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Hourly Global Solar Radiation Estimates on a Horizontal Plane

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Abstract: *The hourly global solar radiation (I_t) model strongly depends on the climatic characteristics of a considered site. In this paper, six empirical models were used to estimate the I_t from daily radiation on the eastern coast of Malaysia. The measured I_t data were obtained from the Malaysian Meteorology Department for the period of 2004–2008. In order to determine the performance of the models, the statistical parameters, normalised mean bias error (NMBE), normalised root mean square error (NRMSE), correlation coefficient (r), and a t-test were used. The I_t values were calculated by using the selected models. The results were compared with the measured data. This study finds that the Collares-Pereira and Rabl model performed better than the other models.*

Keywords: Collares-Pereira and Rabl model, global solar radiation, hourly solar radiation *(I_t)* models, statistical tests, solar energy design

Abstrak: *Pilihan model sinaran solar global perjam (I_t) adalah sangat bergantung kepada ciri-ciri iklim lokasi yang ditentukan. Dalam kertas kerja ini, enam model empirikal digunakan untuk menganggar I_t dari sinaran harian di pantai timur Malaysia. I_t yang diukur diperolehi dari Jabatan Meteorologi Malaysia bagi jangka masa 2004–2008. Bagi menentukan prestasi model, parameter statistik, ralat pincang purata ternormal (NMBE), ralat punca ganda dua ternormal (NRMSE), pekali korelasi (r) dan ujian t digunakan. Nilai I_t dihitung menggunakan model-model tersebut dan keputusan dibandingkan dengan data yang diukur. Kajian ini mendapati bahawa model Collares-Pereira dan Rabl adalah merupakan model yang terbaik.*

Kata kunci: model Collares-Pereira dan Rabl, sinaran solar global, model sinaran solar perjam *(I_t)*, ujian statistik, rekabentuk/corak tenaga solar

1. INTRODUCTION

The data on solar radiation and its components at a given location are essential for studies of solar energy. In other words, reasonably accurate knowledge of the availability of solar resources at a given place is required. The average values for the hourly, daily and monthly global irradiation on a horizontal surface are needed for many applications of solar energy designs.[1–5]

Malaysia is a country that has abundant solar energy. The annual average daily solar irradiations for Malaysia have a magnitude of 4.21–5.56 $kWhm^{-2}$, and the sunshine duration is more than 2,200 hours per year.[6] Unfortunately, for many developing countries such as Malaysia, solar radiation measurements are not easily available due to high equipment and maintenance costs and the calibration requirements of the measuring equipment. A solution to this problem is to estimate solar radiation by using a model. Indeed, the prediction of the hourly global solar radiation, I_t, for a given day was the target of many research attempts.[7–16]

Mean I_t values are useful for problems such as the effective and reliable sizing of solar power systems (PV generators) and the management of solar energy sources in relation to the power loads that must be met (output of the PV systems affected by meteorological conditions). Modelling solar radiation also provides an understanding of the 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 I_t on a horizontal surface against the measured dataset for the Kuala Terengganu site in Malaysia and, thereby, to retain the most accurate model. The models that are considered for comparison and examination are as follows: the Jain model,[13,14] the Baig *et al.* model,[10] a new approach to the Jain and Baig models,[16] the S. Kaplanis model[15,16] and the Collares-Pereira and Rabl model.[11] We first performed a literature review of the existing models and created a description of each model. This step was followed by a statistical comparison of the hourly retained models to the measured data that were obtained from the Terengganu state.

2. EXPERIMENTAL

2.1. The Models

2.1.1 The Jain model

Jain[13,14] proposed a Gaussian function to fit the recorded data and established the following relation for global irradiation:

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

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:

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

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

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

$$I_t = r_t.H_n \tag{3}$$

2.1.2 The Baig model

The Baig *et al.*[10] model modified Jain's model to fit the recorded data during the starting and ending periods of a given day better. In this model, r_t is estimated by:

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

S_o is the daily length of a day, n, at a specific site, and it is defined by:

$$S_o = \frac{2}{15}\cos^{-1}\left[-\tan\varphi\,\tan\delta\right] \tag{5}$$

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

$$\delta = 23.45\sin\left[360\,(\mathrm{n}+284)/365\right] \tag{6}$$

2.1.3 A new approach to the Jain and Baig models

This work proposes a different approach for determining σ without using the values of I (t = 12), which was proposed by S. Kaplanis.[16] Two versions of this approach are presented because this approach concerns the determination of σ.

The first approach: The day length, S_o, of a day, n, as determined from equation (5), is equated with the time-distance between the points, where the tangents at the two turning points of the hypothetical Gaussian distribution, which fits the hourly I_t data, intersect the (temporal) hour, or t, axis. These two points are at a $\pm 2\sigma$ distance from the axis of origin. Then, σ is related directly to S_o by 4σ.

The second approach: If one draws a tangent at the two points that correspond to the full width at the half-maximum of a Gaussian curve, it can be determined that the tangent at each point intersects the horizontal axis, i.e., the hour, or t, axis at the points of $\pm 2.027\sigma$ instead of at $\pm 2\sigma$, as in the first version. Hence, in this case, $S_o = 4.054\sigma$ or $\sigma = 0.246\, S_o$. In these new approaches, either method for determining σ does not require any recorded data.

2.1.4 The Kaplanis model

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

Let, $$I = a + b.\cos\ {2\pi.t}/{24} \tag{7}$$

Integrating equation (7) over t, from sunrise, or t_{sr}, to sunset, or t_{ss}, one obtains:

$$\int_{t_{sr}}^{t_{ss}} Idt = \mathrm{H} = 2a\ \ t_{sr} - 12\ + \frac{24b}{\pi}\sin\left(\frac{2\pi.t_{ss}}{24}\right) \tag{8}$$

A boundary condition provides a relationship between a and b. That is, at $t = t_{ss}$, I = 0. Hence, from equation (7), one obtains:

$$a + b\cos\ \ 2\pi t_{SS}/24\ = 0 \tag{9}$$

Equations (8) and (9) provide the values of a and b by using the H values that are taken from the recorded data.

2.1.5 The Collares-Pereira and Rabl model

Collares-Pereira and Rabl[11] proposed a semi-empirical expression for r_t, as follows:

$$r_t = \frac{\pi}{24}\left(x + y\cos w\right)\frac{\cos w - \cos w_s}{\sin w_s - \left(2\pi . w_s / 360\right)\cos w_s} \tag{10}$$

This equation yields the coefficients given by:

$$x = 0.409 + 0.5016\sin\left(w_s - 60\right) \tag{11}$$

$$y = 0.6609 - 0.47676\sin\left(w_s - 60\right) \tag{12}$$

where w is the hour angle in degrees for the considered hour, and w_s is the sunset hour angle in degrees calculated by the following equation:

$$w_o = \cos^{-1}\left[-\tan(\varphi)\tan(\delta)\right] \tag{13}$$

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 Method of Statistical Comparison

There are numerous studies in the literature that address the assessment and comparison of I_t estimation models.[17–20] The most popular statistical parameters are the normalised mean bias error (NMBE) and the normalised root mean square error (NRMSE). In this study, to evaluate the accuracy of the estimated data from the models described above, some statistical tests [the NMBE, NRMSE and coefficient of correlation (*r*)] to verify the linear relationship between the predicted and measured values are used. For better data modelling, these statistics should be close to zero, but *r* should approach one as closely as possible. In addition, the *t*-test for the models was carried out to determine the statistical significance of the predicted values by the models.

2.2.1 The normalised mean bias error (NMBE)

$$NMBE\,(\%) = \frac{\frac{1}{n}\sum_{I}^{n} \left(I_{i,calc} - I_{i,\,meas} \right)}{\frac{1}{n}\sum_{I}^{n} I_{i,meas}} * 100 \tag{14}$$

This test, given above, provides information on long-term performance. A low NMBE value is desirable. A negative value gives the average amount of underestimation in the calculated value. Thus, one drawback of these two tests is that an overestimation of an individual observation will cancel the underestimation in a separate observation.

2.2.2 The normalised root mean square error (NRMSE)

$$NRMSE\,(\%) = \frac{\left[\frac{1}{n}\sum_{I}^{n} \left(I_{i,calc} - I_{i,meas} \right)^{2} \right]^{\frac{1}{2}}}{\frac{1}{n}\sum_{I}^{n} I_{i,meas}} * 100 \tag{15}$$

The NRMSE, given above, provides 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 is, the better the performance of the model is.

2.2.3 The coefficient of correlation (*r*)

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

$$r = \left[\frac{\sum \left(I_{meas} - I_{a,meas} \right)\left(I_{calc} - I_{a,calc} \right)}{\sqrt{\sum_{I}^{n} \left(I_{a,\,calc} - I_{calc} \right)^{2}} \sqrt{\sum_{I}^{n} \left(I_{a,\,meas} - I_{meas} \right)^{2}}} \right]^{\frac{1}{2}} \tag{16}$$

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

$$I_{a,meas} = \frac{1}{n}\sum_{I}^{n} I_{meas} \text{ and } I_{a,calc} = \frac{1}{n}\sum_{I}^{n} I_{calc}.$$

2.2.4 The *t*-statistic test

As defined by a student[21] in one of the tests for mean values, the random variable t, with $n - 1$ degrees of freedom, may be written as follows:

$$t = \left[\frac{(n-1)\,MBE^{2}}{RMSE^{2} - MBE^{2}}\right]^{\frac{1}{2}} \tag{17}$$

where MBE is the mean bias error and RMSE is the root mean square error. The smaller the value of t is, the better the performance is. In order to determine whether the estimates of a model are statistically significant, one must determine, from standard statistical tables, the critical t value, i.e., $t_{\alpha/2}$ at the α level of significance and ($n-1$) degrees of freedom. For the estimates of the model to be judged statistically significant at the ($1-\alpha$) confidence level, the calculated t value must be less than the critical value.

2.3 Data Used and Methodology

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

The measured I_t 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, and these account for approximately 0.5% of the entire database. To complete the dataset, missing and atypical data were replaced with the values of the preceding or subsequent hours of the day by interpolation.

An estimation of the I_t was carried out for many data for the above sites applying the six models outlined above. The values of the I_t intensity were estimated on every average day of the month or on the nearest clear day of each month. The corresponding values were compared with the estimated values by using the six models at the station. The estimated and measured values of the I_t

intensity were analysed using the NMBE, NRMSE, *r* values and *t*-test statistical tests for the representative days for 12 months throughout the year. A programme was developed using MATLAB to provide and plot the I_t estimations. The models were checked with repeated runs and different sequences, as is required for the prediction of I_t.

3. RESULTS AND DISCUSSION

Figure 1 shows the recorded and estimated values from the selected six models of I_t for representative days of the months for the Kuala Terengganu sites. During solar noon, the Jain and Baig *et al.* models both gave the same values because these models are based on the solar noon measured values. The estimates of the Jain and Baig *et al.* models of the I_t show symmetry around the solar noon, as imposed by the Gaussian fitting function. The Jain and Baig *et al.* Models seem to provide very reliable performance close to solar noon, which is due to the solar noon recorded values required by the models. For the rest of the day, the estimates of I_t vary within the standard deviation. The estimated values of the Jain models were almost always less than the measured values for the main part of the day. The mismatch was much wider during the early and late hours of the day as the Gaussian function became zero at infinity (time), because there is practically no radiation before sunrise and after sunset.

The Kaplanis model gives an underestimation of about 10% in the worst cases, which are in January, October and December at solar noon. For the rest of the day, the I_t estimates are close to the measured values. The Collares-Pereira and Rabl model gives an overestimation of about 8%–10% in the worst cases, which are in May and September at solar noon. For the rest of the day, the I_t estimates are close to the measured values. The new approach to the first and second approaches (henceforth known as new approaches) from Jain and Baig gives the same estimates of I_t *b*ecause both models are based on the theoretical σ values, which are almost the same values in both cases (σ = 0.25 in the first approach and σ = 0.246 in the second approach). The new approaches for Jain and Baig gives an overestimation of about 5%–8% in the worst cases, which are in January and February, and an underestimation of about 5% (in the worst cases), which are in July and December at solar noon. For the rest of the day, the I_t estimates are close to the recorded values. To make a comparison among the models, the estimated and measured values were compared for each representative day of the various months. The statistical summary of the performance of the combination of the different test indicators is presented in Table 1 for the I_t at the Kuala Terengganu site.

The estimates of the I_t that were obtained by the models for most months are close to the measured values. The difference between the measured and estimated values was $\pm$ 17.00% (at the maximum) for the Kuala Terengganu site. For the I_t, the results presented in Table 1 show that the Collares-Pereira and Rabl model generally leads to the best results. For the Kuala Terengganu site, the NRMSE values that were obtained by using this model were generally 8%–20%. This model appears to perform well at the Kuala Terengganu site. For the Jain and Baig models, the new approaches were carried out. This new approach and the Kaplanis model resulted in the largest NRMSE with values that were generally greater than 25%.

In addition, the low NMBE values are particularly remarkable. The NMBE values show that the Collares-Pereira and Rabl model generally yields the best results. The negative NMBE values presented in Table 1 show that an underestimation of I_t occurs during the period of January to March and September to December, whereas overestimation of I_t occurs during the period of April to August with the Collares-Pereira and Rabl model.

The Jain, Baig, and the Kaplanis models present NMBE values that are higher than those obtained by the Collares-Pereira and Rabl model. The new approaches for Jain and Baig models yields smaller negative NMBE values. This result indicates that there is an underestimation during the entire period of the year, even though the NRMSE values are very high for these models. From the table, it can be seen that the average r of the Collares-Pereira and Rabl model is 0.98. This result indicates that the Collares-Pereira and Rabl model accounts well for the variability in the I_t. The average r of the other models is around 0.96. It is clear that the deviations between the measured and estimated values of these five models are larger than those of the Collares-Pereira and Rabl model. However, all six models may be accepted if one considers only the coefficient of correlation between the measured and estimated values.

In addition, a t-test for the models was carried out to determine the statistical significance of the estimated values from the models. The models having a lower t value than the t critical value are statistically acceptable models. From the standard statistical tables, the critical t value is 2.1788 at a 5% level of significance (95% confidence level) with 12 degrees of freedom. According to the t-tests given in Table 1, the evaluations of the models are good for the Kuala Terengganu site. In particular, the Jain model and the new approaches for Jain and Baig models give the best results for the site.

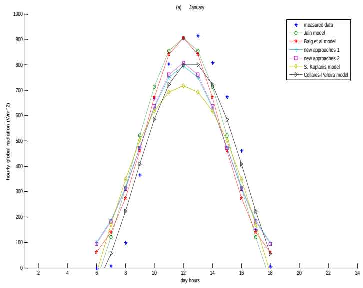
Table 1: Statistical parameters of I_t *models for t*he representative days of the months for the Kuala Terengganu site.

Model	Statistical indicators	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
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

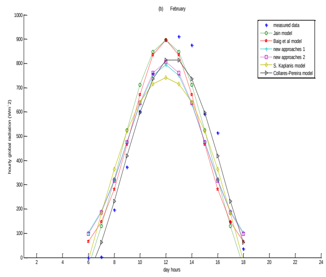
(continued on next page)

Table 1: *continued*.

Model	Statistical indicators	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
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



(a)



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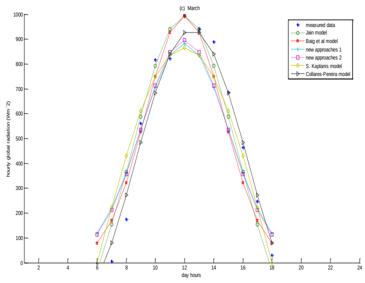

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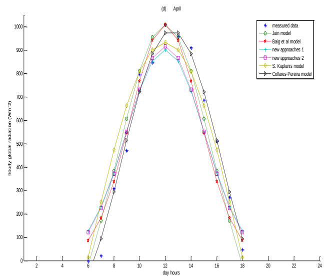

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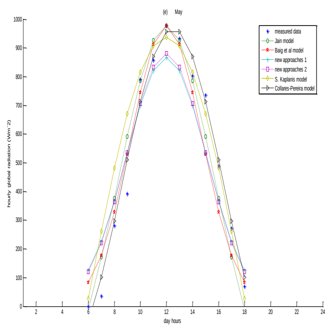

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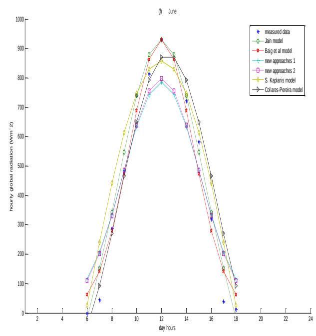

(f)

Figure 1: A comparison between the recorded hourly global radiation and the estimated values from the six models for representative days of the months [January at (a) to December at (l)] for the Kuala Terengganu site *(continued on next page).*

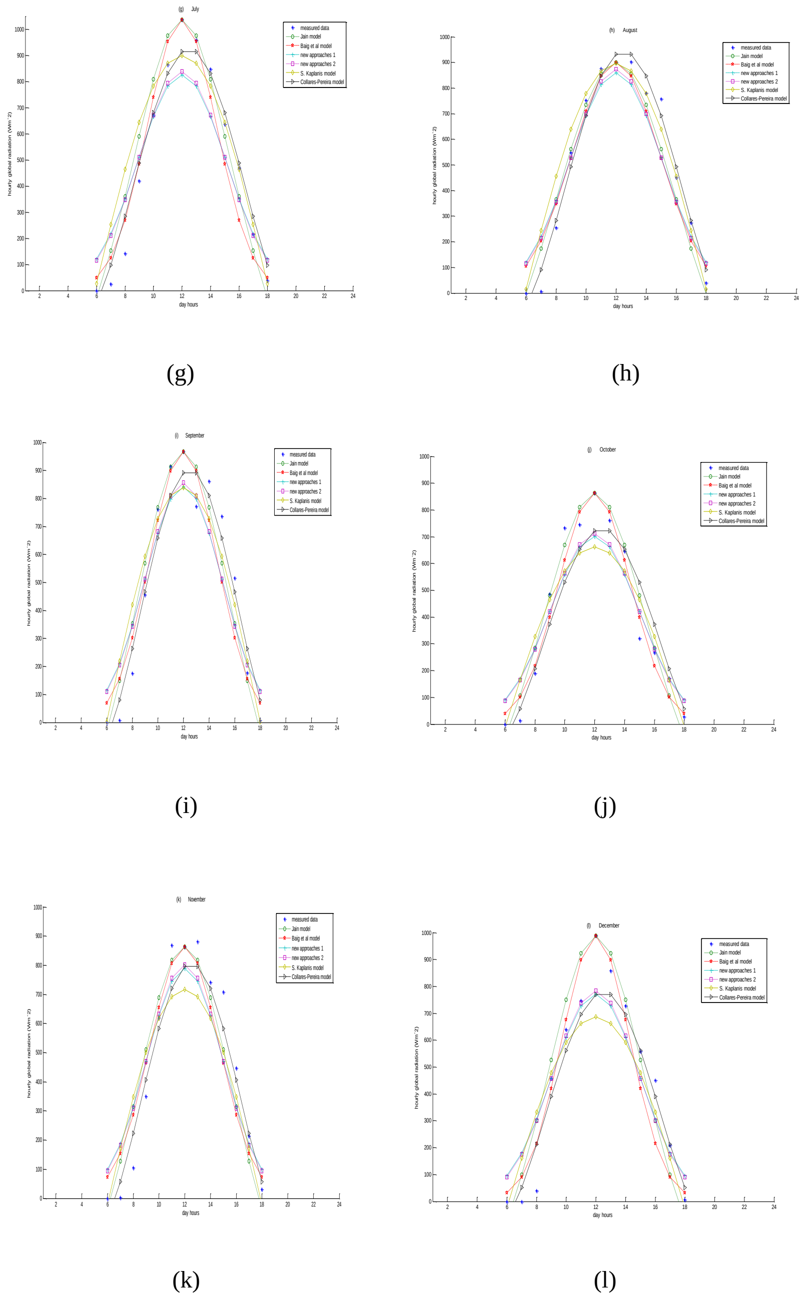

Figure 1: *continued.*

Finally, the estimated values of I_t at the Kuala Terengganu site are in favourable agreement with the measured values for the I_t for all of the months in the year. It was found that the Collares-Pereira and Rabl model shows the best results among all of the models for the site. This is due to the low values of the Collares-Pereira and Rabl model for the NMBE, NRMSE, and the *t*-test, and the fact that the coefficient of correlation is 0.98. Therefore, based on this study, the Collares-Pereira and Rabl model can be recommended for use in estimating the I_t at the Kuala Terengganu site in Malaysia and also for places with similar climatic conditions.

4. CONCLUSION

According to the research based on the statistical parameters of the normalised mean bias error (NMBE), normalised root mean square error (NRMSE), coefficient of correlation *(r)* and a *t*-test, the Collares-Pereira and Rabl model is the most accurate one for estimating the hourly global solar radiation, I_t for Kuala Terengganu in Malaysia and for other locations that exhibit similar climatic conditions. Furthermore, the result of this analysis could be used in the design of solar energy applications and other related mechanisms.

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