Olmo et al. model are in good agreement with the measured values. Therefore, Olmo et al. model is recommended to estimate the global solar radiation on an inclined surface, due to its accuracy, input requirements and simplicity.

6. Conclusions

The first objective of this study was to evaluate various models for the estimation of the monthly average daily global irradiation on a horizontal surface from bright sunshine hours and to select the most appropriate model for the state of Terengganu. All available empirical models that can be used to estimate monthly average daily global solar irradiation have been collected from literature to evaluate their applicability. The collected models were compared on the basis of the statistical error tests such as *MBE*, the *MPE*, *RMSE*, *NSE*, correlation coefficient (*r*) and the *t*-test. According to the results, except the Glover and McCulloch model, all other models, which are based on Ångström and Prescott model showed good estimation of the monthly average daily global solar irradiation on a horizontal surface for Terengganu. Therefore, based on the statistical results, considering that it has been used to estimate monthly average daily solar irradiation for other cities in Malaysia, the Kadir Bakirci linear exponential model is highly recommended to estimate monthly average daily global solar irradiation for state of Terengganu and elsewhere with similar climatic conditions, where the radiation data are missing or unavailable. The recommended linear exponential model is given as $H/H_o = 0.1949 + 0.4771(n/N) + 0.02994\exp(n/N)$.

The Olmo et al. model is a relatively simple model to convert solar global radiation on horizontal surfaces to that incident on inclined surfaces. This model requires only the solar global radiation on a horizontal surface, incidence and solar zenith angles as input parameters. Therefore, Olmo et al. model is recommended to estimate the global solar radiation on an inclined surface due to its accuracy, input requirements and simplicity.

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