HOURLY GLOBAL SOLAR RADIATION FOR KUALA TERENGGANU OF MALAYSIA

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ABSTRACT - In this paper, six selected empirical models were used to estimate the hourly global solar radiation from the daily global radiation in Kuala Terengganu on the east coast of Malaysia. The purpose is to determine the most accurate models to be used for estimating the hourly global solar radiation. The measured hourly global solar radiation data used for the validation of selected models were obtained from the Malaysian Meteorology Department and University Malaysia Terengganu Renewable Energy Station for the period of 2004–2008. In order to indicate the performance of the models, the statistical test methods of the normalized mean bias error, normalized root mean square error, correlation coefficient and *t*- statistical test were used. The hourly global solar radiation values were calculated by using six models and the results were compared with corresponding measured data. All the models fit the data adequately and can be used to estimate the hourly global solar radiation. This study finds that the Collares-Pereira and Rabl model performed better than other models. Therefore the Collares-Pereira and Rabl model is recommended to estimate the hourly global radiations for Kuala Terengganu and elsewhere with similar climatic conditions.

Keywords: Hourly global solar radiation; Hourly solar radiation models; Statistical tests, Terengganu

1.0. INTRODUCTION

A reasonably accurate knowledge of the availability of the solar radiation and its components at any place is required for solar system design. The average values of the hourly, daily and monthly global irradiations on a horizontal surface are needed in many applications of solar energy designs [1]-[9].

The annual average daily solar irradiation for Malaysia has a magnitude more than of 4200 kWhm^{-2}, and the sunshine duration is more than 6 hours per day [10].Unfortunately, for many developing countries like Malaysia, solar radiation measurements are not easily available due to the high equipment cost and maintenance and calibration requirements of the measuring equipment. An alternative solution to this problem is to estimate solar radiation by using a modeling approach. The prediction of the hourly global solar radiation, I_t, for any day, was the target of many attempts [11]-[24].

The average hourly global solar radiation values would be useful in problems such as effective and reliable sizing of the solar power systems and management of solar energy sources in relation to the power loads to be met. Modeling of solar radiation also provides an understanding of dynamics of solar radiation and it is clearly of great value in the design of solar energy conversion systems.

This paper aim to select a model which, reasonably predicts the hourly global radiation for Kuala Terengganu. For this work the following models were considered: the Jain model [20],[21], the Baig et al. model [15], new approaches to Jain's and Baig's models [24], the S. Kaplanis model [23],[24] and Collares-Pereira and Rabl model [16].

2.0. THE MODELS

2.1. The Jain model

Jain [20],[21] has proposed a Gaussian function to fit the recorded data and he established the following relation for global irradiation:

$$r_t = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(t-12)^2}{2\sigma^2}\right] \qquad (1)$$

where r_t is the ratio of hourly to daily global radiation, t is the true solar time in hours, and σ is defined by

$$\sigma = \frac{1}{r_{t(t=12)}\sqrt{2\pi}} \qquad (2)$$

where r_t (t = 12) is the hourly ratio of the global irradiation at mid-day true solar time.

From the hourly data, taking $I(t=12)$ and daily data, H_n, may determine σ from equation (2). Then, from equation (1), r_t values are obtained to provide:

$$I_t = r_t . H_n \quad (3)$$

2.2. The Baig et al. model

The Baig et al. model is based on Jain's model [15]. Baig et al. modified the Jain's model to better fit the recorded data during the start and the end periods of a day.

In this model, r_t is estimated by:

$$r_t = \frac{1}{2\sigma\sqrt{2\pi}}\left\{\exp\left[-\frac{(t-12)^2}{2\sigma^2}\right]+\cos\left[180\frac{(t-12)}{(s_{o-1})}\right]\right\} \quad (4)$$

S_o is the day length of the day n, at a site and defined by

$$S_o = \frac{2}{15}\cos^{-1}(-\tan(\varphi)\tan(\delta)) \quad (5)$$

were φ and δ are the latitude of the considered site and the solar declination , respectively. The declination angle is defined by

$$\delta = 23.45\sin[360(n+284)/365] \quad (6)$$

2.3. The new approach to Jain's and Baig's models

This work proceeded to a different approach to determine σ without using the values of $I(h=12)$, which was proposed by S Kaplanis [24].

1st approach: the day length, S_o, of the day n, as determined from equation (5), is set equal to the time distance between the points, where the tangents at the two turning points of the hypothetical Gaussian, which fits the hourly I_t data, intersect the hour, t, axis. These two points are at $\pm 2\sigma$ distance from the axis origin. Then, σ is interrelated directly with S_o, as

$$S_o = 4\sigma \quad (7)$$

2nd approach: If one draws the tangent at the two points which correspond to the full width at half-maximum (FWHM), of a Gaussian curve it can be easily determined that the tangent at each point intersects the horizontal axis, i.e. the hour, t, axis at points $\pm 2.027\sigma$, instead of $\pm 2\sigma$ as in first version. Hence, in this case;

$$S_o = 4.054\ \sigma \qquad \text{or} \qquad \sigma = 0.246\ S_o \quad (8)$$

In this new approach, the determination of σ, by either way does not require any recorded data.

2.4. The S. Kaplanis model

In this model a and b are parameters have to be determined for any site and for any day, n. Their determination is as follows:

Let, $$I = a + b.\cos\left(2\pi.t/24\right) \quad (9)$$

Integrating equation (9) over t, from sunrise, t_{sr}, to sunset, t_{ss}, obtains:

$$\int_{t_{sr}}^{t_{ss}} Idt = H = 2a(t_{sr}-12)+\frac{24b}{\pi}\sin\left(\frac{2\pi.t_{ss}}{24}\right) \quad (10)$$

A boundary condition provides a relationship between a and b. That is at $t = t_{ss}$, $I = 0$. Hence, from (9) gets:

$$a + b\cos(2\pi\ t_{ss}/24) = 0 \quad (11)$$

Equations (10) and (11) provide the value of a and b by using H values which are taken from recorded data.

2.5. Collares-Pereira and Rabl model

Collares-Pereira and Rabl [16] proposed a semi empirical expression for r_t

$$r_t = \frac{\pi}{24}(x+y\cos w)\frac{\cos w - \cos w_s}{\sin w_s - (2\pi.w_s/360)\cos w_s} \quad (12)$$

yields the coefficients given by

$$x = 0.409 + 0.5016\sin(w_s - 60) \quad (13)$$

$$y = 0.6609 - 0.4767\sin(w_s - 60) \quad (14)$$

where w is hour angle in degrees for the considered hour and w_s is the sunset hour angle in degrees calculated by

$$w_s = \cos^{-1}(-\tan(\varphi)\tan(\delta)) \quad (15)$$

where φ is the latitude of the considered site and δ is the solar declination angle calculated for the representative day of the month.

3.0. METHOD OF STATISTICAL COMPARISON

There are numerous works in literature which deal with the assessment and comparison of hourly solar radiation estimation models [25]-[33]. The most popular statistical parameters are the normalized mean bias error (*NMBE)* and the normalized root mean square error (*NRMSE*). In this study, to evaluate the accuracy of the estimated data, from the models described above, the following statistical tests, *NMBE*, *NRMSE* and coefficient of correlation (r), to test the linear relationship between predicted and measured values are used. For better data modeling, these statistics should be closer to zero, but coefficient of correlation should approach to one as closely as possible. In addition, t-test of the models was carried out to determine statistical significance of the predicted values by the models.

3.1. The normalized mean bias error

$$MBE = \frac{1}{n}\sum_{1}^{n}\left(I_{i,calc} - I_{i,meas}\right) \quad (16)$$

$$NMBE(\%) = \frac{MBE}{\frac{1}{n}\sum_{1}^{n} I_{i,meas}} * 100 \quad (17)$$

This test provides information on long-term performance. A low *NMBE* 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 normalized root mean square error

$$RMSE = \left[\frac{1}{n}\sum_{1}^{n}\left(I_{i,calc} - I_{i,meas}\right)^2\right]^{\frac{1}{2}} \quad (18)$$

$$NRMSE(\%) = \frac{RMSE}{\frac{1}{n}\sum_{1}^{n} I_{i,meas}} * 100 \quad (19)$$

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.

3.3 The coefficient of correlation

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

$$r = \left[\frac{SS_{cm}}{\sqrt{S_c}\sqrt{S_m}}\right]^{\frac{1}{2}} \quad (20)$$

where SS_{cm}, S_c and S_m are defined as follows

$$SS_{cm} = \sum\left(I_{meas} - I_{a,meas}\right)\left(I_{calc} - I_{a,calc}\right) \quad (21)$$

$$S_c = \sum_{1}^{n}\left(I_{a,calc} - I_{calc}\right)^2 \quad (22)$$

$$S_m = \sum_{1}^{n}\left(I_{a,meas} - I_{meas}\right)^2 \quad (23)$$

where $I_{a,meas}$ is the average of the measured values, $I_{a,calc}$ is the average of the calculated values and are given by

$$I_{a,meas} = \frac{1}{n}\sum_{1}^{n} I_{meas} \quad (24)$$

$$I_{a,calc} = \frac{1}{n}\sum_{1}^{n} I_{calc} \quad (25)$$

3.4. t-statistic test

As defined by Student in one of the tests for mean values, the random variable t with $n-1$ degrees of freedom may be written here as follows:

$$t = \frac{\frac{1}{n}\sum_{1}^{n} d_i}{S / n^{1/2}} \quad (26)$$

where S is the standard deviation of the differences d_i, between calculated and measured values, and is given by:

$$S^2 = \frac{1}{n-1}\left[\sum_{1}^{n} d_i^2 - \left(\frac{\sum_{1}^{n} d_i}{n}\right)^2\right] \quad (27)$$

Using equations (16) and (18) in the equation (27), we have:

$$S^2 = \frac{n\left[(RMSE)^2 - (MBE)^2\right]}{n-1} \quad (28)$$

Substituting for S in equation (26) gives:

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2 - (MBE)^2}\right]^{1/2} \quad (29)$$

The smaller the value of 't' the better is the performance. In order 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 $(1-\alpha)$ confidence level, the calculated t value must be less than the critical value.

4.0. USED DATA AND METHODOLOGY

The models were tested for Kuala Terengganu. The geographical co-ordinates of the site are 5^0 10' N latitude, 103^0 06' E longitude and 5.2m altitude. The used hourly global irradiation data from January 1, 2004 to December 31, 2008 were obtained from the recording data station installed at the site by Malaysian Meteorology Department and data was verified with data obtained from University Malaysia Terengganu Renewable Energy Station which is nearly 2 km northwest of the Kuala Terengganu station.

The measured global solar radiation data were checked for errors and inconsistencies. The purpose of data quality control is to eliminate spurious data and inaccurate measurements. In the database missing and invalid measurements were identified. To complete the data, missing and atypical data were replaced with estimated values.

The hourly global solar radiation estimation was tried for a large number of data for the above sites applying the six models as outlined above. The values of hourly global solar radiation intensity estimated at every average day of the month or the nearest clear day of each month. The corresponding measured values were compared with estimated values using the six models at the station. The estimated and measured values of the hourly global solar radiation intensity were analyzed using the statistical tests of *NMBE*, *NRMSE*, r and t-test for the representative days of 12 months of the year. The results are given in Section 5.0.

A program was developed using MATLAB to provide and plot the hourly global solar estimations. The models were checked with repeated runs and different sequences, as required for the prediction of hourly global solar radiation.

5.0. RESULTS AND DISCUSSION

The recorded and estimated values from the six models of hourly global radiations for the representative day of the months are presented in Figure 1 for Kuala Terengganu.

During solar noon for the site investigated, Jain Model and Baig et al. model gave the same values as measured, because, these models are based on solar noon measured values. The Jain model and Baig et al. model estimate of hourly solar radiation show the symmetry around solar noon, as imposed by the Gaussian fitting function. This model seems to provide a very reliable performance, close to solar noon, which is due to the solar noon recorded values required by this model. The rest of the day estimates of hourly solar radiation vary within the standard deviation.

The Jain model estimated values were almost always less than the measured values for the main part of the day. The mismatch was much wider during early hours and late hours of the daytime as the Gaussian function becomes zero at infinity time whereas practically there is no radiation before sunrise and after sunset.

An underestimation of about 10% for the worst cases, was predicted by Kaplanis model, in January, October and December at solar noon. While for the rest of the day, the hourly solar radiation estimates are close to measured values. Collares-Pereira and Rabl model gives an overestimation of about 8-10%, for the worst cases, which are in May and September at solar noon; while for the rest of the day, hourly solar radiation estimates are close to measured values. A new approach to Jain's and Baig's models 1st approach and 2nd approach give the same estimates, because both models are based on the theoretical σ values, which is almost the same value for both cases (σ = 0.25, if the first approach and σ = 0.246, for the second approach). The new approaches to Jain's and Baig's models (1st approach and 2nd approach) give an overestimation of about 5-8%, for the worst cases, which are in January and February and underestimation of about 5%, for the worst cases, which are in July and December at solar noon. While for the rest of the day hourly solar radiation estimates are close to recorded values.

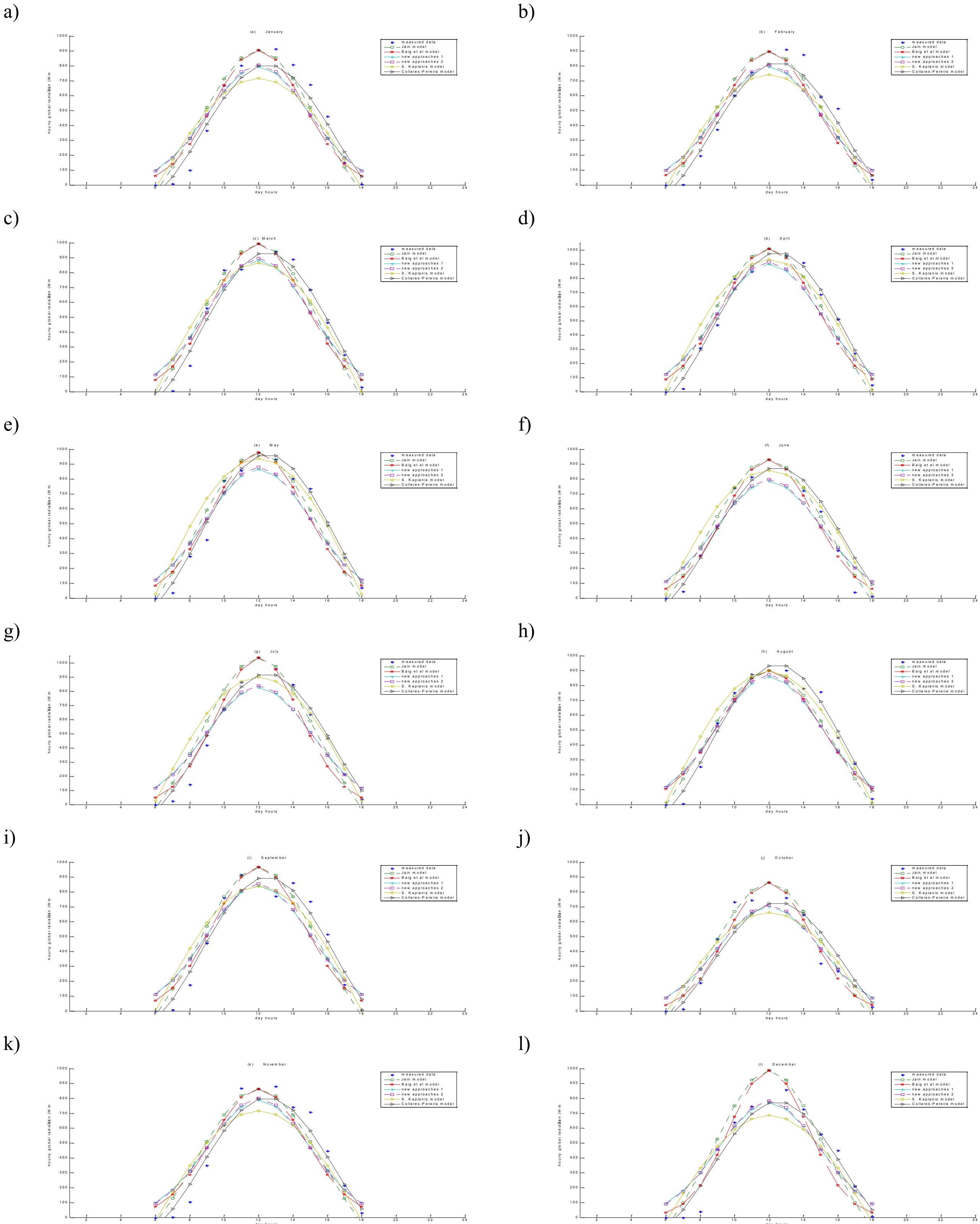

Figure 1 A comparison between recorded hourly global radiations and estimated values from the six models for the representative day of the months (January to December) for Kuala Terengganu.

Table 1 Statistical parameters of hourly global radiation models for the representative days of the months for Kuala Terengganu

Model	Statistical Indicators	January	February	March	April	May	June	July	August	September	October	November	December
Jain	*NMBE* (%)	-1.14	-1.28	-1.40	-1.57	-1.58	-1.13	-0.72	-2.43	-1.26	-0.67	-1.52	-0.43
	NRMSE (%)	25.31	25.13	20.68	18.96	19.96	16.77	20.44	20.88	24.57	15.51	26.42	25.34
	‘*t*’	0.16	0.18	0.24	0.29	0.28	0.23	0.12	0.41	0.18	0.15	0.20	0.06
	‘*r*’	0.95	0.94	0.96	0.96	0.96	0.98	0.96	0.96	0.94	0.98	0.94	0.95
Baig et al.	*NMBE* (%)	-0.09	-0.34	-0.25	-0.31	0.36	3.25	6.66	-3.97	0.85	4.62	-2.22	6.42
	NRMSE (%)	23.90	23.99	18.52	17.12	19.03	15.34	22.03	17.71	22.06	17.96	25.48	26.78
	‘*t*’	0.01	0.05	0.05	0.06	0.07	0.75	1.10	0.80	0.13	0.92	0.30	0.86
	‘*r*’	0.95	0.95	0.97	0.97	0.96	0.98	0.96	0.97	0.95	0.98	0.94	0.95
New Approach I	*NMBE* (%)	-2.67	-2.78	-2.93	-3.11	-3.26	-3.29	-3.28	-3.14	-2.99	-2.82	-2.69	-2.63
	NRMSE (%)	30.60	29.04	24.71	22.19	23.43	28.31	28.81	22.60	28.37	26.04	29.98	30.58
	‘*t*’	0.30	0.33	0.41	0.49	0.49	0.41	0.40	0.49	0.37	0.38	0.31	0.30
	‘*r*’	0.95	0.95	0.97	0.97	0.96	0.99	0.96	0.96	0.95	0.98	0.94	0.95
New Approach II	*NMBE* (%)	-2.43	-2.53	-2.68	-2.84	-2.99	-3.01	-3.01	-2.87	-2.73	-2.57	-2.45	-2.39
	NRMSE (%)	29.71	28.26	23.87	21.41	22.66	27.03	27.75	21.90	27.60	24.81	29.19	29.64
	‘*t*’	0.28	0.31	0.39	0.46	0.46	0.39	0.38	0.46	0.34	0.36	0.29	0.28
	‘*r*’	0.95	0.95	0.96	0.97	0.96	0.99	0.96	0.96	0.95	0.98	0.94	0.95
Kaplanis	*NMBE* (%)	-9.05	-5.80	-1.08	4.53	9.50	10.51	10.30	5.41	0.54	-4.70	-8.43	-10.35
	NRMSE (%)	32.90	29.55	22.83	19.88	23.19	25.99	28.56	19.37	25.57	28.21	32.25	34.41
	‘*t*’	0.99	0.69	0.16	0.81	1.55	1.53	1.34	1.01	0.07	0.59	0.94	1.09
	‘*r*’	0.94	0.93	0.96	0.96	0.95	0.96	0.94	0.96	0.95	0.95	0.93	0.93
Collares-Pereira and Rabl	*NMBE* (%)	-6.05	-4.33	-1.93	0.79	3.07	3.53	3.44	1.20	-1.13	-3.76	-5.72	-6.76
	NRMSE (%)	18.28	15.54	12.65	8.22	10.33	22.25	14.16	10.23	16.24	26.49	17.35	21.33
	‘*t*’	1.22	1.01	0.53	0.33	1.08	0.56	0.87	0.41	0.24	0.50	1.21	1.16
	‘*r*’	0.99	0.99	0.99	0.99	0.99	0.96	0.99	0.99	0.98	0.94	0.98	0.98

To make a comparison between the models, the estimated and measured values were compared for each representative day of the months. The statistical summary of the performance of the combination of the different test indicators discussed previously in Section 3.0 as normalized mean bias error, normalized root mean square error, *t*-test and correlation coefficient are presented in Table 1 for the hourly global irradiations at Kuala Terengganu. In most months, the estimates on solar hourly radiation obtained by the models are close to the measured values. Their differences between the measured and estimated values were $\pm$ 17.20% at the maximum.

For the hourly global irradiation, the results presented in Table 1 show that the Collares-Pereira and Rabl model generally leads to the best results. For the considered site, the normalized root mean square error values obtained using this model were 8-15% in general. This model appears to perform well at the considered site. The Jain model, the Baig et al. model, new approaches to Jain's and Baig's models (1st approach and 2nd approach) and the Kaplanis model resulted in largest normalized root mean square error with values of more than 30% in general.

In addition, the low normalized mean bias error values are particularly remarkable. The normalized mean bias error values show that the Collares-Pereira and Rabl model generally yields the best results. The negative normalized mean bias error values presented in Table 1 show that there is an underestimation during the period from January to March and September to December and overestimated during April to August by the Collares-Pereira and Rabl model. Jain Model, Baig et al., and Kaplanis models present normalized mean bias error values higher than that obtained by Collares-Pereira and Rabl model. The new approach to Jain's and Baig's models yield smaller negative normalized mean bias error values. This indicates that there is an underestimation during the entire period of the year, even though the normalized root mean square error values are very high for these models.

From the table, Collares-Pereira and Rabl model's average coefficient of correlation, r, is 0.97, indicating that the Collares-Pereira and Rabl model accounts well for the variability in the hourly global radiation. The average r, of other models is around 0.91. It is clear that the deviation between the measured and estimated values of these five models is larger than that of Collares-Pereira and Rabl model. However, all six models may be accepted if ones considered only the coefficient of correlation between the measured and estimated values.

The *t*-test for the models was carried out to determine statistical significance of the estimated values of the models. The models having the lower t value than t critical value are statistically acceptable models. From the standard statistical tables, the critical *t* value is 2.1788 at 95% confidence level and 12 degrees of freedom. According to the *t*-tests given in Table 1, the models evaluations are good for the site. In particular the Jain Model and the new approaches to Jain's and Baig's models give the best results for the site. It can be seen that the estimated values of hourly global solar radiation at the site are in favorable agreement with the measured values hourly global solar radiation for all the months of the year. It was found that the Collares-Pereira and Rabl model shows the best results among the all models for the site. from this study, the Collares-Pereira and Rabl model is recommended for use to estimate the hourly global solar radiation at the study area.

6.0. CONCLUSIONS

First, we can affirm that for any given site, the direct use of a model suggested in the literature can lead to erroneous values, and consequently can influence the dimensioning of the solar energy conversion systems considerably. However, the choice of the models strongly depends on the climatic characteristics of the considered site compared to those on which its application is being considered. This was observed from results obtained by selected models in this study.

The empirical models used to estimate the hourly global irradiation have been chosen from literatures to evaluate the applicability of these models over the site in Terengganu state. The models were compared based on the normalized mean bias error, normalized root mean square error, coefficient of correlation and *t*-test. According to the results, the Collares-Pereira and Rabl model is the most accurate in general to estimate the daily global radiations for the site. Furthermore, if only the daily global irradiation is available, one can calculate the hourly global radiations on a horizontal surface using these models with a good accuracy.

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