An Investigation of Modelling Diffuse Solar Radiation Under Tropical Climatic Conditions

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Abstract- This paper reports on the mathematical formulation to determine an appropriate empirical model to estimate diffuse solar radiation under tropical climate conditions. An experimental-mathematical method was developed to estimate diffuse solar radiation by using measured data of incident solar radiation on the horizontal and sloped surfaces based on isotropic and anisotropic models and accuracy of this method was investigated using experimental data for a short and long time-frame. In the analysis section of this paper to discover an accurate empirical model, fifteen decomposition models were compared with calculated results of the experimental-mathematical method developed in this study based on hourly, monthly, and annual mean clearness index. This study revealed that of all models, the Louche model was the most accurate to estimate diffuse radiation on a horizontal surface for tropical climate conditions prevalent in Malaysia. The statistical analysis results for five stations in Peninsular Malaysia exhibited MBE, RMSE, MBE (%), and RMSE (%) in the ranges of 0.02-0.05, 0.12-0.17, 1.00-2.55, and 5.67-8.27 respectively for averaged diffuse solar radiation based on monthly mean daily and annually mean monthly clearness index. This statistical analysis confirmed the accuracy of the methodology developed in this study.

Keywords Solar energy modeling, global solar radiation, diffuse solar radiation, tropical climate.

1. Introduction

Increasing energy demand driven by population growth requires even more reliance on fossil fuels with ensuing destructive impacts on the global environment. Renewable energy originating from natural sources offers the cleanest and globally abundant resource. Solar radiation from the sun is the ultimate renewable energy source, its increasing utilization can be traced to inherent advantages such as accessibility, inexpensive system setup, and scientific advances in solar technology. Therefore, the estimation of incident solar radiation and its components at earth's surface with respect to climate zone is essential in order to design solar energy systems with optimized efficiency. The solar radiation at ground level, also known as the global solar radiation, is determined by earth's movements and atmospheric conditions and, consists of three radiation components: (a) direct, (b) diffuse, and (c) reflected. Accurate determination of solar radiation components is critical to achieve optimum performance of any solar system with its specified location. Historically, researchers have developed universal models based on parametric and decomposition methods to determine direct and diffuse solar radiation [1]. Gueymard (1993) reported on parametric models based on precise knowledge of atmospheric composition and environmental conditions including turbidity, partial sunshine, cloud cover, and perceptible water content. Such parametric models can predict direct, diffuse, and global irradiances under clear sky based on solar zenith angle, solar constant attenuation factors related to a multiplicity of physical factors, and atmospheric data. The decomposition models, in contrast with parametric models, derive empirical relationships based on experimental data without relying on a physical model to estimate diffuse radiation. Decomposition models are a function of the correlation between diffuse and total radiation incident on a horizontal surface. This correlation is the clearness index, which is the ratio of global horizontal to extra-terrestrial radiation [3]. Both parametric and decomposition methods have their advantages and disadvantages in terms of their ability to estimate global solar radiation components. The parametric method is more accurate than the decomposition method using meteorological parameters and environmental conditions, while the decomposition method utilizes the regression analysis based on a clearness index versus the amount of incident solar radiation on a horizontal surface. Although the decomposition method is generally less accurate, it is still applicable due to its simplicity and ability to calculate diffuse radiation in uncertain weather and unpredictable sky conditions when meteorological parameters exhibit rapid variations.

This study addresses global solar radiation and its components in Peninsular Malaysia. Given its location near the equator, Malaysia is blessed with abundant potential for solar energy systems to operate at near optimum efficiency. Malaysia has a tropical climate with uniform temperature, frequent rainfall, and randomly variable sunny-to-cloudy skies [4]. Based on parametric and decomposition models, researchers have investigated accurate models in order to predict direct, diffuse and global solar radiation in terms of weather and sky conditions applicable to various regions of Malaysia. Daut et al. (2011) theoretically investigated the performance of the solar system by maximizing the amount of solar radiation in Perlis, the region of Northern Peninsular Malaysia. They used a clear sky and isotropic diffuse model to determine direct and diffuse solar radiation components. Khatib et al. (2012) developed linear and non-linear decomposition models based on regression analysis and artificial neural networks (ANN) model to estimate diffuse solar energy on a horizontal surface using long term solar energy data (1975 to 2005) for five regions of Peninsular Malaysia. Their statistical analysis revealed that ANN model to be more accurate than linear and non-linear decomposition models. Shavalipour et al. (2013) modified Daneshyar model using the most recent measurements of the average solar constant, sun-earth distance correction factor, altitude factors, and monthly surface albedo factor to determine direct, diffuse and monthly average daily global solar radiation components for Peninsular Malaysia. Ahmad et al. (2015) developed single and multiple-parameter empirical models based on available meteorological parameters including temperature, cloud cover, rain precipitate, relative humidity, wind speed, and pressure. By incorporating regression analysis, they estimated monthly global solar irradiance for five meteorology stations in Malaysia and showed that the accuracy of multiple-parameter was higher than a single parameter; temperature and rain were considered significant parameters in all the multiple-parameter models.

As the seasonal and annual variations change rapidly due to cyclical and global warming effects, it is increasingly important that research work is fully updated to incorporate the latest weather changes and evaluate global solar radiation and its components. Since practically all models have been determined empirically and relate to specific geographical locations, a comprehensive computational method is needed to estimate solar radiation components with adaptability to atmospheric conditions. Accordingly, the principal theme of this research is to develop an integrated experimental-mathematical method based on a combination of measured data and literature models with default sun position in the sky and using a multi-layer calculation network to estimate diffuse solar radiation under tropical climate and unpredictable sky conditions.

2. Experimental Setup

The experimental data used in this study was acquired from two sources consisting of: (a) outdoor testing and (b) National Aeronautics and Space Administration (NASA) data for five stations in Peninsular Malaysia. The outdoor testing was carried out to determine global solar radiation on horizontal and sloped surfaces. The experimental data acquisition system was located at solar energy research institute (SERI), University Kebangsaan Malaysia (UKM) at latitude and longitude angles of 2.93° 'N, 101.78° 'E. The site was picked in such a way that no shadow was cast on the surface and was chosen to be away from any obstruction which might have blocked accurate measurements of incident solar radiation. The measurements were recorded at an interval of 10-seconds of solar radiation on horizontal and sloped surfaces for three time periods (morning, afternoon, and evening) and varied with weather conditions typical to the tropical climate of this location in Malaysia. Outdoor measurements were carried out as a function of two slope angles (7 and 15-degrees) at four main orientations, i.e., north, south, west, east and to consider the variation of diffuse radiation with more accuracy, while the surface in horizontal configuration was used as the reference as described in Fig. 1. Meteorological data, including temperature, relative humidity, global solar radiation, and wind were also recorded.

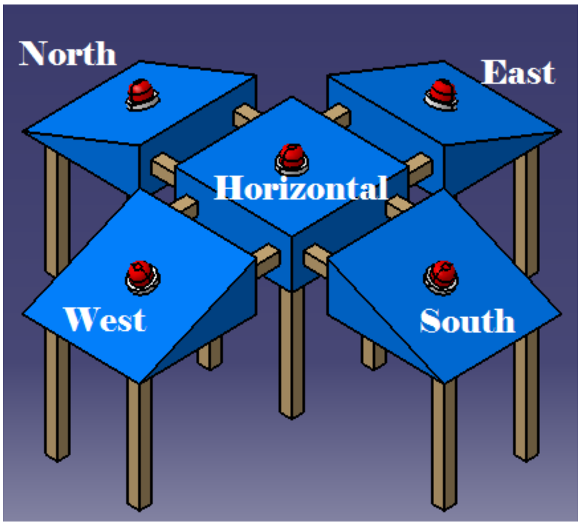

Fig. 1. Experimental configuration for solar radiation measurements as a function of angle and orientation.

Finally, NASA climatology data was used to determine incident solar radiation on the horizontal and sloped surfaces at the latitude of locations to determine the ratio of direct and diffuse solar radiation components for five locations in north, south, west, east and center of Peninsular Malaysia as identified in the map shown in Fig. 2.

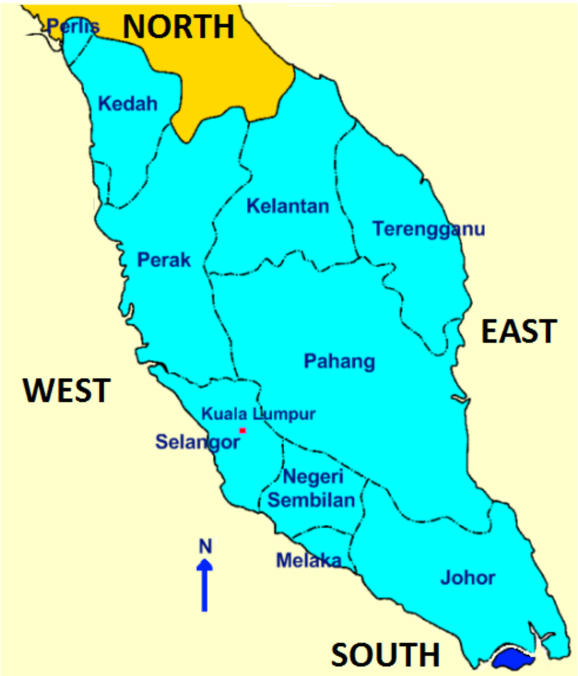

Fig. 2. Map of Peninsular Malaysia identifying five locations for data comparison.

3. Theory and Model

The main objective of this study is to determine the accurate decomposition model to estimate diffuse solar radiation in tropical climate zones. Since the estimation of diffuse radiation is difficult and imprecise, therefore an accurate method should be provided to determine diffuse radiation. In this study the mathematical method is presented based on a combination of experimental and theoretical frameworks, to estimate diffuse solar radiation in various climate zones. In the first section, the calculation method is presented to estimate global solar radiation components using decomposition models as a function of the clearness index. In the second section, the experimental-mathematical method is provided to determine the appropriate empirical model among fifteen decomposition models to estimate diffuse solar radiation, by using the measured data from the incident solar radiation and the mathematical formalism for describing incident solar radiation on horizontal and sloped surfaces, in the terms of a numerical solution and based on a search approach. In the final section, the statistical analysis methods used in this study are presented.

3.1 Determination of the Appropriate Decomposition Model

In this section, the fifteen decomposition models are provided in order to estimate diffuse solar radiation on a horizontal surface by using the average of clearness index of location pertaining to the tropical climate of Malaysia. The horizontal diffuse radiation is determined by:

$$S_{dH} = (R_{dH})_{Deco} . S_H \qquad (2)$$

where S_H is the measured solar radiation on a horizontal surface and R_{dH} is the ratio of diffuse solar radiation (diffuse fraction) on a horizontal surface and can be determined by decomposition models [3]. Following the determination of the clearness index of location (Kt), the appropriate decomposition model is chosen by analyzing fifteen models discussed in Table 1. Linear and non-linear decomposition models have been used extensively to estimate solar radiation components on an hourly basis.

The direct solar radiation on a horizontal surface is then determined by

$$S_{bH} = \left(1-(R_{dH})_{Deco}\right) . S_H \qquad (2)$$

The accurate model must be selected with the lowest error of estimation in comparison with the results of the experimental-mathematical method with the aid of statistical analysis methods.

3.2. Experimental-Mathematical Model to Estimate Diffuse Radiation

In this part of the research, by combining the computational equations of global solar radiation on a horizontal and sloped surface, utilizing the ratio of global solar radiation on the sloped surface to that horizontal surface by using recorded data, geometric factor and isotropic and anisotropic solar diffuse radiation models, the ratio of solar radiation on the horizontal surface can be obtained and the results can be compared with calculation results of appropriate decomposition model. Therefore, In the first step, the equations of global solar radiation on a horizontal and sloped surface are presented and in the second step, the computational network is provided. As illustrated in Figure 3, the calculation steps along with the details are as follows:

1- The experimental configuration is accomplished based on five surfaces arranged at varying slope angles and orientations, to characterize incident solar radiation.

2- Solar radiation data from the horizontal and inclined pyranometers are stored and analyzed.

3- The ratio of global radiation incident on the sloped surface to that on a horizontal surface is determined using measured data.

4- The beam radiation and reflected radiation on a sloped surface are calculated.

5- The ratio of diffuse radiation on the sloped surface to that on a horizontal surface is determined.

6- Diffuse radiation models (isotropic and anisotropic models) considering the slope angle and orientation of the surface are utilized to calculate diffuse radiation on a horizontal surface.

7- Results of decomposition models are obtained to determine the ratio of diffuse solar radiation on a horizontal surface based on the average of the clearness index.

8- Compare the results of the experimental-theoretical method (step 6) and the results of the decomposition models (step 7) by statistical analysis methods to determine the accurate decomposition model.

9- Diffuse solar radiation incident on the horizontal surface is obtained by multiplying the ratio of diffuse radiation on the horizontal surface (step 8) to horizontal global solar radiation (step 2).

10- The horizontal beam solar radiation is determined by subtracting the total solar radiation on the horizontal surface (step9) and horizontal diffuse solar radiation (step 2).

Table 1. Fifteen decomposition models used for the determination of the ratio of diffuse radiation on a horizontal surface.

Model	**Constraints**	**Diffuse Fraction for Horizontal Surface (RdH)**
Spencer [8]	0.35≤ Kt ≤0.75	$(0.94+0.0118\|\phi\|)-(1.185+0.0135\|\phi\|)K_t$
Erbs [9]	0.15≤ Kt ≤0.17	$0.9511-0.1604K_t+4.388K_t^2-16.638K_t^3+12.336K_t^4$
Hawlader [10]	0.225 < Kt ≤ 0.775	$1.135-0.9422K_t-0.387K_t^2$
Muneer [11]	0.3 ≤ Kt ≤ 0.78	$0.9698+0.4353K_t-4.4499K_t^2+2.1888K_t^3$
Reindl [12]	0.3 ≤ Kt ≤ 0.78	$1.45-1.67K_t$
Louche [13]	0.17 < Kt ≤ 1	$0.98-0.059K_t-0.99K_t^2+5.205K_t^3-15.307K_t^4+10.676K_t^5$
Kumar [14]	0.17 < Kt ≤ 1	$1.0086-0.178K_t$
Lok and Li [15]	0.35 ≤ Kt ≤ 0.75	0.273
Orgill [16]	0.21 ≤ Kt ≤ 0.76	$1.57-1.84K_t$
Miguel [17]	0 ≤ Kt ≤ 1	$0.724+2.738K_t-8.32K_t^2+4.967K_t^3$
Blond [18]	0.3 ≤ Kt ≤ 0.78	$1+\exp\left(7.997\left(K_t-0.586\right)\right)^{-1}$
Oliveira [19]	0.3 ≤ Kt ≤ 0.78	$0.97+0.8K_t-3K_t^2-3.1K_t^3+5.2K_t^4$
Karatasou [20]	0.17 < Kt ≤ 1	$0.9995-0.05K_t-2.4156K_t^2+1.4926K_t^3$
Soares [21]	0.17 < Kt ≤ 1	$0.9+1.1K_t-4.5K_t^2-0.01K_t^3+3.14K_t^4$
Jacovides [22]	0.35 ≤ Kt ≤ 0.75	$0.94+0.937K_t-5.01K_t^2+3.32K_t^3$

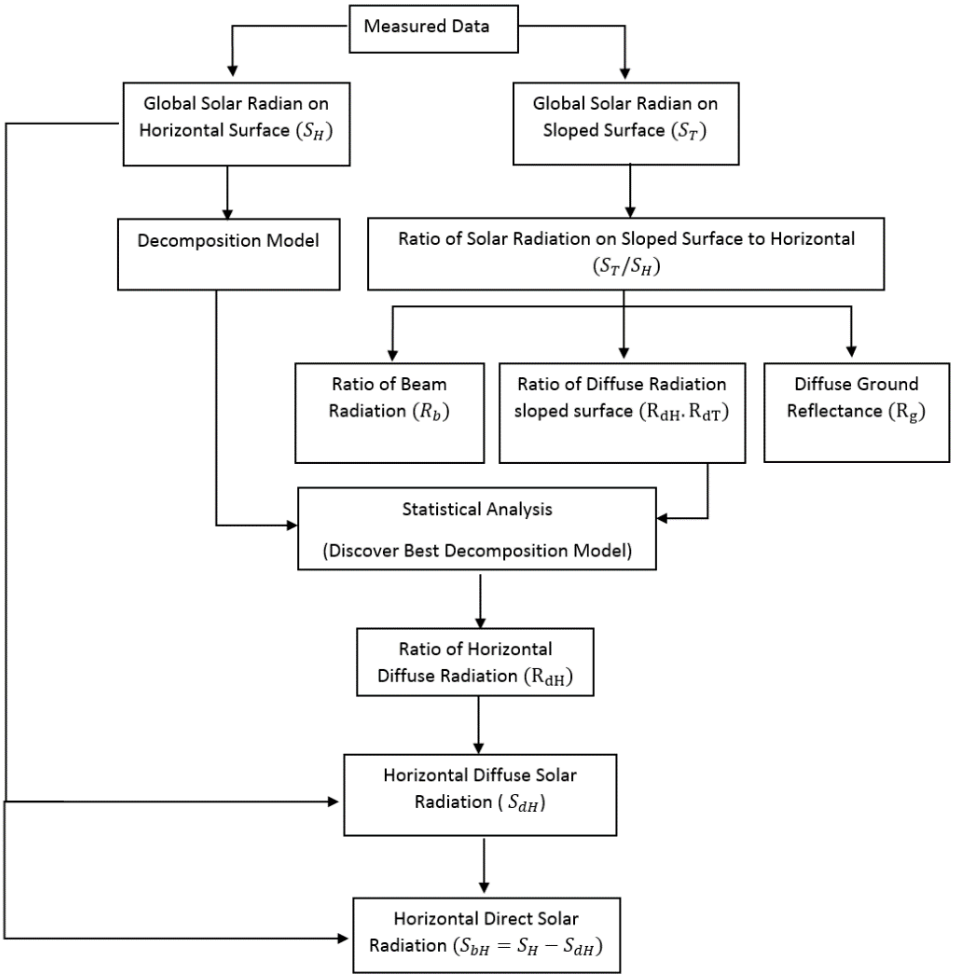

Fig. 3. The flowchart for the determination of global solar radiation components on a horizontal surface.

3.2.1 Solar Radiation on Horizontal Surface

Solar radiation incident on a horizontal surface is assumed to be composed of direct and diffuse radiation components as the reflected irradiance is ignored in the absence of any significant structure specifically directing light towards the receiver. The diffuse radiation component is defined as the fraction scattered from the direct solar beam in the atmosphere. The global solar radiation incident on the horizontal surface is therefore given by [23]

$$S_H = S_{bH} + S_{dH} \tag{3}$$

where SbH and SdH represent horizontal direct and diffuse solar radiation components respectively.

3.2.2 Solar Radiation on Sloped Surface

The total irradiation incident on the sloped surface consists of three components: direct, diffuse, and reflected, and is defined by [24]

$$S_{bT} = S_{bT} + S_{dT} + S_{rT} \tag{4}$$

where SbT, SdH and SrT represent direct, diffuse and reflected solar radiation components respectively.

The intensity of direct solar radiation incident on a surface is a function of its angle of incidence. The direct solar radiation on the sloped surface is determined by multiplying the geometric factor based on incidence angle and the horizontal direct solar radiation and is given by

$$S_{bT} = R_{bT} S_{bH} \tag{5}$$

Table 2. Isotropic and anisotropic models used to determine the ratio of diffuse radiation on the sloped surface.

Model	Diffuse Fraction for Sloped Surface (RdT)	Category
Liu and Jordan [27]	$\frac{1}{2}\left(1+\mathrm{COS}\left(\theta_C\right)\right)$	Isotropic
Korokanis [28]	$\frac{1}{3}\left(2+\mathrm{COS}\left(\theta_C\right)\right)$	Isotropic
Hay and Davies [29]	$F_{Hay}.R_b+C_\beta\left(1-F_{Hay}\right)\left(\frac{1+\mathrm{COS}\left(\theta_C\right)}{2}\right)$	Anisotropic
Reindl [30]	$F_{Hay}.R_b+C_\beta\left(1-F_{Hay}\right)\left(\frac{1+\mathrm{COS}\left(\theta_C\right)}{2}\right)\left[1+F.\mathrm{SIN}^3\left(\theta_C/2\right)\right]$	Anisotropic

where the geometric factor, Rb, is the ratio of solar beam radiation on the inclined surface to that on a horizontal surface and is given by

$$R_{bT}=\begin{cases}\dfrac{\cos(\theta)}{\cos(\theta_Z)} & \text{If } \tan(\alpha)+\tan(\theta_C)\cos(\lambda-\lambda_S)<0\\ 0 & \text{otherwise}\end{cases} \tag{6}$$

where θ is the angle of incidence, θz is zenith angle θc is a slope angle, α is the solar altitude angle, γ is the surface azimuth angle, and γs is the sun azimuth angle [25].

The second term in equation (4) is diffuse solar radiation, and it is determined by multiplying the ratio of diffuse radiation on the sloped surface and the horizontal diffuse solar radiation and is given by

$$S_{dT}=R_{dT}S_{dH} \tag{7}$$

where RdT is the ratio of diffuse radiation on the sloped surface and includes isotropic and anisotropic sky models discussed in Table 2 [26].

The last term in Equation (4) is total reflected radiation incident on the sloped surface from the ground and surrounding regions, it is determined by multiplying the diffuse ground reflectance in horizontal solar radiation and is described by

$$S_{rT}=\rho_g(S_H)(\frac{1-\cos(\theta_C)}{2}) \tag{8}$$

where ρg is the diffuse ground reflectance [31].

By combining Eqs. (3) to (8), the ratio of diffuse solar radiation on the horizontal surface is determined by the following relationship:

$$S_{dH}=\frac{\left(\dfrac{S_T}{S_H}\right)_{EXP}-R_{bT}-\rho_g(\dfrac{1-\cos(\theta_C)}{2})}{R_{dT}-R_{bT}} \tag{9}$$

Based on equation (9), the mathematical formalism to determine the ratio of horizontal diffuse solar radiation is derived by combining four sections: (a) the ratio of global solar radiation on the sloped surface to that horizontal surface which is determined by measuring the incident solar radiation on the horizontal and sloped surfaces at four orientations, (b) the isotropic and anisotropic sky models to compute diffuse solar radiation on a sloped surface, (c) the geometric factor, and (d) ground reflectance.

The computational process, described in Fig. 4 is based on a multi-layer feedforward network consisting of four calculation layers based on input parameters including measured solar radiation incident on a horizontal and sloped surface, diffuse ground reflectance, sloped angle of the solar surface, angle of incidence, and zenith angle, is used to calculate horizontal diffuse solar radiation. In the first layer, the ratio of direct and global solar radiation incident on the sloped surface to that on the horizontal surface, as well as ground reflectance are calculated. In the second layer, the ratio of diffuse solar radiation incident on the sloped surface is calculated based on isotropic and anisotropic sky models. In the third layer, the ratio of diffuse solar radiation on a horizontal surface is computed. In the last layer, using statistical analysis methods and with results from the appropriate decompaction model obtained in the first section, the accuracy of the experimental-mathematical method using a combination model is revealed.

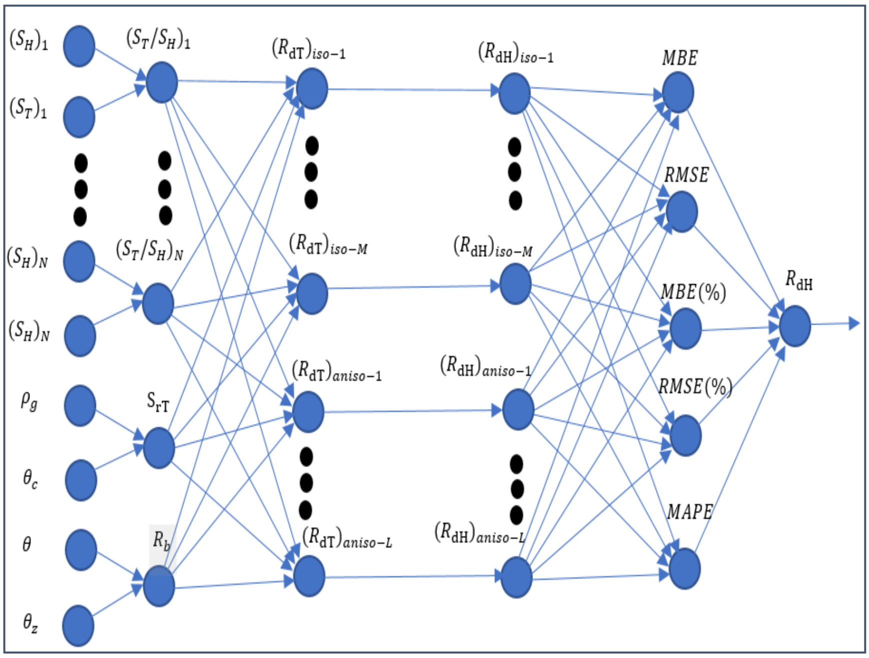

Fig. 4. Network computing architecture to determine horizontal diffuse solar radiation.

3.3. Statistical Analysis

Statistical analysis has been used to determine a comprehensive distribution of errors in the model calculations for the estimation of solar radiation components on a horizontal surface. The estimated diffuse solar radiation at various tropical climate conditions is compared with the measured data to evaluate the accuracy of the developed approach. An ideal model is one with the least error, which is distributed evenly or with small variance in error. The statistical parameters used to validate the methodology in this study include the mean bias error (MBE), root mean square error (RMSE) and mean absolute percentage error (MAPE).

The mean bias error is an indicator for the average deviation of the predicted values from the measured data and provides meaningful information on the long-term model performance, and is defined by:

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}(\mathrm{M}_{\mathrm{cal}} - \mathrm{M}_{\mathrm{meas}}) \tag{10}$$

Similarly, the relative mean bias error is defined by

$$\mathrm{MBE}(\%) = \frac{\mathrm{MBE}}{\frac{1}{n}\sum_{i=1}^{n}(\mathrm{M}_{\mathrm{meas}})} \times 100 \tag{11}$$

The root mean square error (RMSE) provides information on the short-term model performance by comparing the variation of the predicted values around the measured data. RMSE is defined by

$$\mathrm{RMSE} = \left(\frac{1}{n}\sum_{i=1}^{n}(\mathrm{M}_{\mathrm{cal}} - \mathrm{M}_{\mathrm{meas}})^2\right)^{1/2} \tag{12}$$

The expression for relative root mean square error is given by

$$\mathrm{RMSE}(\%) = \frac{\mathrm{RMSE}}{\frac{1}{n}\sum_{i=1}^{n}(\mathrm{M}_{\mathrm{meas}})} \times 100 \tag{13}$$

Finally, the mean absolute percentage error defined by the deviation between the measured values and theoretical results is given by

$$\mathrm{MAPE}(\%) = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\mathrm{M}_{\mathrm{cal}} - \mathrm{M}_{\mathrm{meas}}}{\mathrm{M}_{\mathrm{meas}}}\right| \times 100 \tag{14}$$

Since the errors are squared before they are averaged, the RMSE values should be larger or equal to the MBE. If all errors have comparable magnitude, the difference between RMSE and MBE results can be ignored. In addition, the difference between RMSE and MBE is largest when the signs of error change constantly, which reflects on test data fluctuation related to the climatic condition. The ideal model is a model with a small amplitude of errors in which the RMSE result is minor and equal to the MBE test result, or the result of the RMSE result is minor, and the MBE test is approximately zero. The analysis of the MBE (%) and RMSE (%) results is similar to the MBE and RMSE; both are used to avoid the comparison error between the module in terms of sample size or magnitude of data. The MAPE (%)

test is used to determine the accurate forecasting model by displaying the deviation between the measured values and theoretical results to evaluate the performance of the computational models of solar systems. The low error in this test indicates small differences between experimental data and calculations.

4. Result and Discussion

The results of the developed model and calculations are applied to find an appropriate decomposition model to estimate global solar radiation components as a function of the clearness index in Peninsular Malaysia. Also, the accuracy of the experimental-mathematical method developed in this study to evaluate diffuse radiation with regards to various climate zones has been investigated.

4.1. Estimation of Accuracy of Experimental-Mathematical Method to Determine Horizontal Diffuse Radiation

The statistical analysis, described in Tables 3 and plotted in Fig. 5 is based on the comparison of the diffuse solar radiation determined by using the experimental-mathematical method and experimental data for different time-frames. The results of statistical analysis indicated that the accuracy of the experimental-mathematical method using isotropic models is higher than the combination with anisotropic model and estimation errors are distributed with small variance in this method with isotropic models. Therefore, in the following, the experimental-mathematical method includes the isotropic model is used to determine an appropriate decomposition model.

4.2. Determination of Appropriate Decomposition Model

In the second part of this section, fifteen decompositions models were investigated to determine the most accurate model for the prediction of global solar radiation components within the climate zones of Peninsular Malaysia. This prime model was selected with the lowest error of calculations based on statistical indicators, i.e., MBE (W/m²), MBE (%), RMSE (W/m²), RMSE (%), and MAPE (%). The overall performances of the 15 decomposition models were evaluated based on daily mean hourly, monthly mean daily, and yearly mean monthly clearness index. Based on the result in Table 5, the accuracy of all models has been improved for a long-term timeframe, i.e., monthly and annually mean clearness index, while Lok and Li model is more accurate for a short-term timeframe i.e., daily mean hourly clearness index. The results of statistical analysis methods indicated that Louche model was determined to be far the most accurate for prediction of diffuse solar radiation for all types of clearness index. In this model, the direction of errors has mostly changed with small variance. Furthermore, the statistical analysis results indicated a large error outlier for Spencer, Hawlader, and Lok and Li models which shows the variance of errors in few samples are large while in the rest of the samples, the value of the difference between experimental data and calculation results is small and similar.

Table 3. Statistical analysis of comparison calculated value of developed method based on isotropic and anisotropic models with results of Louche model for three type of clearness index.

Diffuse Model	Statistical Analysis	Daily Average Hourly	Monthly Average Daily	Yearly Average Monthly
ISOTROPIC	MBE	-0.28	-0.05	-0.25
	RMSE	7.63	6.77	6.73
	MBE(%)	-0.06	-0.01	-0.05
	RMSE(%)	1.61	1.43	1.42
ANISOTROPIC	MBE	-2.35	-2.82	-2.99
	RMSE	8.40	7.23	7.76
	MBE(%)	-0.50	-0.60	-0.63
	RMSE(%)	1.77	1.52	1.64

Fig. 5. The mean absolute percentage error (MAPE) of calculated value of developed method

Table 4. Statistical analysis results to discover the appropriate decomposition models

Model	Daily Mean Hourly Clearness Index					Monthly Mean Daily Clearness Index					Annually Mean Monthly Clearness Index				
	MBE	RMSE	MBE(%)	RMSE(%)	MAPA(%)	MBE	RMSE	MBE(%)	RMSE(%)	MAPA(%)	MBE	RMSE	MBE(%)	RMSE(%)	MAPA(%)
Erbs	-1.76	9.79	-0.37	2.07	2.70	-1.85	7.80	-0.39	1.65	1.68	-2.18	9.12	-0.46	1.92	2.00
Spencer	-3.88	20.50	-0.82	4.33	5.24	-4.15	20.79	-0.88	4.39	4.73	-4.37	22.11	-0.92	4.66	5.06
Hawlader	-5.12	16.17	-1.08	3.41	3.95	-5.21	16.19	-1.10	3.41	3.31	-5.45	17.70	-1.15	3.73	3.70
Muneer	-3.31	17.42	-0.70	3.68	4.82	-3.57	17.21	-0.75	3.63	3.86	-3.98	19.64	-0.84	4.14	4.47
Reindl	-2.00	10.18	-0.42	2.15	2.87	-2.23	9.37	-0.47	1.98	2.03	-2.57	11.08	-0.54	2.34	2.45
Louche	-1.31	8.02	-0.28	1.69	1.94	-1.44	7.00	-0.30	1.48	1.46	-1.62	7.26	-0.34	1.53	1.54
Kumar	-4.55	12.68	-0.96	2.67	3.28	-4.54	11.67	-0.96	2.46	2.24	-4.85	13.50	-1.02	2.85	2.71
Lok and Li	-4.86	27.25	-1.03	5.75	6.27	-5.18	27.24	-1.09	5.75	6.30	-5.18	27.23	-1.09	5.74	6.30
Orgill	-1.74	9.61	-0.37	2.03	2.71	-1.90	8.00	-0.40	1.69	1.73	-2.28	9.57	-0.48	2.02	2.10
Miguel	-1.91	9.98	-0.40	2.10	2.80	-2.07	8.65	-0.44	1.82	1.87	-2.40	10.19	-0.51	2.15	2.25
Boland	-1.88	9.71	-0.40	2.05	2.65	-1.99	8.30	-0.42	1.75	1.80	-2.26	9.49	-0.48	2.00	2.08
Oliveira	-2.27	11.47	-0.48	2.42	3.30	-2.48	10.66	-0.52	2.25	2.32	-2.84	12.64	-0.60	2.67	2.81
Karatasou	-2.57	12.57	-0.54	2.65	3.40	-2.81	12.47	-0.59	2.63	2.75	-3.06	13.95	-0.65	2.94	3.11
Soares	-2.55	12.71	-0.54	2.68	3.61	-2.76	12.24	-0.58	2.58	2.69	-3.11	14.22	-0.66	3.00	3.18
Jacovides	-2.36	11.60	-0.50	2.45	3.23	-2.58	11.21	-0.55	2.36	2.45	-2.89	12.90	-0.61	2.72	2.87

4.3. Estimation of Accuracy of Appropriate Decomposition model to Determine Horizontal global Radiation Components

As described in Table 5, the accuracy of the experimental-mathematical method used in this study is applied to 5-stations with geographical locations of south, north, west, east, and center of Peninsular Malaysia. The extensive comparison of experimental data and simulation results indicates good agreement between measured data and calculation results of diffuse radiation on a horizontal surface, which confirms the acceptable accuracy of the method developed in this study. In addition, by comparing the calculated values with results of Louche model for average of diffuse solar radiation based on monthly mean daily and yearly mean monthly clearness index, statistical analysis indicators, i.e., MBE, RMSE, MBE (%), and RMSE (%) have been observed to be in the ranges 0.02-0.05, 0.12-0.17, 1.00-2.55, and 5.67-8.27 for an average of diffuse solar radiation based on monthly mean daily and yearly mean monthly clearness index, which means that calculation errors are evenly distributed with small variance in the calculation of diffuse solar radiation based on the yearly mean monthly clearness index. The direction of the errors is mostly observed for calculation based on the monthly mean daily clearness index that reflects fluctuations in measurements and calculations. The data plotted in Fig. 6 and Table 5 illustrates that the deviation between the results of Louche model and calculations based on the combination method is approximately identical based on monthly mean daily and yearly mean monthly clearness indexes for five specific regions in Peninsular Malaysia.

Table 5. Statistical analysis results of the accuracy of Louche model to estimate diffuse radiation in Peninsular Malaysia.

Station		MBE	RMSE	MBE(%)	RMSE(%)
North	MMDCI	0.17	0.30	8.48	14.50
	AMMCI	0.12	0.31	5.50	13.73
South	MMDCI	-0.07	0.14	-3.31	6.61
	AMMCI	-0.08	0.13	-3.95	6.39
East	MMDCI	-0.18	0.28	-8.58	13.47
	AMMCI	0.06	0.28	3.11	14.62
West	MMDCI	0.15	0.22	7.27	10.38
	AMMCI	0.16	0.23	7.17	9.88
Center	MMDCI	0.11	0.19	5.27	8.83
	AMMCI	0.17	0.22	7.42	9.82
Average	MMDCI	0.02	0.17	1.00	8.27
	AMMCI	0.05	0.12	2.55	5.67

MMDCI : Monthly Mean Daily Clearness Index
AMMCI : Annually Mean Monthly Clearness Index

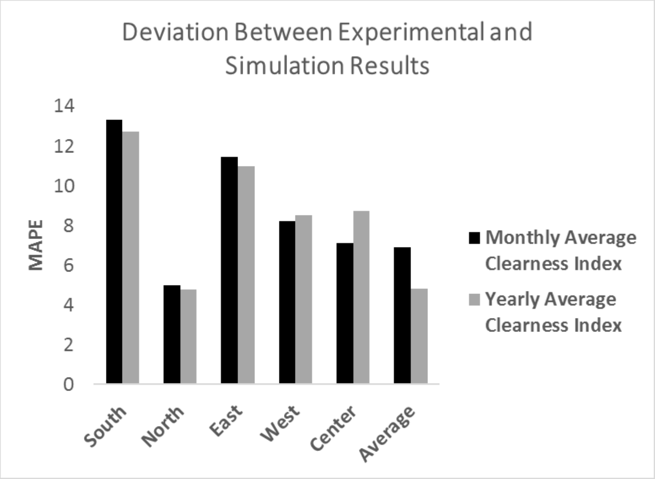

Fig. 6. The mean absolute percentage error (MAPE) of Louche model accuracy for a specific region in Peninsular Malaysia.

Figure 7 plots the NASA climatology data and calculations of the global solar radiation based on Louche model using the monthly mean daily clearness index for five geographical locations in Peninsular Malaysia. In the following subsections, the estimation of horizontal global solar radiation is discussed in terms of the accuracy of the appropriate decomposition model by calculating diffuse solar radiation based on Louche model as a 5th-degree polynomial regression model and measured direct solar radiation.

5. Conclusion

We have developed an experimental-mathematical method to determine appropriate decomposition model to estimate diffuse solar radiation in tropical climate zone. This research consisted of two sections. In the first section, the experimental-mathematical method was developed to estimate diffuse solar radiation by considering the measured data of global solar radiation on the horizontal and sloped surfaces. The calculated results were compared with experimental data for short and long time-frames to discover the accuracy of method. Statistical analysis indicated that the

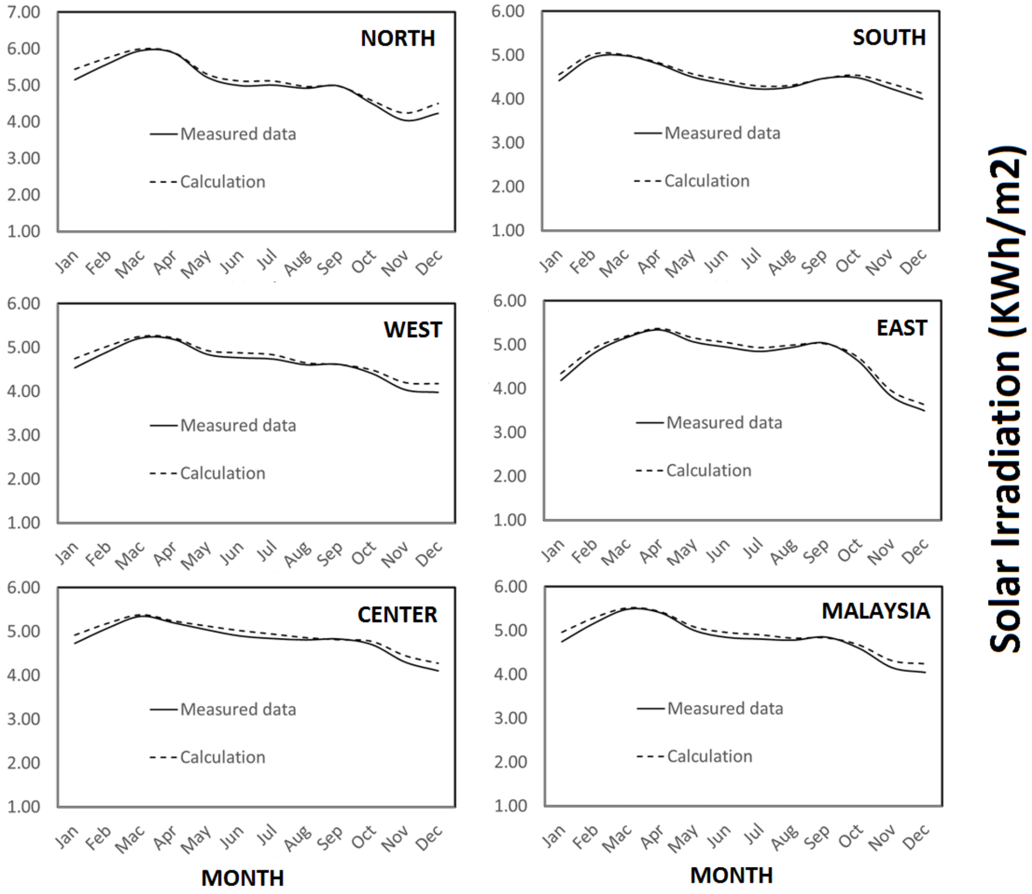

Fig. 7. Comparison of measured data and calculated results of Louche model for five stations in Peninsular Malaysia.

the experimental-mathematical model with isotropic diffuse radiation models is more accurate than the combination with anisotropic models. In the section, fifteen decomposition models were investigates using the experimental-mathematical method utilizing measured experimental data and average of clearness index in order to determine the appropriate model to calculate diffuse solar radiation on a horizontal surface with respect to climate of Peninsular Malaysia. The extensive calculations carried out in this section revealed that Louche model is more accurate for the estimation of diffuse radiation in the tropical climate. Finally, this model accuracy was investigated for 5-states with various geographical locations in Peninsular Malaysia. The results exhibited identical and comparable accuracy of simulations. In conclusion, the method and simulation approach reported here can be reliably used as a universal method for the estimation of diffuse solar radiation on horizontal and sloped surfaces.

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