DIURNAL PATTERN AND ESTIMATION OF GLOBAL SOLAR RADIATION IN EAST COAST MALAYSIA

M. Mahendran[1*], Lee. G.C[1], A. Shahrani[1], Bakar. R.A[1], K. Kadirgama[1], Amir. A.R[1] and K.V Sharma[2]

[1]Faculty of Mechanical Engineering,Universiti Malaysia Pahang,
26600 Pekan, Pahang, Malaysia
*Email: mahen_mu@yahoo.com
Phone: +60176673607; Fax: +609424622
[2]Jawaharlal Nehru Technological University Hyderabad, Kukatpally,
Hyderabad - 500085, Andhra Pradesh, India

ABSTRACT

The solar radiation study have been undertaken at Pekan campus (3.5ºN, 103.4ºE), Faculty of Mechanical Engineering, University Malaysia Pahang to utilize solar energy in east coast of Malaysia. The knowledge of the daily variation of global solar radiation is a necessity at the particular locality to consider the feasibility of solar energy utilisation. Hence, the diurnal patterns of global solar radiation were obtained using measured data from weather station which was installed at the site for three years (2011 – 2013). The patterns have been divided into five conditions such as clear sky, partially cloudy, fully cloudy, afternoon rain, and northeast monsoon season day. It was observed that on a clear sky day in Pekan, the maximum solar insolation was 939 W/m^2 and total solar energy received was 6.51 kWhr/m^2. In contrast, on a fully cloudy day the maximum solar insolation was only 30 W/m^2 and total solar energy received was 0.35 kWhr/m^2. Besides that, the empirical models were developed to estimate the monthly average daily global solar radiation on a horizontal surface with Pekan meteorological station data. Subsequently, the models were evaluated using statistical analysis. Based on analysis results, Eq. (13) and Eq. (15) models are proposed to estimate monthly average daily global solar radiation for Pekan. The present paper describes on advance understanding of daily variation global solar radiation in east coast Malaysia whereby it has significance for designing a solar system. Lastly, the developed Angstrom’s modified linear models are highly recommended to be used to estimate the monthly average daily global solar radiation in Pekan, Pahang and location with similar solar radiation patterns in east coast Malaysia.

***Keywords*:** Solar energy; linear regression; diurnal pattern of global solar radiation.

INTRODUCTION

Malaysian government has created awareness about depletion of fossil fuels and diversify its energy sectors by including the renewable energy in 8th Malaysia Plan (Malaysia, 2001). Solar energy is the most potential renewable energy application in Malaysia, whereby most of its location receives abundant solar radiation yearly. The knowledge of the daily variation of global solar radiation is a necessity at the particular locality to consider the feasibility of solar energy utilisation (Othman et al., 1993). In Malaysia, the global solar radiation is mainly influenced by the climate conditions such as Asian monsoons, high relative humidity and heavy rainfall.

In addition, a preliminary study on solar energy potential in east coast was studied by Noor et al. (2011) and stated that the solar radiation during June 2011 was reached around 982 W/m^2. However, the data was insufficient and requires more data to confirm the solar energy practicability. A recent research was done by Mahendran et al. (2012) on solar energy at Pekan found that the maximum global solar radiation on a clear sky day was 958 W/m^2 and partly cloudy day was 630 W/m^2. Nevertheless, solar radiation measurements are not easily available in all areas and the diurnal pattern of global solar radiation differs from one place to another. Hence, modeling approach is necessary to estimate global solar radiation from the region of similar climate conditions and solar radiation patterns. A number of researchers in Malaysia have developed regression models to estimate the global solar radiation across the country with different methods (Sopian et al., 1992; Azhari et al., 2008; Muzathik et al., 2011; Nik et al., 2012; Khatib et al., 2012). However, all authors concluded that the regression coefficients are varies with different parts of the country although it has comparable geographical and climatic conditions.

Azhari et al. (2008) used satellite images as an alternative method to predict the solar energy in Malaysia and concluded the northern region of Peninsular Malaysia has high potential for solar energy application due to abundant amount of solar energy received throughout year including in month of December. Moreover, Zaharim et al. (2009) used Box-Jenkins method to predict the global solar radiation at Bangi, Selangor. In contrast, Khatib et al., (2012) used Artificial Neural Network (ANN) method to predict a clearness index which is used to calculate global and diffuse solar irradiations of the locality. Furthermore, a comparison study between various angstrom modified linear empirical models was conducted to establish a suitable model for state of Terengganu (Muzathik et al., 2011).

Angstrom modified linear regression models based on sunshine hours is widely used to estimate global solar radiation in many part of the world and these models also can equipped with some meteorological parameters such as based on the sunshine duration, precipitation, elevation, and latitude (Bakiri, 2009; Duzen et al., 2012; Li et al., 2010). Some researchers suggested other empirical relationships in terms of relative humidity and ambient air temperature to estimate the global solar radiation (Togrul and Onat, 1999; Ertekin and Yaldiz, 1999). The objective of this paper is to describe the diurnal pattern of global solar radiation in east coast of Malaysia and develop the suitable models to estimate of monthly average daily global solar radiation in Pekan by using meteorological parameters such as the bright sunshine duration, relative humidity and high-low ambient air temperatures.

METHODOLOGY

Experimental Method

The global solar radiation, outdoor relative humidity, and rain rate data were measured using the Vantage Pro-2 wireless weather station for three year period from 2011-2013. The wireless sensor transmits the readings to a weather-link data logger which kept inside a workstation as shown in Figure 1. Temperature and humidity sensors are located inside the radiation shield. The shield protects the sensors from solar radiation and other sources of radiated and reflected heat. It also included with rain collector where meets the guidelines of the world meteorological organization, with reads rainfall amount in 0.01 to 0.2 mm increments (Noor et al., 2011). The data collected at interval of five minutes and then averaged and integrated it for one day.

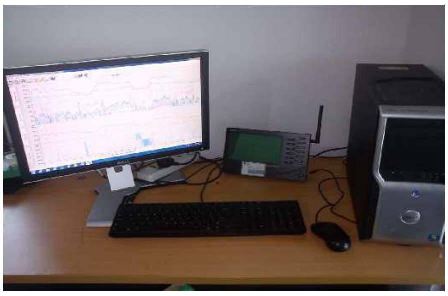

Figure 1. Weather-link data logger workstation.

Empirical Modeling

In the present work, the Angstrom's modified linear model (Sukhatme et al., 2008) was used to estimate the monthly average of the daily global solar radiation on a horizontal surface $\bar{H}$, a_1 and b_1 are regression coefficients with the actual sunshine hours per day $\bar{N}$ as shown in Eq. (1).

$$\frac{\bar{H}}{\bar{H}_o} = a_1 + b_1\left(\frac{\bar{N}}{\bar{N}_{max}}\right) \quad (1)$$

Values of monthly average of the maximum possible sunshine hours per day $\bar{N}_{max}$ calculated from Eq. (2) at the location latitude ϕ (Duffie and Beckman, 2006).

$$\bar{N}_{max} = \frac{2}{15} Cos^{-1}\left[-\tan\phi \tan\delta\right] \quad (2)$$

The extraterrestrial radiation $\bar{H}_o$ is obtained from simplified relationship shown in Eq. (3) and I_{sc} is solar radiation constant (Sukhatme et al., 2008).

$$H_o = \frac{24}{\pi} I_{sc}\left[1 + 0.033\, cos\frac{360n}{365}\right]\left[cos\phi\, cos\delta\, sin\omega_s + \omega_s sin\phi\, sin\delta\right] \quad (3)$$

The sunset or sunrise hour angle ω_s and the solar declination angle δ are defined by the relations in Eq. (4) and Eq. (5) (Gordon et al., 2001).

$$\omega_s = cos^{-1}\left[-\tan\phi \tan\delta\right] \quad (4)$$

$$\delta = 23.45\, Sin\left[360\left(284 + n\right)/365\right] \quad (5)$$

The value determined on a particular day n of a month. Usually, the 15th of each month is the day n of the month is used to determine the solar declination (Sukhatme et al., 2008).

The linear Angtrom modified model presented by Muzathik et al. (2011) for Terengganu and Sopian et al. (1992) for Kota Bharu was evaluated in this present study in Eq. (6) and Eq. (7) is shown respectively.

$$\frac{\bar{H}}{\bar{H}_o} = 0.2207 + 0.5249\left(\frac{\bar{N}}{\bar{N}_{\max}}\right) \tag{6}$$

$$\frac{\bar{H}}{\bar{H}_o} = 0.20 + 0.47\left(\frac{\bar{N}}{\bar{N}_{\max}}\right) \tag{7}$$

The multiple linear regressions based on latitude, relative humidity and high-low mean temperatures were developed in the present study as shown in Eq. (8) and Eq. (9). The regression coefficients $a_1, b_1, ..., d_3$ have been obtained from SPSS software using stepping method for the purpose of estimation.

$$\frac{\bar{H}}{\bar{H}_o} = a_2 \cos\phi + b_2\left(\frac{\bar{N}}{\bar{N}_{\max}}\right) \tag{8}$$

$$\frac{\bar{H}}{\bar{H}_o} = a_3 + b_3\left(\frac{\bar{N}}{\bar{N}_{\max}}\right) + c_3\left(R_h\right) + d_3\left(\frac{\bar{N}}{\bar{N}_{\max}}\right) \tag{9}$$

Statistical Analysis

All models were analyzed with three statistical analyses the Root Mean Square Error (RMSE), Mean Bias Error (MBE) and percentage error to evaluate the accuracy of the estimated global solar radiation. The MBE and RMSE provide, respectively, the long-term performance of an equation and the short term performance of an equation. The equation's performance is excellent when value is small. The percentage error provides the variation in predicted and measured value for each month.

The RMSE is determined using Eq. (10).

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(H_{i,predict} - H_{i,measured})^2\right]^{\frac{1}{2}} \tag{10}$$

The MBE is determined using Eq. (11).

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(H_{i,predict} - H_{i,measured}) \tag{11}$$

The percentage error is determined using Eq. (12).

$$Percentage\ error = \left(\frac{H_{i,predict} - H_{i,measured}}{H_{i,measured}} \right) \times 100\% \tag{12}$$

RESULTS AND DISCUSSION

It was observed that the trends of the diurnal pattern of the global solar radiation are maintained at similar pattern for minimum three days repeatedly. Therefore, the diurnal pattern was plotted three days consecutively for global solar radiation, outdoor relative humidity and rain rate. The diurnal patterns of the global solar radiation were classified into five patterns as follow;

Global solar radiation pattern for the clear sky days

The global solar radiation pattern on the clear sky days were recorded from 18th - 20th August 2012 is shown in Figure 2. It was observed that on 19th August 2012, the maximum instantaneous solar insolation for a clear sky day was reaching about 939 W/m^2 at 1.25 p.m. and total solar energy received was 6.51 kWhr/m^2. The solar energy received was slightly lower about 6.4% than in west Malaysia (Othman et al., 1993). Consequently, relative outdoor humidity is high approximately 75 to 80% during the daylight which may obstruct the incoming solar radiation and at night the outdoor humidity can reach up to 96%. Likewise, the clear sky day radiation pattern is occasional throughout the year in east coast Malaysia. This is due to the strong winds from seaside, clouds cover and high outdoor relative humidity. This pattern is common in the month of March until May and August until October whereby high solar energy received in east coast of Malaysia and similar variation was observed in Figure 7.

Global solar radiation pattern for the partially cloudy days

Figure 3 shows the global solar radiation pattern for the partially cloudy days were recorded from 1st - 3rd December 2012. On 1st December 2012, the average solar insolation for these days was less than 425 W/m^2 and total solar energy received was 2.21 kWhr/m^2. The contrary relationship of relative outdoor humidity and global solar radiation can be observed clearly at a number of points in partially cloudy day. This pattern is unpredictable, thus solar energy received may differ with the degree of cloudiness at location.

Global solar radiation pattern for the fully cloudy days

Global solar radiation pattern for the fully cloudy days were recorded from 23rd - 25th December 2012 is shown in Figure 4. This pattern is only occurs when the clouds cover for the entire day, from early morning until late afternoon, sometimes with occasional rain. It was noticed that relative outdoor humidity was very high ranged from 90 – 98% and it also reached up to 99% which was near to the saturation point of the measuring sensor although there were no rains during this pattern. On 24th December 2012, the maximum solar insolation received was 30 W/m^2 and total solar energy received was 0.35 kWhr/m^2. The solar energy value was only 5.38% as compared with that of a clear sky day. The average insolation for the entire day was less than 200W/m^2 for 23th and 25th December 2012 and total solar energy received was 1.74 and 0.46 kWhr/m^2

respectively. This pattern of solar radiation is unusual but it can be observed during winter solstice where the sun's position at most southerly position.

Global solar radiation pattern for the afternoon rain days

Figure 5 shows the global solar radiation pattern for the afternoon rain days were recorded from 6th – 8th October 2012. From the figure, the maximum solar insolation during midday on 7th October 2012 was 1048 W/m^2. Then, a heavy rain started to fall at late afternoon with peak rain rate about 500 mm/hr which was highest recorded in the year of 2012 and it last for 2 hours. Total solar energy received for the day was 4.07 kWhr/m^2. The similar patterns can be observed on 6th and 8th October 2012 with peak rain rate at 150mm/hr and 50mm/hr respectively. In general, the probability of rain falling in the afternoon or dusk is due to convection currents in the morning.

Global solar radiation pattern for the northeast monsoons rain season days

Global solar radiation pattern for the northeast monsoons rain season days were recorded from 19th – 21st January 2013 is shown in Figure 6. The northeast monsoon brings rains and clouds to the east coast from November to March. On 20th January 2013, the maximum solar insolation was 1051 W/m^2 and total solar energy received was 1.22 kWhr/m^2. However, the sudden peak in solar insolation may caused by the refraction and reflection of solar radiation by the cloud and particles in the air (Othman et al., 1993) or clear sky occurrence immediately after rain stop for a moment. Total solar energy received on 19th and 21st January 2012 was 1.63 and 2.44 kWhr/m^2 respectively. The average rain rate for those entire days were less than 3.8 mm/hr and relative outdoor humidity was approximately 90 – 95 %.

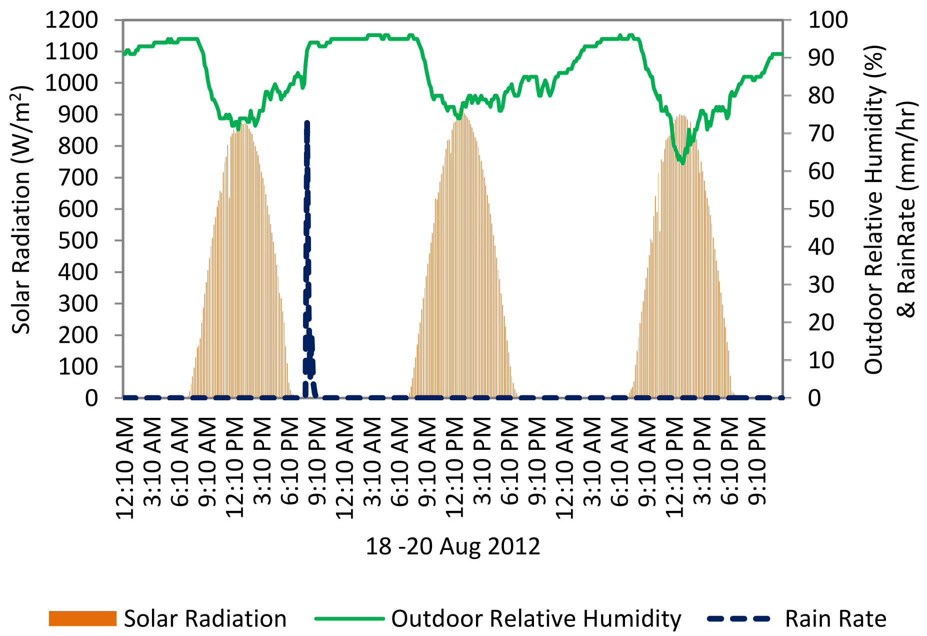

Figure 2. Global solar radiation pattern for the clear sky days.

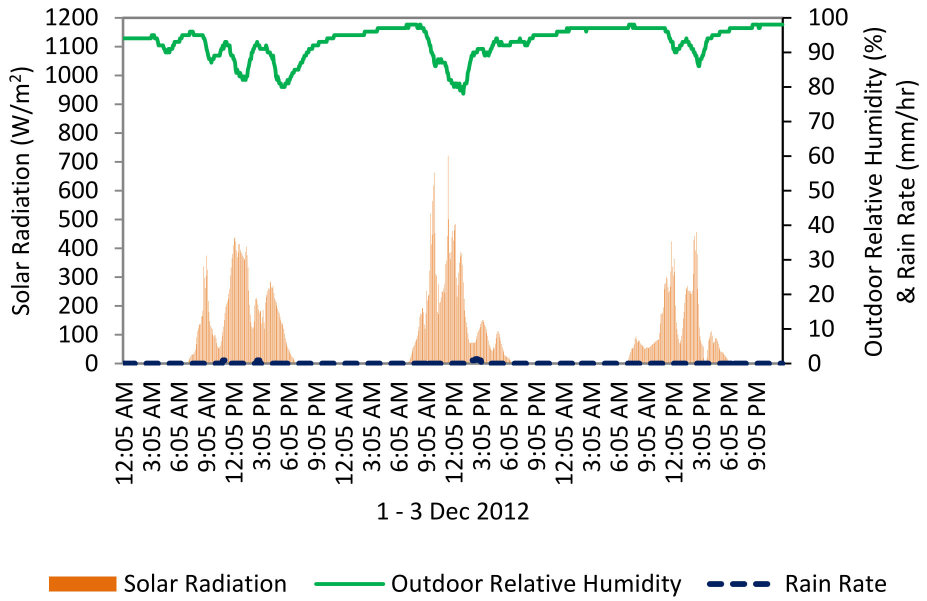

Figure 3. Global solar radiation pattern for the partially cloudy days.

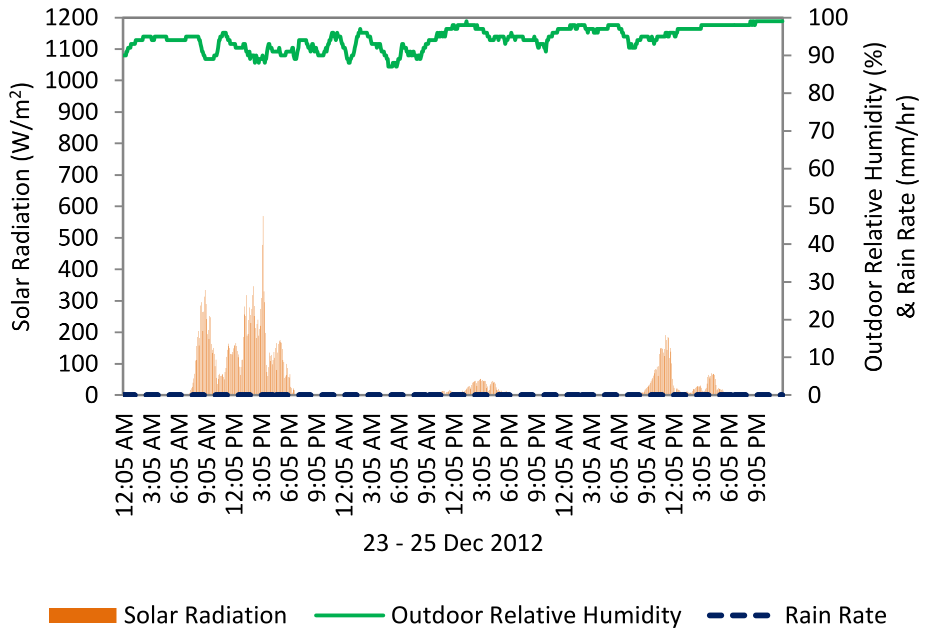

Figure 4. Global solar radiation pattern for the fully cloudy days.

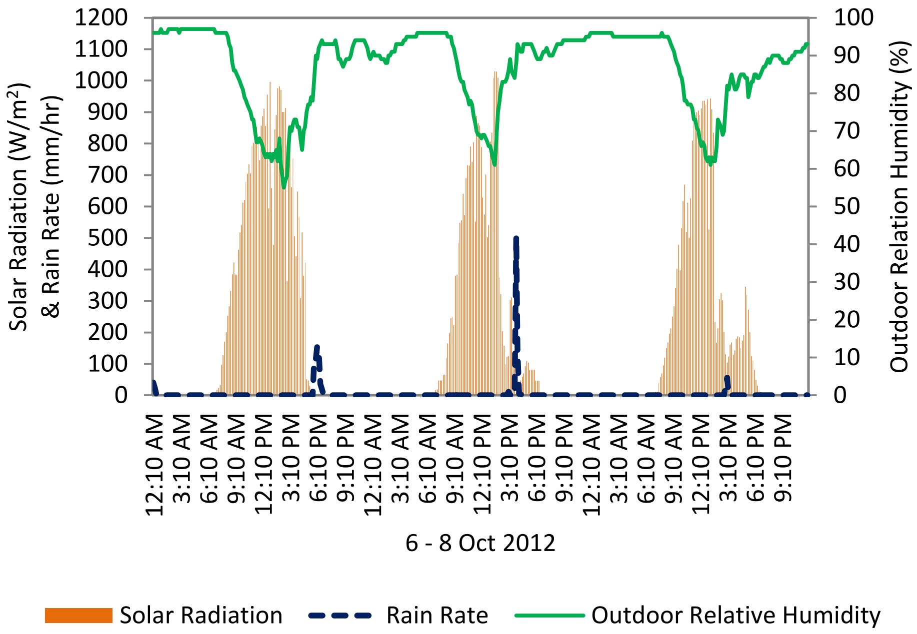

Figure 5. Global solar radiation pattern for the afternoon rain days.

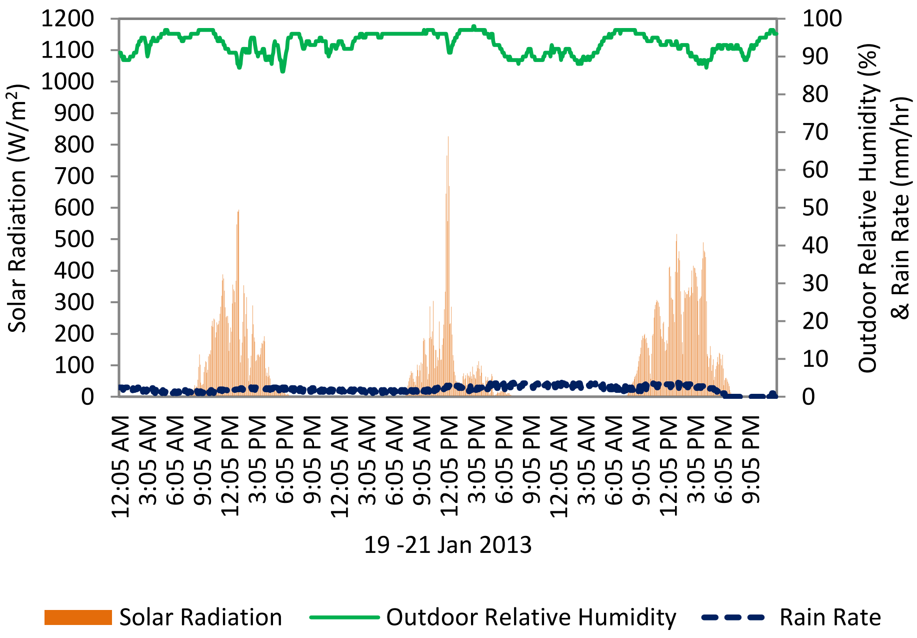

Figure 6. Global solar radiation pattern for the northeast monsoons rain season days.

Regression Modeling

The regression parameters for the estimation of monthly average daily global solar radiation are listed in Table 1. The parameters were obtained from observation of Pekan meteorology station observation from 2006-2012.

Table 1. The regression parameters for the estimation of monthly average daily global solar radiation.

Month	$\bar{H}$ (kWhr/m²)	$\bar{H}_o$ (kWhr/m²)	$\frac{\bar{N}}{\bar{N}_{max}}$	$\frac{\bar{H}}{\bar{H}_o}$	R_h	$\frac{T_L}{T_H}$
January	3.829	9.691	0.379	0.395	0.809	0.783
February	4.536	10.165	0.492	0.446	0.783	0.759
March	4.840	10.467	0.534	0.462	0.806	0.747
April	5.160	10.365	0.595	0.498	0.800	0.726
May	4.879	9.953	0.554	0.490	0.803	0.713
June	4.458	9.658	0.486	0.462	0.798	0.712
July	4.457	9.749	0.482	0.457	0.802	0.711
August	4.928	10.125	0.559	0.487	0.795	0.708
September	4.903	10.362	0.549	0.473	0.795	0.702
October	4.597	10.194	0.502	0.451	0.808	0.722
November	4.061	9.766	0.420	0.416	0.833	0.749
December	4.034	9.503	0.426	0.424	0.838	0.783

The Angstrom's modified linear regressions were developed for Pekan is shown in Eqs. (13) - (15).

$$\frac{\bar{H}}{\bar{H}_o} = 0.22 + 0.47\frac{\bar{N}}{\bar{N}_{max}} \quad (13)$$

$$\frac{\bar{H}}{\bar{H}_o} = 0.22\cos\phi + 0.47\left(\frac{\bar{N}}{\bar{N}_{max}}\right) \quad (14)$$

$$\frac{\bar{H}}{\bar{H}_o} = 0.35 + 0.41\left(\frac{\bar{N}}{\bar{N}_{max}}\right) + 0.065\left(R_h\right) - 0.206\left(\frac{T}{T_{max}}\right) \quad (15)$$

Figure 7 shows the variation of actual to maximum sunshine hour, $\bar{N}/\bar{N}_{max}$ and the clearness index, $\bar{H}/\bar{H}_o$ for Pekan. In the months of November – March shows less sunshine hours and heavy cloudy cover similar to the pattern in Figure 4 which was discussed earlier. The $\bar{N}/\bar{N}_{max}$ goes as low as 0.379 in month of January and it was due to the northeast monsoon season in east coast of Malaysia during this period.

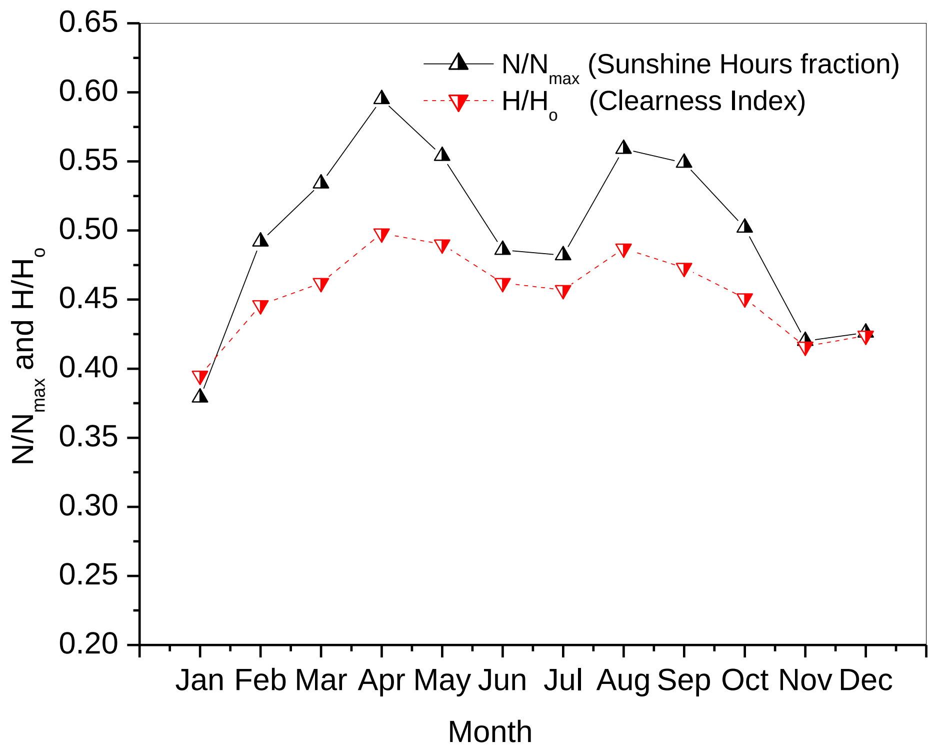

Figure 7. Variation of actual to maximum sunshine hour, $\bar{N} / \bar{N}_{max}$ and the clearness index, $\bar{H} / \bar{H}_o$ for Pekan.

Table 2. Estimation of monthly average daily global solar radiation from various models for Pekan.

Month	$\bar{H}$ Measured	Mutahik et al. 2011 Eq. (6)	Sopian et al. 1992 Eq. (7)	Eq.(13)	Eq.(14)	Eq.(15)
January	3.829	4.064	3.662	3.856	3.852	3.842
February	4.536	4.870	4.384	4.588	4.584	4.537
March	4.84	5.243	4.719	4.929	4.924	4.892
April	5.160	5.523	4.970	5.178	5.173	5.144
May	4.879	5.090	4.581	4.780	4.776	4.801
June	4.458	4.596	4.138	4.332	4.328	4.390
July	4.457	4.619	4.159	4.354	4.350	4.420
August	4.928	5.207	4.687	4.889	4.885	4.912
September	4.903	5.271	4.744	4.951	4.947	4.994
October	4.597	4.936	4.444	4.648	4.644	4.685
November	4.061	4.308	3.881	4.076	4.072	4.122
December	4.034	4.220	3.801	3.992	3.988	3.969

All numerical values are in units of kWhr/m²

Table 3. Percentage error, RMSE, and MBE of the models.

Month	Mutahik et al. 2011 Eq. (6)	Sopian et al. 1992 Eq. (7)	Eq.(13)	Eq.(14)	Eq.(15)
January	6.15%	-4.3%	0.71%	0.61%	0.35%
February	7.35%	-3.3%	1.14%	1.05%	0.02%
March	8.32%	-2.5%	1.83%	1.74%	1.07%
April	7.04%	-3.7%	0.34%	0.26%	-0.31%
May	4.32%	-6.1%	-2.03%	-2.11%	-1.60%
June	3.10%	-7.2%	-2.83%	-2.92%	-1.53%
July	3.63%	-6.7%	-2.31%	-2.40%	-0.84%
August	5.67%	-4.9%	-0.78%	-0.87%	-0.32%
September	7.50%	-3.2%	0.98%	0.90%	1.86%
October	7.37%	-3.3%	1.10%	1.01%	1.92%
November	6.09%	-4.4%	0.37%	0.27%	1.49%
December	4.62%	-5.8%	-1.05%	-1.15%	-1.61%
RSME	0.285	0.219	0.069	0.069	0.057
MBE	0.272	-0.209	-0.009	-0.013	0.002

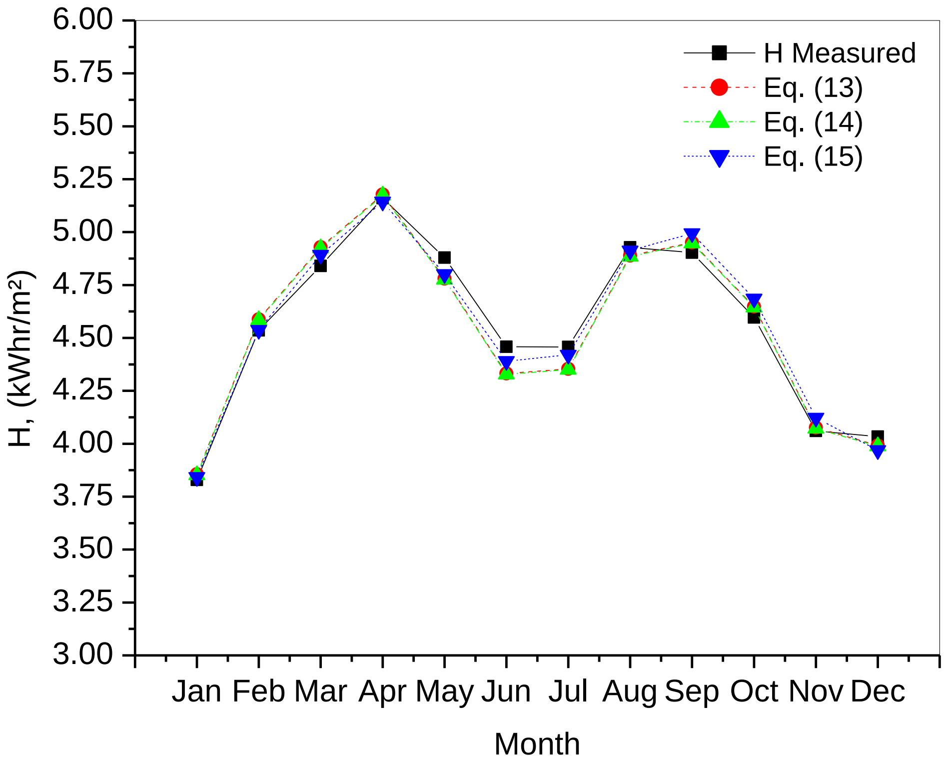

Figure 8. Comparison between estimated values of present developed models Eq. (13) - (15) and measured value of global solar radiation in Pekan.

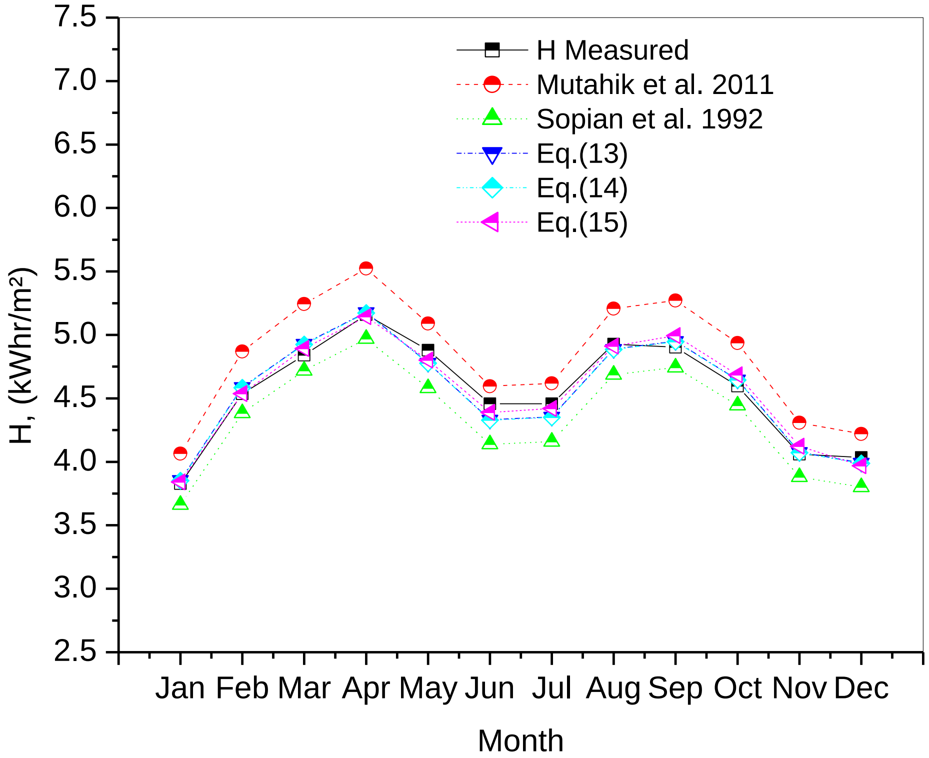

Figure 9. Comparison between estimated values of present developed and established models with measured value of global solar radiation in East Coast Malaysia.

The monthly average daily global solar radiation estimated values using Eqs. (13) - (15) for Pekan are given in Table 2, along with the measured values and the estimated values from the models of Sopian et al. (1992) and Mutahik et al. (2011) Eqs. (6) and (7) respectively. The percentage errors, RMSE, and MBE of the models are shown in Table 3. The RSME and MBE of Eq. (6) was 0.285 and 0.272, while for Eq. (7) was 0.219 and -0.209. The lower value of RSME and MBE were noticed in present developed models and nearly to zero. The minimum and maximum percentage errors in Muzathik et al. (2011) model were 3.10% and 8.32%, whereas in Sopian et al. (1992) model were -2.5% and 7.2%. The present developed models Eq. (13) and (14) have maximum percentage errors about 2.83% and 2.92% respectively, for the month of June. However, the model developed in term of relative humidity and high-low air ambient temperature Eq. (15) shows less percentage error about -1.53% for the same month. Therefore, there is significant influence from meteorology parameters such relative humidity and air temperature in estimation of global solar radiation.

The present developed models predicted values using Eqs. (13) - (15) was compared with measured value of monthly average daily global solar radiation is shown in Figure 8. All present developed models estimated values are in excellent agreement with measured values in Pekan. This finding is also supported by RSME and MBE value which is nearly to zero. In addition, Figure 9 shows that present developed and established models have fine agreement with the measured and estimated values in Pekan because models in the range of ±10.0%. Hence, this range is acceptable due to different type of weather conditions at the particular locality.

CONCLUSION

The knowledge of global solar radiation patterns is extremely important in designing a solar system to utilize the available solar energy efficiently. The five described patterns were generally observed in the east coast region. These patterns information are very useful especially to the local community and solar system manufacturer to employ the solar energy in east coast Malaysia and similar weather condition locations. The orientation of solar panels and collector should also be considered of northeast monsoon period from November to March in order to optimize the solar energy throughout the year. The developed regression models Eq. (13) and (15) are highly recommended to be used to estimate the monthly average daily global solar radiation in Pekan, Pahang and location with similar solar radiation patterns in east coast Malaysia.

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