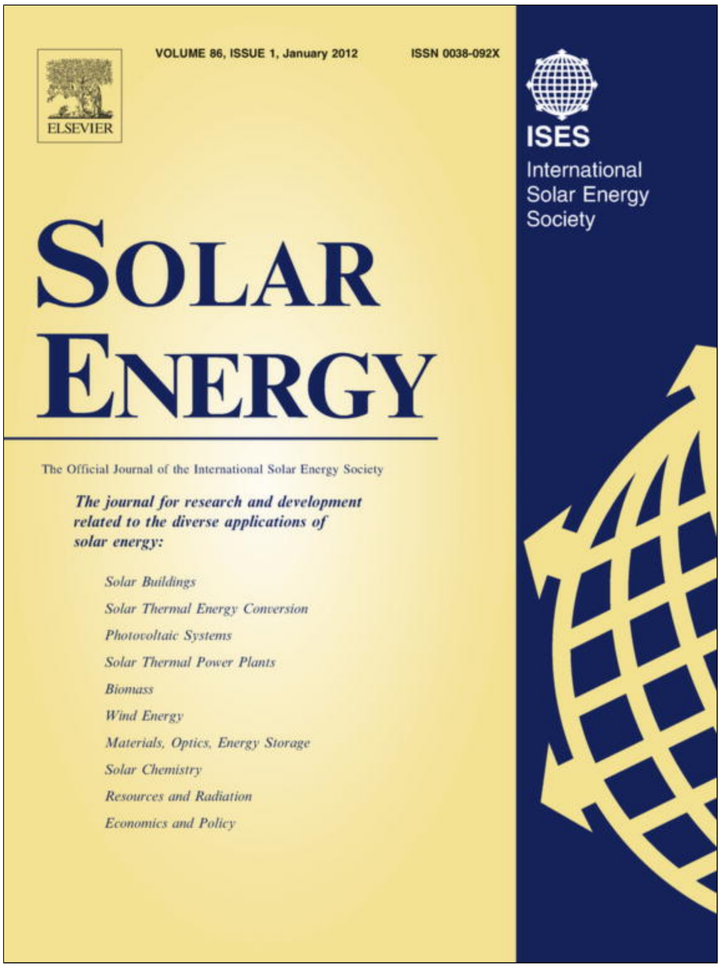
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Monthly mean hourly global solar radiation estimation

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Abstract

In this paper, selected empirical models were used to estimate the monthly mean hourly global solar radiation from the daily global radiation at three sites in the east coast of Malaysia. The purpose is to determine the most accurate model to be used for estimating the monthly mean hourly global solar radiation in these sites. The 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. 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 monthly mean 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 monthly mean hourly global solar radiation. This study finds that the Collares-Pereira and Rabl model performed better than the other models. Therefore the Collares-Pereira and Rabl model is recommended to estimate the monthly mean hourly global radiations for the east coast of Malaysia with humid tropical climate and in elsewhere with similar climatic conditions.

Keywords: Hourly global radiation; Hourly radiation models; Statistical tests; Collares-Pereira and Rabl model

1. Introduction

In the studies of solar energy, data on solar radiation and its components at a given location are very essential. In other words, a reasonably accurate knowledge of the availability of the solar resource at any place is required. The average values of the hourly, daily and monthly global irradiations on horizontal surfaces are needed in many applications of solar energy designs (Iqbal, 1983; Rahman and Chowdhury, 1988; Duffie and Beckman, 1991; Kamaruzzaman and Othman, 1992; Li and Lam, 2000; Wong and Chow, 2001; Al-Mohamad, 2004; Almorox and Hontoria, 2004; Kumar and Umanand, 2005).

Malaysia is one of the countries, which has abundant solar energy. The annual average daily solar irradiations for Malaysia have a magnitude of 4.21–5.56 kW h m^{-2}, and the sunshine duration is more than 2200 h per year (Muzathik et al., 2010). 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 modeling approach. The prediction of the hourly global solar radiation, I_t, for any day, was the target of many attempts (Collares-Pereira and Rabl, 1979; Jain, 1984, 1988; Gordon and Reddy,

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1988; Baig et al., 1991; Aguiar and Collares-Pereira, 1992a,b; Gueymard, 1993, 2000; Kaplanis, 2006; Wazira Azhari et al., 2008; Zekai, 2008; Bakirci, 2009).

The mean I_t values would be useful in problems such as effective and reliable sizing of the solar power systems (PV generators) and management of solar energy sources in relation to the power loads to be met (output of the PV systems affected by the meteorological conditions). 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.

The main objective of this paper is to validate the available models that predict the monthly mean hourly global radiation on a horizontal surface against measured data set for different sites over Malaysia and, thus, to retaining the most accurate model. The models which were considered for comparison and examination work are the Collares-Pereira and Rabl model (1979), the Jain model (1984, 1988), the Baig et al. model (1991) and a new approach to Jain's and Baig's models by Kaplanis (2006) Furthermore in our paper, we first performed a literature review of existing models and we made a description of each retained model. This was followed by a statistical comparison of the hourly retained models to the measured data obtained from three Malaysian states, which are in the same climatic zones.

2. Mathematical models

2.1. Collares-Pereira and Rabl model

Collares-Pereira and Rabl (1979) proposed a semi empirical expression for r_t;

$$r_t = \frac{\pi}{24}(x + y\cos w)\frac{\cos w - \cos w_s}{\sin w_s - (2\pi \cdot w_s/360)\cos w_s} \quad (1)$$

yields the coefficients given by

$$x = 0.409 + 0.5016\sin(w_s - 60) \quad (2)$$

$$y = 0.6609 - 0.4767\sin(w_s - 60) \quad (3)$$

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

$$w_s = \cos^{-1}(-\tan(\varphi)\tan(\delta)) \quad (4)$$

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

2.2. The Jain model

Jain (1984, 1988) has proposed a Gaussian function to fit the recorded data and he established the following relation for global irradiation:

$$r_t = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(t-12)^2}{2\sigma^2}\right] \quad (5)$$

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

$$\sigma = \frac{1}{r_{t(t=12)}\sqrt{2\pi}} \quad (6)$$

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 Eq. (6). Then, from Eq. (5), r_t values are obtained to provide:

$$I_t = r_t \cdot H_n \quad (7)$$

2.3. The Baig et al. model

The Baig et al. model is based on Jain's model (1991). 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:

$$r_t = \frac{1}{2\sigma\sqrt{2\pi}}\left\{\exp\left[-\frac{(t-12)^2}{2\sigma^2}\right] + \cos\left[180\frac{(t-12)}{(s_o-1)}\right]\right\} \quad (8)$$

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

$$S_o = \frac{2}{15}\cos^{-1}(-\tan(\varphi)\tan(\delta)) \quad (9)$$

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

$$\delta = 23.45\sin[360(n + 284)/365] \quad (10)$$

2.4. Kaplanis 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 is proposed by Kaplanis (2006). These approaches are presented as it concerns the determination of σ.

1st approach: the day length, S_o, of the day n, as determined from Eq. (9), 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

$$S_o = 4\sigma \quad (11)$$

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;

$$S_o = 4.054\sigma \quad \text{or} \quad \sigma = 0.246 S_o \quad (12)$$

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

Table 1
Geographical co-ordinate of the considered cities.

Location	Latitude in degrees	Longitude in degrees	Altitude (m)
Kuala Terengganu	5°10′N	103°06′E	5.2
Kota Bharu	6°10′N	102°17′E	4.6
Kuantan	3°47′N	103°13′E	15.3

2.5. The Kaplanis model

The model was proposed by Kaplanis (2006). In this model a and b are parameters to be determined for any site and for any day, n. Their determination is as follows:

$$\text{Let,}\quad I = a + b \cdot \cos(2\pi \cdot t/24) \tag{13}$$

Integrating Eq. (13) over t, from sunrise, t_{sr}, to sunset, t_{ss}, obtains:

$$\int_{t_{sr}}^{t_{ss}} I\,dt = H = 2a(t_{sr} - 12) + \frac{24b}{\pi} \sin\left(\frac{2\pi \cdot t_{ss}}{24}\right) \tag{14}$$

A boundary condition provides a relationship between a and b. That is at $t = t_{ss}$, $I = 0$. Hence, from Eq. (13):

$$a + b\cos(2\pi t_{ss}/24) = 0 \tag{15}$$

Eqs. (14) and (15) provide the values of a and b by using H values which are taken from measured data.

3. Method of statistical comparison

There are numerous works in literature which deal with the assessment and comparison of hourly solar radiation estimation models (Bevington, 1969; Ma and Iqbal, 1984; Bahel et al., 1987; Stone, 1993; Gueymard, 1993, 2000; Bulet and Büyükalaca, 2007; Koussa et al., 2009; Şenkal and Kuleli, 2009). 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 were 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.

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.

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.

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

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.

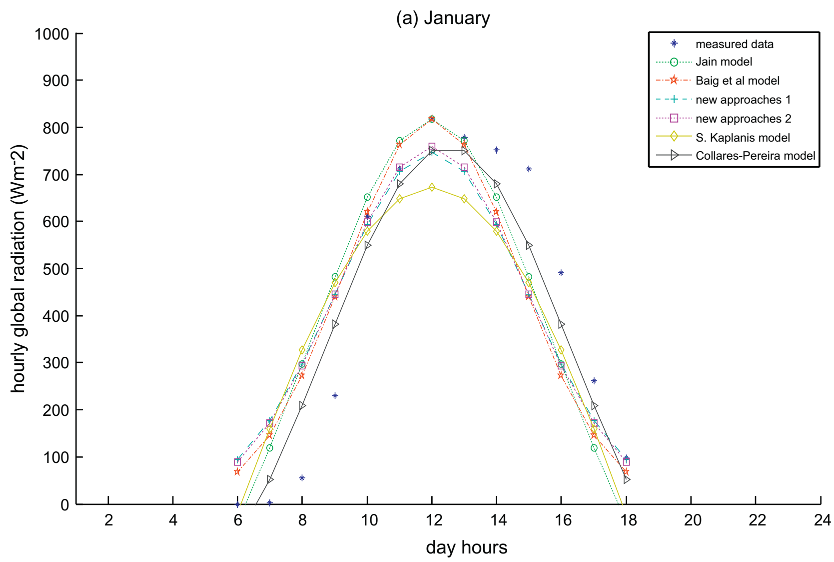

Fig. 1. A comparison between recorded hourly global radiations and estimated values from the six models for the representative day of January for Kota Bharu.

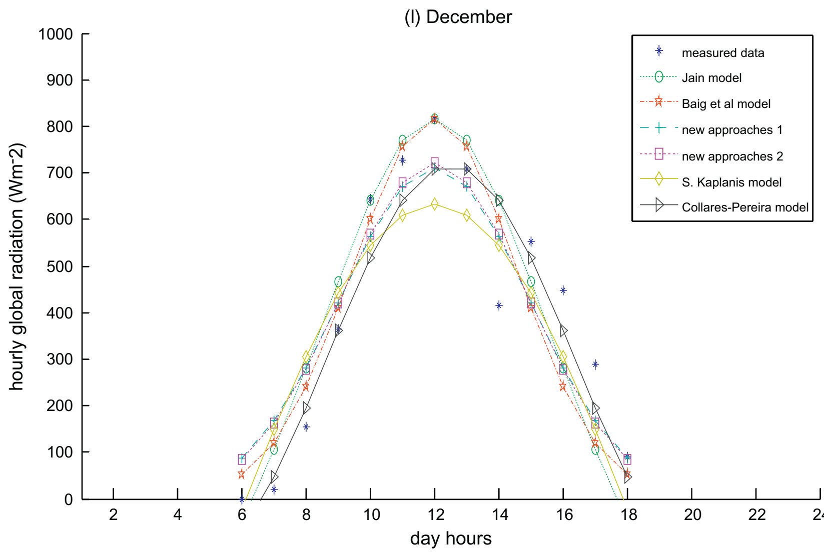

Fig. 2. A comparison between recorded hourly global radiations and estimated values from the six models for the representative day of December for Kota Bharu.

4. Used data and methodology

The models were tested for different Malaysian cities: Kuala Terengganu, Kota Bahru and Kuantan. The geographical co-ordinates of these sites are listed in Table 1.

The used hourly global irradiation data from January 1, 2004 to December 31, 2006 were obtained from three recording data stations installed at sites by Malaysian Meteorology Department. Kuala Terengganu data was verified with data obtained from University Malaysia Terengganu Renewable Energy Station which is nearly 2 km North West to the Kuala Terengganu station.

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 for the three cities, 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 were replaced with the values of preceding or subsequent hours of the day by interpolation.

The estimation of monthly mean hourly global solar radiation 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 months or nearest clear day of each average day of the months. The corresponding measured values

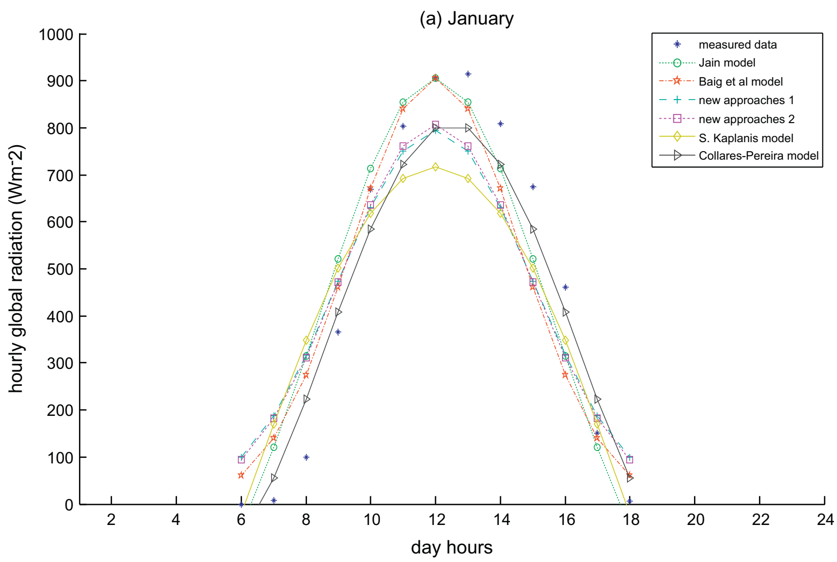

Fig. 3. A comparison between recorded hourly global radiations and estimated values from the six models for the representative day of January for Kuala Terengganu.

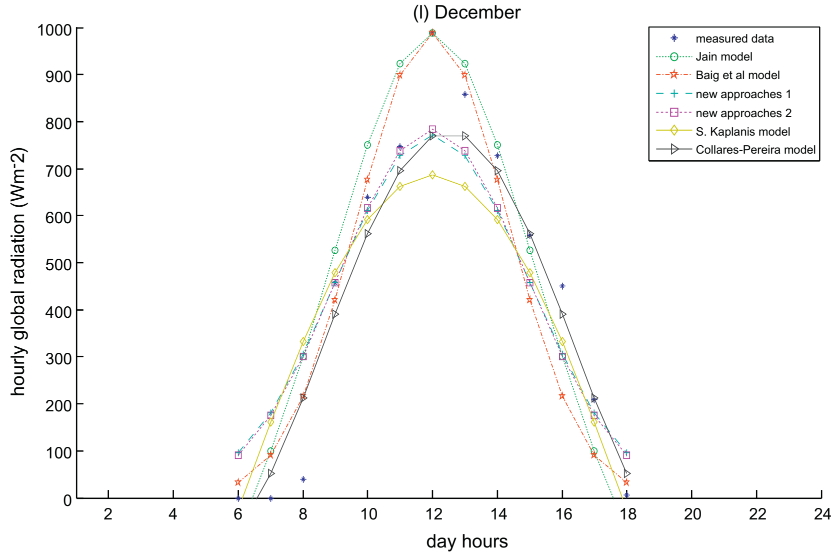

Fig. 4. A comparison between recorded hourly global radiations and estimated values from the six models for the representative day of December for Kuala Terengganu.

were compared with estimated values using the above six models at three stations. 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 result and discussion.

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. Results and discussion

The recorded and estimated values from the six models of hourly global radiations for the representative day of the selected months of January and December are presented in Figs. 1 and 2 for Kota Bharu, in Figs. 3 and 4 for Kuala Terengganu and in Figs. 5 and 6 for Kuantan, respectively.

During solar noon for three sites investigated, Jain Model and Baig et al. model give same values as measured, because, these models are based on solar noon measured values. The Jain model and Baig et al. model estimate of monthly mean 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's estimates of monthly mean hourly solar radiation vary within the standard deviation. In estimation of monthly mean hourly solar radiation, the results obtained from the models for Kuantan site was poor compared to other sites.

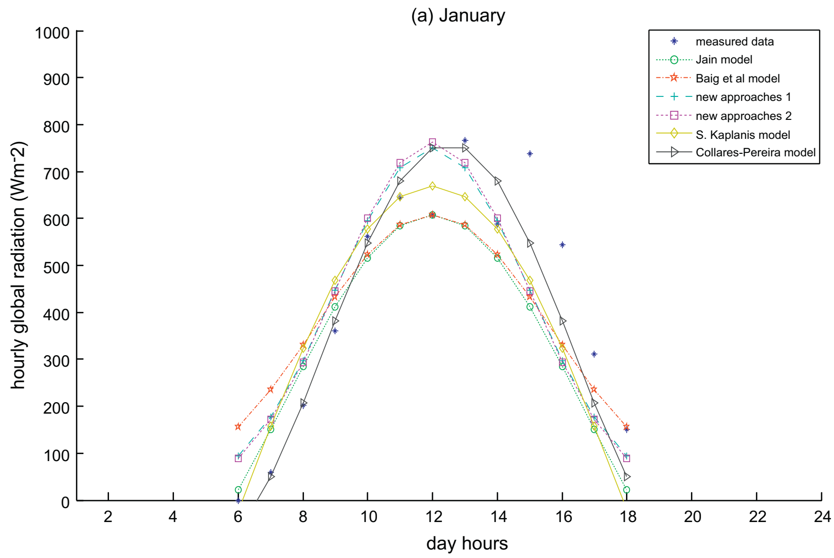

Fig. 5. A comparison between recorded hourly global radiations and estimated values from the six models for the representative day of January for Kuantan.

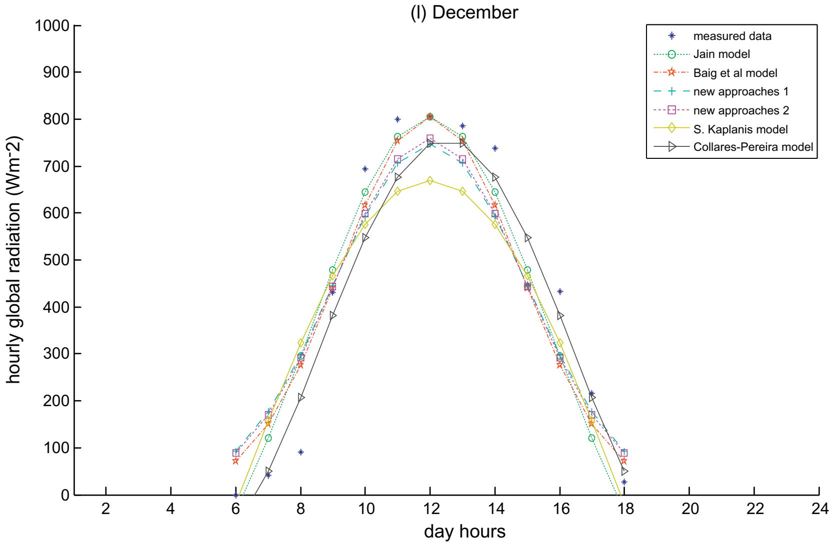

Fig. 6. A comparison between recorded hourly global radiations and estimated values from the six models for the representative day of December for Kuantan.

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

Table 2
Statistical parameters of monthly mean 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

Table 3
Statistical parameters of monthly mean hourly global radiation models for the representative days of the months for Kota Bharu.

Model	Statistical Indicators	January	February	March	April	May	June	July	August	September	October	November	December
Jain	NMBE (%)	−1.53	−3.31	−2.42	−2.33	−3.59	−2.70	−2.52	−3.91	−7.61	−1.71	−3.37	−1.05
	NRMSE (%)	34.09	38.49	28.23	23.09	33.80	20.59	34.45	27.62	32.53	21.36	28.59	27.08
	‘t’	0.16	0.30	0.30	0.35	0.37	0.46	0.25	0.50	0.83	0.28	0.41	0.13
	‘r’	0.89	0.82	0.93	0.93	0.86	0.95	0.82	0.91	0.95	0.95	0.92	0.92
Baig et al.	NMBE (%)	−2.44	−8.48	−5.03	−3.89	−7.44	−4.34	−3.76	−8.67	−17.09	−2.52	−9.15	0.28
	NRMSE (%)	34.62	38.96	27.77	23.31	34.25	20.22	35.29	26.47	29.98	19.84	27.25	29.19
	‘t’	0.24	0.77	0.64	0.59	0.77	0.76	0.37	1.20	2.40	0.44	1.23	0.03
	‘r’	0.88	0.82	0.92	0.93	0.86	0.95	0.83	0.92	0.95	0.96	0.92	0.92
New approach I	NMBE (%)	−2.66	−2.79	−2.91	−3.07	−3.21	−3.29	−3.26	−3.13	−2.99	−2.81	−2.69	−2.63
	NRMSE (%)	35.47	38.44	29.32	23.37	33.49	21.48	33.73	26.78	23.64	23.87	27.77	26.93
	‘t’	0.26	0.25	0.35	0.46	0.33	0.54	0.34	0.41	0.44	0.41	0.34	0.34
	‘r’	0.89	0.82	0.93	0.93	0.86	0.95	0.82	0.91	0.94	0.96	0.91	0.92
New approach II	NMBE (%)	−2.42	−2.55	−2.65	−2.81	−2.94	−3.01	−2.99	−2.87	−2.73	−2.56	−2.45	−2.39
	NRMSE (%)	35.07	38.51	28.73	23.17	33.32	21.01	33.91	26.61	23.40	23.18	27.61	26.58
	‘t’	0.24	0.23	0.32	0.42	0.31	0.50	0.31	0.38	0.41	0.39	0.31	0.31
	‘r’	0.89	0.82	0.93	0.93	0.86	0.95	0.82	0.91	0.94	0.96	0.91	0.92
Kaplanis	NMBE (%)	−9.37	−5.37	−1.92	3.19	7.95	10.38	9.54	5.26	0.54	−4.85	−8.43	−10.33
	NRMSE (%)	37.93	38.46	30.10	23.55	35.93	23.90	36.50	25.92	19.79	23.63	27.61	30.34
	‘t’	0.88	0.49	0.22	0.47	0.79	1.67	0.94	0.72	0.09	0.73	1.11	1.25
	‘r’	0.87	0.82	0.91	0.93	0.85	0.94	0.83	0.92	0.95	0.95	0.92	0.91
Collares-Pereira and Rabl	NMBE (%)	−6.23	−4.11	−2.35	0.15	2.37	3.47	3.09	1.13	−1.13	−3.84	−5.72	−6.74
	NRMSE (%)	21.86	25.12	14.51	10.17	20.37	13.09	24.62	12.38	14.10	10.17	14.27	23.01
	‘t’	1.03	0.57	0.57	0.05	0.41	0.95	0.44	0.32	0.28	1.41	1.52	1.06
	‘r’	0.96	0.93	0.98	0.99	0.95	0.98	0.93	0.98	0.98	0.99	0.98	0.94

zero at infinity time whereas practically there is no radiation before sunrise and after sunset.

Kaplanis model gives an underestimation of about 10%, for the worst cases, which are in January, October and December at solar noon. While for the rest of the day, the monthly mean hourly solar radiation estimates are close to recorded 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, monthly mean hourly solar radiation estimates are close to recorded values. Kaplanis's 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 same value for both cases ($\sigma = 0.25$, if the *first approach* and $\sigma = 0.246$, for the *second approach*). A new approach 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 they are close to recorded values.

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 as NMBE, NRMSE, *t*-test and *r* are presented in Tables 2–4 for the hourly global irradiations at Kuala Terengganu, Kota Bharu and Kuantan, respectively.

The estimates on monthly mean hourly solar radiation obtained by the models in most months are close to the measured values. Their differences between the measured and estimated values were ±17.20%, ±17.73% and ±21.39% at the maximum for Kuala Terengganu, Kota Bharu and Kuantan, respectively.

For the monthly mean hourly global irradiation, the results presented in Tables 2–4 show that Collares-Pereira and Rabl model generally leads to the best results. For the three considered sites, the NRMSE values obtained by using this model was 8–15% in general, but for February in Kuantan site was 28.85% at maximum. This model appears to perform well at the considered sites. Jain model, Baig et al. model, a new approach to Jain's and Baig's models *1st approach* and *2nd approach* and Kaplanis model

Table 4
Statistical parameters of monthly mean hourly global radiation models for the representative days of the months for Kuantan.

Model	Statistical Indicators	January	February	March	April	May	June	July	August	September	October	November	December
Jain	NMBE (%)	−7.25	−5.05	−2.12	−3.27	−3.67	−3.21	−1.66	−2.14	−2.07	−1.58	−6.66	−1.67
	NRMSE (%)	33.48	41.57	35.66	28.50	27.26	23.98	30.84	32.53	24.74	23.79	37.74	21.36
	‘t’	0.77	0.42	0.21	0.40	0.47	0.47	0.19	0.23	0.29	0.23	0.62	0.27
	‘r’	0.86	0.77	0.85	0.90	0.93	0.94	0.90	0.87	0.93	0.94	0.86	0.96
Baig et al.	NMBE (%)	−17.85	−13.16	−4.01	−7.22	−7.68	−6.01	−0.11	−2.65	−3.11	−1.85	−16.59	−3.21
	NRMSE (%)	34.43	42.78	37.02	28.25	25.74	22.67	31.92	31.91	24.47	23.22	36.82	20.49
	‘t’	2.10	1.12	0.38	0.92	1.08	0.95	0.01	0.29	0.44	0.28	1.75	0.55
	‘r’	0.87	0.77	0.85	0.90	0.93	0.94	0.89	0.88	0.93	0.95	0.87	0.96
New approach I	NMBE (%)	−2.63	−2.55	−2.87	−3.02	−3.21	−3.29	−3.25	−3.18	−3.01	−2.82	−2.68	−2.64
	NRMSE (%)	31.63	41.35	35.95	28.29	26.51	24.11	33.02	32.68	25.89	26.48	35.30	24.80
	‘t’	0.29	0.21	0.28	0.37	0.42	0.48	0.34	0.34	0.41	0.37	0.26	0.37
	‘r’	0.85	0.77	0.85	0.90	0.92	0.94	0.90	0.87	0.93	0.95	0.84	0.96
New approach II	NMBE (%)	−2.40	−2.30	−2.62	−2.76	−2.94	−3.01	−2.98	−2.91	−2.75	−2.57	−2.44	−2.41
	NRMSE (%)	32.02	41.58	35.79	28.11	26.13	23.69	32.51	32.52	25.46	25.81	35.54	23.92
	‘t’	0.26	0.19	0.25	0.34	0.39	0.44	0.32	0.31	0.38	0.35	0.24	0.35
	‘r’	0.85	0.77	0.85	0.90	0.92	0.94	0.90	0.87	0.93	0.95	0.84	0.96
Kaplanis	NMBE (%)	−10.17	−4.98	−3.06	3.06	7.95	10.38	9.26	6.79	1.40	−4.70	−8.73	−9.87
	NRMSE (%)	31.25	41.95	37.46	28.34	26.29	25.10	35.11	32.26	25.49	27.05	32.67	28.49
	‘t’	1.19	0.41	0.28	0.38	1.10	1.57	0.95	0.75	0.19	0.61	0.96	1.28
	‘r’	0.87	0.77	0.83	0.90	0.92	0.93	0.87	0.88	0.92	0.93	0.87	0.94
Collares-Pereira and Rabl	NMBE (%)	−6.66	−3.78	−2.93	0.11	2.37	3.47	2.97	1.84	−0.71	−3.76	−5.88	−6.49
	NRMSE (%)	22.45	28.85	22.87	13.44	12.42	11.94	19.24	18.05	9.65	12.42	23.46	18.39
	‘t’	1.08	0.46	0.45	0.03	0.67	1.05	0.54	0.35	0.26	1.10	0.90	1.31
	‘r’	0.94	0.90	0.94	0.98	0.98	0.99	0.96	0.96	0.99	0.99	0.94	0.97

resulted in largest NRMSE with the values more than 30% in general.

In addition, the low NMBE values are particularly remarkable. The NMBE values show that Collares-Pereira and Rabl model generally yields the best results. The negative NMBE values presented in Tables 2–4 show that there is an underestimation for all sites 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 NMBE values higher than that obtained by Collares-Pereira and Rabl model. A new approach to Jain's and Baig's models *1st approach* and *2nd approach* yields smaller negative NMBE values. This indicates that there is an underestimation for all sites during the entire period of the year, even though the NRMSE values are very high for these models.

The following assumption was made in this analyses that, the available hourly data is distributed according to the Gauss probability distribution function. From the tables, 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. 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.

In addition, t-test of 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 5% level of significance (95% confidence level) and 12 degrees of freedom. According to the t-tests given in Tables 2–4, the models evaluations are good for all the sites. In particular Jain Model and a new approach to Jain's and Baig's models *1st approach* and *2nd approach* give the best results for all the sites.

Finally, it can be seen that the estimated values of monthly mean hourly global solar radiation at each site are in favorable agreement with the measured values hourly global solar radiation for all the months of the year. It was found that Collares-Pereira and Rabl model shows the best results among the all models for all three sites. This is due to Collares-Pereira and Rabl model's lower values of

NMBE, NRMSE, and *t*-test and very high coefficient of correlation. Therefore, from this study, Collares-Pereira and Rabl model can be recommended for use to estimate the monthly mean hourly global solar radiation at any location in the east coast of Malaysia and places with similar climatic condition.

6. 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 monthly mean hourly global irradiation have been chosen from literatures to evaluate the applicability of these models over three sites in east coast of Malaysia. The models were compared based on the normalized mean bias error (NMBD), normalized root mean square error (RMSE), coefficient of correlation (r) and t-test. According to the results, Collares-Pereira and Rabl model is the most accurate in general to estimate the monthly mean daily global radiations for all three sites with humid tropical climate. Furthermore, if only the daily global irradiation is available, one can calculate the monthly mean hourly global radiations on a horizontal surface using these models with a good accuracy. The Collares-Pereira and Rabl model can be recommended for predicting the monthly mean hourly global radiation.

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